Agricultural Journal 2 (3): 375-383, 2007

Growth of Rice Plants (*Oryza sativa* L.) Under Non-Flooded Water-Saving Paddy Fields

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Abstract: The effects of water saving non-flooded irrigation management on growth and yield components of a lowland *japonica* rice cultivar Nipponbare was examined in a well-drained paddy field with low ground water table for 4 years from 2001 to 2004 in Nishitokyo, Japan. The significant reduction in tiller number and aboveground biomass after about 1 month of non-flooded water management (e.g., 7th August in 2003) was the primary cause for yield reduction. Infertile tiller was fewer but spikelet development was reduced to a small extent under non-flooded conditions, with greater numbers of spikelet abortion. All these subsequently reduced both sink (e.g., panicle number and grain number per area) and source (e.g., LAI) capacities. Non-flooded water management, intended to maintain near saturated soil conditions, recorded slightly lower soil volumetric water content and soil water potentialand also lower leaf and plant water content and tendency of delayed recovery of leaf water potential during evening. Both root length density (at maturity) and bleeding sap rate (at heading) were reduced under non-flooded conditions, which may be due to the reduced shoot growth and hence assimilate supply to rootsand increased soil strength. Transpiration was reduced and leaf temperature increased in non-flooded conditions. Plant nitrogen content was lower in non-flooded conditions. The 1000-grain weight to a small extent also reduced under non-flooded conditions (except for 2001 when ripened grain percentage was extremely low), which was associated with its earlier leaf senescence after flowering. Ripened grain percentage was not reduced in 3 years except for 2001, because sink size was not very large and there was no severe water deficit after heading in non-flooded conditions. Our study indicated that water supply from transplanting to panicle initiation should not be extremely omitted in well-drained paddies to achieve sufficient vegetative growth for minimizing yield reduction under water-saving non-flooded conditions.

Key words: Non-flooded, *Oryza sativa*, water-saving, plants, rice, growth

INTRODUCTION

Availability of fresh water resources for food production has become of great concern in the global community from the end of 1990's (Baker *et al*., 1999). Both the available quantity of fresh water resources in future including its distribution among the regions and its utilization for food production have been discussed (Bouman, 2007; Bouman *et al*., 2007; Dawe, 2005; Lafitte *et al*., 2006; Passioura, 2006; Rijsberman 2006; Tuong *et al*., 2005; Turner, 2006). In Japan, while the former aspect has been discussed among scientists and government (JIID, 2003; MILT 2006) the latter aspect of agricultural water use is of much smaller concerns compared with the global communities.

Without doubt, paddy rice production is by far the greatest fresh water using system in Japan, with its proportion 90% of agricultural water, which is about 70% of total available fresh water resources of the country (Tsuboi, 2003). Compared with arid or semi-arid regions such as north Africa, western Asia and northern China, where water scarcity has become already substantial problem and alternative social and technological innovation for agricultural water use has been initiated (Dawe, 2005; Rijsberman, 2006; Wang *et al*., 2002) the average rainfall in Japan is much higher (ca. 1700 mm) and the situations of water balance in Japan is often optimistically interpreted that water-saving is not required or relevant in Japanese farming. But it is recognized that the amount of annual rainfall in Japan is slightly declining over the last 100 years and that its year-to-year variability has increased recently (MILT, 2006). Some regions in Japan, such as Tone river basin, Setouchi regions, Tsukushi river basin, are apt to fresh water shortage more

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than 8 years over the last 20 years (Kamoshita, 2003; MILT, 2006). In Setouchi region, severe water shortage occurred in 1994 (Nagamachi, 2003) and traditional water saving irrigation methods were used to alleviate drought damages to paddy rice production. Paddy fields near urban areas have to share fresh water resources with city residents or industrial usesand more likely to suffer water shortages.

The perspective of Japanese inefficient water use will be emphasized if considering the country's extremely low food sufficiency rate among the developed countries (i.e., 40% on the original calorie basis), which means importation of virtual water (estimated amounts of allocation of water associated with food import/export) (Allan, 1998) from abroad without utilizing domestic fresh water resources. Improvement of efficient water use for food production and water-saving agriculture need to be developed within the country; if intending to increase food sufficiency rate substantially, as advocated by Japanese government, at least several proportion of the irrigation water for paddy rice production need to be allocated for production of other crops.

