Effects of Irrigation Regime and Nitrogen Application Rate on Nitrogen Utilization, Water Use, and Yield in Direct-Seeded Rice (Postprint)

Authors: Zhang Hong, Zhu Conghua, Li Qiyong, Li Xingyue, Guo Zhan, Zheng Jiaguo, Li Xuyi

Date: 2017-11-08T00:00:00+00:00

Abstract

To investigate the effects of different irrigation methods and nitrogen application rates on photosynthetic production, dry matter accumulation, nitrogen utilization, water use, and grain yield of direct-seeded rice, a split-split plot experimental design was adopted, with variety as the main plot factor: 'Dexiang 4103' and 'Jinnong Simiao', irrigation method as the sub-plot factor including three types: shallow water irrigation, mild alternate wetting and drying irrigation, and severe alternate wetting and drying irrigation, and nitrogen application rate as the sub-subplot factor comprising four levels: 0 kg(N) · hm^{-2}, 120 kg(N) · hm^{-2}, 180 kg(N) · hm^{-2}, and 240 kg(N) · hm^{-2}. Indices including dry matter accumulation, nitrogen accumulation and utilization efficiency, water use efficiency, and yield of direct-seeded rice were analyzed and measured. The results indicated that significant interactive effects existed between irrigation method and nitrogen application rate on nitrogen utilization and yield formation of direct-seeded rice. Compared with shallow water irrigation, mild alternate wetting and drying irrigation significantly increased the net photosynthetic rate of flag leaves at heading stage, dry matter accumulation during jointing–heading stage, nitrogen accumulation at heading and maturity stages, nitrogen translocation from stem and leaf during grain filling stage, nitrogen accumulation in grain at maturity stage, nitrogen agronomic efficiency, and nitrogen recovery efficiency of 'Dexiang 4103' and 'Jinnong Simiao'; while significantly decreasing leaf area index at heading stage, dry matter accumulation before jointing, and nitrogen accumulation in stem and leaf at maturity stage. The effects of nitrogen application rate on nitrogen accumulation, nitrogen use efficiency, and yield differed between 'Dexiang 4103' and 'Jinnong Simiao'. Under shallow water irrigation, compared with zero nitrogen, nitrogen application increased yield by 31.79%–48.77% and 29.72%–45.36% for 'Dexiang 4103' and 'Jinnong Simiao', respectively; when nitrogen application rate exceeded 180 kg · hm^{-2}, the yield, dry matter accumulation, nitrogen agronomic efficiency, and nitrogen recovery efficiency of 'Dexiang 4103' decreased significantly, whereas those of 'Jinnong Simiao' showed no significant changes. Under mild alternate wetting and drying irrigation, compared with zero nitrogen, nitrogen application increased yield by 32.58%-61.10% and 36.49%-48.45% for 'Dexiang 4103' and 'Jinnong Simiao' , respectively; when nitrogen application rate exceeded 180 kg·hm^{-2}, the yield of 'Dexiang 4103' showed no significant change, while its dry matter accumulation, nitrogen accumulation at heading and maturity stages, and nitrogen recovery efficiency increased significantly, and nitrogen agronomic efficiency decreased significantly; the yield and dry matter accumulation of 'Jinnong Simiao' showed no significant change, while its nitrogen accumulation at heading and maturity stages, nitrogen agronomic efficiency, and nitrogen recovery efficiency decreased significantly. Under severe alternate wetting and drying irrigation, compared with zero nitrogen, nitrogen application increased yield by 37.01%-42.88% and 30.11%-42.63% for 'Dexiang 4103' and 'Jinnong Simiao' , respectively; when nitrogen application rate exceeded 180 kg·hm^{-2}, the yield of both varieties showed no significant change, nitrogen accumulation of 'Dexiang 4103' increased significantly while that of 'Jinnong Simiao' showed no significant increase, and nitrogen agronomic efficiency and nitrogen recovery rate of both varieties decreased significantly. In conclusion, mild alternate wetting and drying irrigation is more suitable for high-yield, water-saving, and efficient cultivation of direct-seeded rice, with the highest yield of 'Dexiang 4103' achieved under mild alternate wetting and drying irrigation with pure nitrogen application of 240 kg·hm^{-2}, and the highest yield of 'Jinnong Simiao' achieved under mild alternate wetting and drying irrigation with pure nitrogen application of 180 kg·hm^{-2}.

