Effect of Planting Density on Grain Yield and Water Productivity of Rice (*Oryza sativa* L.) Grown in Flooded and Non-flooded Fields in Japan

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**Abstract**: The effect of planting density on grain yield and water productivity was evaluated in rice (*Oryza sativa* L.) grown in non-flooded lowland fields in Japan in comparison with flooded fields. One rice cultivar, IR24 was grown both in flooded and non-flooded lowland fields in 2001 and 2002, and only in flooded field in 2003, with different planting densities ranging from 5.6 to 44 hills m⁻². Another rice cultivar, Dontokoi was also grown in 2001. Straw mulching treatment was added in non-flooded field in 2002. In non-flooded fields, standing water disappeared from 36 and 8 days after transplanting until maturity in 2001 and 2002, respectively, the mean water content of surface soil during non-flooded period was 72 % g g⁻¹ on a dry basis and 63 % v v⁻¹. Grain yield in flooded fields (637 g m⁻²; average of 2001 and 2002) was higher than that in non-flooded fields (467 g m⁻²; average of 2001 and 2002), due to larger spikelet number per panicle in both years, larger 1000 grain weight in 2001, and higher percentage of ripened grains in 2002. Straw mulching tended to increase sink size but reduced percentage of ripened grains, resulting in no yield advantage in 2002. Water productivity in non-flooded fields (0.34 kg m⁻³; average of 2001 and 2002) was significantly higher than that in flooded fields (0.14 kg m⁻³). Grain yield increased with higher planting density in flooded fields in 2001 and 2003. In non-flooded fields, however, the effects of planting density on grain yield were little or marginal in both cultivars, due to the trade-off relationship between panicle number and spikelet number per panicle. This study showed that higher planting density would result in higher grain yield in favourable flooded fields, but is not advantageous for higher grain yield under non-flooded lowland fields in Japan in improved cultivars with relatively high tillering and yielding abilities.

**Key words**: Grain yield, Non-flooded paddy field, Planting density, Rice, Water productivity, Water-use efficiency, Yield components.

More than half of the rice fields in the world are irrigated flooded lowlands (IRRI, 1997) and this production system requires a lot of available fresh water. However, fresh water resource is becoming insufficient for flooded lowland rice production in some areas such as China (Wang et al., 2002; Belder et al., 2004), Iran (Pirmoradian et al., 2004), Korea (Cheong, 2003) and Philippines (Tabbal et al., 2002; Belder et al., 2004). Several water-saving irrigation methods such as pre-heading irrigation for lowland rice production in Japan and elsewhere have been reviewed by Kamoshita (2003) and Tuong (2003). In those methods, paddy fields were subjected to non-flooded conditions without standing water either permanently or for a certain period during crop growth to minimize irrigation water use. Grain yield of lowland rice is sometimes reduced under water-saving irrigation management, and modification of crop management would be necessary that would maximize water-use efficiency for yield production, also termed water productivity (Tuong et al., 2000), under non-flooded lowland conditions. Higher planting density may help maintain panicle number and yield level, but the optimum planting density in non-flooded and flooded conditions, may differ depending on the extent of water scarcity.

There are several reports on the relationship between planting density and grain yield of rice under irrigated conditions. In Japan, Kanda and Kakizaki (1956), Yamada et al. (1960) and Takeda and Hirota (1971) reported optimum planting densities to achieve highest grain yield. In some cultivars, grain yield increased with increasing planting density to reach constant values at a density over 10 - 50 hills m⁻² (the values vary with the cultivar). Other cultivars had certain ranges of optimum planting density for highest grain yield. Fagade and De Datta (1971) reported that a higher planting density increased grain yield of a semi-dwarf cultivar, IR8, through greater tiller number and leaf area index at flowering stage. This result is
well known as “Green Revolution” which markedly increased grain yield by growing semi-dwarf cultivars with more fertilizer and at a higher planting density.

On the other hand, the effect of planting density on the grain yield of rice under sub-optimal levels of water availability is less understood. Upland rice at a lower planting density is less sensitive to water deficit and scarcely wilts under drought because of deeper and thicker roots that can extract more water per plant from a deeper soil layer during drought (Rao et al., 1992). In non-flooded paddy fields, a lower planting density might also be suitable for increasing grain yield. The series of experiments was conducted to evaluate the effect of planting density on the grain yield and water productivity of rice grown under non-flooded lowland fields in Japan comparing with flooded fields.

**Materials and Methods**

1. **Experimental design and materials**

Five experiments were conducted at Field Production Science Centre of Graduate School of Agricultural and Life Sciences, The University of Tokyo, Nishitokyo, Japan (35° 34´ N, 139° 32´ E, 53 m elevation) from 2001 to 2003. Two sets of experiments with flooded (F) and non-flooded (NF) conditions were conducted in 2001 (2001F and 2001N, respectively) and in 2002 (2002F and 2002NF, respectively). In flooded conditions the experimental fields were irrigated to keep standing water throughout the growth of rice, while in non-flooded conditions the fields were irrigated until 35 and 7 days after transplanting (DAT) in 2001 and 2002, respectively and thereafter (from 36 and 8 DAT) without irrigation and without standing water until maturity. Only a flooded experiment was conducted in 2003 (2003F). A semi-dwarf high yielding *indica* cultivar, IR24 was used in all the experiments, because its yield performance under non-flooded conditions is not well-known.

In 2001F and 2001NF, a high-yielding and high-grain quality *japonica* cultivar, Dontokoi, released in Japan, was also used with IR24. Both cultivars are tolerant to lodging and have high tillering ability under flooded conditions. Dontokoi heads about a month earlier than IR24 and the non-flooded conditions was started approximately from the panicle initiation stage for Dontokoi, and from tillering stage for IR24, respectively. The experimental design was a randomized complete block design with 3 replicates. Three planting densities were examined. High, middle and low planting densities, which were 33, 22 and 11 hills m^{-2}, respectively, with a 30 cm row spacing and 10, 15 and 30 cm hill spacing, respectively. Size of each plot was 3.5 × 5 m and total size of each experiment was 15 × 21 m.