Water-saving rice production in upland fields, similar to aerobic rice as advocated by International Rice Research Institute (Tuong *et al*., 2005) has been studied at field level in Nishitokyo in Japan by Kato *et al*. (2006ab, 2007ab). They provided some evidences of comparable (high) yield level of rice production in temperate upland fields with much less water input compared with flooded lowland fields, recording much higher values of water productivity (0.59 vs 0.18 kg m^{-3}). Water-saving rice production system, however, is very little reported in lowland system in Japan (Kamoshita, 2003) and only a few studies that had made its technical and biological assessment (Lu *et al*., 2000; Kamoshita *et al*., 2007). In general, unlike upland system, saving of irrigation water usually cause reduction in yield in lowland fields, in spite of their higher soil moisture content than upland fields. One would assume that more sophisticated water control, more appropriate agronomic management and choice of more adapted cultivars might be required. So that these innovations be successfully attained, crop physiological reasons for yield reduction in water-saving lowland system should be studied first of all. In this study, we aimed to clarify the reasons for yield reduction in water-saving non-flooded lowland field of low groundwater table. The information would be helpful to design water management or genetic improvement under water-saving paddy culture.

MATERIALS AND METHODS

The experiments were conducted for 4 years from May 2001 to October 2004 in Field Production Science Center, Nishitokyo, Japan (lat. 35°43 N., Long. 139°32 E, Alt. 67 m). The area is located in Northern Tama (Kamoshita, 2007), also known as Musashino Tablel and with its soil from surface to about 30 cm depth Haplic Andosols (FAO/Unesco, 1990), Loamy soil (L), with pH 6.7, made of volcanic ash with well-developed hume layersand the soils below 30 cm depth are called Tachikawa loam, a Clay Loam soil made of volcanic ash (CL).

Experimental design: The details of sequences of experiments including post-rice land management were already described by Kamoshita *et al*. (2007). In brief, one paddy field with 27 m×36 m was divided into half by the central bunds of 20 cm height and 2 m width; one for conventional flooded trialand the other for water-saving non-flooded trial. Rice was grown during summer with flooded irrigation with the presence of standing water and with non-flooded irrigation for the sake of minimizing water supply, in flooded and non-flooded trials, respectively.

Cultural details: Seeds of a lowland *japonica* rice cultivar Nipponbare were pre-germinated and raised in nursery and 21 days old seedlings were transplanted as 1 plant per hill from 2001 to 2003 and 2 plants per hill in 2004, with the hill density 0.3×0.15 m (22.2 hills m^{-2}). Transplanting time of rice was slightly earlier in 2002 (31st May) than in 2001 (15th June), 2003 (13th June)and 2004 (25th June). All the fertilizers were applied 1 week prior to transplanting with 3 g m^{-2} of nitrogen, 1.9 g m^{-2} of phosphorus and 3.3 g m^{-2} of potassium (as ammonium sulfate, di-ammonium phosphate and potassium chloride) and twice puddled.

Flooded irrigation was similarly applied in both trials for 10 days after transplanting to facilitate rooting and establishment. After that, irrigation supply was reduced

Table 1: Soil penetrometer resistance (MPa) at 10, 20, 30, 40 and 50 cm depthand their maximum resistance and its depth in Flooded (F) and Non-Flooded (NF) trials on 11 October 2002 (n = 8)

	Penetration resistion (M Pa)					Maximum values resistance (M Pa)	
	10 cm	20 cm	30 cm	40 cm	50 cm		Depth (cm)
F	0.3	1.3	1.3	0.7	0.9	3.0	24.5
NF	0.8	2.5	1.7	1.0	0.8	3.8	22.9
t-test	**	ns	ns	**	ns	ns	ns

s; Not significant at p = 0.10, **; significant at p = 0.01

in water-saving trial and standing water never present except at times of heavy rain and occasional irrigation. The extent of water-saving was different between years, with the year 2002 receiving relatively large amounts of irrigation water (3468 mm), year 2001 least amounts (504 mm) and years 2003 (629 mm) and 2004 (903 mm) in between (Kamoshita *et al*., 2007). In water-saving trial, weeds were controlled by application of herbicides at one time and by hand weeding at one time. Nets of 2 cm mesh were used to protect from bird damage after heading. Rice plants were harvested in early to middle of October.