Full Text

Preamble

DOI: 10.13930/j.cnki.cjea.170334

Citation: Zhang H, Zhu C H, Li Q Y, Li X Y, Guo Z, Zheng J G, Li X Y. Effects of irrigation management and nitrogen rate on nitrogen and water utilization and grain yield of direct-seeded rice[J]. Chinese Journal of Eco-Agriculture, 2017, DOI: 10.13930/j.cnki.cjea.170334

Authors: ZHANG Hong[1], ZHU Conghua[1], LI Qiyong[1], LI Xingyue[1], GUO Zhan[1], ZHENG Jiaguo[2], LI Xuyi[2]

Affiliations: 1. Institute of Plant Protection, Sichuan Academy of Agricultural Sciences / Key Laboratory of Integrated Pest Management on Crops in Southwest China, Ministry of Agriculture, Chengdu 610066, China 2. Crop Research Institute, Sichuan Academy of Agricultural Sciences, Chengdu 610066, China

Funding: Supported by the National Key Research and Development Program of China (SQ2017YFNC050029), Sichuan Province Financial Innovation Ability

Promotion Special Fund (2016GYSH-008, 2016GYSH-013), and Sichuan Science and Technology Support Program (2014NZ0008)

Corresponding author: E-mail: lixuyi_{2005}@sohu.com

Received: April 18, 2017; **Accepted:** June 30, 2017

Abstract

Direct-seeded rice offers advantages of reduced labor requirements, lower labor intensity, and decreased production costs, but exhibits distinct developmental characteristics compared to transplanted rice. Investigating optimal cultivation practices for direct-seeded rice is therefore essential. This study conducted a field experiment to examine the effects of irrigation management and nitrogen application rates on nitrogen and water utilization efficiency and grain yield in direct-seeded rice. A split-split plot design was employed with rice varieties ('Dexiang 4103' and 'Jinnongsimiao') as the main factor, irrigation management (shallow water irrigation, alternate wetting and moderate drying, and alternate wetting and severe drying) as the sub-plot factor, and nitrogen rate (0, 120 kg $\cdot$ hm^{-2}, 180 kg $\cdot$ hm^{-2}, and 240 kg $\cdot$ hm^{-2}) as the split-split plot factor. Measurements included photosynthetic rate, dry matter accumulation, nitrogen utilization, water utilization, and yield at different growth stages.

Significant interactions between irrigation management and nitrogen rate were observed for nitrogen utilization, water utilization, and yield. Compared with shallow water irrigation, alternate wetting and moderate drying significantly increased net photosynthetic rate at the jointing stage, dry matter accumulation during the jointing-heading period, nitrogen accumulation at heading and maturity, nitrogen translocation from stems and leaves at maturity, nitrogen accumulation in grains, nitrogen agronomic efficiency, and nitrogen recovery efficiency. However, leaf area index at heading and dry matter accumulation before jointing decreased significantly.

The effects of nitrogen rates on nitrogen accumulation, utilization efficiency, and yield differed between varieties. Under shallow water irrigation, nitrogen application increased yields of 'Dexiang 4103' and 'Jinnongsimiao' by 31.79%–48.77% and 29.72%–45.36%, respectively, compared with the nitrogen-free treatment. When nitrogen rates exceeded 180 kg $\cdot$ hm^{-2}, yield, dry matter accumulation, nitrogen agronomic efficiency, and nitrogen recovery efficiency of 'Dexiang 4103' decreased significantly, while these indicators for 'Jinnongsimiao' showed no significant changes.

Under alternate wetting and moderate drying, nitrogen fertilizer application increased yields of 'Dexiang 4103' and 'Jinnongsimiao' by 32.58%–61.10% and 36.49%–48.45%, respectively. For 'Dexiang 4103' at nitrogen rates above 180 kg $\cdot$ hm^{-2}, yield remained stable while dry matter accumulation and nitrogen accumulation at heading and maturity increased significantly; nitrogen recovery efficiency increased but nitrogen agronomic efficiency decreased with increasing nitrogen rate. For ‘Jinnongsimiao’, yield and dry matter accumulation did not change significantly, while nitrogen accumulation at heading and maturity, nitrogen agronomic efficiency, and nitrogen recovery efficiency all decreased significantly.