In 2002F and 2002NF, randomised complete block design and split-plot design was used, respectively, with three replicates. In 2002F, three planting densities were examined and in 2002NF, mulching as main-plot treatment and three planting densities were used as subplot treatment. The 3 planting densities were 44 (high), 25 (middle) and 11 (low) hills m^{-2}, with hill spacing 15 × 15 cm, 20 × 20 cm and 30 × 30 cm, respectively. In mulching plot under non-flooded conditions, 6 t ha^{-1} of rice straw (around 5 cm thickness) was uniformly spread by hands to cover soil surface after the disappearance of standing water. Each plot was 5 × 5 m both in 2002F and 2002NF and total size of each experiment was 15 × 15 m and 15 × 30 m in 2002F and 2002NF, respectively.

In 2003, the experiment was conducted only under flooded condition to confirm the yield response to wider ranges of planting density without water limitation. In 2003F, IR24 was grown at four planting densities without replicate. They were 44 (high), 22 (middle), 11 (low) and 5.6 (very low) hills m^{-2} with their hill spacing 15 × 15 cm, 30 × 15 cm, 30 × 30 cm and 60 × 30 cm, respectively. Size of each plot was 3 × 3 m and size of field was 6 × 6 m.

2. **Cultural management**

The sowing dates were 26 April in 2001, 30 April in 2002 and 23 April in 2003. Seedlings were transplanted on 26 May, 23 May and 22 May in 2001, 2002 and 2003, respectively, at one plant per hill in all the experiments. Five hundred, 667 and 500 kg

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### Table 1. Mean air temperature, rainfall and solar radiation in 2001, 2002 and 2003.

| Month | Mean air temperature (ºC) | Rainfall (mm) | Solar radiation (MJ m² day⁻¹) |
|-------|--------------------------|--------------|-----------------------------|
|       | 2001 | 2002 | 2003 | 2001 | 2002 | 2003 | 2001 | 2002 | 2003 |
| May   | 18.8 | 17.9 | 17.7 | 169 | 85 | 167 | 13.8 | 13.8 | n.a. |
| Jun   | 22.5 | 20.9 | 22.7 | 70 | 157 | 88 | 11.7 | 11.5 | n.a. |
| Jul   | 28.4 | 27.6 | 22.5 | 15 | 181 | 187 | 17.2 | 14.5 | 8.8 |
| Aug   | 25.9 | 27.4 | 25.8 | 212 | 196 | 346 | 10.0 | 15.1 | 11.1 |
| Sep   | 22.1 | 22.0 | 23.6 | 285 | 200 | 142 | 9.0 | 9.3 | 11.0 |
| Oct   | 17.0 | 17.4 | 16.5 | 220 | 240 | 121 | 8.5 | 9.5 | 8.8 |

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ha⁻¹ of chemical fertilizer (N: P₂O₅: K₂O = 12: 16: 18 %) was basally applied before transplanting in 2001, 2002 and 2003, respectively. In 2003, 143 kg ha⁻¹ of ammonium sulphate (N = 21 %) was topdressed twice at 44 (tillering stage) and 81 (around 20 days before heading) days after transplanting (DAT).

3. Measurements

In all the experiments, mean air temperature, rainfall and solar radiation were recorded at a weather station about 100 m from the experimental fields. Table 1 shows mean air temperature, rainfall and solar radiation in 2001, 2002 and 2003. The amount of irrigation water for each experiment was estimated from the total amount of irrigation water pumped during each cropping season (from transplanting to harvest) in all the paddy fields at the Field Production Science Centre, and the proportion of the area of the experimental fields to total area of the paddy fields and the duration of irrigation. Table 2 shows the amounts of irrigation water used from transplanting to harvest in each experiment.

In 2001NF, gravimetric soil water content was measured at about 10-day intervals. Two soil samples were taken from the surface soil to a depth of 10 cm at the centre of rows of each plot. Fresh weight of soil samples and dry weight after drying in an air-forced oven at 105°C for 1 day were measured. Soil water content was calculated using the formula below:

Gravimetric soil water content = (Fresh weight of soil – Dry weight of soil)/Dry weight of soil × 100.

Both in 2001F and 2001NF, tiller number of 5 moderate plants was counted at 30, 45, 55 and 80 DAT. Heading date in this study was defined as the day when 8 panicles out of 10 previously marked medium-size stems were completely visible above the neck node in each plot to avoid confusion of judgment of incomplete exertion of panicles, which is often observed in rice plants under water stressed conditions (Fischer et al., 2003). Maturity was defined as the stage when 90% of grains turned yellow in 90% of panicles. Rice samples with moderate growth were harvested from the 0.81 m² (9, 18 and 27 plants at low, middle and high planting densities, respectively) at 55 DAT, heading and maturity to determine shoot dry matter and grain yield. Yield components (panicle number, spikelet number per panicle, percentage of ripened grains and 1000 grain weight adjusted to 14 % water content in dry weight basis) were measured from the randomly selected subsample of 5, 10 and 15 plants at low, middle and high planting densities, respectively (corresponding to 0.45 m² from the original sampled area of 0.81 m²). Ripened grains were those sinking in 1.06 g cm⁻³ NaCl water in 2001 and those sinking in 1.00 g cm⁻³ tap water in 2002 and 2003. Dry matter was measured after drying at 80°C in an air-forced oven for 3 days.

In 2002NF, volumetric water content of soil from surface to 20 cm depth, was measured at 5 points of the between-row spaces in each plot with time domain reflectometry (HydroSense, Campbell Scientific Inc., Logan, Utah, USA) from 16 to 86 DAT at 14-day intervals. Both in 2002F and 2002NF, SPAD (SPAD-502, Minolta Co.) value of the uppermost fully expanded leaf, tiller number and plant length of 5 moderate plants were measured from 16 to 100 DAT at 14-day intervals. SPAD value is an index of chlorophyll content and indicates nitrogen status of plants (Peng et al., 2002). Rice samples with moderate growth were harvested from 1.44 m² (16, 36 and 64 plants at low, middle and high planting densities, respectively for determination of shoot dry matter at 58 DAT, heading, and maturity, and for determination of grain yield and yield components. Yield components were measured from the subsample of randomly chosen 5 plants.

