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# RICE ROOT SYSTEM SPATIAL DISTRIBUTION CHARACTERISTICS AT FLOWERING STAGE AND GRAIN YIELD UNDER PLASTIC MULCHING DRIP IRRIGATION (PMDI)

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## ABSTRACT

Plot experiments and field investigations were conducted with NingGeng28 (*japonica*) in 2011 and 2012 to investigate rice root spatial distribution at flowering and grain yield under PMDI. The results showed that fewer roots at the 0–20 cm soil layer were present under PMDI than under flooding irrigation, but more roots were observed at 20–60 cm soil layer under PMDI than under flooding irrigation. In the horizontal direction, the root length density (RLD) at the 0–20 cm soil layer decreased with increasing horizontal distance away from the hill sites (A1 > B1 > C1) and significantly decreased with decreasing irrigation application amount in each soil column. At the 20–40 cm and 40–60 cm soil layers, RLD were relatively constant under flooding irrigation but increased with increasing horizontal distance away from the hills under PMDI (C2 > B2 > A2; C3 > B3 > A3) and significantly increased with decreasing irrigation application amount in each soil column. Significant differences in roots and aboveground performance were observed between the near and far rows. Moreover, the grain yield ranged from $3.35\times10^3$ Kg ha$^{-1}$ to $6.86\times10^3$ Kg ha$^{-1}$ under PMDI, which was 19.3–60.31% lower than that under flooding irrigation. Correlation analysis showed that the roots at the A1 and B1 sites were positively significantly correlated with yield components and aboveground agronomic traits. Therefore, improving root development at the A1 and B1 sites at flowering stage could be a key factor to obtain higher grain yield and good agronomic performance under PMDI.

**Key words:** Rice; Plastic mulching drip irrigation; Root distribution characteristics; Grain yield.

## INTRODUCTION

Rice cultivation in flooded irrigation fields (paddies) is very water demanding. Statistics indicate that the water consumption of rice accounts for approximately 54% of the total water consumption and for more than 65% of the total agricultural water consumption in China (Mao, 2002).With increasing industrial and urban development, the need for fresh water is also increasing, thereby leading to fresh water shortage. Thus, reducing agricultural water consumption, especially for rice, is an effective approach for alleviating the shortage of water resources (Wu *et al*., 2003).

Previous studies showed that upland rice cultivation has higher water-saving space and productivity than that of conventional flooding irrigation (Bouman *et al*., 2001, Cheng *et al*., 2006). Aerobic rice and ground cover rice production system are considered as very important rice upland cultivation technologies, in aerobic rice and ground cover rice production systems, rice is grown under upland conditions with adequate inputs and supplementary irrigation according to the water demand characteristics of rice when rainfall is insufficient (Bouman *et al*., 2002, Tao *et al*., 2006). These technologies also revealed high yield and water saving space (Tao *et al*., 2006, Bouman *et al*., 2006).Thus, adequately exploring rice water-saving cultivations under the upland condition could help to ease fresh water resources crisis in China and even the world.

Plastic mulching drip irrigation (PMDI) technology has been applied to many crops because of its effectiveness in reducing soil surface evaporation and promoting crop growth and development (Ma *et al*., 1999). PMDI has tremendous water-saving capacity and higher water productivity than the furrow irrigation and sprinkler irrigation for some upland crops, such as grapes, cotton, and tomato, etc. (Malash *et al*., 2008). This technology can obviously improve the economic, social, and ecological benefits of crops. Hence, PMDI may have an important role in solving global water safety problems in the future (Shao *et al*., 2004). Although PMDI is universally accepted as an advanced water saving technology for upland crops, but supplementary irrigation of pre-existing rice upland cultivation is applied through furrow irrigation or sprinkler irrigation (Zhang *et al*., 2009, Kato *et al*., 2010). Almost no document records rice upland cultivation under PMDI so far. In recent years, limited preliminary studies have suggested that rice has high grain yield and water saving capacity under the drip irrigation with plastic mulching. Therefore, it is very interesting to know rice growth and development characteristics and productivity potential under PMDI.

The cultivation of rice under conventional flooding provides long-term growth in a stable micro-ecological environment during the growing season; however, changes in environmental conditions (i.e., flooding to upland cultivation) break the stable state and thus would affect root growth and development, root distribution, and well grain yield formation. In general, rice root distribution is less in topsoil layer and more in deep soil layer under the upland cultivation than under the conventional flooding irrigation (Kato *et al*., 2011, Zhang *et al*., 2008). However, it is widely believed that the drip irrigation cultivation promotes the upward movement of the root distribution zone (Hodgson *et al*., 1990); moreover, plastic mulching also plays an important role on facilitating rice root growth and development (Zhang *et al*., 2008). Therefore, the changes in root distribution and growth characteristics when multiple factors (upland cultivation effect, plastic mulching effect, and drip irrigation effect) interact should be determined. The surface drip irrigation system is used to provide water to plant roots. It ensures that water is available to a substantial fraction of the plant root system and that soil moisture content is non-uniformly distributed and gradually reduced with increasing distance away from the dripper sources in the soil vertical and horizontal directions (Patel *et al*., 2008). However, whether the spatial distribution characteristics of rice root vary with the non-uniform spatial distribution of water remains and the effect of root spatial distribution on aboveground part are unclear.

Based on above hypotheses, this paper aims to investigate the spatial distribution characteristics of the rice root system at the flowering stage and grain yield under plastic mulching drip irrigation.

## MATERIALS AND METHODS

**Site description:** Plot experiments were conducted at Agricultural Drought Research Institute of TianYe Group Company, XinJiang Province, China (44°26.5′N, 86°01′ E) during the rice growing season (May to October) in 2011. The soil physical and chemical properties of the experimental sites and investigation fields were similar, i.e., heavy loam (U.S.taxonomy) with 25.46 mg $kg^{-1}$ organic matter, 60.83 mg $kg^{-1}$ Alkeline-N, 25.46 mg $kg^{-1}$ Olsen-P, 342.54 mg $kg^{-1}$ available potassium, PH 8.1, and 30.11% soil saturation volume moisture content at 0-60 cm soil layer. On average over two years, the amount of solar radiation, average temperature, evaporation and precipitation were 3594.35–3686.01 MJ $m^{-2}$, 20.21–22.42 $^{o}$C, and 105.53–130.04 mm during the rice growing season (May to October) during the rice growing season (May to September), respectively. The highest month average temperature was 26.28–28.22 $^{o}$C in July.

