

Effects of Non-flooded Cultivation with Straw Mulching on Rice Agronomic Traits and Water Use Efficiency

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Abstract: A field experiment was conducted to study water use efficiency and agronomic traits in rice cultivated in flooded soil and non-flooded soils with and without straw mulching. The total amount of water used by rice under flooded cultivation (FC) was 2.42 and 3.31 times as much as that by rice under the non-flooded cultivation with and without straw mulching, respectively. The average water seepage was 13 560 m³/ha under the flooded cultivation, 4 750 m³/ha under the non-flooded cultivation without straw mulching (ZM) and 4 680 m³/ha under non-flooded cultivation with straw mulching (SM). The evapotranspiration in the SM treatment was only 38.2% and 63.6% of the FC treatment and ZM treatment, respectively. Compared with the ZM treatment, straw mulching significantly increased leaf area per plant, main root length, gross root length and root dry weight per plant of rice. The highest grain yield under the SM treatment (6 747 kg/ha) was close to the rice cultivated in flooded soil (6 811.5 kg/ha). However, the yield under the ZM treatment (4 716 kg/ha) was much lower than that under the FS treatment and SM treatment. The order of water use efficiency and irrigation water use efficiency were both as follows: SM> ZM> FC.

Key word: rice; non-flooded cultivation; straw mulching; water use efficiency; irrigation water use efficiency; agronomic traits

Rice (*Oryza sativa*) is one of the main foodstuffs of Chinese people. More than 30% crop field is used for rice cultivation in China. It provides 45% of crop yields in our country. However, the production of irrigated rice requires considerable water, up to 13 500 m³ per hectare. In drought and water limited areas, it is very important and necessary to develop water-saving irrigation, especially the techniques of non-flooded rice cultivation.

Recently, non-flooded rice cultivation, especially combined with mulching techniques, has been developed fast^[1-7]. It was reported that the crop yields of non-flooded rice cultivation could be equal to or even more than the yields of conventional flooded rice system^[8].

Up to now, most of the studies of non-flooded rice cultivation are concentrated on drought areas of northern China^[3,7,9-10]. However, in southeast China, seasonal drought is prevailing in summer. This is significantly different from the general opinion of most people. In southeast China, because the total

rainfall is plentiful, it is generally accepted that there is no water stress. However, in fact, the whole area of seasonal drought has reached 6.181×10⁵ km² in these areas^[11]. What's more, the shortage of available water and the high water demand of crops happened at the same time. Seasonal drought exerts a tremendous influence on physiological metabolism, growth, yield, and grain quality of crops, especially on lowland rice. So, it is very important to develop the water-saving irrigation technique in these areas.

Quantitative understanding of water balance of the rice system, in particular with respect to evapotranspiration and seepage, usually the main components of the rice field water loss, is important to efficient use of water resources. Studies on water management in different rice ecosystems have been carried out, especially in conventional flooded soils^[12-17]. However, experimental evidence is still unavailable. Furthermore, there are few studies on water-saving irrigation and water saving measures in southeast China.

Compared with the conventional rice cultivation system, non-flooded rice cultivation can change living

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environments for plants, oxidation status and soil temperature, water content, and air conditions^[18]. In this experiment, we set up a new farming and water management system in a typical seasonal drought area (Yingtang, Jiangxi Province). A field experiment was conducted with successive observation and measurement to compare the components of water loss and the effect on rice growth as well as water use efficiency under different treatments in dry season of the second rice. It is very important to find the rules of water loss in paddy field and to know the effect of different water-saving measures on rice agronomic traits. By this, we tried to set up a reasonable regime to maintain the high yield of rice with less water consumption.

MATERIALS AND METHODS

Site description

The field experiments were conducted at Plantation of Dengjia Town, Yujiang County, Jiangxi Province of southeast China (28°15' N, 116°55' E) in 2003. The weather in the research area is a typical subtropical moist climate with a mean annual temperature of about 17.6°C and the total rainfall of 1752.1 mm. The uneven distribution of rainfall causes strong seasonal drought in summer and/or autumn (Fig. 1). In general, the cumulative rainfall was about 750 mm during the early rice period (from late April to middle July). However, the rainfall was only 281 mm during the late rice period (from late July to early November). Furthermore, the drought occurs simultaneously with hot season. In the same period of drought season, the potential evapotranspiration (calculated by Penman-Monteith formula) was 540 mm. The rice growth was affected greatly by seasonal drought.