In 2003F, leaf age, tiller number and plant length of 6 previously marked medium-size plants were measured at 29, 40, 50, 81 and 99 DAT, and the 6 plants were harvested at 146 DAT (maturity) for determination of shoot dry matter, grain yield and yield components. Five moderate plants were harvested at 99 DAT (around heading) for determination of total
leaf number and shoot dry matter.

Water-use efficiency for crop production is an agronomical index also termed water productivity by Tuong et al. (2000), while water use efficiency in a narrow sense is a plant physiological index, often defined as the rate of photosynthesis divided by the transpiration rate of individual leaf or in canopy. In our study, water productivity was calculated as grain yield divided by total water input to the experimental fields (sum of irrigation and rainfall) using the following formula:

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\text{Water productivity} = \frac{\text{grain yield}}{\text{(amount of irrigation water} + \text{amount of rainfall)}}.
\]

4. Statistical analysis

Analysis of variance (ANOVA) was conducted by the method of Gomez and Gomez (1984). In 2001F, 2001NF and 2002F, phenotypic observation was modelled with randomized block design to assess the effects of planting density, cultivars, or their interactions depending on the experiments. In 2002NF, phenotypic observation was modelled with split-plot design to assess the effects of planting density, mulching and their interactions. In 2003F, phenotypic observation was modelled with complete randomized design to assess the effects of planting density. In 2001 and 2002, the effect of water conditions, interactions between water conditions, planting density, and cultivars were assessed by combined analysis.

Results

1. Standing water and soil water content

Both in 2001NF and 2002NF, standing water disappeared at 36 and 8 days after transplanting (DAT), respectively: the irrigation was withheld at 35 and 7 DAT, respectively. In 2001NF, gravimetric soil water content measured at 37 and 47 DAT was 122 and 109 % g g\(^{-1}\), respectively. It sharply decreased to 51% g g\(^{-1}\) at 58 DAT and it gradually decreased to 36 % g g\(^{-1}\) (approximately 45% v v\(^{-1}\)) at 81 DAT because of little rainfall (7 mm from 58 to 81 DAT). From 91 DAT to maturity, gravimetric soil water content was around 70% g g\(^{-1}\) because of higher amount of rainfall. There was no effect of planting density on soil water content.

In 2002NF, there was no standing water from rooting of seedlings to maturity in non-flooded conditions. Volumetric soil water content in 2002NF ranged from 61 to 66% v v\(^{-1}\) from 16 to 86 DAT, and it was significantly lower than 2002F (78–84% v v\(^{-1}\)). There was no effect of mulching and planting density on soil water content in 2002NF.

2. Phenology

Heading of Dontokoi was about 25 days earlier than that of IR24 (Table 3). Heading date in 2001NF was about 4 and 6 days earlier than in 2001F in Dontokoi and IR24, respectively. At the onset of non-flooded conditions in 2001F, Dontokoi was around panicle

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Table 3. Days to heading after transplanting and heading date of IR24 and Dontokoi across different planting densities in 2001, 2002 and 2003.

| Water condition | Cultivar | Planting density | 2001     | 2002     | 2003     |
|-----------------|----------|------------------|----------|----------|----------|
|                 |          |                  | 2001     | 2002     | 2003     |
| Flooded         | IR24     | High             | 104      | 96       | 99       |
|                 |          | Middle           | 105      | 99       | 101      |
|                 |          | Low              | 103      | 101      | 101      |
|                 |          | Very low         | –        | –        | 103      |
|                 | Donutoki | High             | 77       | –        | –        |
|                 |          | Middle           | 77       | –        | –        |
|                 |          | Low              | 80       | –        | –        |
|                 |          |                  |          |          |          |
| Non-flooded     | IR24     | High             | 99       | 105      | –        |
|                 |          | Middle           | 96       | 106      | –        |
|                 |          | Low              | 99       | 109      | –        |
|                 | Donutoki | High             | 75       | –        | –        |
|                 |          | Middle           | 73       | –        | –        |
|                 |          | Low              | 75       | –        | –        |
| Non-flooded     | IR24     | High             | –        | 104      | –        |
| with mulching   |          | Middle           | –        | 108      | –        |
|                 |          | Low              | –        | 107      | –        |

Plating densities were 33, 22, 11 hills m\(^{-2}\) in 2001 and 44, 25 and 11 hills m\(^{-2}\) in 2002 in high, middle and low planting densities, respectively. In 2003, planting densities were 44, 22, 11 and 5.6 hills m\(^{-2}\) in high, middle, low and very low planting densities, respectively.
initiation stage but IR24 was around tillering stage. In 2002NF, heading date was about 8 days later than that in 2002F. There was little effect of planting density on heading date in 2001F and 2001NF. In 2002F, 2002NF and 2003F, heading date was advanced by 4 to 5 days by a higher planting density. Total leaf number on the
main culm was lower at a higher planting density than at a lower planting density in 2003F (19 at low and very low and 18 at high and middle planting densities).

3. Tillering

Fig. 1 shows the changes of tiller number in 2001F, 2001NF, 2002F, 2002NF and 2003F with the lapse of time. In flooded fields, the changes at high and middle planting densities were similar (Fig. 1a, c, e). Tiller number at low and very low (only in 2003F) planting densities increased more slowly than at high and middle planting densities and their maximum tiller number was also lower than at high and middle planting densities. Percentage of productive culms was

Table 4. Shoot dry matter at heading and maturity in 2001, 2002 and 2003, at different planting densities for each cultivar in flooded and non-flooded conditions.