**Plant materials and experimental design:** The NingGeng28 (*japonica*) cultivar was used in the experiments. The plots used for the experiments were covered with plastic film before sowing. Holes were punched on the membrane surface during sowing. Each plastic film had a width of 160 cm, and eight rows of rice were planted, with two drip tapes that lay under the plastic film. A drip tape was located between the second and third rice plant rows, and another was located between sixth and seventh rice plant rows. In the drip irrigation system, the emitter discharge rate was 3.20 L $h^{-1}$, and emitter spacing was 0.30 m. The row spacing configuration was 10-30-10-30-10-30-10-45 cm (Figure-1), where 10 cm represents narrow row spacing, 30 cm represents wide row spacing, and 45 cm represents the distance between the adjacent rows of the two films. The spacing of the hills within row was 10 cm, and the planting density in all treatments was 45 hills $m^{-2}$ with eight plants per hill. Seeds were sown in the dry soil by artificial hand dibbled at 3 cm depth on April 28$^{th}$ and then irrigated at 450 $m^3$ $ha^{-1}$ on April 29$^{th}$ to ensure germination because of sowing with low soil water content. Up to 50% of the plants flowered from July 30 to August 4 for all the water treatments in 2011. Root samples were collected on August 5$^{th}$ and measured the grain yield on September 5$^{th}$ for the 2011 growing season.

The experiment comprised five treatments in a complete randomized block design with three replicates, and each plot size was 31.5 $m^2$ (6 m × 5.25 m). The five treatments comprised flooding irrigation (F) as control and four drip irrigation treatments (w4, w3, w2, and w1). The treatments of w4, w3, w2, and w1 received 14, 11, 8, and 5 mm $day^{-1}$ of supplementary irrigation from the three-leaf stage to 20 d before the harvest at 2 d intervals, respectively. The intensity of supplementary irrigation was mainly based on the recent preliminary trial results of the Agricultural Drought Research Institute of TianYe Group Company, in which the average water consumption strength per day was 11 mm during the entire growing season. Thus, F was controlled at 2.25–3 × $10^4$ $m^3$ $ha^{-1}$; whereas w4, w3, w2, and w1 were controlled at 1.5 × $10^4$, 1.2 × $10^4$, 0.85 × $10^4$, and 0.55 × $10^4$ $m^3$ $ha^{-1}$, respectively. Flooding plots were also artificial hand dibbled on April 28$^{th}$ in the paddies, in which the configuration model of row space and hill space in a row was the same as that under drip irrigation. Flooding irrigation was maintained 3–5 cm free water table from three-leaf stage to 20 d before the harvest. The water was drained, and the field was left without supplementary irrigation until the grain harvest time. The irrigation application amounts was monitored with water meters installed in the irrigation pipelines of each plot, and the total amount of rainfall was calculated from rainfall gauges installed in the experimental sites. The plots were separated by water proof membranes (waterproof membranes were 0.35 mm black plastic films buried 60 cm under the soil surface) to prevent water exchange between the plots. The fertilizers applied were 270 kg N per hectare as urea, 100 kg $K_2O$ per hectare as potassium chloride, 90 kg $P_2O_5$ per hectare as calcium superphosphate and 30 kg zinc sulfate per hectare, of which 10% N, all $K_2O$, all $P_2O_5$ and all Zn were applied as basal fertilizer, the rest of N was applied in four splits: 20% at three leaf blades stage, 35% at tillering stage, 35% at panicle initiation, 10% at flowering stage.

Field investigation (FI) for PMDI was carried out at flowering and mature stages at the Agricultural Drought Research Institute of TianYe Group Company during 2011 and 2012. The irrigation application amounts of field was controlled at 1.2–1.35 × $10^4$ $m^3$ $ha^{-1}$, in which low supplementary irrigation (10–12mm $day^{-1}$) was adopted before flowering stage, whereas high supplementary irrigation intensity (25–30 mm $day^{-1}$) was adopted during grain filling stage. NingGeng28 was sown on dry soil by mechanical dibbling at 3 cm depth on April 23rd, 2011 and April 18th, 2012, respectively, and then irrigated at 450 $m^3$ $ha^{-1}$ on the next days to ensure germination due to sowing on dried soil. The cultivation mode and planting density, field management, sampling sites, and irrigation frequency were the same as that as the plot experiments. Root samples were taken on August 5th, 2011 and August 2nd, 2012 using the same sampling method and sites. No significant differences in all parameters were found between the two years for the field investigation; therefore, data from the two study years were averaged (data not presented).

**Measurements:** Root morphology was monitored at flowering stage during 2011 and 2012 by the core sampling method (Kato *et al*., 2010, 2011). Given the non-uniform distribution of water in the horizontal direction under the DI system (Patel *et al*., 2008), plant performance may exhibit differences between the near and far rows (Figure-1). Hence, three hills were taken for each row with a soil sampler (5 cm in diameter) under the DI water treatment (Figure-2). In the horizontal direction, sampling sites were set at 0, 5, and 10 cm away from the hills and then averagely divided the 0–60 cm soil layer into three layers (0–20 cm, 20–40 cm, and 40–60 cm) in the vertical direction for each horizontal sampling site (Figure-2). The samples were washed with tap water on a 0.5 mm mesh screen, and removed scraps and grass roots. A flatbed image scanner (Epson V500; Epson America, Inc., San Jose, CA, USA) was used to scan roots, and the image was saved as TIF format. The method details are available in the study of Kato *et al*. (2010, 2011). The root lengths were analyzed using WinRHIZO commercial software (Regent Instruments, Montreal, QC, Canada). After the samples were dried in an oven at 75 $^oC$ for 72 h, their root dry weight was measured. Root characteristics are shown by root length density (RLD, root length of unit volume basis, cm $cm^{-3}$), root weight density (RWD, root weight of unit volume basis, mg $cm^{-3}$) and specific root length (the ratio of root length to root weight, m $g^{-1}$). The root-to-shoot ratio (the ratio of root weight to shoot weight), root-to-leaf ratio (the ratio of root weight to leaf blade weight), and root-to-sheath ratio (the ratio of root weight to sheath weight) were also calculated. Moreover, another 18 hills per water treatment (nine hills were sampled at near row, and another nine hills were sampled at far row; Figure-2) were harvested to determine the aboveground biomass and then oven dried at75 $^oC$ for 72 h.

