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Short Communication

Site-specific nutrient management enhances sink size, a major yield constraint in rainfed lowland rice

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ABSTRACT

Nutrient management can increase crop yield and income, but its effects on yield components are rarely dissected in on-farm research. In this study, we compared aboveground biomass and yield components of rainfed lowland rice under site-specific nutrient management and farmer management from 69 demonstration sites prone to mild to moderate intermittent drought across 9 Philippine provinces over 3 years (the 2011–2013 wet seasons). The sink size (spikelets m^{-2}) was most closely associated with grain yield in all years. Panicle size (spikelets per panicle) increased by 10.4% and 13.0% in 2011 and 2012, respectively, under site-specific nutrient management, with N application around the early reproductive stage of < 25 kg N ha^{-1} in farmer nutrient management versus 30–33 kg N ha^{-1} in site-specific management. Higher N application during seedling establishment in farmer nutrient management (55 kg N ha^{-1}) than in site-specific management (22 kg N ha^{-1}) did not increase panicles m^{-2} in any year. Our results demonstrate the yield advantage of site-specific nutrient management in rainfed lowland rice in relatively fertile and less drought-prone environments: enhancing sink size should be the major target of nutrient management; it is unnecessary to apply high amounts of N during seedling establishment to secure a sufficient panicle number; and N application is most important during the early reproductive stage to increase panicle size.

1. Introduction

The concept of site-specific nutrient management was proposed as a component of an integrated crop management strategy for irrigated rice ecosystems in the 1990s, with the goal of accounting for the quantitative relationship between nutrient supply and crop demand by paddy field (Dobermann et al., 2002; Witt et al., 1999). Site-specific nutrient management has been extensively assessed in on-farm trials during the last two decades, and has increased farmer income in tropical Asia by around 100 USD ha^{-1} (Pampolino et al., 2007; Wang et al., 2007). These findings were consolidated in 2013 to support the public release of a user-friendly, Web-based decision-support tool for automatic computation of the most appropriate timing and rate of fertilizer application for irrigated rice in the tropics: the *Rice Crop Manager* (RCM; www.knowledgebank.irri.org/decision-tools/crop-manager) (Banayo et al., 2018). To date, RCM is available in Bangladesh, India, Indonesia, the Philippines, and Vietnam. In the Philippines, recommendations for more than 1.3 million individual paddy fields have been downloaded by local extension staff and farmers (Rowena Castillo, International Rice Research Institute, IRRI, pers. comm.).

However, improvement of nutrient management in rainfed lowland rice has been slow compared with that in irrigated rice owing to the fluctuating hydrological conditions under rainfed conditions (Fukai and Ouk, 2012; Haefele et al., 2016; Kato et al., 2016). Recently, Banayo et al. (2018) compared RCM at 93 rainfed lowland sites in the Philippines with conventional management by the participating farmers. The major difference in nutrient management between RCM and farmer practice (FP) was the N application regime. Under RCM, less total N was more equally split among the seedling, vegetative, and reproductive growth stages than under FP, leading to increases of 0.36 t ha^{-1} of rice yield and 154 USD ha^{-1} in net income (Banayo et al., 2018). The study suggested that the concept of site-specific nutrient management would be also applicable to rainfed rice and would enhance both yield and income.

Abbreviations: DAT, days after transplanting; FP, farmer practice; IRRI, International Rice Research Institute; RCM, Rice Crop Manager

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Another concept for improved nutrient management is based on plant development and yield components (Peng et al., 2010; Yang et al., 2003). Grain yield is a function of panicle density, sink size, grain-filling capacity, and weight of the individual grains. In theory, the yield response to nutrient management should be based on the response of each of these yield components to N availability during a specific growth stage (Yoshida, 1981), but evidence from observations in rainfed farm fields is lacking. To provide that information, we designed a study of rainfed rice ecosystems. We hypothesized that the yield advantage of RCM over FP in rainfed lowlands (Banayo et al., 2018) would be attributable to the response of sink size or panicle size to greater N input during the early reproductive stage; and that excess N input during the seedling stage in FP would not improve any yield components. Our goal was to characterize the agronomic traits associated with rainfed lowland rice yield in RCM and FP in on-farm trials.

2. Materials and methods

On-farm trials of nutrient management in rainfed lowlands were conducted in the northern Philippines during the wet season (June to November) from 2011 to 2013, in which 69 farm households participated (Banayo et al., 2018). The soil at the sites was heavy clay, silty clay, or clay loam, and relatively fertile with high cation exchange capacity (> 15 cmol kg^{-1}; Haefele et al., 2013). The mean temperature of around 27 °C was similar throughout the study region. The rainfall across the regions was lower in 2013 (1279 mm) than in 2011 (2180 mm) and 2012 (1769 mm). Mild to moderate intermittent drought often occurred during the vegetative stage according to observations by farmers and local extension staff.