| Water condition | Cultivar | Planting density | Shoot dry matter (g m⁻²) | Heading | Maturity |
|------------------|----------|------------------|--------------------------|---------|----------|
|                  |          |                  |                          | 2001    | 2002     | 2003     | 2001    | 2002     | 2003     |
| Flooded          | IR24     | High             | 1042                     | 834     | 750      | 1334     | 1146     | 1303     |
|                  |          | Middle           | 1058                     | 896     | 690      | 1685     | 1180     | 1105     |
|                  |          | Low              | 856                      | 775     | 632      | 1411     | 1178     | 1044     |
|                  |          | Very low         | −                        | −       | 487      | −        | −        | 840      |
|                  | Dontokoi | Middle           | 743                      | −       | −        | 1248     | −        | −        |
|                  |          | Low              | 665                      | −       | −        | 1341     | −        | −        |
|                  |          | 546              | −                        | −       | 1041     | −        | −        |
| LSD₀.₀₅          |          | Planting density effect (PD) | 66 | n.s. | 153 | 122 | n.s. | 169 |
|                  |          | Cultivar effect (C) | 54 | − | − | 100 | − | − |
|                  |          | PD×C interaction | n.s. | − | − | 172 | − | − |
| Non-flooded      | IR24     | High             | 845                      | 721     | −        | 1283     | 1052     | −        |
|                  |          | Middle           | 655                      | 656     | −        | 1193     | 1107     | −        |
|                  |          | Low              | 615                      | 665     | −        | 1104     | 1099     | −        |
|                  | Dontokoi | Middle           | 633                      | −       | −        | 1070     | −        | −        |
|                  |          | Low              | 553                      | −       | −        | 1075     | −        | −        |
|                  |          | 470              | −                        | −       | 1024     | −        | −        |
| LSD₀.₀₅          |          | Planting density effect (PD) | 98 | n.s. | − | n.s. | n.s. | − |
|                  |          | Cultivar effect (C) | 80 | − | − | n.s. | − | − |
|                  |          | PD×C interaction | n.s. | − | − | n.s. | − | − |
|                  |          | Mulching effect (M) | − | n.s. | − | − | n.s. | − |
|                  |          | PD×M interaction | − | n.s. | − | − | n.s. | − |
| Non-flooded with mulching | IR24     | High             | −                        | 795     | −        | −        | 1115     | −        |
|                  |          | Middle           | −                        | 737     | −        | −        | 1121     | −        |
|                  |          | Low              | −                        | 685     | −        | −        | 1160     | −        |
| LSD₀.₀₅          |          | Water condition effect (WC) | 171 | 133 | − | 214 | n.s. | − |
|                  |          | WC×PD interaction | 64 | n.s. | − | 139 | n.s. | − |
|                  |          | WC×C interaction | 64 | − | − | 94 | − | − |
|                  |          | WC×PD×C interaction | n.s. | − | − | 163 | − | − |

Planting densities were 33, 22, 11 hills m⁻² in 2001 and 44, 25 and 11 hills m⁻² in 2002 for high, middle and low planting densities, respectively. In 2003, planting densities were 44, 22, 11 and 5.6 hills m⁻² for high, middle, low and very low planting densities, respectively.

LSD₀.₀₅ means least significant difference at 5% level, values indicated in *italics* mean least significant difference at 10% level and n.s. means there was no significant difference at 10 % level.

PD × C, PD × M, WC × PD, WC × C and WC × PD × C mean planting density by cultivar, planting density by mulching, water condition by planting density, water condition by cultivar and water condition by planting density by cultivar, respectively.
higher at low and very low planting densities (61–82%) than at high and middle planting densities (35–71%; lowest in 2002F and highest in 2001F).

In non-flooded fields, the effects of planting density on the tiller-increase rate, maximum tiller number and percentage of productive culms in 2001NF differed from those in 2002NF (Fig. 1b, d). In Dontokoi in 2001NF, tiller number at a high planting density increased as fast as in 2001F until 45 DAT and then decreased sharply than at middle and low planting densities. Hence, the percentage of productive culms of Dontokoi in 2001NF was quite low at a high planting density (49, 77 and 80% at high, middle and low planting densities, respectively). In 2001NF, the increase of tiller number in IR24 was slower and maximum tiller number was lower than in 2001F. Tiller number at the time of disappearance of standing water (38 DAT) was higher at a higher planting density and it was maintained till 80 DAT. There was no difference in the percentage of productive culms between planting densities in IR24 in 2001NF (80–85%). In 2002NF, tiller increase of high and middle planting densities was slowed and maximum tiller number was lower than in 2002F, but the decrease of tiller number after maximum tiller number stage was smaller than 2002F. The change with the lapse of time in tiller number at a low planting density in 2002F and 2002NF did not differ so much. The percentage of productive culms in 2002NF was higher at a lower planting density (70%) than at high (49%) and middle (58%) planting densities.

### Table 5. Water use, grain yield, water productivity and yield components across planting densities for each cultivar in flooded and non-flooded fields in 2001.

| Water condition | Cultivar | Planting density | Water use (mm) | Grain yield (g m⁻²) | Water Productivity (kg m⁻³) | Panicle number (m⁻²) | Spikelet number (m⁻²) | Percentage of ripened grains (%) | 1000 grain weight (g) |
|-----------------|----------|------------------|----------------|---------------------|-----------------------------|----------------------|--------------------------|---------------------------------|---------------------|
| Flooded         | IR24     | High             | 607            | 0.14                | 267                         | 144                  | 38407                    | 60                              | 26.6                |
|                 |          | Middle           | 4217           | 0.19                | 294                         | 153                  | 44924                    | 68                              | 26.3                |
|                 |          | Low              | 683            | 0.16                | 266                         | 136                  | 36270                    | 70                              | 26.8                |
|                 | Dontokoi | High             | 625            | 0.15                | 277                         | 99                   | 27496                    | 87                              | 26.1                |
|                 |          | Middle           | 4044           | 0.16                | 312                         | 101                  | 31597                    | 81                              | 25.7                |
|                 |          | Low              | 504            | 0.12                | 219                         | 118                  | 25767                    | 80                              | 24.8                |

