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*Full Length Article*

# Water and Fertilizer Utilization and Characteristics of Rice Root Growth under Rainwater Storage Irrigation

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## Abstract

Root system is the main organ for absorbing water and nutrients and its morphological characteristics are related to the development status of above ground part and final grain yield of rice. This study investigated utilization of water and fertilizer under rainwater storage irrigation (RI) and changes of root growth indicators. Results showed that, the averaged root weight for RI was lower than conventional flooding irrigation (CI), while the main root length for RI was higher. The white root ratio (the percentage of white root) was reduced relatively slower in whole growth stage. Rainfall utilization efficiency (RUE) for RI was 2.6 and 3.5 times CI in 2013 and 2014, showing a rather better rainfall utilization efficiency. Water utilization efficiency (WUE) for RI was almost twice and 1.5 times of CI in 2013 and 2014, respectively. The irrigation regimes showed significant effect on RUE and WUE. Nitrogen use efficiency (NUE) for CI was 8.5 and 8.7% higher than RI in 2013 and 2014, respectively. Nitrogen accumulation in above ground part of rice plant and WUE both showed positive correlation with root activity, while NUE showed no relevance to root activity. Therefore, under rainwater storage irrigation mode, root activity and WUE was promoted, preventing premature aging of roots in the late growth stage of rice. 

**Keywords:** Root growth; Water utilization efficiency; Nitrogen accumulation; Regression analysis

## Introduction

Water is an important factor for yield formation. Water-saving irrigation technology is particularly important because of large amount of water is required during growth period of rice. Excessive water irrigation could result in lower water utilization efficiency (WUE), while deficit irrigation could improve yield and water utilization (Hu *et al*. 2008; Zhang *et al*. 2014). Moreover, many rainfall events occur at rice growth stage in southern China, and most of the rainwater is wasted through paddy field runoff, resulting in low rainwater utilization efficiency and non-point source pollution (Xiao *et al*. 2019). Therefore, rainwater storage irrigation is developed to improve the rainfall utilization efficiency based on the response characteristics of rice growth and yield to water stress (Chen *et al*. 2011). It showed that the plant height and yield was higher under rainwater storage and control irrigation than under flooding irrigation, while the leaf area index was lower. The irrigation quota was reduced, while use efficiency of rainfall increased obviously (Guo *et al*. 2010). Also, the effective nutrients in soil increased obviously and could be transferred to grain (Li and Xie 2001; He *et al*. 2006; Xu *et al.* 2018). Therefore, rainwater storage irrigation has great potential for development in southern China.

Root system is the main organ for absorbing water and nutrients and its amount, weight and length determine the development status of above ground part and final grain yield of rice (Liu *et al*. 2002; Yang 2011; Guo *et al*. 2012; Zhang *et al*. 2013). The effect of water stress on root activity was different according to the degree of stress, and water treatment mode (Ma *et al*. 2010; Zhang *et al*. 2017). Previous studies have found that water stress at different growth stages of rice could result in difference on root growth and yield (Wang *et al*. 2013; Yang *et al*. 2016; Zhao *et al.* 2018). The total amount of root was higher and stronger under intermittent irrigation, compared to flooding. Light water stress or drought could promote root activity and photosynthetic performance and yield will not be decreased significantly after re-watering. However, at water sensitive period of rice growth could result in reduction of grain number and thousand grain weight (Wei *et al*. 2010; Liang *et al*. 2015). Ahmadi *et al.* (2014) found that, the growth of root system was promoted under moderate drought condition, while it was restricted and root length decreased with severe drought. Xiao *et al.* (2016) found that

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root growth and activity was promoted with aeration irrigation.

The water-saving effect of rainwater storage irrigation showed that irrigation frequency and amount was reduced, however, the mechanism of rainwater storage irrigation is not clear (Li *et al.* 2016). The present study evaluated the effect of water and fertilizer utilization under rainwater storage irrigation mode on root growth for improving yield and fertilizer utilization.

## Materials and Methods

### Experimental site

This study site was located at Vegetables (Flowers) Scientific Institute, (latitude 31°43′N, longitude 118°46′E), Jiangning District of Nanjing, Jiangsu province in China during rice growing season from June to October in 2013 and 2014. The experimental site has the average annual rainfall of approximately 1107 mm, 2017.2 sunshine hours, average annual temperature of about 15.7℃, average yearly evaporation about 1472.5 mm and maximum average humidity was 81%.

