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Tillering and Yield of Rice Cultivars under a Water Storage-Type Deep-Irrigation Regime

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Abstract : This study aimed to clarify the effects of water storage-type deep irrigation (WSDI) on the yields of various rice cultivars used in the Tohoku district of Japan. We compared a WSDI plot (DP) with a standard irrigation plot (SP) with regard to the growth, yield, and yield components of the rice cultivars grown in these plots during 4 years (2002–2005) in Sendai, Japan. In 2003, which had a cool summer, the yields in DP were considerably higher than those in SP, thus confirming that WSDI mitigated the cool summer-induced damage to rice. The yields in DP were not lower than those in SP during the other 3 years (normal climatic years), indicating that various cultivars could adapt to WSDI. Although high-yielding rice plants cultivated by well-experienced farmers under deep-water irrigation regimes have large panicles, the spikelet number per panicle and the yield in DP were not higher than those in SP. Based on the results of the comparison between the cultivation system of WSDI and that of high-yielding deep-water irrigation regimes practiced by such farmers, we speculated that to achieve a higher yield under WSDI, other cultivation techniques need to be incorporated into WSDI.

Key words : High-yielding cultivation technique, Mitigation of cool summer-induced damage, Rice cultivars, Tillering, Water management, Water storage-type deep irrigation, Yield and yield components.

For rice cultivation in Japan, deep-water irrigation regimes have been adopted by some farmers with the objective of mitigating damage induced by cool summer, controlling weeds, and achieving high yields (Goto, 1996; Ohe, 2005).

Recently, Goto et al. (1999, 2002) indicated another advantage of deep-water irrigation: the use of deep-water irrigation allows the storage of large amounts of water for agricultural, living, and industrial purposes in paddy fields (i.e., paddy fields can be used as reservoirs). They also designed the water storage-type deep-irrigation regime (WSDI; Fig. 1).

In the present standard cultivation of rice in Japan, irrigation measures such as midseason drainage and intermittent irrigation are used to control rice growth and achieve high yields. Midseason drainage involves the drying of soil from the last productive tiller emergence stage to the maximum tiller number stage; the soil is dried until the soil surface of the rice field cracks. This technique, in particular, is regarded as essential water management and is generally employed by Japanese farmers. In brief, midseason drainage is considered to help prevent root rot, reduce nonproductive tillers (which is aimed to suppress overluxuriant growth and improve light-interception characteristics of rice plants), and improve lodging tolerance (see Horie et al., 2005 for a review). On the other hand, WSDI involves neither intermittent irrigation nor midseason drainage to store as much water as possible. This raises concern that the yield under WSDI may be lower than that obtained under standard irrigation. Therefore, it is necessary to examine the yield under WSDI in comparison with that under standard irrigation in order to effectively implement WSDI. Previous studies confirmed that WSDI produced the same yield as standard irrigation,

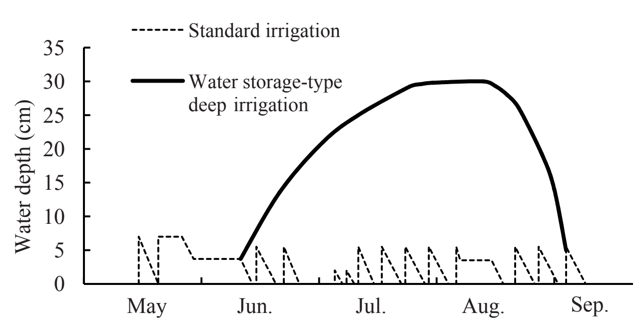

Fig. 1. Scheme of water-depth management in the two irrigation plots. Water management before the initiation of deep-water irrigation in the water storage-type deep irrigation was the same as that in the case of standard irrigation.

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Abbreviations : DP, WSDI plot ; SP, standard irrigation plot ; WSDI, water storage-type deep irrigation.

irrespective of the year of cultivation in Sasanishiki (the past leading cultivar in the Tohoku district, northeast Japan) (Goto et al., 1999, 2002; Sugai et al., 1999; Nakamura et al., 2003; Ishibashi et al., 2006) and Hitomebore (the most popular cultivar in the Tohoku district currently; Saito et al., unpublished data). In the Tohoku district, various cultivars other than Hitomebore, such as Akitakomachi and Haenuki, are widely planted. Thus, we need to examine their yields under WSDI.