Measurements: Mean daily air temperatures, daily solar radiationand rainfall during rice growing periods were measured by the weather station inside Field Production Science Center (Kamoshita *et al*., 2007). Rainfall was less in 2001 (347 mm) but more than 800 mm in the other 3 years and mean air temperature and daily solar radiation was lower in 2003 (23.1°C, 10.1 MJ m^{-2}) compared with the other years.

In 2003, soil volumetric water content from surface to 10 cm depth was measured at randomly chosen 5 to 18 spots in each trial on 12 July, 4 August, 5 and 12th September by time domain reflectometry (Hydrosense12, Meiwashoji, Co., Japan). In 2004, soil water potential at 10 cm depth was recorded by tensiometers (DIK-3054, Daiki Rika Kogyo, Japan) everyday during plant growth through a data logger (DIK-9411, Daiki Rika Kogyo, Japan). In 2002, the profiles of penetrometer resistance were measured at 8 spots in each trial from surface to 50 cm depth by a cone penetrometer (DIK-5521, Daiki Rika Kogyo, Japan). Plant Water Content (PWC) was measured for 10 plants at randomly chosen 18 spots (in total 180 plants) in each trial on 7 August and 5th September, according to the following equation;

$$\text{PWC (\%)} = (\text{FW} - \text{DW}) / \text{FW} * 100,$$

Where FW and DW were fresh and dry weights of aboveground of rice plants. In the similar manner, Leaf Water Content (LWC) was measured on fresh weight basis for 3 plants in each trial on 14th August in 2003;

$$\text{LWC (\%)} = (\text{FLW} - \text{DLW}) / \text{FLW} * 100,$$

where FLW and DLW were fresh and dry weights of leaf blade of rice plants. Water potential of 3 to 4 latest fully expanded leaves were measured for each trial by a pressure chamber (DIK-7002, Daiki Rika Kogyo, Japan) at 3 to 4 h intervals from 3:30 till 19:30 on 15th August in 2002 (about 2 weeks prior to heading). Leaf temperature, its differences from air temperature, stomatal resistance and transpiration rate were measured for 4 flag leaves for each trial by a steady-state porometer (LI-1600, LI-COR, USA) at noon on 25th August in 2003 (about a week prior to heading).

Heading dates of rice were recorded for each trial. Number of tillers per plant and SPAD readings were measured with 90 plants per trial several times during rice plant growth in 2003. At heading in 2002, plant height and panicle length were measured for 8 to 11 plants at 18 spots for each trialand numbers of primary and secondary rachis branches, total and aborted spikelet numbers were counted for 3rd medium size panicles at 18 spots for each trial. On 3rd October (around maturity) in 2002, roots were sampled by a cylinder monolith method (Morita *et al*., 1995) of 15 cm diameter from surface to 30 cm soil depth below 3 hills and 3 inter-row spaces. The sampled roots were carefully washed from soils and divided by 0-5, 5-10, 10-20 and 20-30 cm layers. Root length density of each soil depth and their totals, total root mass, rooting depth index both by mass and length basis, specific root length were determined. On 11th September in 2003, about a week after heading, bleeding sap rate (Morita and Abe 2002; Sakaigaichi *et al*., 2007) was measured for 6 hills with average panicle number in each trial, together with SPAD values of flag and 3rd leaves. Bleeding sap rate was presented both per hill and per panicle basis.

In 2003, above-ground biomass of rice was determined on 7th August from 18 spots of 0.75 m × 0.6 m and on 5th September from 18 spots of 0.6 m × 0.6 m. Leaf area index on 5th September was calculated by multiplying the above-ground biomass by ratio of leaf to above-ground dry weights and specific leaf area (leaf area divided by leaf dry weight), which were determined from 6 plants for each trial. In all the 4 years, above-ground biomass was harvested at maturity from 18 spots of 0.6 m × 0.9 m in each trial. All the samples were dried at 80°C for more than 3 daysand grain yield, yield components and harvest index were determined, with grain yield and 1000-grain weight adjusted to 14% of moisture and with ripened grain percentage determined as the ratio of numbers of fertile grains (those floating in tap water of specific gravity of 1.0) to total grains. Nitrogen concentration per dry matter was measured at maturity in 2002 and 2004 by NC analyzer (Sumigraph NC-90A, SCAS, Oosaka, Japan).