The paddy field soil was clayey loam, with organic matter 21.7 g $kg^{-1}$, field capacity 28%, pH 5.87, bulk density 1.35 g $cm^{-3}$, hydrolysis nitrogen 86.5 mg $kg^{-1}$ and available phosphorus 25.3 mg $kg^{-1}$ at the 0–60 cm soil layer.

### Experiential design

Paddy rice (*Oryza sativa* L. cv. Kaohsiung 139) was grown using the random block method with three replications of equal size (2 m×5 m). Two water irrigation schemes were set up in this study, conventional irrigation (CI) and rainwater storage irrigation (RI). All plots were treated with the same fertilizer management. Basal fertilizer was applied before rice transplantation according to local practice, with total nitrogen 193 kg $hm^{-2}$ and 214 kg $hm^{-2}$ in 2013 and 2014, $P_2O_5$ 134 kg $hm^{-2}$ and $K_2O$ 120 kg $hm^{-2}$. Then dressing nitrogen fertilizer was applied at tillering and heading-flowering stages, accounting for 70 and 30% of basal nitrogen fertilizer amount, respectively. The experimental site layout is shown in Fig. 1.

For rainwater storage irrigation, both paddy soil moisture and rainfall amount were considered as the controlling targets for irrigation regime after the green-returning stage. Depending on different growth stages of the paddy rice, the lower limit was 60–80% of saturated water content, while the upper control limit of soil moisture was the saturated water content during irrigation, with no field water layer after the re-greening stage. If precipitation happened, the upper limit of rain ceiling storage was controlled at 20–70 mm according to different growth stages (Table 1). The main advantage for rainwater storage irrigation is making full use of natural rainwater compared to CI treatment.

### Indicators and methods

At each growth stage, 3 rice plants were selected randomly, then the root part was separated from the above ground part and washed for measurement. Fresh root weight was measured, main root length was measured by the ruler, ratio of white root was calculated by counting. Nitrogen content in root part and above ground part of rice plant was measured by Kjeldahl method (Bao 2000). Actual yield of rice was weighed by the scale.

The rainfall amount during the whole rice growth period in 2013 and 2014 was measured by SM1-1 type rainfall recorder. Soil water content was measured by TDR. Field leakage was calculated by lysimeter. The water amount of irrigation and drainage along with the experimental period was obtained by water meter and measure pit (Fig. 2).

Water requirement is the sum of plant transpiration and evaporation, reflecting the need for water of crop. In this study, the actual water requirement at each growth stage was calculated according to water balance in paddy field. The formulas of water balance with water layer (1) and without water layer (2) in paddy field were as follows;

$$ET=Re+I-D-P-\Delta S \quad (1)$$

Where, ET (mm) is evapotranspiration, or water requirement; Re (mm) is effective rainfall; I (mm) is irrigation amount; D (mm) is drainage amount in field surface; P (mm) is field leakage; ΔS (mm) is the change of field water layer.

$$ET=Re+I-P-0.1\Delta SA_0H \quad (2)$$

Where, ET (mm) is evapotranspiration, or water requirement; Re (mm) is effective rainfall; I (mm) is irrigation amount; P (mm) is field leakage; ΔS (%) is the change of soil water content; $A_0$ (%) is soil porosity; H (mm) is the depth of crop root water absorption.

### Data analysis

Chart was drawn according to Excel 2013. Data was statistically analyzed using one-way analysis of variance to test the difference of two irrigation treatments through SPSS statistical software.

## Results

### Changes in fresh root weight and main root length under different water treatments

The change in fresh root weight and main root length for different water treatments showed that root weight in whole growth stage of rice varied greatly in relatively dry year 2013 compared to the relatively wet year 2014, showing increasing and then decreasing trend, reaching its peak at joint-booting and heading-flowering stages for 2013 and

**Table 1:** Controlling targets of soil moisture during paddy rice growth stages in two irrigation regimes

| Treatment | Re-greening | Tillering | | | Jointing-Booting | Heading-Flowering | Milking |
|---|---|---|---|---|---|---|---|
| | | Early | Mid-term | Late | | | |
| RI | 100% (5-25) | 70% (0-50) | 65% (0-50) | 60% (0-0) | 80% (0-70) | 80% (0-70) | 65% (0-20) |
| CI | 100% (30-50) | 100% (0-30) | 100% (15-30) | 60% (0-0) | 100% (30-50) | 100% (30-50) | 100% (15-30) |