As mentioned above, in Japan, deep-water irrigation has been used as a high-yielding cultivation technique. For example, with deep-water irrigation technique, one of well-experienced farmers achieves extremely high yields (of approximately 800 g m^{-2} of brown rice, equivalent to 1200 g m^{-2} of unhulled rice) of high-quality temperate *japonicas* in Japan, such as Koshihikari (Usui, 1999). His high-yielding rice plants was characterized to have a slightly lower panicle number per square meter but extremely higher spikelet number per panicle (approximately 130 spikelets as compared to the average of 70 spikelets in this region), which results in a high spikelet number per square meter (about 47000 spikelets as compared to 29000 spikelets for the average rice). Because the water management in WSDI was modeled on the deep-water irrigation regime of well-experienced farmers (Goto et al., 1999), the use of WSDI was expected to offer higher-yielding rice plants with large panicles.

In the present study, we examined the yield of various rice cultivars, which are used in the Tohoku district, under WSDI in comparison with that under standard irrigation and assessed the possibility of a higher yield with WSDI than with standard irrigation. We compared WSDI and standard irrigation with regard to the growth, yield, and yield components of popular rice cultivars cultivated on these plots in the Tohoku district during 2002–2005.

Materials and Methods

Field experiments were conducted on the experimental paddy field of Miyagi University (latitude 38º22´N, longitude 140º82´E), Sendai, Miyagi Prefecture, which is one of the prefectures in the Tohoku district, Japan.

We used 11 rice cultivars (*Oryza sativa* L.) that are popular in the Tohoku district. We selected (1) Akitakomachi and Haenuki, which are the leading cultivars, with the second and fourth largest planting area, respectively, in the Tohoku district; (2) Okiniiri, Koimusubi, Kokoromachi, Manamusume, Yamauta, and Yumemusubi, the cultivars recommended in Miyagi Prefecture; and (3) Takaneminori and Yumesansa, the cultivars recommended in Iwate Prefecture and Hatsuboshi recommended in Fukushima Prefecture, which are prefectures adjacent to Miyagi Prefecture.

The above-mentioned cultivars were planted under two different irrigation plots: a standard irrigation plot (SP) and a WSDI plot (DP) in 2002–2005.

The irrigation system was used to form main plots; these plots were divided into subplots, each of which contained one type of cultivar. In detail, the experimental paddy field containing light clay soil was partitioned equally using wooden boards and concrete U-shaped drains to form main plots. Each main plot was then divided equally into 8.5-m^2 sections to form subplots.

Seeds were sown in nursery boxes at a concentration of 100 g per box (30×60 cm) in early April. The seedlings were transplanted manually (3 seedlings per hill) in mid-May at a density of 22.2 hills m^{-2} (30×15 cm). A high-quality mixed fertilizer containing controlled-release N fertilizer (IB042; Mitsubishi Chemical Agri, Inc., Tokyo, Japan) was applied at a concentration of 7.5–10.5–9.0 g m^{-2} of $N\text{-}P_2O_5\text{-}K_2O$ before plowing.

Standard irrigation and WSDI were conducted as described by Goto et al. (1999, 2002). In SP, the water level was maintained at 5–7 cm from the time of transplanting until late May (rooting stage; Fig. 1). During the tillering period (from late May to mid-June), the water depth was controlled at 2–3 cm. The field was then irrigated intermittently from mid-June to late June and drained from late June to early July. After midseason drainage, intermittent irrigation was repeated. At the heading stage, the water depth was maintained at 2–5 cm for approximately 10 d.

In DP, water management was identical to that in SP until mid-June. Thereafter, the water level was raised gradually to approximately 25 cm until mid-July in accordance with the progress of the phyllochron (i.e., up to a level at which the lamina joints of the uppermost unfolding leaves of all cultivars were just below the water surface). This water level was maintained from mid-June to late August, after which the water level was lowered to approximately 5 cm (Fig. 1).

The maximum tiller number was obtained by periodically determining the tiller number in 0.3×0.75-m quadrants after transplanting until heading. Days to heading were determined as the duration from the time of sowing to the time at which 50% of the panicles showed heading. At maturity, 50 hills (10 hills [2 rows×5 hills]×5) were harvested from each subplot. The numbers of panicles and total spikelets were counted. The spikelet number per panicle was calculated by dividing the total spikelet number by the panicle number. The percentage of ripened grains was calculated as the number of brown rice grains with more than 1.8-mm grain thickness×100/total spikelet number. The yields were determined as the weight of brown rice containing 15.5% water, with grain thickness of more than 1.8 mm. The 1000-grain weight was calculated as the yields×1000/the number of brown rice grains with more than 1.8-mm grain thickness.