Statistics: The differences between flooded and non-flooded trials were examined by t-test.

RESULTS AND DISCUSSION

Soil moisture and strength: Soil volumetric water content measured on 4 occasions from 12 July to 12th September in 2003, was consistently lower in water-saving non-flooded trial 0 (68-75%) compared with conventional flooded trial (74-78%) (p = 0.05 or 0.01). Average soil water potential around 10 cm depth from soil surface were 9 and 1 kPa, respectively from transplanting in June till early grain filling in September in 2004, with the lowest value -86 kPa in non-flooded trial (data not shown). Soil penetrometer resistance measured from 10 to 40 cm depth around harvest time in 2002 were higher in non-flooded trial (Table 1).

Yield formation: Grain yield of rice in non-flooded trial was always smaller than flooded trial, with the average value of the former about 63% of the latter (Table 2). The reduction rate (yield differences between the 2 trials divided by yield in flooded trial) was higher in 2001 (53%) and smaller in 2002 (21%) and in between in 2003 and 2004, which generally followed the differences in the amounts of water supply (irrigation plus rainfall) among the 4 years. The analysis of yield components showed differences in panicle number, grain number and ripened grain number per area (in every year), grain number per panicle (in 2003 and 2004)and ripened grain percentage (only in 2001) (Table 3). One thousand grain weight was generally higher in flooded trial than non-flooded trial except for 2001.

It depends on the environmental and managemental practices which yield components are more affected by the levels of water supply. Scientific publications often emphasized large reduction in spikelet number per panicle and ripened grain percentage as a result from water stress, because of their designs to impose stress during reproductive stage while providing full water and nutrient resources during vegetative stage (Boonjung and Fukai, 1996; Kato *et al.*, 2006ab, 2007c; Liu *et al.*, 2006). More balanced assessment is needed on water-saving rice production system. Our study showed little reduction in ripened grain percentage in general, because sink size was not very large and there was no severe water stress after heading (end of August to early September in our experiments) in Japanese climate conditions.

Correlation analysis between the daily amount of water supply for each growth duration and yield components showed that significant positive correlation between grain yield in non-flooded trial and daily water supply from transplanting to panicle initiation, as well as daily water supply for 15 days around heading time (p = 0.05) (Table 3). The daily water supply during these 2 periods also correlated with the total grain number per area and aboveground biomass. The relationship between the amount of daily water supply from transplanting to panicle initiation and the relative value of each yield component (non-flooded trial divided by flooded trial) was shown in Fig. 1, showing the positive association with the relative values of aboveground biomass, panicle number, grain number per area and grain yield.

Plant growth responses: In 2003, tiller number and aboveground biomass became smaller in non-flooded trial than flooded trial on 7th August (about 40 days after transplanting and 1 month after non-flooded water management) (Table 4), which subsequently reduced both source and sink capacity. The levels of tiller number, LAIand aboveground biomass in non-flooded trial were about 70% of flooded trial on 5th September (heading time) (Table 4). Because of this inferior vegetative growth in non-flooded conditions final panicle number at maturity

Table 2: Grain yield and yield components in conventional Flooded (F) and water-saving Non-Flooded (NF) cultures from 2001-2004

Year	Water management	Grain yield (gm^{-2})	Panicle number (gm^{-2})	Grain number (panicle $^{-1}$)	Grain number (m^{-2})	Pipened grain Per (%)	Pepened grain number (m^{-2})	1000-grain weight (g)
2001	F	394	199	90.2	18101	83.4	15182	24.9
	NF	187*	130*	82.5	10770+	69.4+	7518+	25.5+
2002	F	535	234	96.3	22487	87.7	19652	27.2
	NF	424+	210*	86.5	18190^a	90.2	16385+	25.9
2003	F	392	187	89.0	16664	87.9	14621	26.8
	NF	239*	145*	71.4*	10371*	89.1	9242*	25.9**
2004	F	455	249	78.2	19464	93.3	18155	25.0
	NF	293+	203	64.0+	12998+	92.3	12000+	24.5+

