Nitrogen Uptake and Utilization by No-Tillage Rice under Different Soil Moisture Conditions – A Model Study under Simulated Soil Conditions

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Abstract: Most of the existing studies regarding water-saving cultivation on rice are based on tillage rice, rather than no-tillage rice. The purpose of this study was to quantify the effects of nitrogen fertilizer on no-tillage rice cultivation under various soil moisture conditions, in order to determine the suitable soil moisture content for rice production by no-tillage cultivation. Pot experiments were conducted in the early seasons of 2010 and 2011. In each season, a hybrid rice cultivar, Jiyou716, was planted under the soil moisture contents of 95 – 100\% (W100), 80 – 85\% (W85) and 65 – 70\% (W70). 15N was used as the nitrogen fertilizer. Yield, dry matter accumulation, nitrogen concentration and 15N abundance of maturity were determined for each sample. The nitrogen loss of basal N-fertilizer (BF) and tillering N-fertilizer (TF) in W70 was 22 – 24\% and 18 – 45\% larger than in W100, respectively, resulting in reduction in nitrogen uptake and total nitrogen accumulation in plants. The yield of rice by no-tillage in W70 was 47 – 42\% lower in 2011 and 2010. There was no significant difference between W85 and W100 in yield, nitrogen uptake and utilization in no-tillage cultivation. It was concluded that the N uptake and yield were decreased by decreasing soil moisture contents to 70\% of saturation in no-tillage cultivation. Soil content of around 85\% was proposed as a suitable condition without a large reduction in the yield and N use in water-saving cultivation, although a field test is essential for practical use.

Key words: Soil moisture, No-tillage, Nitrogen uptake and utilization, Rice (\textit{Oryza sativa} L.).

Rice is the world’s most widely consumed grain, serving as a staple food for nearly half of the world’s population (Sepaskhah and Barzegar, 2010). However, rice production requires a large amount of water. In China, agricultural water consumption accounts for more than 70\% of total water consumption, among which paddy water consumption accounts for 65–70\% (Liu et al., 2009). Despite having the most intensive irrigation system for rice in the world, China has the lowest fresh water availability per capita in Asia (Cabangon et al., 2004). Therefore, irrigated rice production is the major consumer of water in the agricultural sector, and with rice as the world’s most widely consumed staple crop, methods to reduce the need for water for growing irrigated rice will benefit both the producer and consumer (Satyanarayana et al., 2007).

Saving water is a concern in rice production. In fact, rice has a high adaptation ability to flood and dry environments due to its aquatic, semi-aquatic and even xerophytic biological characteristics (Qian et al., 2003; Guo et al., 2007). It thus has high potential ability in saving water, and many scholars have confirmed that flooding is not necessary to obtain a high yield of rice (Gupta et al., 2002; Yang et al., 2007). Borrell et al. (1997) showed that rice water consumption under the saturated water irrigation was 32\% lower than that under traditional flooding irrigation with almost the same yield and quality. In addition, some researchers showed that light water stress also reduced water consumption without...
compromising yield in rice (Peng et al., 2006; Li et al., 2008). Reasonable water management not only greatly reduces water consumption in rice production, but also promotes the growth of rice roots (Qian et al., 2003), and improves the water and N utilization rate (Lin et al., 2006; Liu et al., 2009). Haefele et al. (2008) showed that soil moisture mainly affected soil indigenous N uptake, but had little effect on fertilizer N uptake. However, studies on the fate of fertilizer N, as well as that of N uptake source and their relationship with grain yield, showed that the total N uptake and utilization by rice were both quite low under reduced soil moisture.

Studies on water saving cultivation techniques for rice are mostly based on tillage cultivation (Bouman and Tuong, 2001; Won et al., 2005; Satyanarayana et al., 2007; Yang et al., 2007; Liu et al., 2009), and few studies on no-tillage cultivation have been conducted. No-tillage is also known as conservation tillage. It involves direct seeding or transplanting in the original stubble, without the use of tools for soil management during all growth periods after seeding (Alletto et al., 2010). At present, research has been conducted in nearly 30 countries. China has been promoting the use of no-tillage rice cultivation for 12 years, but the current no-tillage system is far from perfect. The physiological characteristics and soil environment of no-tillage rice cultivation are very different from those of tillage cultivation. Compared with tillage rice cultivation, the evaporation, seepage and leaching in no-tillage rice cultivation are all significantly reduced (Chichester and Richardson, 1992; Levaron, 1993; Zhang et al., 2002), which is beneficial to the water-saving cultivation of rice (Xie et al., 2007). The ammonia volatilization characteristic in no-tillage rice cultivation is not yet clear, but ammonia volatilization is positively correlated with soil pH (Song and Fan., 2003; Johnny et al., 2012), and the soil pH in no-tillage rice cultivation is decreasing (He et al., 2012). In addition, soil organic matter and N are accumulated in the surface soil under no-tillage (Doran 1980; Wander et al., 1998), the root distribution is shallower, and the root activity is higher in rice without tillage than that with tillage (Jiang et al., 2005; Ren et al., 2007). These findings show that the effects of soil moisture on N uptake and utilization in rice differ in no-tillage and tillage rice cultivation. The aim of this study was to quantify the fate of nitrogen fertilizer applied in no-tillage rice cultivation under different soil moisture conditions, and the relationship of N fertilizer with total N uptake and grain yield, thereby identifying the suitable soil moisture for no-tillage rice production.