For the plot experiments, we dynamically measured the soil water potential at the 0–60 cm soil layer (Figure-1) using a tensiometer (watermark; Irrometer Company, Riverside, CA) from July 19th to August 9th (the maximum water consumption period) to observe the spatial and temporal distribution of soil water content. Grain yield was determined from a 2 $m^2$ site (except border plants) in each plot and adjusted to a moisture content of 0.14 g $H_2O$ $g^{-1}$ fresh weight. Panicles dry weight and yield components were determined from 18 hills sampling for the water treatment (nine hills were sampled at the near row, and another nine were sampled at far row). The root-to-panicle ratio is the ratio of the root weight at the flowering stage to the panicle weight at the mature stage). The percentage of the field grains is defined as the number of grains that sank to the bottom of a beaker filled with salt solution with a specific gravity of 1.06 as a percentage of the total spikelets.

Analysis of variance was performed using SPSS17.0 statistical analysis package. Differences between means were compared by Fisher's least-significant-difference test at the 5% and 1% probability level.

## RESULTS

**Soil water potential spatial and temporal distribution:** The soil water potential increased with increasing soil layer depth (Figure-3). During the entire monitoring period, the average soil water potential at the 0–20 cm soil layer ranged from − 25 KPa to − 141 KPa from the booting stage to the flowering stage. Soil water potential exhibited great fluctuation at the 0–60 cm soil layer under low irrigation application amount (e.g., w2 and w1) but demonstrated small fluctuation at the 0–60 cm soil layer under high irrigation (e.g., w4 and w3) (Figure-3). The differences in soil water potential between before irrigation and after irrigation were much larger for the w1 and w2 treatments than for w3, w4 treatments, respectively. However, little differences were observed at the 20–40 cm and 40–60 cm soil layers for all water treatments.

**Rice roots growth and development:** As shown in Table-1, the root dry weight, aboveground biomass, and the root-to-shoot ratio at flowering stage were significantly higher under flooding irrigation than under PMDI. The field investigations showed the same trend. Significant differences in root dry weight, aboveground biomass, and root-to-shoot ratio were found among the water treatments at 5% level, with a tendency of w4>field investigation > w3 > w2 > w1. Further analysis showed that the levels of root-to-leaf ratio and root-to-stem ratio were in the order of flooding irrigation > w4 > field investigation > w3 > w2 > w1. The root-to-panicle ratio was higher under flooding irrigation than under other treatments. However, no significant differences were observed among the treatments.

**Rice roots vertical distribution characteristics:** As shown in Figure-4, RWD and RLD decreased with increasing soil layer depth. Approximately 93% and 75–87% of the root dry weight were distributed at the 0–20 cm soil layer under flooding irrigation and PMDI, respectively. Meanwhile, more than 90% and 51–78% of the root length concentrated at the 0–20 cm soil layer under flooding irrigation and PMDI, respectively (Table-2). RWD and RLD significantly increased with increasing irrigation application amounts at 1% level. At the 20–40 cm and 40–60 cm soil layer, RWD and RLD were significantly higher under PMDI than under flooding irrigation at 5% level (Figure-4A and 4B), RWD and RLD obviously increased with decreasing irrigation amounts, but no significant differences in RWD were observed. The RWD and RLD in field investigations showed similar vertical distribution characteristics with the plot experiments compared with flooding irrigation (Figure-4C and 4D)

**Rice root length density spatial distribution characteristics:** Table-3 shows that RLD was obviously higher at the near rows than at the far rows for the plot experiments and field investigations, with slight differences among the A1, A2, and A3 sites but great differences among the other soil profile sites between the near and far rows, especially at the C1, C2, and C3 sites. The RLD changing tendencies at the near row were A1 > B1 > C1, A2 > C2 > B2, and A3 > C3 > B3, whereas those at the far row were A2 > B2> C2, A2 > B2 > C2, and A3 > B3 > C3.

For all water treatments, the RLD in both plot experiments and field investigations was in the order of A1 > B1 > C1 > C2 > B2 > A2 > C3 > B3 > A3 (Table-3). The RLD significantly decreased with decreasing irrigation application amounts at the A1, B1, and C1 sites. However, contrary tendencies were observed at other sites (A2, B2, C2; A3, B3, C3). Under flooding irrigation, the RLD at A2, B2, and C2 sites and A3, B3, and C3 sites was relatively stable; under the drip irrigation, the RLD at the C2 and C3 sites were significantly higher than that at the B2 and B3 sites, respectively (Table-3).

**Rice grain yield and its component:** Grain yield ranged from 3.35–6.86 × $10^3$ kg $ha^{-1}$ under PMDI, which was 19.30–60.31% lower than that under flooding irrigation (Table-4). Yield components analysis showed that both seed setting percentage and 1000-grain weight increased with increasing irrigation application amounts, and the differences between flooding irrigation and PMDI were significant at 5% level (Table-4). The number of spikelets per panicle can be arranged as follows: w3 > F > field investigation > w4 > w2 > w1.Under drip irrigation, grain yield and it components were obviously higher at the near row than at the far row. Except for the 1000-grain weight, significantly differences were observed for the other parameters at 5% level (Table-4).

**Correlation characteristics between RLD and aboveground agronomic traits:** Correlation analysis showed that the RLD at the A1, A2, and A3 sites had positive correlation with the aboveground dry matter parameters of the flowering and agronomic traits of panicles (Table-5). A1 and B1 had significantly positive correlation with the dry weight of leaf blades, dry weight of sheaths and culms, seed setting percentage, and 1000-grain weight at 5% or 1% level; only C1 had significant correlation with the 1000-grain weight at 1% level. The A2, B2, C2, A3, B3, and C3 sites had negative correlation with the aboveground dry matter parameters of the flowering and agronomic traits of panicles (Table-5).

