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Brief Report

The Fraction of Intercepted Radiation to Nitrogen Absorption as an Indicator for Assessing Physiological Nitrogen Use Efficiency in Rice

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Abstract: Improving nitrogen (N) use efficiency is important for achieving sustainable rice production in China. Physiological N use efficiency (PNUE) is a measure of a plant's ability to convert absorbed N into biomass, and can be calculated as the product of the fraction of intercepted radiation to N absorption (FIRNA) and radiation use efficiency (RUE). This study evaluated the relationships between PNUE with FIRNA and RUE in three widely grown, high-yielding rice varieties using data obtained from two N fertilization experiments conducted in 2020 and 2021. The results show that PNUE was significantly positively related to FIRNA, but not significantly related to RUE in all three rice varieties. PNUE increased by 7.4–10.3 g g^{-1} for each 10 MJ g^{-1} increase in FIRNA. These results suggest that FIRNA can serve as an indicator for assessing PNUE in rice, which has implications for the phenotypic identification of rice varieties with high PNUE.

Keywords: nitrogen use efficiency; radiation interception; radiation use efficiency; rice

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Improving rice yields by overcoming yield-limiting factors, such as soil nutrient deficiencies, is critical to ensuring food security in China [1], where approximately 65% of the population consumes rice as a staple food [2]. Nitrogen (N) is the most limited nutrient for rice growth and development in almost all environments [3]. With the advent of the fertilizer industry, synthetic N fertilizer application became a common means of supplementing N-deficient indigenous soils for rice production and has immensely contributed to increased rice yields in China [4].

However, over the past several decades, increases in N fertilizer inputs in China have resulted in diminishing returns [5] and led to large amounts of N lost to the environment by leaching, volatilization, and denitrification [6]. The lost N has had various environmentally damaging impacts, including surface water eutrophication [7], soil acidification [8], and enhanced N deposition [9]. These environmental impacts have posed substantial challenges to the sustainable development of rice production in China, highlighting an urgent need to improve the N use efficiency of rice.

Physiological N use efficiency (PNUE) is a measure of the ability of a plant to produce biomass using absorbed N [10], and can be calculated using Equation (1). Taking into consideration that biomass production is a product of canopy intercepted radiation and radiation use efficiency (RUE, i.e., biomass produced per unit of radiation intercepted) [11], the calculation of PNUE can be expressed by Equation (2) and rearranged as in Equation (3).

$$\text{PNUE} = \frac{\text{Biomass production}}{\text{N absorption}} \tag{1}$$

$$\text{PNUE} = \frac{\text{Intercepted radiation} \times \text{RUE}}{\text{N absorption}} \tag{2}$$

$$\text{PNUE} = \frac{\text{Intercepted radiation}}{\text{N absorption}} \times \text{RUE} \quad (3)$$

In Equation (3), the fraction of intercepted radiation to N absorption (FIRNA) can be regarded as the effect of absorbed N on radiation intercepted by the plant canopy. This effect is biologically significant as changes in N absorbed by the plant can alter architectural characteristics of the canopy, such as leaf area and angle [12,13], which are critical factors determining the capacity of the canopy to intercept incoming radiation (i.e., the percent of radiation intercepted) [14,15]. RUE itself is related to N absorption because N is a major constituent of numerous chloroplast components and plays an important role in photosynthesis [16].

From Equation (3), it is clear that PNUE can be improved by increasing FIRNA, RUE, or both. However, our recent study shows that there is a negative relationship between RUE and FIRNA [17]. Therefore, an increase in PNUE only can be achieved by increasing FIRNA or RUE, but not both. In the present study, we evaluated the relationships of PNUE with FIRNA and RUE in rice plants by using data obtained from two N fertilization experiments (I and II) conducted in 2020 and 2021. Our objective was to determine whether FIRNA or RUE can serve as an indicator for assessing PNUE in rice.

Three hybrid rice varieties (i.e., Deyou 4727, Guiliangyou 2, and Y-liangyou 900) were used in this study. These three varieties had been approved as "super" rice varieties by the Ministry of Agriculture and Rural Affairs of China due to their high-yield performance, and have been widely grown by Chinese rice farmers. In the experiment I, Deyou 4727 and Y-liangyou 900 were grown under four N application rates (0, 120, 180, and 240 kg N ha^{-1}) in each year. The experiment was arranged in a split-plot design with three replicates, where the main plot was assigned to N rate and the subplot (33 m^2) to variety. In experiment II, Guiliangyou 2 was grown under a factorial combination of two N application rates (150 and 225 kg N ha^{-1}) and three N split-application ratios at the basal, early-tillering, and panicle-initiation stages (6:3:1, 5:3:2, and 4:3:3) in each year. The N treatments in factorial combinations were arranged in a completely randomized block design with three replicates and a plot size of 35 m^2. In both experiment I and II, transplanting was conducted at a hill spacing of 20 cm $\times$ 20 cm with two seedlings per hill.