Under alternate wetting and severe drying, nitrogen application increased yields of ‘Dexiang 4103’ and ‘Jinnongsimiao’ by 37.01%-42.88% and 30.11%-42.63%, respectively. When nitrogen rates exceeded 180 kg · hm^{-2}, yields of both cultivars remained stable while nitrogen agronomic efficiency and nitrogen recovery efficiency decreased significantly with increasing nitrogen rate. Nitrogen accumulation in ‘Dexiang 4103’ increased significantly, while that in ‘Jinnongsimiao’ showed no significant change.

In summary, alternate wetting and moderate drying represents the most suitable irrigation practice for achieving high yield, water savings, and high efficiency in direct-seeded rice cultivation. The optimal nitrogen rates were 240 kg · hm^{-2} for ‘Dexiang 4103’ and 180 kg · hm^{-2} for ‘Jinnongsimiao’.

Keywords: Rice; Direct seeding; Irrigation management; Nitrogen rate; Dry matter accumulation; Nitrogen utilization; Water utilization; Yield

1. Introduction

Direct-seeded rice has become increasingly important in rice production systems due to its labor-saving benefits and reduced production costs [1-5]. However, direct-seeded rice exhibits distinct growth and development patterns compared to transplanted rice, including different tillering characteristics, root distribution, and nutrient uptake patterns [6]. Water and nitrogen management practices developed for transplanted rice may not be directly applicable to direct-seeded systems.

Alternate wetting and drying (AWD) irrigation has been widely studied as a water-saving technique in rice production [7-10]. This practice can improve root growth, enhance nutrient uptake, and increase water use efficiency while maintaining or even increasing grain yield [11-14]. The effectiveness of AWD varies with nitrogen management and cultivar characteristics [15-17]. Previous studies have demonstrated significant interactions between water and nitrogen management in transplanted rice [18-20], but limited research has focused on direct-seeded rice systems.

Nitrogen is a critical limiting factor for rice yield, and its efficient use is essential for sustainable production [21-23]. The interaction between irrigation regime and nitrogen rate affects nitrogen mineralization, leaching, and plant uptake, thereby influencing nitrogen use efficiency [24-26]. Direct-seeded rice may have different nitrogen requirements and utilization patterns due to its unique root architecture and growth dynamics [27-28]. Therefore, optimizing the combination of irrigation and nitrogen management is crucial for maximizing yield and resource use efficiency in direct-seeded rice.

This study investigated the effects of different irrigation management strategies and nitrogen application rates on growth, nitrogen and water utilization, and grain yield of direct-seeded rice. The objectives were to: (1) evaluate the interactive effects of irrigation and nitrogen management on yield formation and resource use efficiency; (2) determine optimal nitrogen rates under different irrigation regimes for two direct-seeded rice varieties; and (3) provide theoretical and practical guidance for high-yield, water-saving, and efficient cultivation of direct-seeded rice.

---

2. Materials and Methods

2.1 Experimental Site and Design

A field experiment was conducted in 2013 at the experimental station of the Sichuan Academy of Agricultural Sciences. The soil was a typical paddy soil with the following properties: pH 6.3, organic matter 23.40 $g \cdot kg^{-1}$, total nitrogen 1.70 $g \cdot kg^{-1}$, available phosphorus 10.41 $mg \cdot kg^{-1}$, available potassium 61.01 $mg \cdot kg^{-1}$, and bulk density 1.32 $g \cdot cm^{-3}$.

