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A simple bund plugging technique for improving water productivity in wetland rice

Mukund D. Patil, Bhabani S. Das *, Pratap B.S. Bhadoria

Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, Kharagpur, West Bengal 721302, India

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ABSTRACT

Seepage and percolation (SP) loss of water is a major reason behind the poor water productivity in wetland rice. Recent studies have indicated that preferential water flow through bunds around rice fields is primarily responsible for high SP loss in rice. To prevent such water loss, we took advantage of a critical observation made by Huang et al. (2003) that the laying of new bunds over existing paddy field retains plow sole in under-bund soil profile, which has the potential to restrict downward percolation through bunds. Accordingly, we developed a simple bund plugging technique to extend the plow sole into the under-bund soil. The method consists of three steps: temporary removal of existing bunds, puddling of under-bund soil, and replacement of bunds above the puddled under-bund soil. The effectiveness of such a bund plugging method was evaluated by measuring physical and hydraulic properties of different soil layers both before and after bund treatment in several pits excavated both on the bunds and within the field. *In situ* infiltration characteristics were also measured using a tension infiltrometer. Measured bulk density and saturated hydraulic conductivity (K_s) values for under-bund soil before and after bund plugging treatment showed the development of a plow sole in treated under-bund soil. Analysis of tension infiltration data indicated that such a bund plugging treatment could reduce the infiltration flux at near-saturation conditions by about 68%. Similarly, the results of dual permeability modeling showed that the K_s values for soil fracture domain in treated bunds were also reduced by similar magnitude. Comparison of the total amount of water input for the growing seasons in these plots showed that the bund-plugging method could reduce the SP loss by about 50% during the Kharif season (i.e. July–October) and about 22% during the Rabi season (i.e. December–April).

1. Introduction

Rice is the staple food for almost half of the world's population. With a total annual production of about 685 million tons covering an area of 159 m ha (FAO, 2010a), rice is also the largest consumer of irrigation water (Tuong et al., 2005). About 25–33% of world's fresh water is used for irrigation exclusively in rice. In addition to the large water requirement, there is a wide range of total water use (irrigation + rainfall) in rice varying from 40 cm for heavy-textured soil to more than 300 cm for coarse-textured soil (Bouman and Tuong, 2001; Cabangon et al., 2004). Tabbal et al. (2002) reported as high as 350 cm of water input in paddy fields in Philippines. More recently, Garg et al. (2009) reported that the total water input in irrigated lowland rice in the red laterite soils of eastern India during wet season may be as high as 600 cm. High water input has a negative influence on nutrient availability and uptake by plants, causing yield reduction (Patil et al., 2010). Consequently, the total water productivity, defined as the grain yield per unit mass of total water applied through irrigation and rainfall, is low for paddy ranging from 0.05 to 1.1 g kg^{-1} as compared to 0.79–1.6 g kg^{-1} for wheat and 1.6–3.9 g kg^{-1} for maize (Tuong and Bouman, 2003). Interestingly, the water productivity with respect to consumptive water use (0.4–0.5 and 0.6–0.7 cm day^{-1} during wet and dry season, respectively) alone is comparable to that of wheat crop (Tuong et al., 2005; Zwart and Bastiaansses, 2004). This suggests that water in excess of consumptive use is due to losses through other channels. Specifically, water loss through seepage and percolation (SP) constitutes about 50–85% of total applied water in rice (Sharma et al., 2002; Singh et al., 2002). High water loss would typically involve greater loss of added agrochemicals from crop root zone leading to groundwater contamination (Castaneda and Bhuiyan, 1996; Shrestha and Ladha, 1998; Bouman et al., 2002; Kundu and Mandal, 2009).

Puddling is traditionally done to reduce percolation in rice soil. Churning of top soil during puddling generally destroys soil aggregates, reduces macropores, and increases micropore volume (Moormann and van Breeman, 1978; Sharma and De Datta, 1985).

* Corresponding author. Tel.: +91 3222 283162; fax: +91 3222 282244.
E-mail address: bsdas@iitkgp.ac.in (B.S. Das).

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Finer soil particles in the muddy suspension get deposited at/near puddling depth to form a consolidated soil layer called plow sole between 10 and 25 cm soil depth (Garg et al., 2009). In addition to plow sole, small dykes (also, called as bunds) are generally constructed around paddy fields to restrict water flow horizontally through seepage. In practice, seepage and percolation are not easily separable because of the difficulty in classifying the transition between seepage and percolation (Wickham and Singh, 1978). The SP rate may vary depending on soil properties, ponded water depth, groundwater level, and maintenance of field and bunds. For example, SP rate for well puddled heavy textured clay soil may range from 0.2 to 2.4 cm day^{-1} (Tabbal et al., 2002) compared to 29.6–68.6 cm day^{-1} in non-puddled fields containing similar type of soil (Wopereis et al., 1994). Tuong et al. (1994) found that percolation rate was high in poorly puddled soil and was significantly influenced by ponded water depth.