+, *, **; Significant differences between flooded and non-flooded cultures with in a year at p = 0.10, 0.05 and 0.01, respectively a; different at p = 0.11

Table 3: Correlation coefficients between yield components and daily water use in each growth period in non-flooded trials from 2001 to 2004 (n = 4)

Period	Grain yield	Panicle number	Grain number per panicle	Grain number per aera	Ripened grain percentage	Ripened grain number	1000-grain weught	Above ground biomass	Hravest index
TP-PI	0.981*	0.823	0.460	0.995*	0.489	0.974*	0.195	0.996**	0.569
PI±15	0.872	0.546	0.566	0.837	0.458	0.830	0.607	0.866	0.640
PI-H	0.883	0.562	0.658	0.891	0.355	0.846	0.562	0.897	0.529
H-15	0.870	0.581	0.729	0.932	0.227	0.843	0.458	0.909	0.377
H±15	0.962*	0.731	0.535	0.965*	0.468	0.942	0.364	0.973*	0.591
H-M	0.405	0.771	-0.692	0.290	0.749	0.467	-0.756	0.350	0.552

TP-P I; From transplanting to panicle initiation, PI±15;15 days around panicle, P-H; from panicle inition to heading, H-15;15 days before heading, H±15;15 days around heading, H- M; from heading to maurity

Table 4: Aboveground biomass (g m^{-2}), Leaf Area Index (LAI), tiller number (m^{-2}) and SPAD values in Flooded (F) and Non-flooded (NF) trials on several occasions during growing season in 2003

	Above ground biomass (gm^{-2})		LAI	Tiller number (m^{-2})		Infertile tiller[a] (m^{-2})		SPAD value	
	7-Aug	5-Sep	5-Sep	7-Aug	5-Sep		12-Jul	12-Sep	25-Sep
F	131	486	1.95	229	193	41	44	41.7	35.2
NF	116	333	1.33	171	140	27	44.6	35	26.9
t-test	**	**	**	**	**	-	ns	**	**

ns; not significant at p = 0.10, **; significant at p = 0.01. A; calulated as the diffenences between tiller number on 7th August and panicle number at maturity

Table 5: Leaf temperature, its reduction from cuvette air temperature, stomatal resistance and transpiration rate measured on flag leaf at noon on 25th August (1 week prior to heading) in Flooded (F) and Non-Flooded (NF) trials in 2003. (n = 4)

	Leaf temperature (°C)	Reduction of leaf temperature (°C)	Stomatal resistance (s cm^{-1})	Transpiration rate (μg cm^{-2} S^{-1})
F	34.5±0.5	0.50±053	0.300±0061	69.9±8.1
NF	35.4±0.6	0.03±0.50	0.395±0.097	61.3±7.5
t-test	*	+	+	*

+, *; significant at p = 0.10, 0.05, respectively

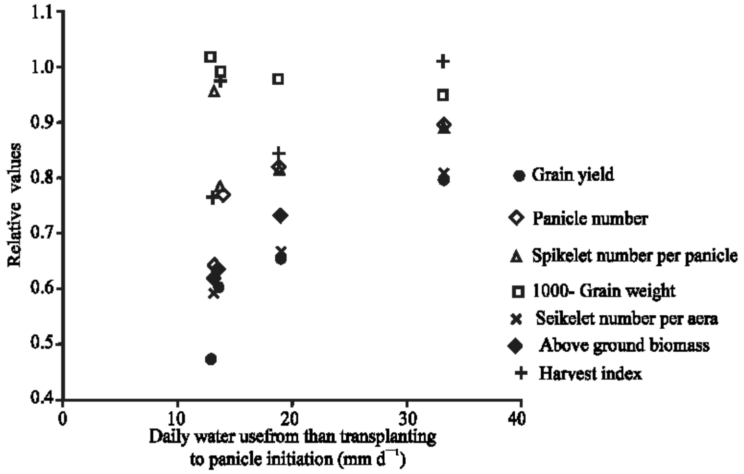

Fig. 1: Relationship between daily water use from transplanting to panicle initiation and relative values of yield components in water-saving trials to conventional trials from 2001 to 2004