**Table-1: Root length, root dry weight, aboveground biomass (dry matter), panicles dry weight (maturation stage), root-to-shoot ratio, root-to-leaf ratio, root-to-sheath ratio, and root-to-panicle ratio for the plot experiments and field investigations.**

| | Root length (km $m^{-2}$) | Root dry weight (g $m^{-2}$) | Dry matter (kg $m^{-2}$) | Panicles weight (kg $m^{-2}$) | Root –to-shoot ratio | Root-to-leaf ratio | Root –to-sheath ratio | Root –to-panicle ratio |
|---|---|---|---|---|---|---|---|---|
| Plot experiment | | | | | | | | |
| F | 2.52±0.12[a] | 53.72±2.35[a] | 1.73±0.05[a] | 1.03±0.04[a] | 0.031±0.001[a] | 0.120±0.01[a] | 0.041±0.002[a] | 0.052±0.002[a] |
| W4 | 1.67±0.03[b] | 42.21±3.11[b] | 1.45±0.08[b] | 0.84±0.02[b] | 0.029±0.005[a] | 0.112±0.01[a] | 0.039±0.001[a] | 0.05±0.001[a] |
| W3 | 1.3±0.05[c] | 33.76±2.18[c] | 1.25±0.04[b] | 0.69±0.04[c] | 0.027±0.004[ab] | 0.089±0.01[b] | 0.037±0.001[ab] | 0.049±0.002[a] |
| W2 | 1.27±0.08[c] | 29.94±1.95[c] | 1.17±0.10[c] | 0.61±0.03[c] | 0.026±0.002[b] | 0.088±0.02[b] | 0.037±0.001[ab] | 0.049±0.001[a] |
| W1 | 1.29±0.11[c] | 27.18±1.56[c] | 1.05±0.07[c] | 0.57±0.09[c] | 0.026±0.004[b] | 0.087±0.01[b] | 0.035±0.001[b] | 0.048±0.002[a] |
| Field investigation | | | | | | | | |
| F | 2.52±0.12[a] | 53.72±2.35[a] | 1.73±0.05[a] | 1.03±0.04[a] | 0.031±0.001[a] | 0.120±0.01[a] | 0.041±0.002[a] | 0.052±0.002[a] |
| FI | 1.45±0.11[b] | 38.73±3.13[b] | 1.36±0.11[b] | 0.92±0.03[b] | 0.028±0.001[a] | 0.109±0.02[a] | 0.039±0.001[a] | 0.051±0.001[a] |

Within columns followed by different lower-case letters are significantly different at 5%.

**Table-2: Percentage of root weight and root length distribution at the 0–60cm soil layer for the plot experiments and field investigations**

| | 0-20cm | 20-40cm | 40-60cm |
|---|---|---|---|
| Percentage accounted for total root weight (%) | | | |
| F | 93.23±2.22 | 5.22±1.42 | 1.55±0.30 |
| w4 | 87.17±2.13 | 10.10±1.91 | 2.73±0.31 |
| w3 | 84.10±1.52 | 12.59±1.63 | 3.31±0.52 |
| w2 | 80.73±0.51 | 13.80±1.21 | 5.46±0.81 |
| w1 | 75.03±1.50 | 15.30±2.12 | 9.67±0.72 |
| FI | 85.15±1.32 | 12.01±1.81 | 2.84±0.81 |
| Percentage accounted for total root length (%) | | | |
| F | 91.06±3.32 | 7.93±2.80 | 1.01±0.81 |
| w4 | 78.89±5.31 | 15.43±1.09 | 4.97±0.62 |
| w3 | 68.67±1.31 | 16.36±1.22 | 9.84±1.53 |
| w2 | 62.37±2.92 | 20.64±1.76 | 16.41±2.22 |
| w1 | 51.52±2.48 | 24.45±0.88 | 20.81±1.51 |
| FI | 73.52±2.41 | 15.85±1.12 | 8.65±0.90 |

Data are represented as mean±standard error, n=3

**Table-3: Spatial changes in rice root length density of the plot experiments and field investigations**

| | | A1 | B1 | C1 | A2 | B2 | C2 | A3 | B3 | C3 |
|---|---|---|---|---|---|---|---|---|---|---|
| Plot experiment | Water treatment | | | | | | | | | |
| | F | 7.23±0.66$^{a}$ | 3.17±0.55$^{a}$ | 3.51±0.65$^{a}$ | 0.42±0.11$^{bc}$ | 0.41±0.11$^{b}$ | 0.41±0.02$^{a}$ | 0.05±0.01$^{c}$ | 0.09±0.01$^{b}$ | 0.10±0.01$^{c}$ |
| | W4 | 5.08±0.15$^{b}$ | 2.05±0.35$^{ab}$ | 1.22±0.33$^{b}$ | 0.34±0.08$^{c}$ | 0.38±0.05$^{b}$ | 0.47±0.07$^{a}$ | 0.13±0.02$^{c}$ | 0.14±0.02$^{b}$ | 0.21±0.04$^{c}$ |
| | W3 | 2.67±0.41$^{c}$ | 1.83±0.01$^{ab}$ | 1.01±0.15$^{b}$ | 0.37±0.12$^{bc}$ | 0.50±0.08$^{ab}$ | 0.54±0.07$^{a}$ | 0.15±0.02$^{c}$ | 0.24±0.08$^{ab}$ | 0.37±0.02$^{b}$ |
| | W2 | 2.02±0.11$^{c}$ | 1.18±0.27$^{b}$ | 1.11±0.31$^{b}$ | 0.46±0.05$^{b}$ | 0.61±0.05$^{a}$ | 0.67±0.16$^{a}$ | 0.34±0.02$^{b}$ | 0.34±0.01$^{a}$ | 0.46±0.03$^{b}$ |
| | W1aaaw | 1.57±0.17$^{c}$ | 1.32±0.09$^{b}$ | 1.23±0.14$^{b}$ | 0.65±0.06$^{a}$ | 0.69±0.04$^{a}$ | 0.79±0.04$^{a}$ | 0.65±0.05$^{a}$ | 0.65±0.03$^{a}$ | 0.77±0.05$^{a}$ |
| | Rows | | | | | | | | | |
| | Near row | 3.76±0.36$^{a}$ | 2.17±0.28$^{a}$ | 1.32±0.05$^{a}$ | 0.51±0.02$^{a}$ | 0.29±0.04$^{a}$ | 0.40±0.01$^{a}$ | 0.21±0.01$^{a}$ | 0.13±0.01$^{a}$ | 0.19±0.02$^{a}$ |
| | Far row | 3.7±0.28$^{a}$ | 1.62±0.13$^{b}$ | 0.89±0.07$^{b}$ | 0.5±0.03$^{a}$ | 0.22±0.01$^{b}$ | 0.13±0.01$^{b}$ | 0.21±0.01$^{a}$ | 0.09±0.02$^{b}$ | 0.07±0.01$^{b}$ |
| | Difference (%) | 1.60 | 25.35 | 32.60 | 1.96 | 24.14 | 42.50 | 0 | 42.67 | 56.40 |
| Field investigation | Water treatment | | | | | | | | | |
| | F | 7.23±0.66$^{a}$ | 3.17±0.55$^{a}$ | 3.51±0.65$^{a}$ | 0.42±0.11$^{a}$ | 0.40±0.11$^{a}$ | 0.41±0.02$^{a}$ | 0.05±0.01$^{b}$ | 0.09±0.01$^{b}$ | 0.12±0.01$^{b}$ |
| | FI | 4.92±0.46$^{b}$ | 1.93±0.22$^{b}$ | 1.12±0.33$^{b}$ | 0.35±0.09$^{a}$ | 0.43±0.05$^{a}$ | 0.50±0.03$^{a}$ | 0.14±0.04$^{a}$ | 0.18±0.03$^{a}$ | 0.28±0.03$^{a}$ |
| | Rows | | | | | | | | | |
| | Near row | 5.19±0.55$^{a}$ | 2.09±0.12$^{a}$ | 1.26±0.02$^{a}$ | 0.69±0.08$^{a}$ | 0.29±0.02$^{a}$ | 0.32±0.02 | 0.41±0.04$^{a}$ | 0.17±0.01$^{a}$ | 0.19±0.02$^{a}$ |
| | Far row | 5.03±0.51$^{a}$ | 1.84±0.08$^{b}$ | 0.92±0.05$^{b}$ | 0.68±0.09$^{a}$ | 0.27±0.02$^{a}$ | 0.25±0.01 | 0.40±0.05$^{a}$ | 0.16±0.02$^{a}$ | 0.15±0.01$^{a}$ |
| | Difference (%) | 4.57 | 10.46 | 11.5 | 1.45 | 10 | 17.24 | 0 | 11.11 | 21.05 |