The soil was developed from alluvial deposits and had been used for rice cropping more than 50 years. The soil (0-20 cm, pH 5.5) before the experiment contained 14.79 g/kg soil organic carbon, 1.54 g/kg total N, 95.1 mg/kg available N, 16.1 mg/kg available P, and 74.2 mg/kg available K.

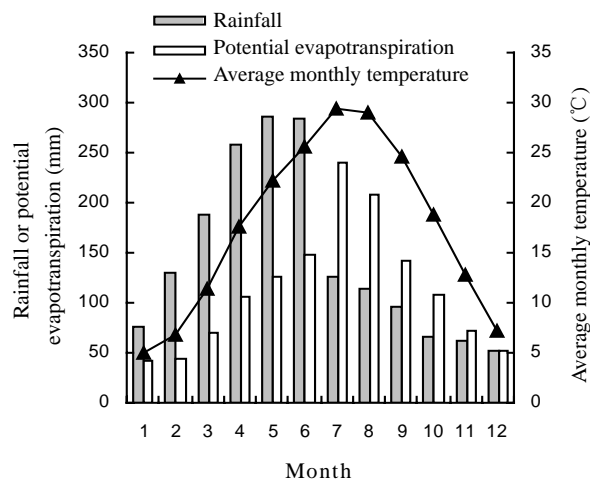


Fig. 1. Average monthly temperature, rainfall and potential evapotranspiration recorded at Yujiang County during the period of 1954-1995.

Treatments and cropping

The crop system was early rice followed by late rice. The experiment was conducted in the late rice with rice variety Zhongxuan 10 as materials. Water management treatments were conventional flooded cultivation (FC), non-flooded cultivation without straw mulching (ZM) and with straw mulching (SM). The rice straw was applied after transplanting at 5000 kg/ha in dry weight. Each treatment was triplicate in the field with a randomized complete block design. The plot area was 60 m² (6 m × 10 m). Rice seedlings were transplanted at a density of 18 hills/m² and two to three plants per hill. Rice under the FC treatment was ripened on 24th of October, and that under SM and ZM treatments was on 29th of October.

Urea, superphosphate and potassium chloride were applied at the rates of 11.25 g N, 9 g P₂O₅ and 7.5 g K₂O per m² as basal fertilizer after transplanting and thoroughly incorporated in the soils by hand. Additional urea was spread over the surface soil at a rate of 45 and 67.5 kg N/ha at the tillering and heading stages respectively after the fields were irrigated. Weeds were controlled by herbicides. Organophosphate insecticides were used to control the Asiatic rice striped borer (*Chilo suppressalis*), and the rice stem borer (*Tryporyza incertulas*).

Measurements

Irrigation water

The plots were separated by sealed ridge (ridges were sealed by double layer of plastic films, and the buried depth was 25 cm under the soil surface) to prevent water exchange between the plots. In the flooded plots, the field continuously submerged by irrigation. Once the water depth was less than 5 cm, new irrigation water would be supplied to increase the water depth to more than 10 cm. Water depth was measured with fixed scales before and after irrigation. The difference of water depth was taken to calculate the amount of irrigation water ^[19]. Percolation during irrigation assumed negligible in the flooded plots. When need irrigation, the non-flooded plots were irrigated after applying irrigation to flooded plots. By the time and the volume of irrigation water for the flooded plots, the water flux was calculated. We also use a turbine flowmeter to measure the amount of irrigation water for each plot.

Water seepage and evapotranspiration measurement

Three steel cylinders, 40 cm high and 30 cm in inner diameter, were embedded into the soil in each plot. One of them (A) was inserted 30 cm into the soil with its top 10 cm above the soil surface and other two (B and C) were just completely embedded into the soil. One of the completely embedded cylinders (B) was perforated on the cylinder wall and the bottom to allow water exchange in all direction and the other two cylinders (A and C) were intact ones, which only allow water movement through evapotranspiration. Rice plants were grown inside the cylinders with the same space between each other as outside.