Notes: (1) The first number is a percentage of the saturated water content of soil. (2) The numbers in parenthesis is a range of the storage depth of surface water in mm in the paddy field

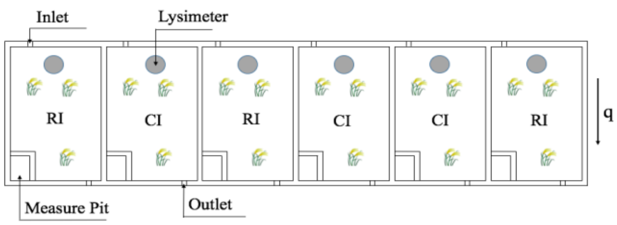


**Fig. 1:** Test Area Layout

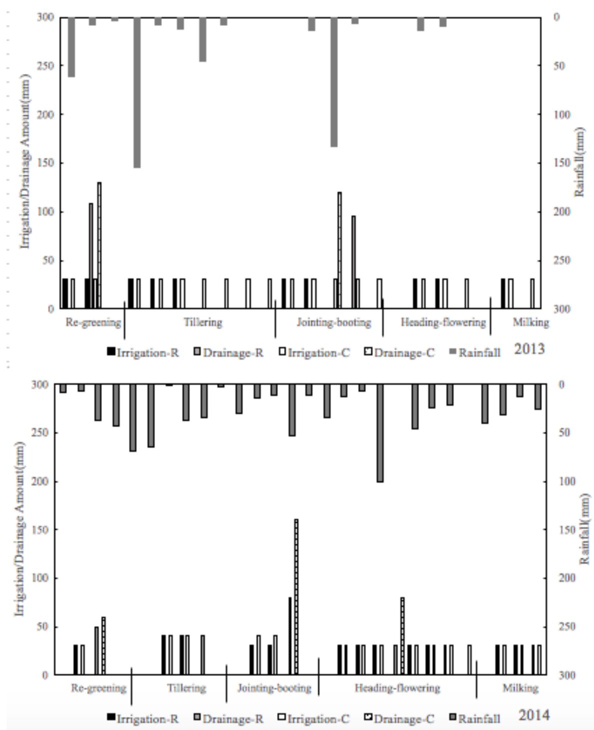


**Fig. 2:** Rainfall received and irrigation & drainage applied in the entire rice growth period

2014, respectively (Fig. 3). In 2013, the maximum difference of root weight for CI and RI treatments was at tillering stage, which was 23.38 g and water showed extremely significance. Then at jointing-booting stage, there was no difference under two irrigation modes. However, the root weight for CI was higher than RI at all growth stages in 2014 (Fig. 3).

The length of main rice root increased quickly from re-greening stage to tillering stage and then it was rather stable in the other growth stages in 2013. The change trend of main root length in 2014 showed increasing slowly till heading-flowering stage, and then decreased at milking stage, with the maximum values of 26.1 cm and 24.6 cm for CI and RI. The main root length for CI was slightly lower than RI except at heading-flowering stage both in 2013 and 2014. The effect of water on main root length at whole growth stages was not significant.

**Change of rice white root ratio**

There is white root, yellow root and black root distributed during growth of rice. The color of root could reflect the root activity, and the growth of rice was positively related to the proportion of white root. The better the soil ventilation, the higher the proportion of white roots. The ratio of white root was highest at re-greening stage for both RI and CI treatments, then it decreased quickly at tillering stage and gradually reduced at jointing-booting and heading-flowering stages, till reducing to a rather lower level at milking stage (Fig. 4).

The white root ratio for CI treatment was 88.8 and 51.9% higher respectively in 2013 and 2014, compared to RI at the re-greening stage, and water showed extremely significant effects. However, it was lower for CI or little difference with RI in the other growth stages. The decreasing rate of root activity for RI was slower than CI during whole growth period.

