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Crop performance and water- and nitrogen-use efficiencies in dry-seeded rice in response to irrigation and fertilizer amounts in northwest India

G. Mahajan[a], B.S. Chauhan[b,*], J. Timsina[b], P.P. Singh[a], Kuldeep Singh[a]

[a] *Punjab Agricultural University, Ludhiana 141004 Punjab, India*
[b] *International Rice Research Institute, Los Baños, Philippines*

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ABSTRACT

Because of increasing constraints of labor and water availability, dry-seeded rice (DSR) is now considered to be a new and emerging rice production system in the northwest Indo-Gangetic Plains of India. However, limited information is available on optimizing nutrient and water management in DSR to produce high yields. The effects of four amounts of N (0, 60, 120, and 180 kg ha^{-1}) applied with or without P and K fertilizers under two irrigation regimes (10 and 20 kPa; irrigated when soil water potential at 15-cm soil depth reached 10 and 20 kPa, respectively) were studied on rice yield, and N- and water-use efficiencies. Grain yield with irrigation threshold increasing from 10 to 20 kPa did not decrease with the application of P and K fertilizers at 120 kg N ha^{-1}, leading to substantial savings in irrigation water. At the soil moisture potential of 20 kPa, application of P and K fertilizers along with 120 kg N ha^{-1} resulted in a 14% increase in rice vis-à-vis when P and K fertilizers were not applied. However, this effect was not observed at the soil moisture potential of 10 kPa. Applying P and K fertilizers along with N at 20 kPa compared with 10 kPa resulted in higher water- and N-use efficiencies. Water-use efficiency was significantly correlated with yield-contributing parameters when P and K were supplied along with N; whereas, without P and K application, water-use efficiency was not correlated with any yield-contributing parameters. It was concluded that, in DSR, the addition of P and K along with N could compensate for the yield loss under water-stress conditions. Our study suggests that there is a need to study the effects of applying different amounts of P and K along with N under a range of water regimes on dry matter partitioning and soil characteristics to understand the mechanism of yield loss in DSR.

1. Introduction

The northwestern Indo-Gangetic Plains (NW-IGP) of India have played a leading role in the agricultural transformation of India and they are considered as the most fertile plains for the livelihood of hundreds of millions of people of India (Dhillon et al., 2010). Food security of India is highly dependent on the NW-IGP as evident from the contribution of this region to the national buffer stock of food grains, which has generally been 50–75% in wheat and 30–48% in rice (Timsina and Connor, 2001; Rockström et al., 2007). Therefore, sustainable production of rice and wheat in the NW-IGP of India is crucial for the food security of India.

The traditional method of rice cultivation requires a large amount of labor, water, and energy. Water and labor, however, are becoming increasingly scarce in the region, raising questions about the sustainability of rice production and the overall environment. In the NW-IGP of India, increasing use of groundwater for rice cultivation has led to a decline in the water table by 0.1 to 1.0 m year^{-1}, resulting in water scarcity and increased cost for pumping water (Hira, 2009; Rodell et al., 2009; Humphreys et al., 2010). Implementation of the Mahatma Gandhi National Rural Employment Guarantee Act, introduced by the Indian government in 2005 (GOI, 2011), promising 100 days of paid work in people's home village, has been creating a labor scarcity in Punjab as rice transplanting in this region is dependent on migrant laborers from eastern Uttar Pradesh and Bihar. Since rice is primarily grown by transplanting seedlings in flooded puddled fields, it requires a large amount of water (∼150 cm), of which 15–20 cm (Singh et al., 2001) is used only for puddling (intensive cultivation in wet conditions). This suggests that alternatives to puddled transplanted rice (TPR) are required to save water and increase crop, water, and labor productivity.

One way to reduce water and labor demands is to grow dry-seeded rice (DSR) without prolonged periods of flooding instead of TPR with flooding (Mahajan et al., 2009). Dry seeding of rice with subsequent aerobic soil conditions eliminates the need for ponding water, thus reducing the overall water demand and providing

* Corresponding author at: Crop and Environmental Sciences Division, International Rice Research Institute, DAPO Box 7777, Metro Manila 4031, Laguna, Philippines.
E-mail address: b.chauhan@irri.org (B.S. Chauhan).

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opportunities for water and labor savings (Bouman and Tuong, 2001; Sharma et al., 2002). DSR is now considered to be an emerging production system in the NW-IGP but its response to nutrients and interactions between water and nutrients have rarely been studied in the region. The shift from puddled to aerobic soil conditions causes changes in soil water status, soil aeration, and nutrient availability (Timsina and Connor, 2001; Prasad, 2011). Rice plants are very sensitive to water stress when exceeding critical levels of soil drying below saturation. Leaf expansion stops completely when root-zone soil water potential exceeds 50 kPa (Woperies et al., 1996). Information on the physiological responses of rice to various levels of water stress under dry-seeding conditions is limited in the literature (Sudhir-Yadav et al., 2010). High water-use efficiency (WUE) and water productivity have been reported for DSR, whose yield penalty is relatively small compared with the savings in water use (Bouman et al., 2005; Mahajan et al., 2011b).

In studying crop response to nutrients, interactions between nutrient and water management may play a significant role. In TPR, ammonium is the dominant form of available N, whereas, in aerobic rice systems, the dominant form of N is nitrate, which results in different pathways of N losses and N availability (Belder et al., 2005; Prasad, 2011). Belder et al. (2005) reported that yield of rice grown under aerobic conditions is more limited by N than yield under flooded conditions. A recent study also showed that N requirement is higher for DSR than for TPR (Mahajan et al., 2011a). In the rice-wheat cropping system, which is the most predominant system in the NW-IGP, the general trend is to apply P to wheat and skip P application to rice if it is grown under puddled conditions (Prasad, 2005).