The experiment employed a split-split plot design with three replications. Main plots consisted of two rice varieties: 'Dexiang 4103' (medium maturity, 150-day growth period) and 'Jinnongsimiao' (early maturity, 142-day growth period). Sub-plots comprised three irrigation management treatments: - **W1 (Shallow water irrigation):** Maintained 1–3 cm water layer from 2.1-leaf stage to maturity - **W2 (Alternate wetting and moderate drying):** From 64 days after sowing, irrigated to 2–3 cm when soil water potential (soil) reached -15 kPa - **W3 (Alternate wetting and severe drying):** From 64 days after sowing, irrigated to 2–3 cm when soil water potential (soil) reached -30 kPa

Split-split plots consisted of four nitrogen rates: 0 $kg \cdot hm^{-2}$ (N0), 120 $kg \cdot hm^{-2}$ (N120), 180 $kg \cdot hm^{-2}$ (N180), and 240 $kg \cdot hm^{-2}$ (N240). Nitrogen was applied as urea in three splits: 50% basal, 20% at tillering, 20% at panicle initiation, and 10% at heading. Phosphorus (90 $kg \cdot hm^{-2}$ as P_2O_5) and potassium (180 $kg \cdot hm^{-2}$ as K_2O) were applied basally to all plots.

Plot dimensions were 5 m × 3 m (15 m^2). Seeds were sown on March 28 at a rate of 4.5$×10^{5}$ grains per hm^2, with row spacing of 30 cm. Plant protection and other management practices followed local recommendations for direct-seeded rice.

2.2 Measurement Methods

2.2.1 Sampling and Growth Analysis Plant samples were collected at four growth stages: before jointing, jointing, heading, and maturity. Five representative hills were sampled per plot and separated into stems, leaves, and panicles. Leaf area was measured using a LI-3000C leaf area meter. All samples were oven-dried at 70°C to constant weight for dry matter determination.

2.2.2 Leaf Area Index (LAI) LAI was measured at heading stage using the following method: three representative 1-m row segments were selected per plot, and all leaves were measured for length and maximum width. LAI was calculated as: LAI = (Leaf length × Leaf width × 0.75 × Plant density) / Land area.

2.2.3 Dry Matter Accumulation Dry matter was determined by oven-drying plant samples at 70°C to constant weight. Accumulation rates were calculated for different growth periods.

2.2.4 Photosynthetic Rate Net photosynthetic rate (Pn) of flag leaves was measured at heading stage between 9:00–11:30 AM using a LI-6400 portable photosynthesis system. Measurements were taken on three sunny days with photosynthetic photon flux density of 1000 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ and ambient CO_2 concentration of 400 $\mu\text{mol} \cdot \text{mol}^{-1}$.

2.2.5 Yield and Yield Components At maturity, plants from two 4-m^2 areas per plot were harvested to determine grain yield (adjusted to 14% moisture content). Yield components including effective panicle number, grains per panicle, seed-setting rate, and 1000-grain weight were measured from five representative hills per plot.

2.2.6 Calculation of Nitrogen and Water Use Efficiency

The following formulas were used:

1. Nitrogen dry matter production efficiency ($\text{kg} \cdot \text{kg}^{-1}$) = Dry matter accumulation / Plant nitrogen accumulation
2. Nitrogen grain production efficiency ($\text{kg} \cdot \text{kg}^{-1}$) = Grain yield / Plant nitrogen accumulation
3. Nitrogen agronomic efficiency ($\text{kg} \cdot \text{kg}^{-1}$) = (Grain yield with N - Grain yield without N) / Nitrogen application rate
4. Nitrogen recovery efficiency (%) = (Plant N accumulation with N - Plant N accumulation without N) / Nitrogen application rate × 100%
5. Water use efficiency ($\text{kg} \cdot \text{hm}^{-2} \cdot \text{mm}^{-1}$) = Grain yield / (Irrigation amount + Precipitation - Runoff)

2.3 Data Analysis

All data were analyzed using DPS 7.05 statistical software. Analysis of variance (ANOVA) was performed to evaluate treatment effects, and means were compared using LSD test at $P < 0.05$ significance level. Figures were prepared using Origin 2017 software.

---

3. Results

3.1 Effects on Yield and Yield Components

Significant interactions between irrigation management and nitrogen rate affected yield and yield components of direct-seeded rice (Table 1). Under shallow water irrigation (W1), nitrogen application significantly increased yields of both varieties compared with N0. For 'Dexiang 4103', yields increased by 31.79%-48.77% with nitrogen application, with the highest yield (9.64 $\mathrm{t \cdot hm^{-2}}$) achieved at N180. For 'Jinnongsimiao', yields increased by 29.72%-45.36%, with the highest yield (9.94 $\mathrm{t \cdot hm^{-2}}$) at N240.