Two rulers were fixed on the two sides (inside and outside) of the wall of cylinder A. During the flooded period, changes of water surface outside the cylinder A were the total water loss (including seepage and evapotranspiration); and that inside the cylinder A was the loss of evapotranspiration. During non-flooded period, the water in the cylinder A was quantified by a scale everyday. The weight changing of cylinder B was the total water loss (including water seepage and evapotranspiration); the changing of cylinder C was the water loss of evapotranspiration. The field seepage was calculated from the difference between the weights of cylinders B and C.

Weather data

Daily weather data were collected from the weather stations of Yujiang County, Jiangxi Province. In 2003, most of areas in south China suffered the heaviest seasonal drought since the record of 1954. Table 1 showed that the average monthly temperature of 41-year mean value from seeding to harvest was 25.0°C. The average temperature of the same period in 2003 (26.3°C) was much higher. The cumulative rainfall and potential evaporation from seeding to maturity were 49.6 mm and 213.5 mm, respectively. Compared with the 41-year mean values, the cumulative rainfall reduced by 50%, and the potential evaporation increased by 20%.

Soil water content measurement

Volumetric soil water content was measured using frequency domain reflectometer probes (MP-406), which were embedded to the depth of 10 cm in the soil. Three probes were used as replicates in each plot. Soil water content was recorded using a portable readmeter at around 8:00 everyday.

Table 1. Weather data during the cropping season.

Weather factor	Year	Month				Average
		July	Aug	Sept	Oct	
Mean air temperature (°C)	2003	31.3	29.8	25.9	18.2	26.3
	41-year mean ^a	29.4	28.1	24.8	17.6	25.0
Potential evaporation (mm)	2003	285.9	245.0	198.0	125.0	213.5
	41-year mean	237.0	211.4	142.5	119.0	177.5
Rainfall (mm)	2003	38.5	88.2	50.7	21.1	49.6
	41-year mean	123.0	118.0	92.6	71.2	101.2

^a41-year mean values from 1954 to 1995.

Plant height and tillering number

Plant height and tillering number were measured on three different days (10th and 25th of August and 15th of September). Ten plants were selected randomly along the diagonal of each plot to measure every time.

Root and leaf area

Rice roots (3 hills per plot) were sampled and washed before heading, and measured by Win RHIZO 2003b. Leaf area was determined by using CI-203 AREA METER (CID, INC.USA) in field (20 plants were selected randomly).

Yields

The crop was harvested from an area of 40 m² at the maturity stage, and grain yield and its components were recorded (nine plants per plot were sampled randomly before harvesting).

Data analysis

Statistical analyses were conducted by SPSS11.0.

RESULTS AND DISCUSSION

Field water consumption and water content in the topsoil

The non-flooded cultivation system had shorter time with standing water layer in the field than the conventional flooded cultivation system. The duration with flooded irrigation in the flooded plots for late rice was 63 d in 2003 (Table 2), less than the 85 days reported for Tebonnet in Arkansas, USA [20]. The days with standing water in the SM and ZM treatments were five and six days, respectively. In the non-flooded plots, because of the high temperature during the period of land preparation and transplanting, all the plots were prepared under submerged conditions to ensure that rice seedling would survive. This needed the field to be under submerged conditions for several days in non-flooded plots. There were not submerged conditions caused by the rainfall during growing period of the late season rice in non-flooded plots.

Table 2. Effects of the three treatments on water consumption during the whole developmental period.

Treatment	Flooded duration (d)	Irrigation (m ³ /ha)	Evapotranspiration (m ³ /ha)	Field seepage (m ³ /ha)
FC	63 a	19 950 a	7990 a	13 560 a
ZM	6 b	8 230 b	5080 b	4 750 b
SM	5 b	6 030 c	3050 c	4 680 b

Within a column, values followed by the common letter represent no significant difference at 5% level (Duncan's method).