Although flooding increases the supply of native P to rice, drying following flooding induces P deficiency due to changes in the inorganic fractions (Willett and Higgins, 1978; Sah and Mikkelsen, 1989).

Rice soils in the IGP are rich in illites, which fix K^+ under both dry and moist conditions. Malvolta (1983) reported that when soils were mixed and shaken with a K solution, K^+ fixation was 25%, while it was 68% when K^+-saturated soils were dried. K^+ fixation was 2–3 times greater after drying than after wetting. This suggests that intermittent drying conditions in DSR may cause temporary K deficiency in rice.

We hypothesized that appropriate amounts of P and K applications to DSR will have a positive effect on rice yield. Further, proper irrigation scheduling will reduce the losses of water and increase crop growth and yield by influencing nutrient-use efficiency of the crop. It is expected that excessive irrigation in DSR may increase N loss in soil through leaching and may increase nitrate pollution in underground water. So, improved irrigation management practices leading to increased fertilizer N-use efficiency (NUE) can reduce the potential for nitrate pollution in groundwater (Bijay-Singh et al., 1995; Cassman et al., 2002). The use of N can be increased by balanced application of N, P, and K and by more frequent light irrigation (Bijay-Singh et al., 1995; Bijay-Singh and Sekhon, 1997). Although many studies have investigated the productivity and water-use efficiency of DSR (Zhang et al., 2009; Sudhir-Yadav et al., 2010; Mahajan et al., 2011b), no studies have looked into the interactive effect of irrigation and fertilizer amounts for DSR. The objectives of this study were to quantitatively evaluate the yield response to irrigation and N application, and the effects of P and K omission on yield formation and on the associated NUE and WUE under different irrigation regimes.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted at the research farm of Punjab Agricultural University (PAU), Ludhiana, India (30°54′N, 75°98′E; 247 m above sea level), during the summer seasons of 2010 and 2011. The rice-growing season (mid-June-September) coincides with the monsoon rains. Average annual rainfall is 734 mm, 85% of which falls during the monsoon season. The soil at the experimental site was a Fatehpur, loamy sand (Typic Ustipsament) with pH 7.1, total N content 0.04%, organic carbon content 0.38%, 0.5 N $NaHCO_3^-$-extractable P 5.5 $\mu g\,g^{-1}$, and NH_4OAc-extractable K 150 $\mu g\,g^{-1}$. Groundwater depth at the site was below 25 m and the water was non-saline. The soil had a bulk density of 1.6 $Mg\,m^{-3}$ and the saturated hydraulic conductivity was 22 $mm\,h^{-1}$. The site was under a lowland rice-wheat cropping system for 5 years before the establishment of the experiment.

2.2. Weather parameters

Rainfall, sunshine hours, and maximum and minimum temperatures were measured at the PAU meteorological station, located about 500 m away from the experimental site.

2.3. Experimental design

The experiment in each year was laid out in a factorial randomized complete block design with 16 treatments (2 × 2 × 4) in three replicates. The first factor included two irrigation regimes (10 and 20 kPa), the second factor included fertilization treatments (with and without P and K fertilizer application: 30 kg P ha^{-1} and 30 kg K ha^{-1}), and the third factor included N amounts (0, 60, 120, 180 kg ha^{-1}). The plots were irrigated with 50-mm water depth when soil water potential in the respective irrigation regime reached 10 or 20 kPa. For the first 15 days after sowing (DAS), the crop was irrigated to keep soil water tension below 10 kPa at 15-cm soil depth to avoid water deficit during crop establishment and thereafter irrigation treatments commenced. The crop received a total of 874 and 1274 mm water (irrigation + rainfall) in 20 and 10 kPa irrigation regimes, respectively, in 2010 and 1279 and 1679 mm, respectively, in 2011. The size of the subplots was 4.5 m × 2.4 m. The subplots were separated with double bunds and the distance between the bunds was 75 cm to prevent the flow of water from one plot to another.

2.4. Crop management

Fields were prepared by cultivating twice using a disc-harrow, followed by leveling with a wooden board. Seeds were sown by a single-row drill at a seeding rate of 30 kg ha^{-1} at 20-cm row spacing on June 6 in 2010 and on June 4 in 2011 using a medium-duration rice variety, 'PR-120′. The field was surface-irrigated immediately after sowing. Fertilizers were applied to each plot as per the treatment. Full doses of P (as diammonium phosphate) and K (as muriate of potash) were applied through broadcasting in the respective treatments as basal doses. N (as urea) was applied in four equal splits at 15, 30, 45, and 60 DAS. Irrigation water support to the irrigation treatments was measured through a Parshall flume (Indian Institute of Technology, Roorkee, India). The Parshall flume was made of galvanized iron and had a throat size of 75 mm. The irrigation treatments were separated with double bunds by having a buffer of 75 cm between them to prevent the flow of water from one plot to another. Soil moisture tension was observed with a tube tensiometer placed at the tail end of the irrigation treatments in the plots having $N_{180} + P_{30} + K_{30}$ fertilizers with the tips at 15-cm depth. The water potential was measured every morning at 09:00 with a SoilSpec vacuum gauge to determine the need for irrigation on that day. Weeds in DSR were controlled by applying a pre-emergence herbicide (pendimethalin 0.75 kg ai ha^{-1}) at 2 DAS and a post-emergence herbicide (bispyribac sodium 25 g ai ha^{-1}) at 20 DAS. Weeds that escaped these treatments were removed manually at