Under alternate wetting and moderate drying (W2), yield responses differed between varieties. 'Dexiang 4103' achieved maximum yield (9.59 $\mathrm{t \cdot hm^{-2}}$) at N180, with no significant difference at N240. 'Jinnongsimiao' showed highest yield (9.56 $\mathrm{t \cdot hm^{-2}}$) at N180, decreasing slightly at N240. Under severe drying (W3), both varieties showed reduced yield potential, with optimal nitrogen rates of 180 $\mathrm{kg \cdot hm^{-2}}$ for 'Dexiang 4103' and 180 $\mathrm{kg \cdot hm^{-2}}$ for 'Jinnongsimiao'.

3.2 Effects on Photosynthetic Rate and Leaf Area Index

Irrigation management and nitrogen rate significantly affected leaf area index (LAI) at heading stage (Figure 1). Compared with W1, W2 and W3 treatments reduced LAI by 8.5%-15.3% for 'Dexiang 4103' and 6.2%-12.8% for 'Jinnongsimiao'. Nitrogen application increased LAI in all irrigation treatments, but the magnitude of increase was smaller under water-deficit conditions.

Net photosynthetic rate (Pn) of flag leaves at heading showed different patterns (Figure 2). Under W2, Pn increased by 12.4%-18.7% compared with W1 across nitrogen treatments. Under W3, Pn decreased by 5.3%-9.8% relative to W1. Nitrogen application enhanced Pn, with optimal effects observed at N180 under W2 conditions.

3.3 Effects on Dry Matter Accumulation

Dry matter accumulation varied significantly among treatments (Table 2). Under W1, total dry matter increased with nitrogen rate up to N180 for 'Dexiang 4103'and N240 for 'Jinnongsimiao'. Under W2, 'Dexiang 4103'accumulated more dry matter (16.07 $\mathrm{t \cdot hm^{-2}}$ at N180) compared with W1, while 'Jinnongsimiao' showed similar accumulation patterns across irrigation treatments.

The harvest index was generally higher under W2 (0.536-0.588) compared with W1 (0.508-0.562) and W3 (0.525-0.575), indicating more efficient conversion of biomass to grain under moderate water stress.

3.4 Effects on Nitrogen Accumulation and Translocation

Nitrogen accumulation and translocation were significantly affected by the interaction of irrigation and nitrogen management (Table 3, Figure 3). Under W2, nitrogen accumulation at maturity increased by 15.3%-22.7% for 'Dexiang 4103' and 8.9%-14.5% for 'Jinnongsimiao' compared with W1. Nitrogen translocation from stems and leaves to grains was enhanced under W2, with translocation ratios increasing by 12.4%-18.6%.

However, excessive nitrogen (N240) under W3 reduced nitrogen recovery efficiency by 8.5%-15.2% for both varieties compared with N180. The nitrogen harvest index was highest under W2 at N180 for both varieties.

3.5 Effects on Nitrogen and Water Use Efficiency

Nitrogen use efficiency parameters showed clear responses to treatments (Table 4). Under W2, nitrogen agronomic efficiency reached maximum values of 37.05 $kg \cdot kg^{-1}$ for 'Dexiang 4103' at N120 and 38.28 $kg \cdot kg^{-1}$ for 'Jinnongsimiao' at N120, decreasing at higher nitrogen rates.

Water use efficiency (WUE) was significantly improved under W2 and W3 compared with W1. W2 increased WUE by 18.7%-24.3% across nitrogen treatments, while W3 increased WUE by 22.4%-28.9% but at the cost of reduced yield potential.

---

4. Discussion

The significant interaction between irrigation management and nitrogen rate demonstrates that optimal nitrogen application depends on water availability and variety characteristics. Alternate wetting and moderate drying (W2) created favorable conditions for nitrogen mineralization and root uptake, enhancing nitrogen accumulation and translocation [24-26]. The improved photosynthetic rate under W2 contributed to higher dry matter accumulation and more efficient nitrogen utilization.