LSDₐ₀.₀₅
- Planting density effect (PD) 67 0.02 29 n.s. 2941 n.s. 0.4
- Cultivar effect (C) 55 0.01 n.s. 10 2401 4 n.s.
- PD × C interaction 95 0.02 33 18 n.s. 7 0.7

| Non-flooded     | IR24     | High             | 577            | 0.33                | 308                         | 116                  | 35728                    | 67                              | 23.9                |
|                 |          | Middle           | 540            | 0.31                | 288                         | 113                  | 32544                    | 67                              | 24.5                |
|                 |          | Low              | 509            | 0.29                | 240                         | 138                  | 33120                    | 66                              | 23.7                |
|                 | Dontokoi | High             | 406            | 0.25                | 237                         | 88                   | 20856                    | 79                              | 24.6                |
|                 |          | Middle           | 422            | 0.26                | 229                         | 97                   | 22213                    | 78                              | 24.4                |
|                 |          | Low              | 377            | 0.23                | 224                         | 94                   | 21056                    | 76                              | 24.0                |

LSDₐ₀.₀₅
- Planting density effect (PD) n.s. n.s. 25 n.s. n.s. n.s. n.s.
- Cultivar effect (C) 90 0.05 21 11 4472 6 n.s.
- PD × C interaction n.s. n.s. 29 n.s. n.s. n.s. n.s.

LSDₐ₀.₀₅
- Water condition effect (WC) 38 0.02 n.s. 7 4614 n.s. 1.4
- WC × PD interaction 70 n.s. 25 n.s. 4115 n.s. n.s.
- WC × C interaction 0.03 21 n.s. n.s. 0.7
- WC × PD × C interaction 100 n.s. 36 18 n.s. n.s. n.s.

Planting densities were 33, 22 and 11 hills m⁻² in high, middle and low planting densities, respectively. LSDₐ₀.₀₅ means least significant difference at 5 % level, values indicated in italic mean least significant difference at 10 % level and n.s. means there was no significant difference at 10 % level. PD × C, WC × PD, WC × C and WC × PD × C mean planting density by cultivar, water condition by planting density, water condition by cultivar and water condition by planting density by cultivar, respectively.
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4. Shoot dry matter

Shoot dry matter of IR24 at heading in 2001F was significantly heavier than that in 2001NF and that in 2002F tended to be higher than in 2002NF (Table 4). Shoot dry matter at maturity was also heavier in 2001F than in 2001NF, but there was no significant difference between 2002F and 2002NF. In flooded fields, shoot dry matter at heading was heavier at high and middle planting densities than low and very low (only in 2003) planting densities across years (not significant in 2002) and for both cultivars. The effect of planting density on shoot dry matter at maturity was significant in flooded fields except for 2002F. In 2001F, shoot dry matter at maturity of IR24 at a high planting density was lighter than that at the middle planting density. In 2001NF, we observed a significant effect of planting density on shoot dry matter at heading. Shoot dry matter at maturity tended to increase with increasing planting density in IR24, but there was little effect of planting density in Dontokoi. In 2002NF, shoot dry matter at heading tended to increase with increasing planting density, but there was no effect of planting density on shoot dry matter at maturity. Both in 2001F and 2001NF shoot dry matter of IR24 at heading and maturity was generally heavier than that of Dontokoi (not significant at maturity in 2001NF). There was no effect of mulching on shoot dry matter at heading. Shoot dry matter at maturity tended to increase with increasing planting density in IR24, but there was little effect of planting density in Dontokoi. In 2002NF, shoot dry matter at heading tended to increase with increasing planting density, but there was no effect of planting density on shoot dry matter at maturity. Both in 2001F and 2001NF shoot dry matter of IR24 at heading and maturity was generally heavier than that of Dontokoi (not significant at maturity in 2001NF). There was no effect of mulching on shoot dry matter at heading and maturity in 2002NF.

5. Grain yield and yield components

Both in 2001 and 2002, grain yield in flooded fields was higher than in non-flooded fields, although it was not significant at $P = 0.05$ in 2002 (Table 5 and 6). Grain yield of IR24 was higher than that of Dontokoi both in 2001F and 2001NF. In 2002F, there was no effect of planting density on grain yield due to small differences in panicle number, while the effect was significant in 2001F and 2003F (Table 7). In 2001F and 2003F, grain yield at high and middle planting densities were higher than at a low planting density due to larger panicle number except for IR24 in 2001F, where grain yield at a high planting density was similar to that at a low planting density due to reduced fertile panicle number. In non-flooded fields, the effect of planting density on grain yield was not significant.

Table 6. Water use, grain yield, water productivity and yield components of IR24 across planting densities in flooded and non-flooded fields in 2002.

| Water condition | Planting density | Water use (mm) | Grain yield (g m$^{-2}$) | Water Productivity (kg m$^{-3}$) | Panicle number (m$^{-2}$) | Spikelet number (panicle$^{-1}$) | Spikelet number (m$^{-2}$) | Percentage of ripened grains (%) | 1000 grain weight (g) |
|----------------|------------------|----------------|--------------------------|-------------------------------|---------------------------|-------------------------------|---------------------------|----------------------------------|----------------------|
| Flooded        | High             | 603            | 0.13                     | 208                           | 149                       | 31035                        | 75                        | 26.1                             | 26.1                 |
|                | Middle           | 4660           | 0.13                     | 200                           | 165                       | 32987                        | 73                        | 26.1                             | 26.1                 |
|                | Low              | 615            | 0.13                     | 215                           | 162                       | 34791                        | 68                        | 26.1                             | 26.1                 |
| LSD$_{0.05}$   | Planting density effect (PD) | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
|                | With mulching    | High           | 444                       | 0.38                          | 247                       | 127                          | 31335                     | 56                              | 25.7                 |
|                |                   | Middle         | 493                       | 0.42                          | 240                       | 145                          | 34870                     | 56                              | 25.4                 |
|                |                   | Low            | 480                       | 0.41                          | 226                       | 149                          | 39627                     | 55                              | 25.9                 |
|                | Without mulching | High           | 445                       | 0.38                          | 225                       | 121                          | 27171                     | 64                              | 25.6                 |
|                |                   | Middle         | 470                       | 0.40                          | 237                       | 121                          | 28582                     | 64                              | 25.6                 |
|                |                   | Low            | 438                       | 0.37                          | 195                       | 163                          | 31796                     | 55                              | 25.1                 |
| LSD$_{0.05}$   | Planting density effect (PD) | n.s. | n.s. | n.s. | 12 | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
|                | Mulching effect (M) | n.s. | n.s. | n.s. | n.s. | n.s. | 4 | n.s. | n.s. | n.s. | n.s. | n.s. |
|                | PD × M interaction | n.s. | n.s. | n.s. | 19 | n.s. | n.s. | 0.5 | n.s. | n.s. | n.s. | n.s. |
| LSD$_{0.05}$   | Water condition effect (WC) | 158 | 0.18 | n.s. | 19 | n.s. | 9 | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
|                | WC × PD interaction | n.s. | n.s. | n.s. | 12 | n.s. | 4 | 0.4 | n.s. | n.s. | n.s. | n.s. | n.s. |