FC, Conventional flooded cultivation; ZM, Non-flooded cultivation without straw mulching; SM, Non-flooded cultivation with straw mulching.

The irrigation water during the whole growth period of the late rice was 19 950 m³/ha in 2003 for the flooded cultivation treatments. During the same period, it was 8 230 m³/ha in the ZM treatment and 6 030 m³/ha in the SM treatment. In the non-flooded cultivation system, the irrigation water consumption was less than the conventional flooded cultivation. The difference of the flooded duration between treatments affected the evapotranspiration and seepage directly (Table 2). For evapotranspiration and seepage, there were both significant differences between the non-flooded plots and flooded plots. In the non-flooded plots, straw mulching reduced the water evapotranspiration greatly, and there was significant difference in evapotranspiration between the SM and ZM treatments. In the flooded plots, field seepage was the main way of water loss. The water loss by seepage was 61.8% of the total water loss. The result in this study was in good agreement with other reports [3,7].

Straw mulching treatment decreased the evapotranspiration and delayed the soil drying process after irrigation as compared with the ZM treatment (Fig. 2). The reasons for this were that: (1) water must change from liquid into vapor at the soil surface before evaporation. The water vapor must then diffuse through the thick mulching layer, which significantly reduced the rate of evaporation, and decreased water loss compared with bare soil surface; (2) the mulching reduced the quantity of direct solar radiation reaching the soil surface, and reduced the soil temperature, thereby decreased the amount of energy available for change of state of water from liquid to vapor; and (3) mulches acted as insulators to downward conduction of heat into the soil [21].

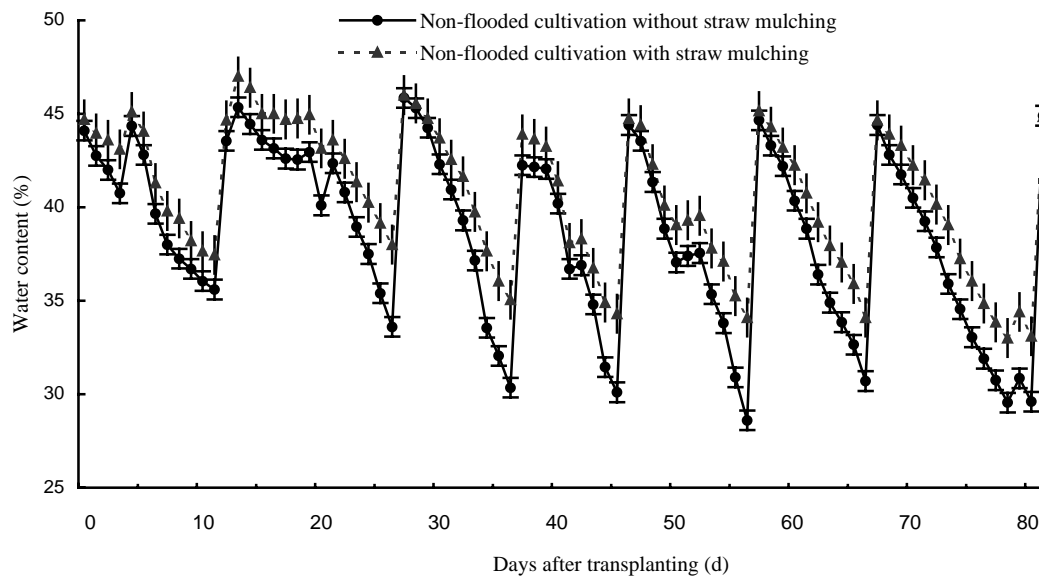


Fig. 2. Water content in surface soil (10 cm) under the non-flooded cultivation conditions.

Effects of straw mulching on plant growth of rice

Different water managements changed rice growth period and rice growth performance (Table 3). In the non-flooded treatments, the whole growth duration was longer than in the FC treatment [22]. The reasons for this were that: (1) During early periods, rice grew better, and absorbed more nitrogen from soil in flooded plots. So before harvesting, nitrogen content in the non-flooded soil was higher than that in the flooded plots. This needs further research to be verified. (2) In non-flooded plots, water stress delayed tillering in early growth period (Fig. 3), which caused whole growth to be delayed.