The differential responses of the two varieties reflect their distinct genetic characteristics. 'Dexiang 4103' , a medium-maturity variety, showed greater responsiveness to moderate water stress, likely due to its more extensive root system and higher drought tolerance. In contrast, 'Jinnongsimiao' , an early-maturity variety, was more sensitive to severe water deficit but maintained relatively stable nitrogen use efficiency across nitrogen rates.

The decline in nitrogen use efficiency at high nitrogen rates (N240) under all irrigation treatments highlights the importance of optimizing nitrogen application to minimize environmental losses [27-28]. The combination of W2 with N180 for 'Dexiang 4103' and N180 for 'Jinnongsimiao' achieved the best balance of high yield, high nitrogen efficiency, and water savings.

These results align with previous studies on transplanted rice [18-20] but provide specific guidance for direct-seeded systems. The enhanced nitrogen translocation under moderate water stress suggests that AWD irrigation can promote remobilization of stored nitrogen to grains, a critical factor for yield formation in direct-seeded rice [11, 15].

---

5. Conclusion

Alternate wetting and moderate drying irrigation combined with appropriate nitrogen rates significantly improved nitrogen and water use efficiency while maintaining high yields in direct-seeded rice. The optimal management practices were: - For 'Dexiang 4103' : Alternate wetting and moderate drying with 180-240 $kg \cdot hm^{-2}$ nitrogen - For 'Jinnongsimiao' : Alternate wetting and moderate drying with 180 $kg \cdot hm^{-2}$ nitrogen

These findings provide a scientific basis for developing water-saving, high-efficiency cultivation techniques for direct-seeded rice production. Future research should investigate the long-term effects of these practices on soil fertility and environmental sustainability.

References

[1] Zhu G, Zhan M F, Zhu K Y, et al. Effects of alternate wetting and drying irrigation on yield and water use efficiency of rice[J]. Acta Agronomica Sinica, 2016, 42(7): 1026-1036

[2] Lampayan R M, Rejesus R M, Singleton G R, et al. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice[J]. Field Crops Research, 2015, 170: 95-108

[3] Tabbal D F, Bouman B A M, Bhuiyan S I, et al. On-farm strategies for reducing water input in irrigated rice: Case studies in the Philippines[J]. Agricultural Water Management, 2002, 56(2): 93-112

[4] Yang J C, Yuan L M, Tang C, et al. Effect of dry-wet alternate irrigation on rice quality and activities of some enzymes in grains during the filling[J]. Acta Agronomica Sinica, 2005, 31(8): 1052-1057

[5] Sun Y J, Sun Y Y, Liu S J, et al. Effects of water management and nitrogen application strategies on nutrient absorption, transfer, and distribution in rice[J].

Acta Agronomica Sinica, 2011, 37(12): 2221-2232

[6] Zhang Z C, Li H W, Chen T T, et al. Effect of furrow irrigation and alternate wetting and drying irrigation on grain yield and quality of rice[J]. Scientia Agricultura Sinica, 2011, 44(24): 4988-4998

[7] Liu Y, Sun W T, Gong L, et al. Effects of water regulation on rhizosphere soils and yield of rice[J]. Journal of Irrigation and Drainage, 2014, 33(2): 98-100

[8] Wang W X, Liu X J, Tian Y C, et al. Effects of different soil water treatments on photosynthetic characteristics and grain yield in rice[J]. Acta Ecologica Sinica, 2012, 32(22): 7053-7060

[9] Chi D C, Tong Y X, Chen T T, et al. Effects of water stress coupling in different growth stage on rice yield and water productivity[J]. Journal of Shenyang Agricultural University, 2016, 47(1): 71-77

[10] Chen X H, Xu G W, Sun H S, et al. Effects of soil moisture and nitrogen nutrition during grain filling on the grain yield and quality of rice[J]. Journal of Yangzhou University: Agricultural and Life Sciences Edition, 2003, 24(3): 37-41

[11] Fu J, Liu J, Cao Z Q, et al. Effects of alternate wetting and drying irrigation during grain filling on the seed-setting rate and grain weight of two super rice cultivars[J]. Acta Agronomica Sinica, 2014, 40(6): 1056-1065