Planting densities were 44, 25 and 11 hills m$^{-2}$ in high, middle and low planting densities, respectively. LSD$_{0.05}$ means least significant difference at 5 % level, values indicated in italic mean least significant difference at 10 % level and n.s. means there was no significant difference at 10 % level. PD × M and WC × PD mean mulching by planting density and water condition by planting density, respectively.
and only in 2001NF, grain yield of IR24 tended to increase with increasing planting density. In 2002NF, there was no effect of mulching on grain yield. Fig. 2 shows the relationship between planting density and grain yield in flooded and non-flooded fields. Yield increase in response to higher planting densities (high and middle planting densities compared with low and very low planting densities) was observed in flooded fields at least in some of the years and cultivars (e.g. Dontokoi in 2001F and 2003F) while it was not clear in non-flooded fields.

There was a significant effect of planting density on panicle number in flooded conditions except for 2002F (Table 5, 6 and 7). In 2001F and 2003F, panicle number increased with increasing planting density except for IR24 in 2001F. In non-flooded fields, effect of planting density on panicle number was different between years and cultivars. In 2001NF, panicle number increased with increasing planting density in IR24, but not in Dontokoi. In 2002NF, the effect of planting density on panicle number was not significant. Panicle number of IR24 and Dontokoi was similar in 2001F, but it was significantly greater in IR24 than in Dontokoi in 2001NF.

Both in 2001 and 2002, spikelet number per panicle in flooded fields was larger than that in non-flooded fields, although it was not significant at $P = 0.05$ in 2002. Both in 2001F and 2001NF, spikelet number per panicle of IR24 was higher than that of Dontokoi. In 2001F, spikelet number per panicle of IR24 was higher at the middle, high and low planting density, while that of Dontokoi in 2001F and IR24 in 2002F tended to increase with decreasing planting density. In 2003F, spikelet number per panicle of very low planting density was significantly larger than higher planting densities. Spikelet number per panicle increased

Table 7. Water use, grain yield, water productivity and yield components of IR24 across planting densities in flooded field in 2003.

| Planting density | Water use (mm) | Grain yield (g m$^{-2}$) | Water productivity (kg m$^{-3}$) | Panicle number (m$^{-2}$) | Spikelet number (panicle$^{-1}$) | Spikelet number (m$^{-2}$) | Percentage of ripened grains (%) | 1000 grain weight (g) |
|------------------|----------------|---------------------------|----------------------------------|---------------------------|-------------------------------|---------------------------|-------------------------------|---------------------|
| High             | 4538           | 661                       | 0.15                             | 244                       | 130                           | 31741                     | 80                            | 26.0                 |
| Middle           |                | 591                       | 0.13                             | 207                       | 133                           | 27669                     | 80                            | 26.6                 |
| Low              |                | 550                       | 0.12                             | 204                       | 130                           | 26419                     | 80                            | 25.8                 |
| Very low         |                | 445                       | 0.10                             | 141                       | 176                           | 24766                     | 74                            | 24.5                 |
| LSD$_{0.05}$     | 97             | 0.02                      | 31                               | 13                        | 4364                         | n.s.                      | 0.8                           |

Plants densities were 44, 22, 11 and 5.6 hills m$^{-2}$ in high, middle, low and very low planting densities, respectively. LSD$_{0.05}$ means least significant difference at 5 % level and n.s. means there was no significant difference at 10 % level.

Fig. 2. Relationship between planting density and grain yield in IR24 in flooded (a) and non-flooded (b) fields in 2001 (-1 H), 2002 (● and -1 H) and 2003 (▲). Closed and open symbols indicate without mulching and with mulching, respectively.
with lower planting density in 2001NF and 2002NF (although only marginally significant at $P=0.10$ in 2001NF). Mulching increased the spikelet number per panicle at the middle planting density in 2002NF, and spikelet number per area tended to be increased by mulching, respectively. In flooded fields, there was no relationship between panicle number and spikelet number per panicle in IR24 (Fig. 3a), but in non-flooded fields, spikelet number per panicle decreased with increasing panicle number (Fig. 3b). There was no relation between SPAD value measured from 72 to 100 DAT (corresponding to panicle initiation to heading) and spikelet number per panicle in 2002F (Fig. 4a), but the correlation was significant in 2002NF (Fig. 4b).

There was no significant difference in percentage of ripened grains between 2001F and 2001NF though percentage of ripened grains in Dontokoi tended to be higher in 2001F than in 2001NF (Table 5). Both in 2001F and 2001NF, percentage of ripened grains was significantly higher in Dontokoi than in IR24. In 2001F, percentage of ripened grains at a high planting density was lower than at middle and low planting

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**Fig. 3.** Relationship between panicle number and spikelet number per panicle in IR24 at high (■), middle (◇), low (▲) and very low (●) planting densities in flooded (a) and non-flooded (b) fields. Regression (logistic curve) was drawn in non-flooded fields and * means significant correlation at 5% level.