**Analysis on rainfall for different water control treatments**

According to the comparative analysis on rainfall at growth stages of rice (Table 2), the rainwater amount in 2013 (488.2 mm) was much lower than in 2014 (778.3 mm). The rainfall in 2013 was mainly concentrated at tillering and jointing-booting stages of rice, with the total amount of 388.4 mm, accounting for 79.6% of total rainfall in whole growth period. Most rainfall occurred at tillering stage, accounting for 47.7%, while there was no rainfall during milking stage. The rainfall in 2014 was much more uniform for each growth stage. It rained most at heading-flowering stage, accounting for 27.1% of the total rainfall, while it was smallest at milking stage, accounting for 12.9%. Therefore, the distribution of rainfall in different years varied greatly among different growth stages. Basically, June and July are the rainy season at the study area, and the rice at the tillering stage received abundant rainfall while 2013 is relatively dry year and 2014 is the relatively wet year.

**Table 2:** Water requirement for different water control treatments at each growth stage

| Year | Growth Stage | Rainfall (mm) | Growth Days (d) | RI | | CI | |
|---|---|---|---|---|---|---|---|
| | | | | Water Requirement (mm) | DWR (mm $d^{-1}$) | Water Requirement (mm) | DWR (mm $d^{-1}$) |
| 2013 | Re-greening | 75.2 | 11 | 21.7 | 1.97 | 22.5 | 2.05 |
| | Tillering | 232.8 | 36 | 112.7 | 3.13 | 138.4 | 3.84 |
| | Jointing-Booting | 155.6 | 30 | 143.5 | 4.78 | 182.7 | 6.09 |
| | Heading-Flowering | 24.6 | 25 | 154.9* | 6.16 | 213.2* | 8.53 |
| | Milking | 0 | 16 | 47.5 | 2.97 | 50.7 | 3.17 |
| | Whole Period | 488.2 | 118 | 480.3* | 4.07 | 607.5* | 5.15 |
| 2014 | Re-greening | 156.3 | 10 | 44.0 | 4.40 | 45.0 | 4.50 |
| | Tillering | 166.6 | 31 | 182.6 | 5.89 | 192.9 | 6.22 |
| | Jointing-Booting | 143.7 | 31 | 189.8 | 6.12* | 216.3 | 6.98* |
| | Heading-Flowering | 211.3 | 45 | 169.0 | 3.76 | 201.0 | 4.47 |
| | Milking | 100.4 | 16 | 63.2 | 3.95 | 54.8 | 3.43 |
| | Whole Period | 778.3 | 133 | 648.6 | 4.88 | 710.0 | 5.34 |