We regarded 3 years (2002, 2004, and 2005) as 3 replications and performed two-way ANOVA to evaluate the effects of cultivar, irrigation, and their interaction. The data of 2003 was excluded from the two-way ANOVA because of the cool summer in 2003. Moreover, the significance of the difference in the average values between SP and DP was examined using a *t* test for each cultivar. The difference of each trait between SP and DP in 2003 was examined from the average values over cultivars using a *t* test. These statistical analyses were conducted using JMP ver.5.1 (SAS Institute Inc. 2002, Cary, NC, USA).

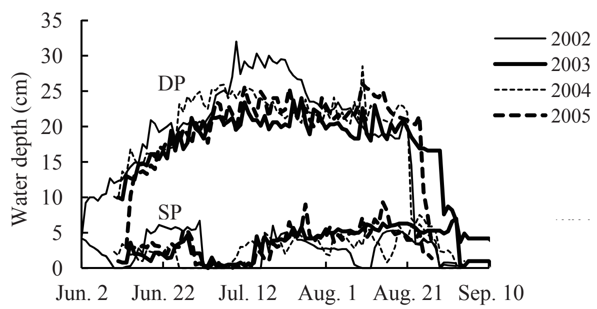

Fig. 2. Water-depth management during water storage-type deep irrigation. SP: standard irrigation plot, DP: water storage-type deep-irrigation plot.

Weather data were obtained from the data presented on the website of the Sendai District Meteorological Observatory, located near the experimental site.

Results

1. Water management and weather conditions

Fig. 2 shows the change in the water depth after the initiation of deep-water irrigation. In general, we could manage the water level as designed in Fig. 1.

In 2004, the climatic condition was favorable during the growing period (Table 1). The weather conditions were not extreme in 2002 and 2005. In 2003, the summer was cool; Tohoku district sometimes experiences a cool summer, which causes severe sterility and a great damage to rice yields. In 2003, the weather condition was usual in May and June, but the average mean temperature in July was the lowest in history and monthly duration of sunshine (hr) in July was 27% of that of an average year.

2. Effect of WSDI on the maximum tiller number, days to heading, yield, and yield components

The effect of irrigation on each trait was assessed by two-way ANOVA. The maximum tiller number and panicle number in DP were significantly lower ($p<0.001$ and $p<0.01$, respectively) than those in

Table 1. Monthly average of daily mean temperature and duration of sunshine during the growth period in Sendai, Japan.

	Mean temperature (°C)					Duration of sunshine (hr)				
Year	May	June	July	Aug.	Sept.	May	June	July	Aug.	Sept.
2002	14.6	17.9	23.3	24.4	20.5	184	160	126	147	141
2003	14.6	19.1	18.4	22.2	20.2	206	121	34	77	104
2004	15.3	19.9	23.8	23.6	21.2	132	189	196	186	109
2005	13.4	19.5	21.4	25.0	21.5	178	138	95	135	150
Average values[1)]	14.9	18.3	22.1	24.1	20.4	199	128	128	155	120

[1)] The averages of the data of 30 years (1971–2000).

Table 2. Mean squares of two-way ANOVA for the maximum tiller number, days to heading, yield, and yield components of rice.

Source of variation	d.f.	Maximum tiller number (m^{-2})	Days to heading	Yield ($g\ m^{-2}$)	Panicle number (m^{-2})	Spikelet number per panicle	Spikelet number ($10^3\ m^{-2}$)	Percentage of ripened grains (%)	1000-grain weight (g)
Replication	2	83642 ***	336 ***	11798 **	21861 ***	915 ***	154 ***	112 ***	42.2 ***
Treatment	21	31696 ***	58 ***	3275 *	4227 **	145 ***	27 ***	98 ***	3.2 ***
Cultivar	10	12499 *	121 ***	5863 **	5685 **	267 ***	47 ***	185 ***	6.3 ***
Irrigation	1	522412 ***	2.2	618	16492 **	134	24	124 **	0.9
Cult.×Irrig.	10	1822	0.4	953	1542	24	6.6	8.1	0.2
Error	42	6052	0.8	1790	1603	42	7.9	13	0.5

Two-way ANOVA was performed using the data of 2002, 2004, and 2005.
d.f.: Degree of freedom.
*, **, and ***: Significant at 0.05, 0.01, and 0.001 probability levels, respectively.

Table 3. Effect of water storage-type deep irrigation on the maximum tiller number, days to heading, yield, and yield components in 11 rice cultivars.