was smaller in non-flooded trial although infertile tiller number, defined as the difference of tiller number on 7th August was fewer in non-flooded conditions. SPAD values were smaller in non-flooded trial than flooded trial on 1 week after heading (12th September) and during grain filling (25th September), which suggested earlier senescence and possibly declining assimilate supply to grain to reduce the 1000 grain weight in non-flooded trial. Kobata and Takami (1983) also showed smaller 1000-grain weight of desiccated rice crops during the whole grain filling period due to reduced assimilate supplyand (Lu *et al*., 2000) showed earlier leaf senescence during ripening period in non-flooded treatments with greater water-saving (more apt to temporal dryness in paddy soils).

In 2002, plant height at heading was reduced in non-flooded trial (61 cm) than flooded trial (68 cm) (p = 0.05). Panicle length and numbers of second rachis branch tended to be slightly smaller in non-flooded trial (18.0 cm, 14 branches) than flooded trial (18.7 cm, 16 branches) (although not significant at p = 0.10). Total spikelet number per panicle tended to be smaller (92 vs 103) (p = 0.10) and aborted spikelet number was large in non-flooded (7.6) than flooded trials (4.9) (p = 0.01). It is known that rice is susceptible to water deficit during reproductive stage (Kato *et al*., 2006b, 2007c). Kato *et al*. (2007c) showed that cultivars with greater water uptake through deeper root system can maintain higher leaf water potential during drought and abort smaller spikelet numbers.

Plant water content (fresh weight basis) on 7th August (73.6 vs 75.2%) (p = 0.01) and 5th September (61.6 vs 64.6%) (p = 0.01) in 2003 and leaf water content on 14th August in 2004 (65.8 vs 67.9%) (p = 0.05) were lower in non-flooded than flooded trial. At noon on 25th August in 2003 (a week prior to heading), the reduction of the leaf temperature from the air temperature was smallerand consequently with the higher leaf temperature by 0.9 degrees in non-flooded trial than flooded trial (Table 5). Stomatal resistance tended to be higher and transpiration rate from the unit leaf area was lower by 12%

Table 6: Diurnal changes in leaf water potential (MPa) measured on 15th August in Flooded (F) and Non-Flooded (NF) trials in 2002 (N = 3 or 4)

	Leaf water potential (M Pa)				
Time	3:30	9:30	12:00	15:00	19:30
F	-0.08±0.02	-1.62±0.12	-1.88±0.09	-1.51±0.41	-0.33±0.13
NF	-0.09±0.03	-1.73±0.08	-1.79±0.06	-1.88±0.06	-0.64±0.09
t-test	ns	ns	ns	ns	ns

Table 7: Root parameters measured on 3rd October in Flooded (F) and Non-Flooded (NF) trials in 2002 (N = 3). Roots were sampled both on hill and between hill space by cylinder monolith method

	Panicle (hill^{-1})	Root length (km m^{-2})	Root mass (g m^{-2})	Rooting depth index (cm)	Rooting depth index^{m} (cm)	Specific root lengthg (m g^{-1})
F	10.3±0.6	11.3±0.6	152.7±6.3	7.8±0.2	7.3±4.0	74.0
NF	8.7±0.3	7.3±0.3	83.7±2.2	7.2±0.3	6.6±0.4	87.2
t-test	+	**	**	ns	ns	-