Materials and Methods

1. Pot experiment

Pot experiments were carried out in a glasshouse at Guangxi University, Guangxi Province, China (22°49’12”N, 108°19’11”E; 75 m elevation; average annual temperature 21.7°C) during the early rice growing seasons (March to July) in 2010 and 2011. The soil used in the experiments was collected from a no-tillage paddy field, and the soil was Laterite (soil bulk density = 1.31 g cm⁻³). The physical and chemical properties of the soil are shown in Table 1. The soil samples were extracted before rice seedling transplanting in a no-tillage paddy field. The soil in the no-tillage paddy field was cut into blocks (thickness 23 cm, length 24.3 cm, width 19.5 cm) with steel plates. and then placed into each pot. The no-tillage soil blocks in the pots remained in the plough layer on the top and plough pan on the bottom. The test pots were square plastic pots 24.3 cm in length, 19.5 cm in width and 28 cm in height. In order to reduce test errors, the size and weight of the soil samples were strictly controlled during the soil digging process, and it was ensured that the soil in each pot remained at the same volume and quality. Each pot was filled with 17 kg of soil (moisture content was 24%), the saturated capacity of the soil was 42%, and the weight of each test pot was 0.5 kg.

The hybrid cultivar Jiyou716 was planted in the pots with a soil moisture content of 95–100% (W100), 80–85% (W85) or 65–70% (W70). The seeds were sown on 12 March, and seedlings transplanted on 7 April, 2010, and 28 March and 16 April, 2011. The rice seedlings were raised in trays, and the nursery periods were 26 d in 2010 and 20 d in 2011. Two seedlings were transplanted per hill and two hills per pot, and the planting period was 126 d in both years.

The amount of water to add to maintain each soil moisture content was determined by measuring the moisture evaporation and transpiration loss by the water balance method using an electrical balance (maximum weight 30 kg, accuracy 1 g) between 1700 and 1800 every day. The soil moisture was controlled after rice seedling was established, according to the estimation of the weight in rice growth to adjust the amount of water to add in the

| Year | pH    | Organic matter (g kg⁻¹) | Total N (g kg⁻¹) | Alkali-hydrolyzable N (mg kg⁻¹) | Available P (mg kg⁻¹) | Available K (g kg⁻¹) |
|------|-------|------------------------|------------------|--------------------------------|----------------------|---------------------|
| 2011 | 6.41  | 22.5                   | 1.41             | 91.4                           | 30.6                 | 67.9                |
| 2010 | 6.30  | 22.5                   | 1.59             | 148                            | 35.0                 | 136                 |
late rice growth stage, to keep the soil moisture within the designated range throughout the entire whole growth period.

$^{15}$N-urea was applied at three stages during the rice growing season, namely basal, tillering and panicle initiation stages, BF, TF and PF, respectively, in each soil moisture treatment. Treatments were arranged in a randomized complete block design with four replications, one pot per replicate for each treatment. When $^{15}$N-urea was applied as BF, conventional urea was applied as TF and PF, and when $^{15}$N-urea was applied as TF or PF, conventional urea was applied as the other fertilizers. $^{15}$N-urea with 10.18% $^{15}$N abundance was provided by the Shanghai Research Institute of Chemical Industry. Fertilizers were applied at the rates of 30 g N m$^{-2}$, 15 g P m$^{-2}$, and 24 g K m$^{-2}$. For the basal application, 50% of N, all of P and 60% of K were broadcasted 1 d prior to transplanting. 20% of N and 40% of K were applied at the
tillering stage (7 d after transplanting), and 30% of N shortly after the panicle initiation stage as the top dressing (40 d after transplanting). Pests and weeds were controlled using chemicals, to avoid biomass and yield loss.