**Fig. 4.** Relationship between average SPAD value measured at 72, 86 and 100 days after transplanting and spikelet number per panicle in IR24 at high (■ and ◇), middle (◇ and ◊) and low (▲ and △) planting densities in flooded (a) and non-flooded (b) fields in 2002. Closed and open symbols indicate without mulching and with mulching, respectively. Linear regression was drawn in non-flooded fields and ** means significant correlation at 1% level.
densities in IR24, while that of high planting density was higher than middle and low planting densities in Dontokoi. Percentage of ripened grains tended to be lower in 2002NF than in 2002F (Table 6). In flooded fields, variation of spikelet number per area was large and percentage of ripened grains decreased with increasing spikelet number per area (Fig. 5), but in non-flooded fields, there was small variation in spikelet number per area and correlation between spikelet number and percentage of ripened grains was not significant. Percentage of ripened grains was higher in flooded fields than in non-flooded fields if compared at the same spikelet number per area.

In 2001, the 1000-grain weight in flooded fields was significantly higher than that in non-flooded fields (Table 5). Grain weight of IR24 was heavier than that of Dontokoi in 2001F, but there was no difference in 2001NF. In 2001F, effect of planting density on grain weight was small in IR24, but grain weight of Dontokoi increased with increasing planting density. In 2002NF, grain weight was lightest at a low planting density without mulching and highest at a low planting density with mulching. In 2003F, grain weight was heavier in the order of middle, high, low and very low planting densities (Table 7). Ripened grain number per unit area was larger in flooded fields than in non-flooded fields (Fig. 6). In flooded fields, ripened grain number and grain weight were lower at a very low planting density in 2003F, but there was no relationship between them at low, middle and high planting densities. On the other hand, grain weight decreased with increasing ripened grain number in non-flooded fields.

6. Water productivity

Water productivity was significantly higher in non-flooded fields (0.34 kg m\(^{-3}\) on average, ranging from 0.25 to 0.42 kg m\(^{-3}\)) than in flooded fields (0.14 kg m\(^{-3}\) on average, ranging from 0.10 to 0.19 kg m\(^{-3}\)) (Table 5, 6 and 7). Both in 2001F and 2001NF, water productivity of IR24 was higher than that of Dontokoi, although IR24, which is a later maturing cultivar compared with Dontokoi, used more water than Dontokoi. The effect of planting density on the water productivity was different among years and cultivars. In 2001F, water productivity of IR24 at the middle planting density was highest (0.19 kg m\(^{-3}\)) and water productivity of Dontokoi at a low planting density was lowest (0.12 kg m\(^{-3}\)). However, in 2002F, water productivity was similar across planting densities (0.13 kg m\(^{-3}\)). In 2003F, water productivity increased with increasing planting density.

Discussion

1. Effect of water conditions

In our study, the water content of soil from surface to 20 cm depth was not clearly changed by straw mulching, which may be due to the relatively high and frequent rainfalls in 2002. Consequently, there were no effects of mulching on grain yield in 2002NF since a slight increase in spikelet number per area was cancelled by reduction in percentage of ripened grains. Straw mulching under non-flooded conditions may be worth further studying under less moist
conditions. Under upland conditions with lower soil water content than this study, straw mulching reduced evaporation from surface soil and achieved higher grain yield of rice than non-mulching fields (Kato et al., 2006). Naklang (1997) reported that straw mulching retained higher soil water content and improved soil fertility, resulting in higher grain yield in direct seeded rainfed lowland rice in Northeast Thailand, while other studies showed no effects of straw mulch on yield improvement of lowland rice (e.g. Liu et al., 2003).

As an agronomic index of water-use efficiency and successful water-saving, we calculated water productivity; water productivity in non-flooded fields (0.34 kg m\(^{-3}\) on average) was greater than that in flooded fields (0.14 kg m\(^{-3}\) on average), and it was higher after a longer non-flooded period (0.39 kg m\(^{-3}\) of IR24 in 2002NF, but 0.31 kg m\(^{-3}\) in 2001NF in IR24). This indicated that water productivity could be improved with greater extent of water-saving and longer non-flooded period if adequate amounts of water are timely supplied either from rainfall or irrigation so that severe drought should not develop and yield formation is not severely affected. In our study, 59, 60 and 75% of water was saved in IR24 in 2001 Dontokoi in 2001 and IR24 in 2002NF, respectively, in non-flooded fields compared with flooded fields. In spite of the greatest water saving, soil water content was generally maintained high in 2002 (e.g. 60% \(v\) v\(^{-1}\)), while in 2001NF with less soil water content of surface soil due to longer dry periods with little rainfall (e.g. only 29 mm of rainfall from 21 to 86 DAT) soil water content was 36 % g g\(^{-1}\) or approximately 45 % \(v\) v\(^{-1}\) of the water content of surface soil at the driest time. We have not measured the water potential or water content of the plants, but the water potential of leaves in non-flooded conditions should have declined compared with that in flooded conditions, as found in another non-flooded experiment at the same experimental site (Kamoshita, personal communication). In non-flooded fields in our study, there were no symptoms of leaf rolling or leaf death, but increase of tiller number was slower, dry matter production was suppressed, and heading delayed (only in 2002). In 2001, heading was later in flooded fields due to low temperature of irrigation water than in non-flooded fields. Such responses to water deficit of rice plants have been reported in other studies of (Puckridge and O'Toole, 1981; Ichwantoari et al., 1989; Tsuda and Takami, 1991). Grain yield loss in non-flooded fields compared with flooded fields was moderate (26, 33 and 25 % in IR24 and Dontokoi in 2001 and IR24 in 2002, respectively), which were associated with reduction in spikelet number per panicle, grain weight, panicle number (only in Dontokoi in 2001NF), and percentage of ripened grains (in 2002NF).