Data are presented as mean±standard error, n=3, within columns followed by different lower-case letters represent significant differences at 5%.

**Table-4: Grain yield and its components in the plot experiments and field investigations**

| | | Spikelets per panicle (No.) | Seed setting percentage (%) | 1000-grain weight (g) | Yield (×10$^{3}$ kg ha$^{-1}$) |
|---|---|---|---|---|---|
| Plot experiment | Water treatment | | | | |
| | F | 106.21±2.35$^{a}$ | 80.01±2.01$^{a}$ | 25.32±0.95$^{a}$ | 8.44±0.35$^{a}$ |
| | W4 | 101.98±1.78$^{ab}$ | 46.13±1.38$^{c}$ | 22.03±0.56$^{b}$ | 5.97±0.27$^{b}$ |
| | W3 | 108.52±3.33$^{a}$ | 42.83±2.22$^{c}$ | 21.36±0.49$^{b}$ | 5.11±0.18$^{c}$ |
| | W2 | 94.52±4.12$^{b}$ | 37.63±1.85$^{c}$ | 21.05±0.33$^{b}$ | 3.98±0.34$^{d}$ |
| | W1 | 86.43±5.11$^{c}$ | 30.83±1.53$^{d}$ | 19.84±0.67$^{b}$ | 3.35±0.26$^{d}$ |
| | Row | | | | |
| | Near row | 103.44±3.33$^{a}$ | 42.45±1.13$^{a}$ | 21.33±0.21$^{a}$ | 5.33±0.24$^{a}$ |
| | Far row | 92.27±2.86$^{b}$ | 36.26±1.05$^{b}$ | 20.81±0.32a | 4.31±0.17$^{b}$ |
| | Difference (%) | 10.79 | 14.58 | 2.44 | 19.14 |
| Field investigation | Water treatment | | | | |
| | F | 106.21±2.35$^{a}$ | 80.01±2.01$^{a}$ | 25.32±0.95$^{a}$ | 8.44±0.35$^{a}$ |
| | FI | 106.43±1.66$^{a}$ | 66.83±1.69$^{b}$ | 22.31±0.33$^{b}$ | 6.86±0.25$^{b}$ |
| | Row | | | | |
| | Near row | 108.11±1.53$^{a}$ | 68.41±1.05$^{a}$ | 22.70±0.21$^{a}$ | 7.25±0.33$^{a}$ |
| | Far row | 105.65±1.75$^{b}$ | 65.35±1.38$^{b}$ | 21.92±0.24$^{a}$ | 6.57±0.28$^{b}$ |
| | Difference (%) | 3.20 | 4.47 | 3.44 | 9.38 |

Data are presented as mean±standard error, n=9, within columns followed by different lower-case letters are significantly different at 5%

**Table-5: Correlation coefficient between RLD and aboveground agronomic traits in the plot experiments and field investigations (n = 16)**

| | A1 | B1 | C1 | A2 | B2 | C2 | A3 | B3 | C3 |
|---|---|---|---|---|---|---|---|---|---|
| Dry weight of leaf blades | 0.944** | 0.98** | 0.82 | -0.51 | -0.85* | -0.87* | -0.78 | -0.77 | -0.90* |
| Dry weight of sheaths and culms | 0.93** | 0.90** | 0.80 | -0.47 | -0.85* | -0.84* | -0.70 | -0.77 | -0.85 |
| Spikelets per panicle | 0.61 | 0.64 | 0.35 | -0.82* | -0.81* | -0.86* | -0.92* | -0.87* | -0.81 |
| Seed setting percentage | 0.91* | 0.91* | 0.82 | -0.65 | -0.81* | -0.90* | -0.85* | -0.86* | -0.94* |
| 1000-grain weight | 0.95* | 0.92* | 0.90* | -0.50 | -0.73 | -0.86 | -0.76 | -0.76 | -0.90* |

* and ** represent significantly different at the 5% and 1% levels, respectively. Each treatment in the plot experiments and field investigations had 2 groups data (i.e., the near rows and far rows)