2. Physiological measurements

The aboveground parts of rice under no-tillage cultivation at the mature stage, and the remaining roots were completely washed in water. The samples of roots, stems and leaves were dried at 75°C until reaching constant weight, and then weighed and ground. Grain yield was measured by hand-harvesting, and drying at 75°C until reaching a constant weight (adjusted to 13.5% moisture). According to the profile of soil sampling, the soil samples were air-dried, then passed through a 1 mm sieve. The N concentrations in plant tissues were determined by the Kjeldahl method with a VAP50 Kjeldahl meter (Gerhart, Germany) and the $^{15}$N abundances were determined using a ZHT-03 isotope mass spectrometer (Beijing Analysis Instrument Factory, China). The determination and calculation of $^{15}$N amount in plant and soil were as described by Pachiauchi et al. (1991), Diekmann et al. (1993) and Acquaye and Inubushi (2004).

Data was calculated on the basis of the dry weights and N measurements, and the parameters were defined as follows.

Total N accumulation (TNA, mg pot$^{-1}$) was plant N accumulation at maturity. Total dry matter accumulation (or biomass) (TDMA, g pot$^{-1}$) was plant matter accumulation at maturity. N grain production efficiency (NGPE, g g$^{-1}$) was defined as grain weight ($W_{\text{grain}}$) divided by TNA. N dry matter production efficiency (NDMPE, g g$^{-1}$) was defined as TDMA divided by TNA. The fate of the N fertilizer was shown by partitioning it into three parts, namely uptake by plant, residue in soil and N loss at maturity. The N uptake by plant was the same as the N accumulation at maturity. Residue in soil was defined as soil N at maturity. N loss was obtained by subtracting the uptake by the plant and residue in soil at maturity from the applied $^{15}$N-fertilizer. The contribution rate of soil N was the soil-N uptake divided by the total N uptake by plant. The contribution rate of the N fertilizer was the mean of the fertilizer-N uptake divided by the total N uptake.

3. Experimental design and statistical analysis

The treatments were completely randomized with four replications. Data were analyzed using statistical program SPSS18.0. Significant differences were calculated from the analysis of variance. The least-squares method was used to fit a line to soil moisture, N loss and N uptake, and the decision coefficient ($R^2$) was calculated to assess the goodness of fit of the curve.

Results

1. Influence of soil moisture on the fate of nitrogen fertilizer (N fertilizer) in different periods of no-tillage rice cultivation

The influence of soil moisture on the fate of BF, TF and PF in no-tillage rice cultivation is shown in Fig. 1. The effects of soil moisture on the fate of N fertilizer in different periods of no-tillage rice cultivation were similar and stable between two years. The results indicate that the influence of soil moisture on the fate of BF and TF was consistent, but that on the fate of PF was dissimilar. The plant N fertilizer uptake of BF and TF with the decrease of soil moisture decreased, that under W70 was significantly lower than under W100 and W85, being 29–36% and 33–46% lower than that under W100 in 2011 and 2010, respectively. There was no apparent difference between W100 and W85. The residue in the soil of BF and TF under different soil moisture conditions was similar. Therefore, the N loss of W70 in BF and TF was the highest in both years of testing, increasing by 24–22% and 18–45% over W100 in 2011 and 2010, respectively. In addition,
that the N uptake from TNF decreased with decreasing soil moisture in both years, but there was no significant difference between W100 and W85, the N uptake from TNF under W70 was lower than that under W100 and W85, by 24% and 27% in 2011 and 2010, respectively. The plant fertilize-Nr uptake and N loss in PF were similar under different soil moisture conditions without a significant difference.

The fate of total N fertilizer (TNF) which is a combination of BF, TF and PF in Fig. 1 is shown in Fig. 2. The data show that the N uptake from TNF decreased with decreasing soil moisture in both years, but there was no significant difference between W100 and W85, the N uptake from TNF under W70 was lower than that under W100 and W85, by 24% and 27% in 2011 and 2010, respectively. The

Fig. 3. The relationship between plant N uptake from fertilizer and N loss in 2011 and 2010. BF: basal N-fertilizer; TF: tillering N-fertilizer; PF: panicle N-fertilizer; TNF: total N-fertilizer uptake.

* Significance at 0.05. ** Significance at 0.01.
residue in the soil of N from TNF under the different soil moisture conditions showed no significant differences. The N loss of TNF under W70 was larger than that under W100 and W85, by 13% and 18% of that in W100 in 2011 and 2010, respectively.