Note: There was significant differences (*) at $P \leq 0.05$

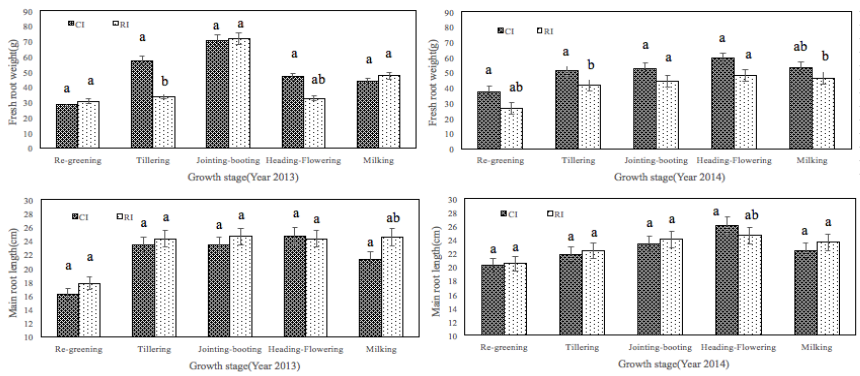


**Fig. 3:** Change of fresh root weight and main root length for different water treatments

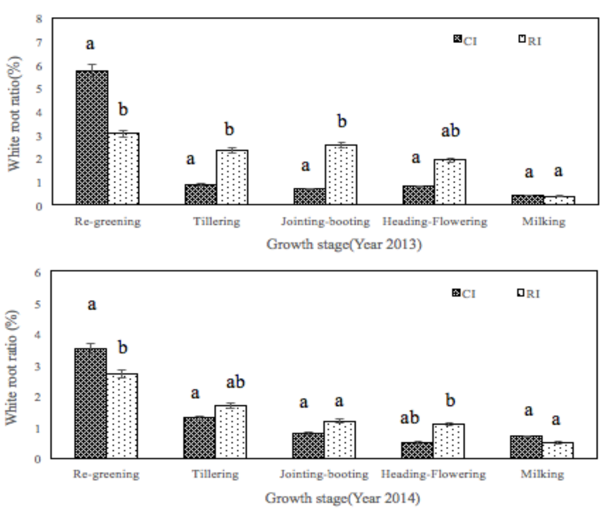


**Fig. 4:** Change of rice white root ratio for different water treatments

## Water requirement and consumption for different water control treatments

The water requirement at heading-flowering stage in 2013 was highest, followed by jointing-booting stage (Table 2). The maximum water demand for rain-storage irrigation (RI) treatment accounted for 32.3% of the whole growth period. As for conventional irrigation (CI), the water demand at heading-flowering stage accounted for 35.1% and the water effect was significant at this stage. In 2014, the water requirement was not much different at the other growth stages in addition to the small water demand during re-greening and milking stages. The maximum water requirement for RI and CI accounted for 29.3 and 30.5% respectively of total water requirement in whole growth period. The water requirement of whole growth period for RI was 127.2 mm and 61.4 mm lower than CI in 2013 and 2014, respectively and was 20.9 and 8.6% lower. Therefore, according to rain-storage irrigation, the water requirement had different degrees of reduction, and the use of rainwater was strengthened under water stress, which was favorable for root growth. The difference was mainly reflected at the late growth stage and results were consistent with the previous results in above section.

For daily water requirement (DWR), it was 21.7% lower for RI compared to CI during whole growth period in 2013. The DWR at heading-flowering stage was highest, followed by jointing-booting stage, while the re-greening stage was smallest. The highest DWR for RI was 2.37 mm $d^{-1}$ lower than CI and water effect was not significant at each growth stage. In 2014, the DWR was 8.6% lower for

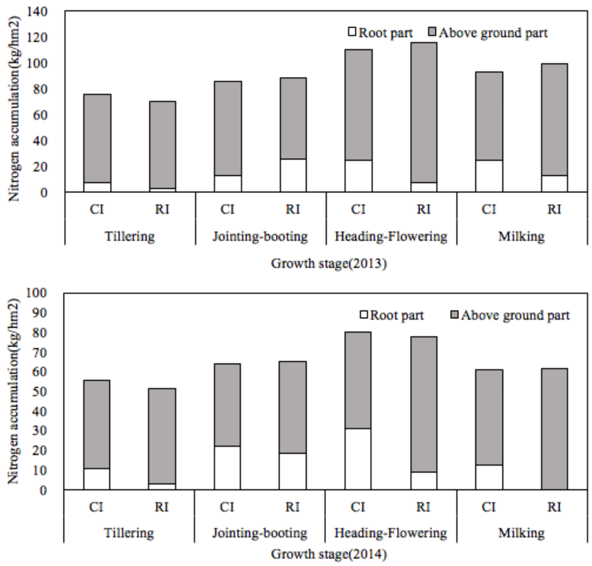


**Fig. 5:** Nitrogen accumulation in above ground and root parts of rice plant

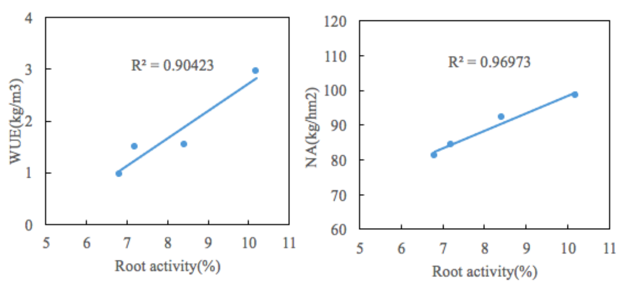


**Fig. 6:** Relationship between root activity, WUE and NA

RI with comparison to CI. It was highest at joint-booting stage and smallest at re-greening stage. The highest DWR for RI was 0.86 mm $d^{-1}$ lower than for CI.

The difference for water requirement between two irrigation modes in relatively wet year was less. The water requirement and DWR at heading-flowering stage in 2013 was highest, while in 2014, it was highest at jointing-booting stage. Therefore, heading-flowering and jointing-booting stages were two critical periods of rice water requirement and this result was consistent with Liu's research (Liu *et al*., 2005).