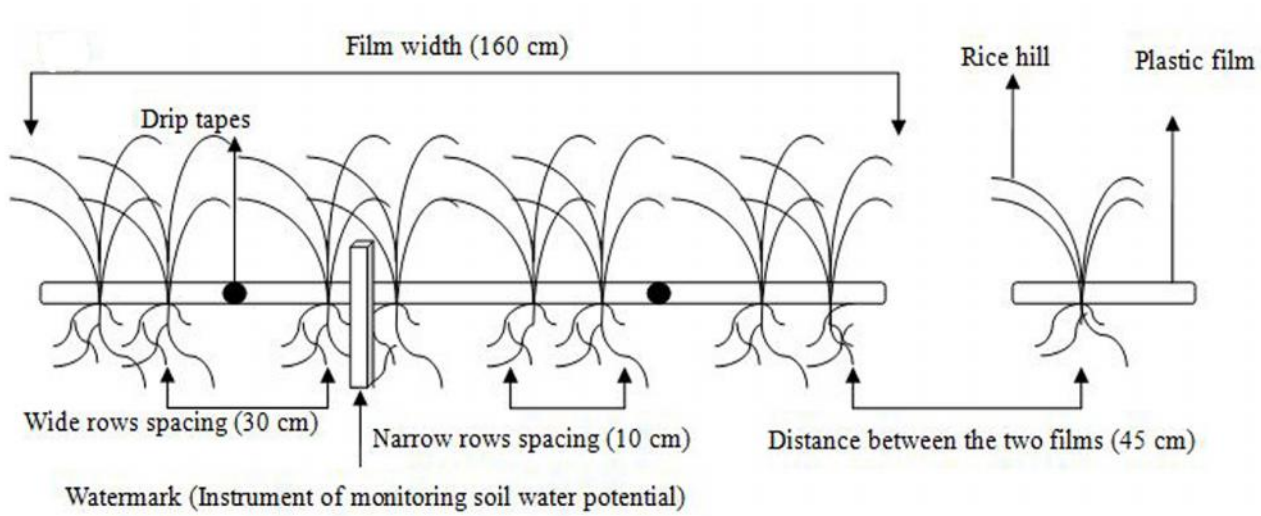


**Figure-1: Sketch map of the planting mode under plastic mulching drip irrigation**

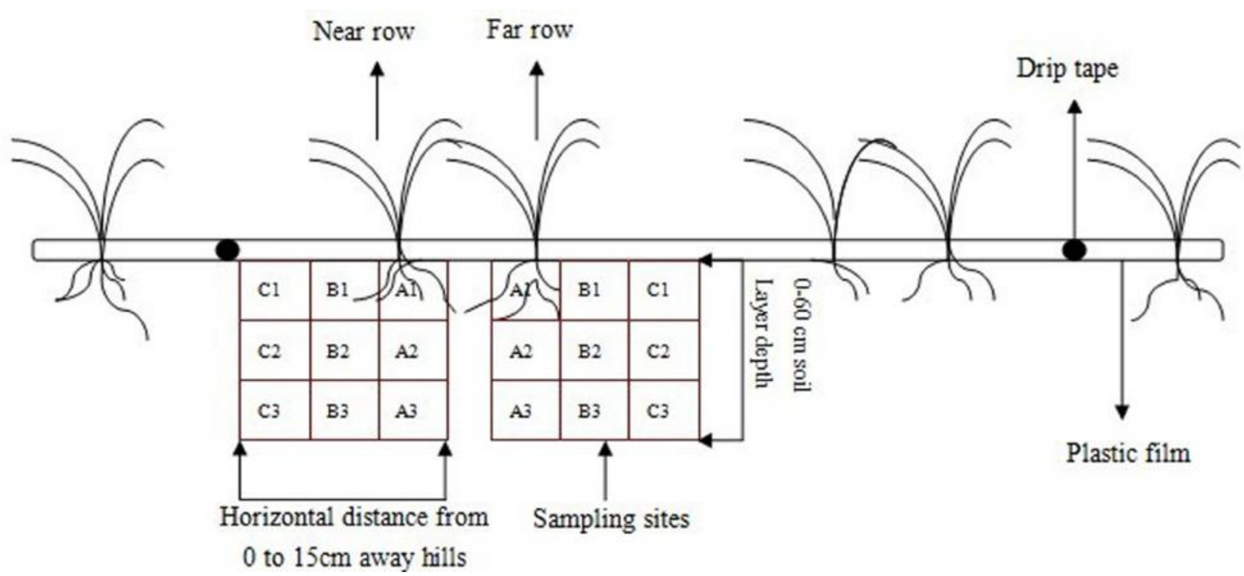


**Figure-2: Sketch map of the spatial sampling sites. Capital letters represented the sample sites, the blank areas between the two rows were averagely divided into two rows. Error span of the root sample sites is ±2.5 cm**

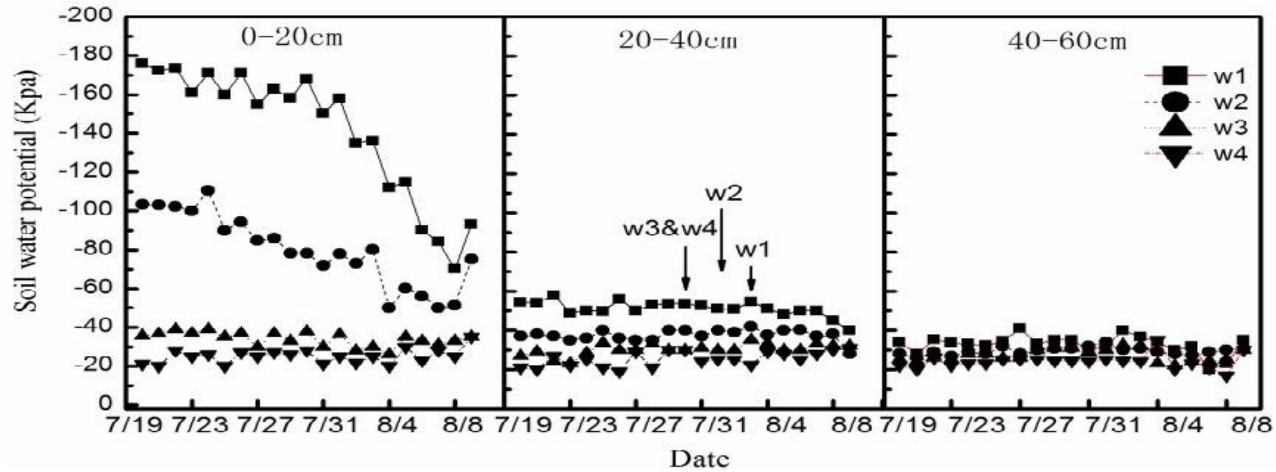


**Figure-3: Spatial and temporal distribution of soil water potential under different water treatments, arrows represent flowering date**