ns; not significant, +, **; significant at p = 0.10, 0.01, respectively

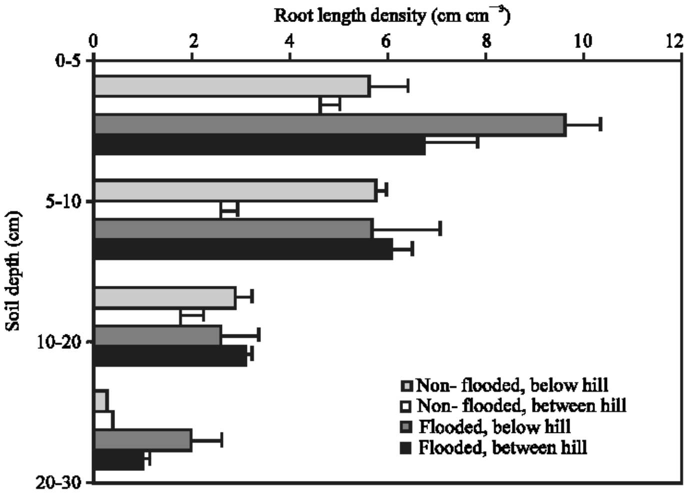

Fig. 2: Root length density from 0 to 30 cm depth between flooded and non-flooded trials. Roots were sampled both below hill and in-between hills

in non-flooded than flooded trials, suggesting that photosynthetic capacity may be also smaller in non-flooded trial (Lu *et al.*, 2000). There was no significant differences in leaf water potential measured predawn (3:30) till after sunset (19:30) on 15th August in 2002, although the values at 15:00 and 19:30 indicated slower recovery of leaf water potential in non-flooded trial compared with flooded trial (Table 6). Non-flooded water management, in spite that it aims soil saturation, is more apt to short term declines of water content and water potential in summer seasons when evapotransiration becomes high. Rice xylem cavitation is often observed in rice (Stiller *et al.*, 2003) which may have reduced plant water conductivity to a greater extent in non-flooded conditions than flooded conditions.

There were no differences in tissue N concentrations either in grain (1.2%) or straw (0.54%) at maturity in 2002 and 2004 between the 2 trials, but grain (3.9 vs 5.2 g m^{-2}) and total (6.1 vs 7.8 g m^{-2}) N content at maturity were significantly smaller in non-flooded trial. N harvest index was lower in non-flooded trial than flooded trial only in 2004 (0.55 vs 0.63). N supply through flooded water should have been reduced in non-flooded conditions.

Both root length and root mass at maturity in 2002 were smaller in non-flooded trial than flooded trial while rooting depth index did not change (Table 7). In every soil depth from 0 to 30 cm, root length density both below hill and in-between hills were smaller in non-flooded trial than flooded trial (Fig. 2). The reduced shoot growth and assimilate supply to rootsand increased soil strength (Table 1), may have limited root system development. During grain filling in 2003, in spite that the soils were relatively moist and the ground water level was high (ca. 1-2 cm below the soil surface) in non-flooded trial, bleeding sap rate both per hill and per panicle were smaller in non-flooded trial than flooded trial (Table 8), which was significantly correlated with SPAD values on flag (39.3 vs 32.8 in flooded and non-flooded trials, respectively with p = 0.01) and 3rd (35.7 vs 27.4 in flooded and non-flooded trials, respectively with p = 0.01) leaves (r = 0.94-0.98 **).

Table 8: Bleeding sap rate during grain filling (measured on 11September) in Flooded (F) and Non-Flooded (NF) trials in 2003 (n = 6)

	Bleeding per hill (g hr^{-1})	Sap rate per panicle (mg hr^{-1})
F	1.64±0.13	223±18
NF	0.45±0.03	73±6
t-test	*	*