Canopy-intercepted radiation, biomass production, and plant N absorption were determined to calculate FIRNA, RUE, and PNUE. Briefly, daily incident solar radiation was recorded during the rice-growing season with an on-site weather station (Vantage Pro2, Davis Instruments Corp., Hayward, CA, USA). At the panicle-initiation, heading, and maturity stages, the percentage of solar radiation intercepted by the canopy was measured using a SunScan canopy analysis system (Delta-T Devices Ltd., Burwell, Cambridge, UK) to calculate the canopy-intercepted radiation. Ten plants were sampled from each plot at the maturity stage. Plant samples were hand threshed, and filled and unfilled grains were separated by submerging them in tap water. After oven-drying at 70 °C to a constant weight, the dry weights of straw and filled and unfilled spikelets were measured to determine the biomass production. N concentration in each organ was determined with a segmented flow analyzer (Skalar SAN Plus, Skalar Inc., Breda, The Netherlands) to calculate the plant N absorption.

The experimental details and the data of FIRNA, RUE, and PNUE are provided in the Supplementary Materials (Methods S1; Table S1). Linear regression analysis was performed for PNUE against FIRNA and RUE for each variety (Statistics 8.0, Analytical Software, Tallahassee, FL, USA).

The results show that PNUE was significantly positively related to FIRNA (Figure 1a), but not significantly related to RUE in all three varieties (Figure 1b); FIRNA explained 74%, 85%, and 79% of the variation in PNUE in Deyou 4727, Guiliangyou 2, and Y-liangyou 900, respectively. From the regression equations presented in Figure 1a, it was shown that PNUE increased by 7.7, 7.4, and 10.3 g g^{-1} for each 10 MJ g^{-1} increase in FIRNA in Deyou 4727, Guiliangyou 2, and Y-liangyou 900, respectively.

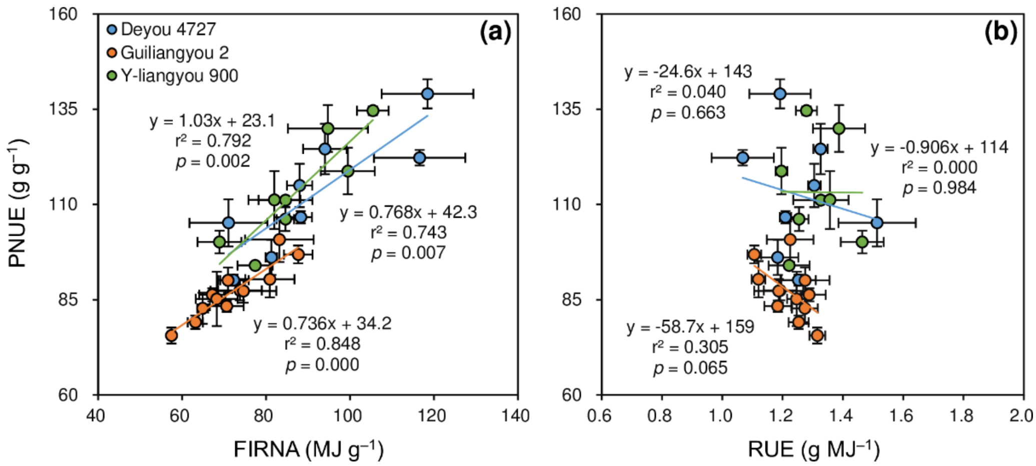

Figure 1. Relationships between physiological N use efficiency (PNUE) and (**a**) the fraction of canopy-intercepted radiation to plant N absorption (FIRNA) and (**b**) radiation use efficiency (RUE) in three widely grown, high-yielding rice varieties (i.e., Deyou 4727, Guiliangyou 2, and Y-liangyou 900).

The results of this study suggest that FIRNA can be used as an indicator for assessing PNUE in rice. Previous studies related to the improvement of PNUE in rice have been mainly focused on canopy physiological and ecological traits, such as leaf photosynthetic N use efficiency (i.e., the ratio of photosynthetic rate to nitrogen content per unit leaf area) [18] as well as canopy N and light distribution [19]. However, the indicator identified in this study that relates to PNUE, i.e., FIRNA, is a composite of canopy radiation interception and plant N absorption. This indicates that not only canopy characteristics but also root traits related to plant N absorption and the effect of absorbed N by the plant on canopy characteristics should be considered in terms of improving PNUE in rice. As for the canopy characteristics, special attention should be paid to the canopy architectural traits (e.g., leaf area and angle) that determine the canopy radiation interception.

FIRNA as an indicator for assessing PNUE has implications for the phenotypic identification of rice varieties with high PNUE. FIRNA can be increased by increasing canopy-intercepted radiation with maintained or reduced plant N absorption. The increase in canopy-intercepted radiation can be achieved by increasing canopy occupation volume through the altering of leaf area and/or leaf angle [20]. Under the condition of increased canopy occupation volume, maintained or reduced plant N absorption can lead to a decrease in leaf color as a result of the N-dilution effect [21,22]. These results suggest that canopy occupation volume and leaf color are important phenotypic traits related to FIRNA and PNUE. The canopy occupation volume can be calculated in a high-throughput manner based on the canopy point clouds [20], while the leaf color can be identified by existing phenotypic diagnostic tools, such as camera-based high-throughput imaging systems [21]. However, to achieve the phenotypic identification of high PNUE in rice, further investigations are required to establish the multiple relationships between PNUE with canopy occupation volume and leaf color.

In conclusion, this study identifies FIRNA as an indicator for assessing PNUE in rice. This finding has implications for the phenotypic identification of rice varieties with high PNUE.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12071603/s1, Method S1: Experimental details; Table S1: The fraction of intercepted radiation to N absorption (FIRNA), radiation use efficiency (RUE), and physiological N use efficiency (PNUE) in rice in two N fertilization experiments.

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