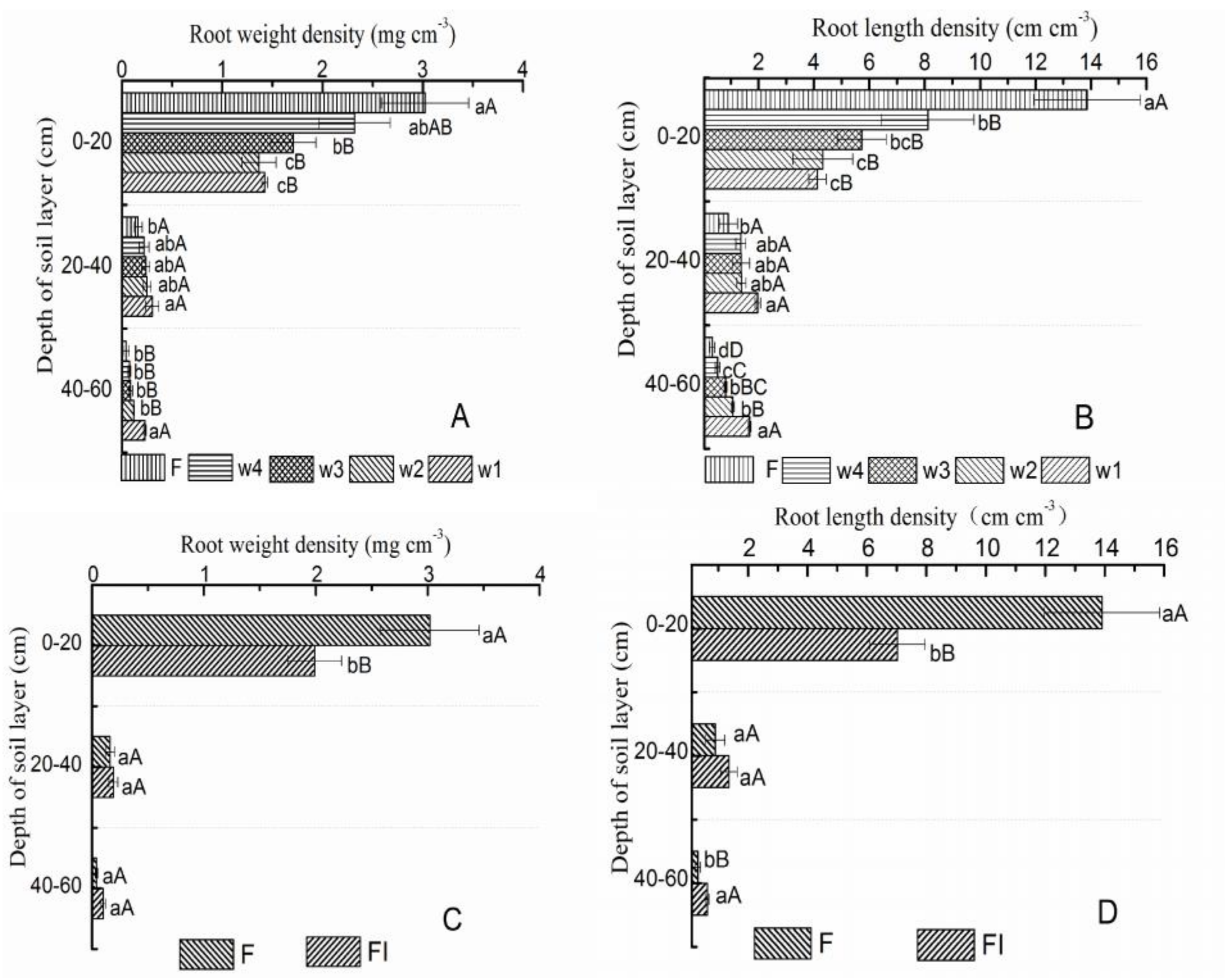


**Figure-4: Root weight density (A and C) and root length density (B and D) of plot experiments (A and B) and field investigations (C and D). Horizontal bars represent standard error of mean, n=3; different lower-case and capital letters represent significantly different at 5% and 1% levels, respectively.**

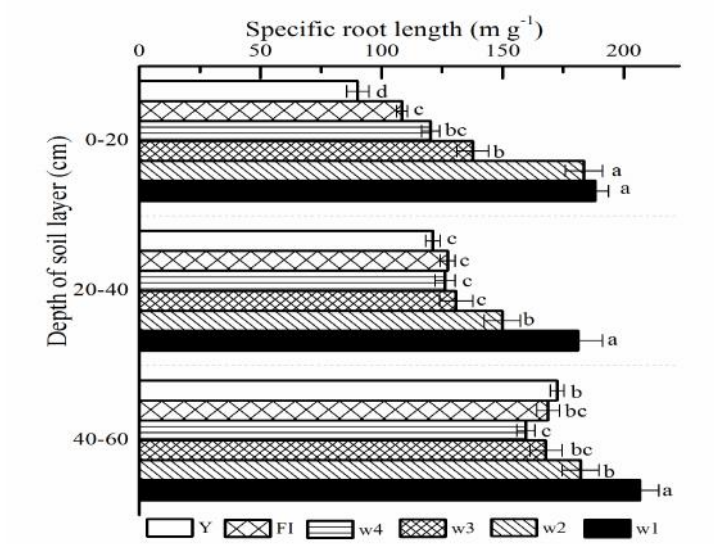


**Figure-5: Specific root length under five water treatments for plot experiments and field experiments, Horizontal bars represent standard error of mean, n=3**

## DISCUSSION

Root biomass obviously decreased under the PMDI than under flooding irrigation (Table-1), which was mainly relevant to the marked reduction at the 0–20 cm soil layer (Figure-2A). These results are consistent with those of previous studies. Kato *et al.* (2010) revealed that rice root biomass mainly depends on the surface soil layer under the upland cultivation system. Dry matter partitioning between the aboveground and underground parts are affected by soil moisture (Kato *et al.,* 2006, 2009; Bibi *et al.,* 2013), which depends on water stress period, degree, and the duration (Chen *et al*., 2004). The ratios of root to shoot, root to leaf ratio, root to sheath ratio, and root to panicle ratio were higher under flooding irrigation than under PMDI; these ratios reduced with decreasing irrigation application amount under drip irrigation (Table-1). These results showed that restricted degree of dry matter partitioning is greater in the root zone than in shoot and that the restricted degree intensified with decreasing irrigation application amount under drip irrigation.