*; Significant at $p = 0.05$

Water-saving paddy rice production: Our finding would qualify the previously most comprehensive Japanese water saving paddy rice production study conducted by Takai (1959) reviewed by Kamoshita (2003). The principle of Takai's method is to save water supply during vegetative period exposing rice plants under non-flooded conditions, with expected reduction of maximum tiller number but with minimization of infertile tiller production to such a level that final productive tiller number (i.e., panicle number) is not reduced. Thereafter irrigation regime is gradually shifted to flooded irrigation during reproductive stage to promote panicle development and to protect the physiological processes of meiosis, heading and fertilization from dehydration and to achieve similar levels of final grain yield with full irrigation treatment. Takai's method was effective in ill-drained paddy fields in western region in Japan, but in our study vegetative growth, root system development, panicle development and grain filling were reduced to a greater extent to cause significant yield reduction. This is partly because our paddy field was well-drained with high percolation rate on the lower valleys of diluvial tableland. In fact we have expected that root system will develop more extensively to capture soil moisture under non-flooded conditions than flooded conditions, from the observation by Kawata and Soejima (1977) that showed larger nodal and lateral root numbers in the soil surface layer through intermittent irrigation compared with through constant flooded irrigation among Japanese farmers paddy fields. The apparent contradiction may be derived from the differences in hydrology of paddy fields; in 1970's when the study of Kawata and Soejima (1977) was conducted, there remained many ill-drained paddies in Japan, while the paddy field of our study has enough permeability to avoid severe soil reduction and hence root system in flooded conditions could grow better. It should be also noted that we intended rather drastic saving of irrigation water in our non-flooded irrigation management (e.g., more than 70% saving in 2001, 2003 and 2003; Kamoshita *et al*., 2007). Cracks easily developed because of substantial proportion of clay component in the soils (Lu *et al*., 2000) if the puddled soils are exposed to non-flooded conditions for several days or a week after reducing soil moisture content. Other studies of water-saving paddy rice production also identified fewer tiller production and reduced final panicle number as one of the primary causes for yield decrease (Tao *et al*., 2006). In such soil and hydrological conditions, the alternative water-saving rice production is by way of aerobic rice (i.e. rice grown in upland fields); the promising evidence of high yield level of aerobic rice production in temperate Japan was presented by Kato *et al*. (2006ab, 2007ab).

The tendency of reduced vegetative growth by water-saving from transplanting to panicle initiation in our study can be solved or at least mediated by effective agronomic management such as dense planting and additional N fertilizer supply. In 2004 where 2 seedlings per hill were transplanted, the reduction of yield was smaller than 2001 and 2003 with transplanting 1 seedling per hill (Kamoshita *et al*., 2007). New innovative agronomic managements such as the ground cover rice production system in China may be worthwhile investigation; ground cover with plastic mulch to minimize soil moisture declines due to evaporation loss has successfully shown only 8% of yield reduction with 34 to 52% levels of water supply compared with traditional flooded irrigation, although cost for the materials should be required (Tao *et al*., 2006). The studies using rice straw as the cheaper material for ground cover showed smaller or no effects for maintaining yield (Hayashi *et al*., 2006; Liu *et al*., 2003, Tao *et al*., 2006). Secondly, the choice of more adapted cultivars to non-flooded conditions can be alternative strategy. Ikeda *et al*. (2007) examined genotypic variation in recovery growth after transplanting both flooded and non-flooded fields. In their study, a lowland cultivar reduced growth to a greater extent under non-flooded conditions compared with flooded conditions while an upland cultivar showed much smaller reduction. They also showed superior recovering ability after transplanting is important for final biomass of harvestable organ only under non-flooded conditions with large transplanting shock through root pruning. Although numbers of studies reported desirable traits and cultivar requirements of rice under high input upland conditions (i.e., aerobic rice) (Atlin *et al*., 2006; Bouman *et al*., 2006; Peng *et al.*, 2006) there are fewer interests in genotypic studies in water-saving lowland rice production system such as non-flooded conditions. It would be also worthwhile to check any promising genotypic variation in traits of interest among rice germplasms in response to non-flooded conditions under lowland cultivation system.

CONCLUSION

Our study showed the crop and agronomic reasons for rice yield reduction under non-flooded irrigation management with drastic water-saving, compared with flooded management from the 4 year experiments in a well-drained paddy field in Nishitokyo, Japan. Water supply from transplanting to panicle initiation should not be saved too much to achieve sufficient vegetative growth that would minimize reduction in both source and sink capacity under water-saving irrigation management. Our study also showed or suggested several possible crop physiological reasons for reduced plant growth in non-flooded conditions such as plant water content, daily recovery of leaf water potential, transpirational properties, root system developmentand nitrogen uptake.

ACKNOWLEDGMENT

We thank Mr. Noboru Washizu, Mr. Ken-ichiro Ichikawa, Ms Shizue Chikazawa, Mr. Hiroshi Kimura, Mr. Ryuichi Soga (Field Production Science Center, The University of Tokyo, Japan) and Ms. Chihiro Chikamori and Ms. Chinatsu Yamazaki for their technical assistance in carrying out the experiment. The experiment was partly financially supported by the special funds for Inter-department Studies for 2002-2003 from Graduate School of Agricultural and Life Science, The University of Tokyo.

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