It was clear that the evapo-transpiration and leakage for CI of paddy field was higher than RI, which was due to the relatively more water loss of evaporation under irrigation with water layer for CI treatment, therefore, the water consumption in paddy field was large (Table 3). As for evapo-transpiration analysis in each growth stage, the evaporation between rice plants and transpiration were both small because the rice plant was small at re-greening stage. At this time, the paddy soils in CI and RI treatments were water-saturated, and also the field leakage was not much different. Therefore, the evapo-transpiration and water consumption of rice plants were the smallest in the whole growth period. At the early tillering stage, it was the critical period of rice growth, and the water requirement of rice plants increased gradually. The water consumption also increased with the increase of temperature. At the late tillering stage, due to factors such as field drying, the water in the paddy field decreased and the amount of evapo-transpiration decreased slightly, while the amount of leakage was significantly reduced. The reproductive growth began from the jointing and booting stage. The early nutrient accumulation laid the foundation for reproductive growth, the solar radiation and temperature reached the best during the whole growth period. At this time, the plant transpiration and water consumption were larger, reaching the maximum at the heading-flowering stage. At the milking stage, the amount of evapo-transpiration and water consumption decreased lowly due to the slower growth of rice plants and the decrease of temperature, and field leakage amount also decreased with the decrease of irrigation water amount.

As for RI treatment, in 2013, the amount of evapo-transpiration during the whole growth period of rice decreased by 20.9% compared with the CI treatment, and it decreased significantly at the jointing-booting and heading-flowering stages, which were 39.2 mm and 58.3 mm, that was 21.5 and 27.3%, respectively, compared with CI. Therefore, the reduction rate of evapo-transpiration amount in the heading-flowering stage was the largest and the irrigation mode had a significant impact on the total evapo-transpiration during the whole growth period. This was because the water condition was the decisive factor affecting the rice evapo-transpiration. Field leakage was mainly related to soil conditions. There was no significant difference in the amount of leakage in paddy fields during the growth stages of rice (Table 2). This reached the lowest at the field drying period. In 2013 and 2014, the leakage of paddy fields under RI was 49.4 and 15.9% lower than CI, respectively, which was mainly caused by the reduction of irrigation water amount. The trend of water consumption in the field was consistent with the change of evapo-transpiration. In 2013, the water consumption of rice under RI treatment was 26.2% lower than CI. The effect of irrigation on water consumption was significant in the mid-tillering and heading-flowering stages, with the largest decrease at the heading-flowering stage, which was 29.8%.

In 2014, the impact of irrigation on evapo-transpiration and leakage in rice fields was not significant. This was because the rainfall in 2014 was sufficient, so the impact of irrigation methods was not obvious. The evapo-transpiration for RI was 8.6% lower than CI during whole growth period, and it decreased the most at the heading-flowering stage, which was 15.9%. However, the amount of rice evapo-transpiration under RI at the milking stage was slightly higher than CI. The change trend of water consumption was consistent the evapo-transpiration. The water consumption of the rice under RI was 10.2% lower than CI and it decreased most significantly at the heading-flowering stage, which was 19.3%. Similarly, the water consumption of the rice under RI at milking stage was

**Table 3:** Water consumption for different water control treatments at each growth stage

| Irrigation Mode | Growth Stage | Year 2013 | | | Year 2014 | | |
|---|---|---|---|---|---|---|---|
| | | Evapo-transpiration (mm) | Leakage (mm) | Water consumption (mm) | Evapo-transpiration (mm) | Leakage (mm) | Water consumption (mm) |
| CI | Re-greening | 22.5 | 16.1 | 38.6 | 45.0 | 20.7 | 65.7 |
| | Early Tillering | 36.9 | 14.3 | 51.2 | 64.4 | 20.9 | 85.3 |
| | Mid-tillering | 53.0 | 17.9 | 70.9* | 68.0 | 23.4 | 91.4 |
| | Late Tillering | 48.5 | 9.5 | 58.0 | 60.5 | 16.0 | 76.5 |
| | Jointing-Booting | 182.7 | 27.6 | 210.3 | 216.3 | 47.6 | 263.9 |
| | Heading-Flowering | 213.2* | 34.3 | 247.5* | 201.0 | 51.6 | 252.6* |
| | Milking | 50.7 | 18.6 | 69.3 | 54.8 | 21.0 | 75.8 |
| | Whole Period | 607.5* | 138.3 | 745.8* | 710 | 201.2 | 911.1 |
| RI | Re-greening | 21.7 | 10.2 | 31.9 | 44.0 | 18.0 | 62 |
| | Early Tillering | 28.7 | 8.4 | 37.1 | 57.9 | 17.4 | 75.3 |
| | Mid-tillering | 44.6 | 6.9 | 51.5* | 68.0 | 19.6 | 87.6 |
| | Late Tillering | 39.4 | 5.5 | 44.9 | 56.7 | 15.0 | 71.7 |
| | Jointing-Booting | 143.5 | 11.2 | 154.8 | 189.8 | 45.0 | 234.8 |
| | Heading-Flowering | 154.9* | 18.8 | 173.7* | 169.0 | 34.8 | 203.8* |
| | Milking | 47.5 | 9.0 | 56.5 | 63.2 | 19.5 | 82.7 |
| | Whole Period | 480.3* | 70.0 | 550.3* | 648.6 | 169.3 | 817.9 |