	Maximum tiller number (m^{-2})		Days to heading		Yield ($g\ m^{-2}$)		Panicle number (m^{-2})		Spikelet number per panicle		Spikelet number ($10^3\ m^{-2}$)		Percentage of ripened grains (%)		1000-grain weight (g)	
	SP	DP	SP	DP	SP	DP	SP	DP	SP	DP	SP	DP	SP	DP	SP	DP
Yama-uta	649	489*	115	114	598	631	406	389	88.7	91.4	36.1	35.7	79.0	83.9	21.4	21.5
Takaneminori	583	423	115	115	607	626	424	369*	76.2	85.9	31.9	31.0	86.4	88.6	22.2	23.0*
Kokoromachi	643	528	116	116	624	625	443	425	74.5	76.2	33.0	32.0	89.0	90.5	21.2	21.6
Yumesansa	690	513**	120	120	599	629	460	430	67.1	71.4	31.0	30.5	85.2	89.7	23.0	23.2
Akitakomachi	773	602*	122	121	585	578	505	443	83.8	81.8	41.6	35.7	66.1	74.3	21.3	21.9*
Haenuki	709	526*	122	122	595	588	480	440	68.3	74.4	32.8	32.8	82.3	83.2	22.2	21.6
Hatsuboshi	674	466**	122	121	645	623	508	423	69.4	75.1	34.8	31.8	82.8	85.4	22.4	23.1
Manamusume	684	453*	123	123	582	637	381	408	74.8	76.2	28.5	31.0	86.1	87.2	23.9	23.7
Okini-iri	635	498	123	122	694	700	413	406	86.7	87.5	35.5	35.3	83.3	83.7	23.6	23.8
Koimusubi	670	472	127	128	605	585	462	404**	73.1	78.8	33.7	31.8	80.5	81.5	22.4	22.6*
Yumemusubi	660	442*	128	128	653	633	395	393	76.6	72.0	30.2	28.2	88.8	91.4	24.4	24.5
Average	670	492	121	121	617	623	443	412	76.3	79.2	33.6	32.3	82.7	85.4	22.5	22.8

The averages of the data of 2002, 2004, and 2005 are shown for each trait.
SP: standard irrigation plot, DP: water storage-type deep-irrigation plot.
Days to heading were determined as the duration from the time of sowing to the day when 50% of the panicles showed heading.
Cultivars are arranged according to their days to heading.
* and **: Significant at 0.05 and 0.01 level of probability, respectively (*t* test).

SP, and the percentage of ripened grains in DP was significantly higher than that in SP ($p<0.01$; Tables 2, 3). In particular, the maximum tiller number was considerably affected by the type of irrigation. Days to heading, yield, spikelet number per panicle, spikelet number per square meter, and 1000-grain weight were not significantly different between DP and SP in two-way ANOVA. Significant cultivar effects were observed for all traits (Table 2). The cultivar×irrigation interactions were not significant in any trait (Table 2). Furthermore, comparison of the yields between SP and DP for each cultivar by *t* tests revealed no significant differences in any cultivar (Table 3).

The yields averaged over cultivars in 2003 were substantially lower than the average yields of the other years (34% and 55% of the average yield in SP and DP, respectively) (Tables 3, 4). The yield averaged over cultivars in DP in 2003 was 64% higher than that in SP (Table 4). In comparison of each yield component averaged over cultivars between SP and DP, it was notable that the percentage of ripened grains in DP was considerably higher than that in SP. The differences in yields and percentages of ripened grains between SP and DP tended to be larger in cultivars such as Yama-uta, Kokoromachi and Takaneminori, that headed at almost the same period and had low percentages of ripened grains in SP.

Discussion

In this study, the yields of popular rice cultivars under WSDI were equivalent to those under standard irrigation during normal climatic years (2002, 2004, and 2005). This suggests that, if required, we can store large amounts of water in paddy fields during the growing period without decreasing the yields of various rice cultivars. Moreover, it was confirmed that WSDI was highly effective in mitigating the damage induced by a cool summer.

The cool summer damage to yields and percentages of ripened grains was largely mitigated by WSDI in severely cool summer-damaged cultivars such as Yama-uta, Kokoromachi and Takaneminori. This was explained by the water temperature in DP and the air temperature during their meiosis stages. Their meiosis stage was estimated to be 106–114 days after sowing (8–14 days before heading) as was inferred by Shimizu and Ito (2004). The low percentages of ripened grains in these cultivars in SP might be caused by the low air temperatures at their meiosis stages (daily minimum air temperature was around 16.1°C during this period) (Fig.3). On the other hand, the daily minimum water temperature in DP at their meiosis stages was around 18.4°C, which was much higher than the daily minimum air temperature.