Fig. 3 shows that the plant N uptake from BF, TF and TNF was significantly and negatively correlated with N loss ($P < 0.01$), but the plant N uptake from PF did not significantly correlate with the N loss in the two years. The decrease in N uptake from BF and TF under reduced soil moisture was due to the increase in N loss (Fig. 3), and was more apparent than that in uptake from PF (Fig. 1).

2. Influence of soil moisture on grain yield and N uptake and utilization in no-tillage rice cultivation

The total N accumulation in rice plants is derived from...
soil indigenous N and fertilizer N (Guo et al., 2007). As described in Fig. 4, the TNA shown by total N uptake from the fertilizer and soil decreased with the decrease in soil moisture, but the amplitude of reduction in N uptake from fertilizer and soil was different. The N uptake from TNA from fertilizer was significantly lower under W70 than under either W100 or W85, but that from the indigenous soil N showed no significant difference among the soil moisture conditions. In addition, the average change contribution ratio of TNA from fertilizer was 62–75% in both 2011 and 2010, which was far higher than from the soil. Therefore, the difference in TNA in no-tillage cultivation under different soil moisture conditions was mainly attributed to the difference in the accumulation of N from the fertilizer.

Fig. 5 shows that the rice grain yield, TDMA, NGPE and NDMPE were significantly lower under W70 than under either W100 or W85, but there was no significant difference between W100 and W85. Rice grain yield, TDMA, NGPE and NDMPE under W70 decreased by 42–47, 32–39, 26–41 and 13–32%, respectively, in comparison to W100 in 2011 and 2010. Thus, the grain yield, TDMA, NGPE and NDMPE were clearly restricted by W70 in no-tillage cultivation.

Table 2 shows that there was no interaction between soil moisture and year on grain yield, total N uptake and fertilizer-N uptake. The effects of soil moisture on grain yield, total N uptake and fertilizer-N uptake were stable in both years.

### 3. Relationship of fertilizer-N uptake with total N accumulation (TNA) and grain yield under different soil moisture conditions in no-tillage cultivation

Figs. 6 and 7 illustrate the relationship of N uptake from BF, TF and PF with TNA and grain yield. The N uptake from BF was significantly correlated with grain yield and TNA \((P < 0.05/0.01)\), but that from PF was not. Thus, the grain yield and TNA in no-tillage cultivation were mainly influenced by the N uptake from BF under all soil moisture conditions examined.

## Discussion

In this study, the fate of N fertilizer and its relationship with plant N uptake and utilization under different soil moisture conditions in no-tillage cultivation were studied. The soil moisture was shown to be less than 70% of saturation adverse to the N uptake of BF and TF in no-tillage cultivation. One reason for this was that the N loss of BF and TF increased significantly. Ammonia volatilization is one of the main channels for N loss when urea is applied to the surfaces of both acidic and alkaline soils (Ernst and Massey, 1960; Chien et al., 2009). Average ammonia volatilization loss worldwide are of the order of 14% (10–19%) of the N fertilizers used (Ferm, 1998), and the loss is greater in warm climates (Bouwman et al., 2002; Shen, 2002). The present study showed that ammonia volatilization increased with the decrease of soil moisture. This may be because the low soil moisture content leads to a high substrate (N) concentration, thereby resulting in high ammonia volatilization (Cui et al., 2004). Zhou et al. (2008) pointed out that when the soil moisture maintains field capacity, the amount of ammonia volatilization was minimum, and a higher or lower soil moisture resulted in an increase in the ammonia volatilization. The second reason is that, when the soil moisture was 65–70% of the saturation, the dry weight of the root decreased significantly (decreased by 18–32% comparison to W100). The root system is the major organ of the absorption of nutrients and water. Zhang et al. (2001) reported that the most suitable soil moisture for root growth was 70–75% of the saturation. Another study showed that light water stress (80% saturation) were advantageous for delaying the senility of root systems at the late stages, but lack of this function resulted in severe water stress (Li et al., 2008). These factors may be responsible for the reduction of the root dry weight in W70. Regardless of the extent of the root dry weight reduction in W70, it seriously restricted the N uptake in no-tillage cultivation.