The plant height was the highest in the FC

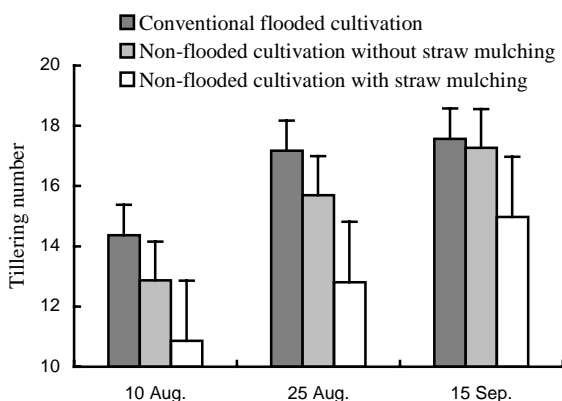


Table 3. Dates of important growth stages of rice cultivated under the three treatments.

Treatment	Date (Month-Day)			
	Seeding	Transplanting	75% heading	Harvest
FC	06-30	07-26	09-12	10-24
SM	06-30	07-26	09-15	10-29
ZM	06-30	07-26	09-18	10-29

FC, Conventional flooded cultivation; ZM, Non-flooded cultivation without straw mulching; SM, Non-flooded cultivation with straw mulching.

treatment, followed by the SM and ZM treatments on 10th and 25th of August (Fig. 3). There was significant difference in plant height between the FC treatment and non-flooded treatments. During the

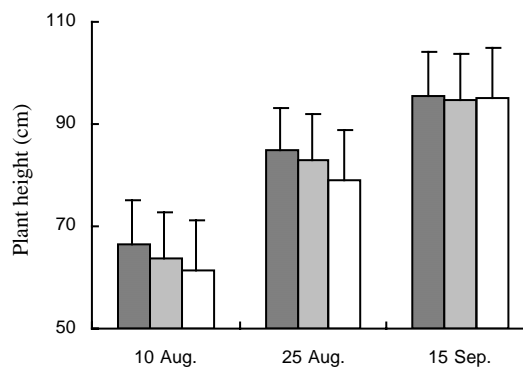


Fig. 3. Tiller number and plant height of rice at three different stages.

early period of tillering, rice growth was affected greatly by water stress. The plant height on 15th of September was not significantly different between the FC and SM treatments, indicating the difference could be reduced in the late period of tillering. The tiller number varied among the treatments and the variation was similar to the trend of plant height. But the magnitudes of the differences between the treatments on 10th and 25th of August were larger. Straw mulching could maintain the water content of soil and reduce the water loss through evapotranspiration. This was also beneficial to reducing the negative effects of water stress.

Rice root and leaf area

The effect of non-flooded treatments on rice root developing and leaf area was very great (Table 4). For gaining more water, rice cultivated under non-flooded plots must extend its root to deep soil. So, the rice root in non-flooded treatments was significantly longer and heavier than that in the flooded treatment. Mulching with rice straw could increase organic input, and consequently change the soil bulk density. The soil bulk density of plowed soil in SM treatment (1.44 g/cm^3) was lower than the ZM treatment (1.58 g/cm^3). This caused the gross length and dry weight of root to be longer and heavier in the SM treatment than in ZM treatment. In order to alleviate the effect of water stress, leaf area was decreased to reduce transpiration in the non-flooded conditions.

Grain yield and IWUE

There was no significant difference in grain yields between the SM treatment and the FC treatment (Table 5). Grain yields in both treatments were significant higher than that in the ZM treatment. In yield components, there was no close correlation between the grain yield and 1000-grain weight. It suggested that the number of effective tillers and the number of total grains had important effect on the yield formation. Especially, quantity and quality of spikelets and panicles played a critical role in grain formation of rice. In 2003, because of the high temperature and heavy drought stress, rice yield was influenced greatly. In our experiment, the yield was much lower than the historical yield, and also lower than those in some reports before [23]. On one hand, the effect of water stress caused by high temperature and less rainfall was a big calamity to crop growth. On the other hand, because of the high temperature during the pollen period, the ratio of unfilled grain was much higher. Those caused less total number of grains and crop yields less than before. It is reported that in the whole southern China, the rice output decreased by more than 20% in 2003.