Another objective of this study was to assess whether the yield can be increased by the use of WSDI, compared with the yield under standard irrigation. By using the deep-water irrigation regimes, well-experienced farmers produce high-yielding rice plants with large panicles. In this study, however, the spikelet

Table 4. Effect of water storage-type deep irrigation on the maximum tiller number, days to heading, yield, and yield components of rice in 2003.

	Maximum tiller number (m^{-2})		Days to heading		Yield ($g\ m^{-2}$)		Panicle number (m^{-2})		Spikelet number per panicle		Spikelet number ($10^3\ m^{-2}$)		Percentage of ripened grains (%)		1000-grain weight (g)	
	SP	DP	SP	DP	SP	DP	SP	DP	SP	DP	SP	DP	SP	DP	SP	DP
Yama-uta	500	376	120	120	126	397	322	338	90.5	97.4	29.0	32.9	23.2	63.8	18.8	18.9
Takaneminori	446	366	122	120	17	141	326	291	77.5	97.5	24.9	27.9	3.9	27.2	17.7	18.5
Kokoromachi	642	337	122	122	28	293	413	302	76.5	77.3	31.4	23.4	5.2	65.8	17.5	19.1
Yumesansa	516	379	129	130	115	257	356	329	68.8	83.5	24.4	27.4	23.4	46.3	20.1	20.2
Akitakomachi	768	497	135	136	170	309	390	419	95.5	80.9	36.9	33.9	24.7	47.1	18.3	19.3
Haenuki	583	396	132	136	305	382	389	307	65.9	95.0	25.6	28.9	59.6	69.4	20.0	19.1
Hatsuboshi	561	385	131	134	186	364	410	326	61.2	70.0	25.1	22.8	36.7	73.1	20.2	21.9
Manamusume	548	457	132	131	223	317	354	324	68.3	76.5	23.9	24.8	43.9	60.1	21.2	21.3
Okini-iri	498	363	130	134	301	418	304	319	87.0	85.1	25.8	27.2	53.1	69.2	22.0	22.3
Koimusubi	722	424	138	140	498	499	436	365	69.7	74.0	30.3	27.0	77.2	85.9	21.3	21.5
Yumemusubi	649	357	140	141	351	419	363	317	78.3	70.5	28.4	22.3	59.9	81.4	20.6	23.1
Average	585	394***	130	131	211	345***	369	331*	76.3	82.5	27.8	27.1	37.3	62.7***	19.8	20.5*

SP: standard irrigation plot, DP: water storage-type deep-irrigation plot.
Days to heading were determined as the duration from the time of sowing to the day when 50% of the panicles showed heading.
Cultivars are arranged in the same order as in Table 3.
* and ***: Significant at 0.05 and 0.001 level of probability, respectively (*t* test).

number per panicle in DP was not significantly higher than that in SP. Therefore, we could not achieve a higher spikelet number per square meter and a higher yield by using WSDI.

In fact, some well-experienced farmers incorporate characteristic cultivation techniques into their deep-water irrigation regimes. For example, one of them applies less basal dressing and more topdressing (40 and 30 d before heading), adopt a sparse planting density (50%–70% density of standard cultivation) and use vigorous mature seedlings grown in pot culture nursery boxes in his deep-water irrigation regime (Usui, 1999). Thus, the extremely high spikelet number per panicle, which is a major factor for high yield in the deep-water irrigation regime of well-experienced farmers, might be achieved by incorporating various cultivation techniques into deep-water irrigation regimes. With the exception of WSDI, all cultivation techniques applied in this study were the same as those used in standard cultivation. Therefore, to develop WSDI as a high-yielding cultivation technique, the combined effect of WSDI and other cultivation techniques on yield and yield components should be analyzed.

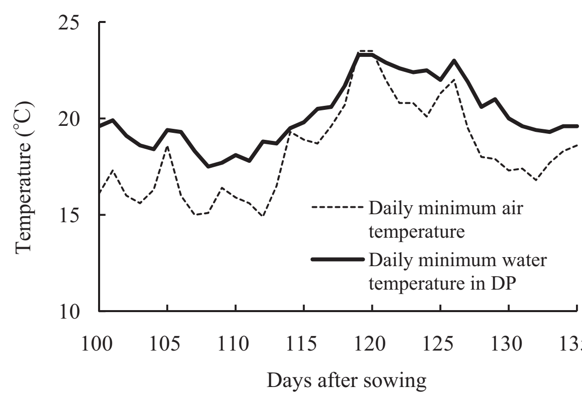

Fig. 3. Temperatures during the estimated meiosis stage in 2003, Sendai, Japan.

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