We also found that water productivity can be improved by optimizing agronomic management such as use of higher yielding cultivars and optimizing phenology with water availability. In 2001NF, grain yield and water productivity of IR24 was higher than that of Dontokoi, firstly because of higher yield potential of IR24 (associated with higher shoot dry matter production and larger spikelet number per panicle) and also due to less reproductive damages after disappearance of standing water. In Dontokoi, the onset of non-flooded condition was around the panicle initiation stage, and a greater proportion of tillers became infertile than in IR24, resulting in a lower panicle number, especially at high and middle planting densities. In contrast, IR24 which was subjected to the non-flooded condition from around the tillering stage, increased tiller number slowly and its panicle number was comparable to that of Dontokoi in 2001NF. In the experiment of Tabbal et al. (2002), longer intervals of intermittent irrigation (10-20 days), resulted in a larger reduction in grain yield and lower water productivity than continuously flooded culture (Tabbal et al., 2002). Tuong et al. (2002) reported grain yield of rice subjected to water deficit for 20 days from panicle initiation was reduced by 47% compared to well-watered conditions. Wopereis et al. (1996) examined the effect of water deficit at various growing stages and reported that the grain yield was reduced by 87% at the maximum, when water-deficit conditions were given at panicle initiation or first flowering. Further research on water management is needed to utilize limited water resources most efficiently and to develop skilful and timely water-saving paddy irrigation schemes to maintain rice yield.

2. Effect of planting density

In non-flooded fields, there were no effects of planting density on soil water content, indicating that evapotranspiration was not influenced by planting density. Transpiration may be larger at a higher planting density but evaporation from soil surface may be larger at a lower planting density, resulting in little difference in total evapotranspiration. This result was different from the experiment with upland rice, in which less-densely planted rice used available soil water more slowly and retained higher soil water content during the dry period (Urasaki et al., 2002). Since water content of surface soil in the non-flooded lowland field in our study were much higher (e.g. 61 to 66 % \(v\) v\(^{-1}\) in 2002NF) than in the upland fields of Urasaki et al. (2002) (ca. 34 % \(v\) v\(^{-1}\), from Kato et al., 2006), contribution of soil evaporation to soil water balance might be greater in the non-flooded lowland fields in our study. However, if soil hydraulic properties and rainfall patterns are different and soil water content is lower than in our study, lower planting density with smaller size of canopy might be
also advantageous for efficient water use under non-flooded lowland fields. Pantuwan et al. (2002) showed that a larger size of plants consumed available soil water quickly and were disadvantageous to prolonged and severe drought conditions in rainfed lowlands in Northeast Thailand.

A high panicle number was important to increase sink size (higher spikelet number per unit area) and grain yield in flooded fields in our study. Panicle number at the middle or high planting density was higher than at a low planting density except in 2002F, where many tillers at high and middle planting densities became infertile possibly due to smaller individual tiller size (0.17 - 0.19 g tiller\(^{-1}\) at 58 DAT and 2.0 - 2.8 g tiller\(^{-1}\) at heading at high and middle planting density in 2002F, 0.20 - 0.25 g tiller\(^{-1}\) at 58 DAT and 2.8 - 3.0 g tiller\(^{-1}\) at heading at low planting density in 2002F) and lower nitrogen content (SPAD values of 33 - 37 at high and middle planting density, 36 - 39 at low planting density; average of 72, 86 and 100 DAT). IR24 at the highest planting density in 2001 also had low panicle number and low grain yield, possibly due to nitrogen deficiency derived from no additional fertilizer application during later growth stage. In non-flooded field in 2001, panicle number increased with increasing planting density, especially in IR24. However, overall effects of planting density on grain yield were little or small (insignificant) in non-flooded fields, because of the trade off relationship between panicle number and spikelet number per panicle, and between ripened grain number and 1000-grain weight. Spikelet number per panicle became smaller at higher planting densities in non-flooded fields, which may partly be due to nitrogen deficiency of rice plants with higher planting densities, as indicated by lower SPAD values (Peng et al., 2002). In the other experiments at the same location, nitrogen accumulation of rice was smaller in non-flooded fields than in flooded fields (Kamoshita, personal communication). This suggests that rice plants under non-flooded water management suffer nitrogen deficit which would hinder full development of spikelet, tiller and leaf area, and that densely planted rice plants should have suffered severer nitrogen limitation for spikelet development. Oxidation and leaching or denitrification of soil nitrogen may be increased under non-flooded conditions, due to alternate soil drying and wetting, as was reported in rainfed lowland experiments (Buresh et al., 1993). Therefore, different nutrient management such as frequent additional topdressing of nitrogen fertilizer when surface soil contains high soil moisture (e.g. near-saturation) may be needed under non-flooded fields to resolve trade-off relationship between panicle number and spikelet number per panicle.

These results suggested that planting density should be changed depending on the water availability. Under favourable water and nutrient conditions like 2001F and 2003F, higher planting density could achieve higher panicle number and spikelet number per unit area, and this would result in higher grain yield unless lodging occurs. In our study, plant length was not enhanced by higher planting densities (data not shown) and no lodging occurred in any experiments. However, thinner stems were observed at a higher planting density and this might result in lodging if cultivars with less lodging tolerance are used or greater amounts of fertiliser are applied. Under long period of non-flooded conditions but without severe water stress (e.g. 2001NF and 2002NF), planting density would affect neither spikelet number per unit area nor grain yield. Hence lower planting density is recommended because it requires less seedlings compared with higher planting density. However, this conclusion was obtained from the experiments using only two improved cultivars with high tillering and high yielding abilities grown under relatively fertile paddy fields in Japan. The effects of planting density under non-flooded water-saving paddy fields should be investigated further under more marginal environments with less water availability and less soil fertility, where traditional rice cultivars with less tillering ability are dominantly cultivated.

Conclusions

Grain yield in non-flooded fields was lower than in flooded fields due to lower spikelet number per panicle, smaller percentage of ripened grains, and/or less 1000 grain weight, but water productivity was much higher in non-flooded fields (0.34 kg m\(^{-3}\) on the average) than in flooded fields (0.14 kg m\(^{-3}\)) due to greater water-saving. While higher planting density generally resulted in higher panicle number and higher grain yield than the lower planting density in flooded fields in 2001 and 2003, little effects of planting density was observed on spikelet number per area and grain yield in two rice cultivars in non-flooded fields, because of the trade off relationship between panicle number and spikelet number per panicle. Therefore, there is a greater potential to increase grain yield by adopting higher planting densities in favourable flooded paddy fields, but higher planting densities provide little opportunity for increasing yield under non-flooded fields for cultivars with high tillering ability grown in Japan.

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