Several researchers have suggested that the major source of SP loss in paddy fields is the bunds surrounding a rice field (Walker and Rushton, 1984; Bouman et al., 1994; Tuong et al., 1994; Kukal and Aggarwal, 2002). Higher hydraulic conductivity of soil under a bund (hereinafter, referred to as under-bund soil) than that within the rice growing area (hereinafter, referred to as within-plot soil) causes water to seep into a bund (Wopereis et al., 1992; Janssen and Lennartz, 2009) and then percolate vertically down to the groundwater (Walker and Rushton, 1984; Bouman et al., 1994; Tuong et al., 1994; Janssen and Lennartz, 2008, 2009). The under-bund percolation rate may vary from 0.04 (Kukal and Aggarwal, 2002) to 3.66 cm day^{-1} (Tuong et al., 1994). Although several bund management practices such as concrete bund, gravel-packed bund, concrete-covered soil bund, and plastic-covered soil bund (Huang et al., 2003) are proposed to reduce the SP losses, most of these methods are either expensive, difficult to implement, or may have adverse effect on environment. For instance, although plastic sheets may reduce the lateral seepage by 450 mm (Bouman et al., 2005), the photocatalytic degradation of plastics is known to produce hazardous chemicals.

More recently, preferential flow processes are shown to be dominant in rice ecosystems (Sander and Gerke, 2007; Janssen and Lennartz, 2009; Janssen et al., 2010; Garg et al., 2009; Neumann et al., 2009). Specifically, preferential transport processes were more evident in under-bund soil (Janssen and Lennartz, 2009; Neumann et al., 2009), which was considered as the cause of high SP losses in rice fields. With a series of measurements, we also concurrently tracked preferential water flow through bunds as a dominant water loss mechanism in our experimental site. To prevent such water loss, we took advantage of a critical observation made by Huang et al. (2003) that the laying of new bunds over existing paddy field retains plow sole in under-bund soil profile, which has the potential to restrict downward percolation through bunds. Accordingly, we developed a simple bund treatment technique to extend the plow sole into the under-bund soil and observed significant amount of water savings in three successive rice growing seasons. This study summarizes the results of these experiments and demonstrates the extension of plow sole in the under-bund soil as a potential water saving technology in rice.

2. Materials and methods

2.1. Site specification

The field site (84 m × 20 m) is located at the experimental farm of Agricultural and Food Engineering Department, Indian Institute of Technology (IIT), Kharagpur, India (22°19′N, 87°19′E). There were a total of 30 plots of size 5 m × 6 m (3 rows and 10 columns). Eighteen new plots were prepared in 2006 and the nearby remaining 12 plots (Plot Nos. 19–30 prepared in 2004 as a part of a field study to examine urea transport under transplanted rice by Garg et al., 2009) were also used in this study. All the 30 plots had 2 m wide buffer strip for preventing mixing of nitrogenous fertilizer among plots. The entire field site (84 m × 20 m) has been used for growing rice as a monocrop over last two decades. Soil of the experimental site is acidic lateritic sandy loam (Typic Haplustalf). The local climate is humid subtropical with an average rainfall of 140–160 cm of which about 100 cm is distributed over July–October (also, called as the Kharif season).

2.2. Field experiment

Field experiments were conducted during 2008–2009 to investigate the effects of the bund treatments on field water loss. Two experiments were conducted during 2008 Kharif (K08) and 2009 Kharif (K09) seasons and one experiment was conducted during 2008 Rabi (December–April) season (R08). The experiment was laid out in a split-plot design with three bund treatments as the main plots and three fertilizer treatments as the sub-plots. Rice seedlings of about 30 days old (var. IR-36, duration = 110 days) were transplanted in puddled soil at a spacing of 20 cm × 20 cm. Transplanting dates for K08, R08, and K09 were 1 August, 31 December, and 14 August, respectively. Basal doses of phosphate and potash (40 kg P_2O_5 and 40 kg K_2O per ha) were applied at the time of transplanting. Three different fertilizer management scenarios adapted for experiments were: (1) K08 season: three treatments with two, four, and five split dose of conventional urea fertilizer at the total nitrogen (N) dose of 56 kg ha^{-1} (30% less than recommended); (2) R08 season: three treatments with total N dose of 80, 104, and 136 N kg ha^{-1} applied in five equal split doses; and (3) K09 season: three treatments with total N dose of 56, 80, and 120 N kg ha^{-1} applied in four equal split doses.

2.2.1. Bund treatment

For the bund treatment, the top 15 cm bund soil was removed and the under-bund soil was exposed such that the exposed surface is at the same level as the plot surface. The removed soil was used to form a temporary bund to retain water required for soaking soil. Typical puddling practice consists of running a single pass of a mechanical puddler or a few passes of animal-driven implement. Laboratory-scale experiments showed that about 14 puddling and compaction activities may be needed to create a plow sole in a fresh field (Liu et al., 2005). In our study, only two puddling operations were done in both under-bund and within-plot soils after which plots left to soak in water for 2–3 days. After puddling, bunds were refilled with previously removed soil of the bund and muddy water from within-plot (Fig. 1). We refer such puddling under-bund soil as bund plugging in the remainder of this article. When the entire bund (60 cm wide) was disturbed, the treatment is called full bund treatment (B_{full}); when only half of the bund was disturbed, the treatment is called half bund treatment (B_{half}). Bunds were also side-dressed using muddy slurry (B_{side}) and some bunds were left undisturbed (B_{none}) as control treatment. Thus, bund treatments were: B_{full}, B_{side} and B_{none} during K08 season, B_{full}, B_{half}, and B_{side} during R08 season and B_{full} and B_{side} during K09 season. Only two bund treatments were used during K09 season after it was observed that there was not much difference between B_{full} and B_{half}.

2.2.2. Soil characterization

Pits were excavated in Plot 7 during December 2007 and in Plot 2 and Plot 8 during April 2010 to investigate the effect of bund treatment on soil properties. Before excavation of these pits, a portion (100 cm long, 50 cm wide, 15 cm high) of the bund was removed to expose the under-bund soil. Pits were then excavated