Specific root length is considered as an important index that characterizes root diameter; small specific root length indicates a thick root system (Kato *et al*., 2010). As shown in Figure-5, the specific root length at the 0–20 cm soil layer was greater under PMDI than under flooding irrigation. It increased with decreasing irrigation amount under PMDI. The results showed that the morphological structure of the topsoil roots was thinner under drip irrigation than under flooding irrigation and that the root diameters significantly decreased with decreasing irrigation application amount under drip irrigation. Soil strength (mechanical impedance) at 0–30 cm soil layer increased greatly with decreasing soil water content during the drought as the soil dried for the rice and the dried soil is likely to have prevented or greatly impaired further nodal root growth within this layer (Cairns *et al*., 2004). In addition, thin roots cannot benefit from the root system penetration strength in the soil, which affected root growth and development (Clark *et al*., 2003, 2008). Therefore, the thin root system and high soil strength may account for the lower root distribution at the 0–20 cm soil layer under drip irrigation than under flooding irrigation. They may also be responsible for the decreased root distribution at this soil layer with decreasing irrigation application amount under drip irrigation. Given the higher soil water content at the 40–60 cm soil layer for all treatments and the significantly higher soil water content than the 0–20 cm soil layer for the same water treatment under drip irrigation (Figure-3), the soil water distribution characteristic could benefit deep root growth and development under drip irrigation, especially under low irrigation. This inference is supported by Asseng *et al*. (1998), who reported that topsoil root growth is restricted and that deep soil root growth is accelerated when the soil water content at the surface soil layer is low and when the plant is exposed to water deficit. As a result, deep roots were larger under PMDI than under flooding irrigation and obviously increased with decreasing irrigation amount (Figure-4).

Under water-limiting conditions, water extraction by dryland crops is limited by the depth of the root system, and by the rate and degree of water extraction (Robertson *et al*., 1993). RLD is an important indicator of potential water uptake (Coelho *et al.,* 1999; Clark *et al.,* 2003), and a positive relationship exists between RLD and water uptake (Clothier *et al*., 1990;

Coelho *et al*., 1999). Therefore, a large rice root system is an important guarantee in adapting to upland environment (Morita *et al*., 1993). Comparing with flooding irrigation, the RLD at 20–60 cm soil layer was approximately 2.5–5 times higher under PMDI than flooding irrigation (Table-2). As the RLD of the roots at the 0–20 cm soil layer decreased, that at the 20–60 cm soil layer increased among the different water treatments (Figure-2B). Rice deep-root system could play an important role on easing water stress and enhancing adaptability by absorbing deep-soil water and nutrition (Lilley *et al*., 1994).

Our study showed that the difference in RLD between the near and far rows increased with decreasing irrigation application amount (data not presented). Soil moisture content is non-uniformly distributed and gradually reduced with increasing distance away from the dripper sources in the soil vertical and horizontal directions (Patel *et al*., 2008). Therefore, based on the water distribution characteristics under drip irrigation, a relatively low root density at the far row could be mainly related to low soil moisture under the same treatment. The root distribution tendencies at the 20–60 cm soil layer were A2 > C2 > B2 and A3 > C3 > B3 at the near row. On average, C2 and C3 sites had remarkably higher roots than B2 and B3 sits, the reason could be related to the higher soil content at the C2 and C3 sites than at the B2 and B3 sites (Figure-2). Finally, high soil water content could promote root growth and development. However, the root distribution trends at the far row were A2 > B2 > C2 and A3 > B3 > C3. These results were also explained by the non-uniform water distribution characteristics of soil at the B2 and C2 and B3 and C3 sites (Figure-2) The B2 and B3 sites could have higher water contents than the C2 and C3 sites, respectively. In addition, the root distribution characteristics at the 0–20 cm soil layer were A1 > B1 > C1 at the near and far rows. Therefore, these results also indicate that the root spatial distribution features at the 0 cm to 20 cm soil layer mainly depend on rice hill sites and not on the location of drip tapes. However, deep root distribution characteristics are principally affected by soil moisture or the location of drip tapes under drip irrigation.

Grain yield and its components significantly decreased under drip irrigation than under flooding irrigation. These results are in agreement with previous studies on upland rice cultivation (Belder *et al*., 2004, 2005, Fan *et al*., 2005, Liu *et al*., 2005, Sarwar *et al.*, 2013). Under drip irrigation, the highest yield reached to $6.86 \times 10^3$ Kg $ha^{-1}$. Meanwhile, the drip irrigation system had twice the water use efficiency of the flooding irrigation (data not presented). Thus, PMDI would play an important role in rice water-saving technology. Correlation analysis between RLD and aboveground agronomic traits showed that the roots at the 0–20 cm soil layer (A1, B1, and C1) had positive correlation with aboveground agronomic traits and that the roots at the 20–60cm soil layer (A2, B2, and C2; A3, B3, and C3) had negative correlation with aboveground agronomic traits (Table-5). These results indicate that the roots at the 0–20cm soil layer, especially at the A1 and B1 sites, could be the main-functional zones that provide material and water from soil to aboveground part. This finding is attributed to their significant correlation with yield component. Therefore, promoting root growth and development at the 0–20 cm soil layer can improve grain yield and performance under drip irrigation, especially at the A1 and B1 sites.

**Conclusions:** Although PMDI had lower grain yield than that of flooding irrigation, but water-saving capacity was clearly higher under PMDI than under flooding irrigation. Meanwhile, the grain yield reached to $6.86 \times 10^3$ Kg $ha^{-1}$ under PMDI. Therefore, PMDI would be considered as innovative water-saving rice cultivation techniques. Under PMDI, root spatial distributions were closely related to soil moisture distribution characteristics. Significant differences in roots and aboveground performance were observed between the near and far rows, but the effect of differences between rows on high yield production need follow-up studies.

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