Note: There was significant differences (*) at $P \leq 0.05$

slightly higher than CI.

Because the rainfall in 2014 is more than in 2013, the reduction in both evapo-transpiration and water consumption was lower than in 2013. Therefore, rain-storage irrigation can effectively use rainfall to reduce evapo-transpiration and consumption. The amount of field leakage also reduced, which improved WUE.

### Nitrogen accumulation in aboveground and root part of rice

The above ground part of rice plant includes the stem, leaf and panicle and the nitrogen accumulation in above ground part was related to final yield. The nitrogen accumulation (NA) in above ground part of rice plant under RI and CI was higher in middle and late growth stage, reaching peak at heading-flowering stage, while nitrogen accumulation in root part (NR) increased then reduced gradually with growth stage, with a relatively lower nitrogen accumulation amount compared to NA (Fig. 5).

At tillering stage, NA was similar under different irrigation treatments and NR was higher because of high root activity. NR for RI was slightly higher than CI due to the better soil aeration for improving water, fertilizer, air and heat condition, which was beneficial to metabolic growth of rice roots. At jointing-booting stage, NA for CI treatment was 14.3% higher than under RI treatment in 2013, while it was 9.7% lower in 2014. NR was highest because of fast root growth, and were almost the same for both CI and RI. At heading-flowering stage, rice entered vegetative growth stage, requiring large amounts of nitrogen. The NA for RI was 26.3 and 39.4% higher than CI, respectively in 2013 and 2014. RI showed a great advantage compared to CI while NR reduced to a lower level because of root senescence. At milking stage, rice converted into reproductive growth, and the NA for CI was 21.1 and 21.9% lower than for RI in 2013 and 2014, respectively.

### Water and nitrogen utilization efficiency

The irrigation water utilization efficiency (WUE) of paddy rice in this study was defined as: WUE = Y/W, where Y (kg $m^{-2}$) is rice production; and W (m) is the total irrigation water amount. From Table 4, it was concluded that the rainfall utilization efficiency (RUE) for RI was higher than CI. In 2013 and 2014, the RUE for RI was 2.6 and 3.5 times of CI, which illustrated that the RI regime showed a rather better rainfall utilization efficiency. The irrigation regimes showed significant effects on RUE.

As for the WUE for RI, it was almost twice of that for CI in 2013, while it was 1.5 times in 2014. The irrigation regimes showed significant effect on WUE. From this table, it also showed that rice production was not reduced with less irrigation water under RI regime. The WUE reduced with more irrigation and rainfall in 2014 for both CI and RI regimes.

Nitrogen utilization efficiency (NUE) is the ratio of grain yield to nitrogen input. It was clear that the EN for CI was 8.5 and 8.7% higher than for RI in 2013 and 2014, respectively (Table 5).

### Regression analysis between root activity, WUE and NA

WUE and NA both showed positive correlation with root activity ($R^2$=0.90; $R^2$=0.97), respectively (Fig. 6). The higher the root activity and the stronger the water absorption ability. Therefore, much more water could be used and nitrogen be transported to the above ground part of rice plant with water. However, NUE showed no relevance to root activity according to the results above. It was mainly related to fertilizer amount and type.