We compared the impacts of two treatments on rice yield and its components ($n = 69$ fields): site-specific nutrient management based on *Rice Crop Manager* for each field (hereafter, the RCM treatment) and conventional farmer practice (hereafter, the FP treatment). Banayo et al. (2018) describe details of the algorithms and operation of RCM. In each year, new farmers were chosen at different locations, and each trial was managed by the participating farmer. We divided a 1000-m^2 rice field into two portions so that the two treatments could be implemented at each site. RCM plots received fertilizer based on the software's calculations (http://webapps.irri.org/ph/rcm/) using information on the history of the field, whereas nutrient management in FP was based on the farmer's decisions. The amount and date of application of N, P, and K fertilizers in each treatment were recorded. At physiological maturity, rice plants were collected from three representative 0.16-m^2 plots in each 500-m^2 plot, and the number of panicles was counted. The panicles were detached from the straw and threshed by hand, and filled and unfilled grains were separated and counted. We measured the dry weights of filled and unfilled grains, rachides, and straw after oven-drying at 80 °C for 72 h. Grain yield was determined from a 5-m^2 area in each plot and expressed at a water content of 0.14 g H_2O g^{-1} grain. We then calculated the number of spikelets per panicle, grain-filling percentage (100 × filled spikelets/total spikelet number), and 1000-grain weight.

We conducted analysis of variance to detect significant differences among yield parameters using the MIXED procedure in SAS 9.1 for Windows (SAS Institute, Cary, NC, USA). In the analysis, all fields studied in a given year were treated as replicates, and treatment effects were analyzed for individual years. Significance was set at $P < 0.05$, but $P < 0.10$ was accepted as the marginal significance level for on-farm studies (Chaney, 2017). We calculated the correlations (Pearson's r) between yield and agronomic characteristics.

3. Results

Table 1 summarizes the fertilizer inputs and grain yield during the study. The total N input in FP was significantly higher than that in RCM in 2011 and 2012, but not in 2013. In all three years, N input during the first 15 days after transplanting (DAT), which represents the seedling stage, was significantly higher in FP than in RCM in all years, whereas more N was applied in RCM than in FP from 31 to 45 DAT (around the panicle initiation stage), although $P < 0.10$ in 2011. P and K inputs did not differ significantly between RCM and FP except for a marginally significant increase in K in the RCM treatment in 2013. The mean yield was similar among the three years (4.4 t ha^{-1} to 4.7 t ha^{-1}), despite the difference in the rainfall. RCM yielded significantly higher than FP in 2011 and 2012, and was marginally significantly higher ($P < 0.10$) in 2013.

Table 2 summarizes the agronomic traits. The aboveground biomass was higher in RCM than in FP in all three years, significantly so only in 2011. The number of panicles m^{-2} did not differ significantly between FP and RCM in any year. In 2011 and 2012, the number of spikelets per panicle (panicle size) and the number of spikelets m^{-2} (sink size) were higher in RCM than in FP, by 10.4% and 8.4% ($P < 0.05$), respectively, in 2011 and by 13.0% and 8.5% ($P < 0.10$), respectively, in 2012. In 2013, when the N input from 31 to 45 DAT was increased to 29.5 kg N ha^{-1} in FP, there was no significant difference between the treatments in any trait. The filled-grain percentage and 1000-grain weight did not differ significantly between treatments in any year.

Table 3 summarizes the correlations between the agronomic characteristics and yield. The number of spikelets m^{-2} was strongly and significantly positively correlated with yield in both treatments and all years ($r = 0.753$ to 0.950**). In FP, the number of spikelets per panicle and aboveground biomass were also significantly positively correlated with yield in 2011 and 2012, but not in 2013, when the N input from 31 to 45 DAT was higher than in the other years. On the other hand, the percentage of filled grains and the 1000-grain weight were significantly positively correlated with yield in 2013. Across years and treatments, yield increased from 1.9 t ha^{-1} to 6.8 t ha^{-1} as the number of spikelets m^{-2} increased from 12 000 to around 38 000 (Fig. 1a). The number of spikelets per unit area was strongly and significantly correlated with yield across years in both FP and RCM (Fig. 1a). However, the number of spikelets m^{-2} was not significantly correlated with the total N input (Fig. 1b); no level of N input always provided 35 000 spikelets m^{-2} (equivalent to a yield of 6.12 t ha^{-1}; Fig. 1a) in rainfed lowlands (Fig. 1b).

4. Discussion

Our results provide evidence that sink size (spikelets m^{-2}) is a major yield constraint for rainfed lowland rice in northern and central Luzon in the Philippines (Table 3; Fig. 1). Aboveground N uptake at anthesis is closely associated with the number of spikelets m^{-2} (Hasegawa et al., 1994; Kato and Katsura, 2010). The average yield in FP was 4.36 t ha^{-1} across years and sites (Table 1), and achieving this yield requires more than 24 000 spikelets m^{-2}. However, sink size was not correlated with the total N input (Fig. 1b), indicating the large variation in the N recovery in farmers' fields (ratio of the N uptake to the applied N). Spikelet sterility and a decreased harvest index due to drought during the booting stage and anthesis have been emphasized as major yield constraints in rainfed rice in breeding trials at research stations (Fischer et al., 2012; Kumar et al., 2014). This may also be applicable to severely drought-affected rice areas, where yield is less than 2 t ha^{-1} (Swain et al., 2017). However, nutrient availability to support increases in panicle number, panicle size, husk size, and grain filling through photo-assimilation at a given phenological stage may be more relevant to the yield of rainfed lowland rice on clayey soils in the Philippines and Indonesia (Boling et al., 2008; Haefele et al., 2013). On the basis of their on-farm studies in Thailand and Laos, Haefele and Konboon (2009) and Haefele et al. (2010) suggested that variation in the yield of rainfed lowland rice can be attributed more to crop biomass (which reflects the soil's nutrient availability) than to the harvest index, even on sandy soils with low water-holding capacity.

The major difference in nutrient management between RCM and FP