In the non-flooded plots, mulching with rice straw could maintain high output of rice. In 2003, the grain yields of rice in the FC and SM treatments were 6811.5 and 6489 kg/ha, respectively, which were 1.44- and 1.38-fold higher than that in ZM treatment (4716 kg/m^3). This suggested that mulching with rice

Table 4. Leaf area and root development of rice under different cultivation conditions.

Treatment	Main root length (cm)	Gross length of root (cm)	Dry weight of root (g/hill)	Flag leaf area (cm ²)	Average leaf area (cm ²)
FC	41.20 b	7649.90 b	7.88 c	48.07 a	42.05 a
ZM	47.63 a	8268.03 a	10.54 b	40.48 c	38.99 b
SM	46.33 a	8478.67 a	12.09 a	44.89 b	41.57 a

Within a column, values followed by the common letter represent no significant difference at 5% level (Duncan's method).

Table 5. Yield and its components and water use efficiency of rice under different cultivation conditions.

Treatment	Effective tiller no. ($\times 10^4$ /ha)	Total no. of grains ($\times 10^3$ /hill)	Unfilled grain rate (%)	1000-grain weight (g)	Yield (kg/ha)	IWUE (kg/m ³)	WUE (kg/m ³)
FC	2.46 a	1661.9 a	15.31 b	22.76 a	6811.5 a	0.341 c	0.311 b
ZM	1.98 b	1219.6 b	18.99 a	21.36 a	4716.0 b	0.573 b	0.462 b
SM	2.43 a	1636.9 a	15.96 b	21.99 a	6489.0 a	1.076 a	0.810 a

Within a column, values followed by the common letter represent no significant difference at 5% level (Duncan's method).

straw reduced the water loss and improved the grain yield of rice significantly.

IWUE (irrigation water use efficiency) and water use efficiency (WUE) are the two key indexes to evaluate the relation between water use and crop production. IWUE and WUE are calculated by grain yields of rice dividing by actual irrigation water input or total water input (including irrigation water and rainfall), respectively.

The values of IWUE under the SM and ZM treatments were 1.076 kg/m³ and 0.573 kg/m³, which were significantly higher than that under FC treatment (0.341 kg/m³). Meanwhile, the values of IWUE and WUE in the SM treatment were also much higher than that from reports of lowland rice experiments carried out in China. This indicated that non-flooded treatments were helpful for the improvement of IWUE and WUE. However, because of the poor output in the ZM plots, there was no significant difference between the treatments of FC and ZM in IWUE and WUE. Only the SM treatment could improve the WUE significantly. In this study, IWUE and WUE values under the SM treatment were significantly higher than that under the ZM treatment. This suggested that mulching with rice straw could promote the absorption of soil moisture and would be beneficial to promoting IWUE and WUE. In our experiment, the results of IWUE and WUE were lower than some reports^[9]. This was caused by two factors: (1) The serious water stress caused by high temperature and less rainfall affected the crop output, and also increased the water input; (2) Because the soil in our experiment is very sandy, water seepage was a main way of water loss.

CONCLUSIONS

(1) Field seepage and evapotranspiration were two main ways of water loss in paddy field. We can shorten the flooded time to reduce water consumption.

(2) Compared with the ZM treatment, straw mulching significantly increased the leaf area per plant, main root length, gross root length and root dry weight per plant of rice. Rice cultivation under non-flooded conditions with straw mulching could maintain its production and reduce water consumption.

(3) The highest IWUE and WUE consistently occurred in the SM treatment in this study, and the yield under the SM treatment was very similar with that under the FC treatment, meaning that rice non-flooded cultivation with rice straw mulching is an optimal water-saving measure in the seasonal drought area of southeast China.

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