## Discussion

Water deficiency could reduce fresh root weight of rice to some extent and this difference was obvious in relatively

**Table 4:** Water utilization efficiency in different irrigation treatments

| Year | Treatment | Effective Rainfall (mm) | RUE (%) | Irrigation Amount (mm) | Yield (kg hm$^{-2}$) | WUE (kg m$^{-3}$) |
|---|---|---|---|---|---|---|
| 2013 | RI | 153.8 | 31.5 a | 300 | 8876.5 a | 2.96 a |
| | CI | 60.2 | 12.3 b | 570 | 8823.8 a | 1.55 b |
| 2014 | RI | 283.5 | 36.4 a | 480 | 7237.4 a | 1.51 a |
| | CI | 81.5 | 10.5 b | 740 | 7145.5 ab | 0.97 b |

Notes: There is significant change between lowercase letters (a and b)

**Table 5:** Accumulation of nitrogen in above ground part and Efficiency of nitrogen

| Year | Treatment | Nitrogen Application Amount (kg hm$^{-2}$) | Yield (kg hm$^{-2}$) | NA (kg hm$^{-2}$) | NUE (kg kg$^{-1}$) |
|---|---|---|---|---|---|
| 2013 | RI | 193 | 6024.5 | 98.54 | 31.22 |
| | CI | 193 | 6535.0 | 92.44 | 33.86 |
| 2014 | RI | 214 | 6415.3 | 84.55 | 28.98 |
| | CI | 214 | 6738.2 | 81.38 | 31.49 |

dry year, while the difference was rather stable in relatively wet year. The rainwater irrigation method could effectively promote root growing downward, and absorbing nutrients in deep soil. The water control for RI treatment showed its advantages in middle and late term of rice growth, which was conductive to maintain higher root activity and ensure the supply of nutrients to the above ground part, preventing premature aging of rice roots, and this effect was more obvious in dry year. This was mainly because of re-watering after water stress under RI, which could improve root activity. The similar study was carried out by Wei *et al.* (2010). The main root length for CI was slightly lower than RI except at heading-flowering stage, and that was might due to the reducing substances ($Fe^{2+}$, $NO_2^-$, $H_2S$) generated by oxygen scarcity under CI treatment, which was unfavorable for root growth. The decreasing rate of root activity for RI was slower than CI in whole growth period, which was mainly because poor soil aeration for CI, which resulted in the respiration of root decreasing, leading to root system death after a long time.

Heading-flowering and jointing-booting stages are two critical periods of rice water requirement; thus, the water requirement was large. The water use control in these two stages was the key for water-saving irrigation technology. According to the water-free layer irrigation of the root layer, plant transpiration and soil evaporation were effectively reduced, that's why rice water demand decreased, which was consistent with the conclusions obtained in the previous section. At milking stage, the NA for CI was lower than for RI in 2013 and 2014, respectively. This was mainly due to the quick growth of rice grain and the water condition in RI was favorable for nitrogen transportation in rice plant as reported for Peng *et al*. (2012).

The WUE for RI was higher than CI, and rice production was not reduced with less irrigation water under RI regime. This was mainly due to much more rainwater retained in paddy field during rice growth stages and the respiration of root decreased because of poor ventilation, resulting in root water absorption blocked. RI had a great water conservation potential without yield reduction compared to CI regime through high utilization efficiency of rainwater in paddy field. However, RI was not favorable for nitrogen utilization compared to CI, mainly because the water condition at the early growth stage of rice in RI restrict root growth and activity (Zhu *et al*. 2017), therefore the field management with timely irrigation should be done to avoid irreversible effects by water stress.

## Conclusion

(1) Root weight of rice showed increasing and then decreasing trend for both CI and RI treatments, and it was lower under RI mode. The change of main root length for CI was slightly lower than RI except at heading-flowering stage both in 2013 and 2014 and water had not significance on main root length. The ratio of white root was highest at re-greening stage for both RI and CI treatments, then it decreased to a rather lower level at milking stage. Water was extremely significant and the water control for RI treatment showed advantages in middle and late term of rice growth.

(2) Transpiration effect was enhanced with higher soil water content for CI. RI regime showed a rather better rainfall utilization efficiency. RUE and WUE for RI was both higher than that for CI. The difference of RUE and WUE between irrigation modes was significant.

(3) Nitrogen accumulation in above ground part of rice plant under RI and CI was higher in middle and late growth stage, reaching peak at heading-flowering stage, while nitrogen accumulation in root part increased then reduced gradually with growth stage, with a relatively lower nitrogen accumulation amount compared to that in aboveground part. Nitrogen utilization efficiency for CI was 8.5 and 8.7% higher than that for RI in 2013 and 2014, respectively.

(4) WUE and NA both showed positive correlation with root activity. Higher the root activity, the stronger was the water absorption ability. NUE showed no relevance to root activity according to the results above.

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