[12] Lin J J, Li G H, Xue L H, et al. Subdivision of nitrogen use efficiency of rice based on 15N tracer[J]. Acta Agronomica Sinica, 2014, 40(8): 1424-1434

[13] Zhang X Z, Yi Q, Zhu P, et al. Agronomic responses to nitrogen application and nitrogen utilization in rice fields[J]. Plant Nutrition and Fertilizer Science, 2011, 17(4): 782-788

[14] Sun Y Y, Sun Y J, Yang Z Y, et al. Nitrogen use efficiency and yield of rice under different nitrogen and water stress conditions at grain-filling stage[J]. Chinese Journal of Eco-Agriculture, 2013, 21(3): 274-281

[15] Sun Y J, Sun Y Y, Liu K, et al. Effects of water-nitrogen interaction on some physiological characteristics and grain yield in hybrid rice during grain filling[J]. Journal of Zhejiang University: Agriculture & Life Sciences, 2009, 35(6): 645-654

[16] Yang J C, Wang Z Q, Zhu Q S. Effect of nitrogen nutrition on rice yield and its physiological mechanism under different status of soil moisture[J]. Scientia Agricultura Sinica, 1996, 29(4): 58-66

[17] Sun Y J, Sun Y Y, Li X Y, et al. Effects of water-nitrogen interaction on absorption, translocation and distribution of nitrogen, phosphorus, and potassium in rice[J]. Acta Agronomica Sinica, 2010, 36(4): 655-664

[18] Wang S H, Cao W X, Ding Y F, et al. Interactions of water management and nitrogen fertilizer on nitrogen absorption and utilization in rice[J]. Scientia Agricultura Sinica, 2004, 37(4): 497-501

[19] Xiao X, Zhu W, Xiao L, et al. Effects of water and fertilizer management on root characteristics and nitrogen, phosphorous and potassium uptakes of rice at tillering stage[J]. Chinese Journal of Soil Science, 2016, 47(4): 903-908

[20] Lu C Q. Effect of different cultivation measures on yield and quality in direct seeding rice[D]. Yangzhou: Yangzhou University, 2010: 12-53

[21] Hua X L. Effect of nitrogen rates on grain yield and nutrient use efficiency of drilling and direct seeding rice and its physiological mechanism[D]. Yangzhou: Yangzhou University, 2015: 16-52

[22] Ni Z R, Chen J W, Ruan M Y. Effect of different modes of fertilizer N application on nitrogen absorption and yield of direct seeding rice[J]. Acta Agriculturae Nucleatae Sinica, 2003, 17(2): 123-126

[23] Jiang M J, Ma J, Sun Y J, et al. Effects of seeding rates and nitrogen fertilizer managements on photosynthetic productivity and nitrogen utilization in direct-seeded rice[J]. Journal of Zhejiang University: Agriculture & Life Sciences, 2015, 41(5): 516-526

[24] Zhang F X, Zhou M Y, Zhou C L, et al. Effects of water and fertilizer coupling on root morphological characteristics and activities of rice[J]. Transactions of the CSAE, 2006, 22(5): 197-200

[25] Xiao X, Zhu W, Xiao L, et al. Suitable water and nitrogen treatment improves soil microbial biomass carbon and nitrogen and enzyme activities of paddy field[J]. Transactions of the CSAE, 2013, 29(21): 91-98

[26] Zhao F, Xu C M, Zhang W J, et al. Effects of rhizosphere dissolved oxygen and nitrogen form on root characteristics and nitrogen accumulation of rice[J]. Chinese Journal of Rice Science, 2011, 25(2): 195-200

[27] Sun Y J, Sun Y Y, Li X Y, et al. Relationship of activities of key enzymes involved in nitrogen metabolism with nitrogen utilization in rice under water-nitrogen interaction[J]. Acta Agronomica Sinica, 2009, 35(11): 2055-2063

[28] Sun Y J, Sun Y Y, Liu K, et al. Effects of water-nitrogen interaction on rice senescence and material transport and yield during grain filling[J]. Plant Nutrition and Fertilizer Science, 2009, 15(6): 1339-1349

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.