Soil moisture mainly affected the fertilizer N uptake, but hardly affected the soil indigenous N uptake, and this conclusion is contrary to that reported by Haegele et al. (2008). This may be responsible for the N fertilization at the surface of the soil under no-tillage, as well as the root distribution of rice in no-tillage cultivation being shallow (Jiang et al., 2005, Ren et al., 2007). Therefore, the spatial distance between the root and fertilizer N is close, which is more conductive to N uptake in no-tillage cultivation. In addition, the N uptake of BF was significantly and positively

### Table 2. The interaction between soil moisture and year on grain yield, total N uptake and fertilizer-N uptake.

| Year | Soil moisture | Yield (g pot⁻¹) | TNA (mg pot⁻¹) | TNF (mg pot⁻¹) |
|------|---------------|----------------|----------------|---------------|
| 2011 | W100          | 55.3 a         | 979 a          | 446 a         |
|      | W85           | 50.1 a         | 911 a          | 395 ab        |
|      | W70           | 29.1 b         | 832 b          | 339 b         |
| 2010 | W100          | 34.2 a         | 891 a          | 433 a         |
|      | W85           | 32.0 a         | 888 a          | 431 a         |
|      | W70           | 19.9 b         | 698 b          | 313 b         |

Within a Figure for each parameter in each year, means were compared by least significant difference at \(P < 0.05\). ** Significance at 0.05. NS denotes non-significance. TNA: plant N accumulation, TNF: total N-fertilizer uptake.
Fig. 6. The relationship between fertilizer-N uptake and total N accumulation (TNA) in 2011 and 2010.
BF: basal N-fertilizer; TF: tillering N-fertilizer; PF: panicle N-fertilizer; TNA: total N accumulation. * Significance at 0.05.
** Significance at 0.01.

Fig. 7. The relationship between fertilizer-N uptake and grain yield in 2011 and 2010.
BF: basal N-fertilizer; TF: tillering N-fertilizer; PF: panicle N-fertilizer. * Significance at 0.05. ** Significance at 0.01.
correlated with the grain yield and total N accumulation, and the BF application was at its maximum. Therefore, the fact that the total N accumulation and grain yield varied with the soil moisture condition was mainly attributed to the N uptake from the basal fertilizer in no-tillage cultivation.

The source of N accumulation in grain can be divided into N absorbed by root after heading and N transferred from the stem and leaf. However, N loss of BF and TF significantly increased under a soil moisture condition of less than 70% saturation (W70), decreasing absorption of fertilizer N by root. In addition, the variation in the total N accumulation under different soil moisture conditions was mainly attributed to the difference in fertilizer N uptake. Therefore, N absorption from the root decreased under a soil moisture condition of less than 70% saturation. Second, the dry weight of root clearly decreased under a soil moisture condition of less than 70% saturation, resulting in the reduced N uptake. Fig. 5 shows that the grain production efficiency and dry matter production efficiency of N in W70 were significantly lower than those in W100 and W85. In W70, the grain dry weight decreased significantly, but the stem and leaf dry weight did not as compared with W100 and W85 (data not shown). The results also showed that the leaves in W70 were greener and narrower than those in W100 and W85 at the mature stage. Therefore, it is concluded that low soil moisture (less than 70% saturation) during the grain filling period can restrict N transfer from stem sheath to spike, leading to a decrease in the N accumulation in grain. These findings show that the decrease in N source under a soil moisture condition of less than 70% saturation, directly causes grain growth and yield decrease. The results obtained by Cai (2010) and Li et al. (2008) were basically consistent.

As described above, the soil moisture should not be less than 70% saturation in no-tillage cultivation, which is important especially for production in humid and irrigated areas under no-tillage cultivation. The present findings confirmed that soil moisture mainly affects fertilizer N uptake, but hardly affects soil indigenous N uptake, and N fertilization is still the key to increasing production in no-tillage cultivation. In addition, based on the spatial distribution of N fertilizer and the relationship of N fertilizer uptake with total N accumulation and grain yield, we may gain a better understanding of the uptake of N from N-fertilizer in no-tillage cultivation.

The soil blocks used in the present pot experiment were whole blocks from the no-tillage paddy field and were consistent with the pot size, thus being close to the natural state of no-tillage paddy fields. In addition, the glasshouse was a network room with a glass roof, so the climate in the glasshouse was similar to that of the paddy field. The pot and field experiments on N uptake and utilization no-tillage cultivation under three water managements (namely wet irrigation, water layer irrigation and alternate irrigation) had been performed by Liang (2008) of our team in the early and late seasons of 2008 in the same glasshouse. The results obtained by the pot and field experiments were consistent. Therefore, the results obtained in the present pot experiment may be used as a reference for the N uptake and utilization characteristics and mechanism in no-tillage cultivation. However, seepage and air flow in soil blocks may differ from field conditions, and further studies in the field are needed for validation.

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