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Least limiting water range for two conservation agriculture cropping systems in India

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ABSTRACT

Deterioration of the soil physical environment is a major reason for decreasing crop productivity in the western Indo-Gangetic Plains (IGP) of India. To address this problem, the least limiting water range (LLWR) for two conservation agricultural (CA) practices was quantified. Three year old rice (*Oryza sativa*)–wheat (*Triticum aestivum*) and cotton (*Gossypium hirsutam*) – wheat CA systems located in New Delhi were evaluated. A novel method for computing the lower LLWR limit was developed by using a linear function to relate penetration resistance (PR) to gravimetric water content and soil bulk density (BD), rather than volumetric water content. During the third year, the 15–30 cm soil layer beneath the puddled transplanted rice, under conventionally tilled wheat (PTR–CTW) plots had PR values that exceeded 2 MPa, but under direct seeded rice with brown manuring, zero tilled wheat (DSR + BM–ZTW) plots had PR values of less than 1.5 MPa throughout the 0–60 cm profile. That said DSR + BM–ZTW plots also had significantly higher gain (over the initial soil) in total soil organic C content in the 0–30 cm soil layer. The 0–45 cm soil layer under permanent broad-beds with residue (PBB + R) had significantly lower PR than permanent narrow-beds with residue (PNB + R) and other plots [PBB; PNB; zero tillage with residue (ZT + R); conventional tillage (CT) and ZT] in the cotton–wheat system. Retaining crop residue resulted in lower BD and PR values in the 0–15 cm soil layer than removing them. The PBB + R plots had ~12% higher LLWR than CT plots (LLWR = 10.1%) in the 15–30 cm layer. In the 0–15 cm soil layer, ZT + R, PBB + R and PNB + R had nearly 13, 24 and 11% higher mean ($n = 24$; 3 replications × 8 sampling events) LLWR values than ZT, PBB and PNB plots, respectively, confirming that crop residue retention improved LLWR. Sub-surface layers under ZT had significantly lower LLWR values than in the CT plots. Results also reveal that there were no significant relationships between the mean (of two years) grain yields with LLWR for all crops, indicating that LLWR was a poor indicator of crop productivity. Overall, among the treatments, PBB + R and DSR + BM–ZTW were the best management practices for improved soil physical environment under cotton–wheat and rice–wheat systems, respectively, and therefore could be adopted.

1. Introduction

The adoption of heavy mechanized farming on large farms in India (*i.e.* >8 ha; Foster and Rosenzweig, 2011) has led to the serious sub-surface soil compaction problems. They are most severe in rice–wheat systems, where puddling is done for rice followed by several tractor and disc harrow passes for wheat cultivation. Several studies have revealed that puddling increased soil bulk density (BD; >1.60 Mg m^{-3}) in the sub-surface layer (15–30 cm) in rice based systems (Sharma and De Datta, 1985; Aggarwal et al., 1995; Hobbs and Gupta, 2002). An increase in BD increases penetration resistance (PR) and obstructs root development. Critical values that severely restrict root growth have been estimated to vary from 1 to 4 MPa depending on the soil, water content and crop type. Furthermore, PR varies with soil water content (SWC) without any variation in other soil characteristics (*e.g.* particle size distribution, mineralogy and porosity (Kukal and Aggarwal, 2003)). Grunwald et al. (2001) and Aggarwal et al. (2006) used multiple regression analysis to compute soil PR as a function of BD, SWC and soil depth. Aggarwal et al. (2006) showed that SWC alone accounted for 59% variation and along with BD accounted for 93–96% variation in PR for a sandy clay loam soil of the western Indo-Gangetic Plains (IGP). Severity of soil compaction induces root deformation, stunted shoot growth, late germination, low germination rate, and high crop mortality rate (Nawaz et al., 2013).

Conservation agriculture (CA) emphasizes the use of minimum or zero tillage along with crop residue retention to address soil

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physical degradation problems by reducing sub-surface compaction (Bautista et al., 1996; Shaver et al., 2002; Sayre and Hobbs, 2004). Madari et al. (2005) showed that zero tillage (ZT) with residue cover had greater aggregate stability and larger aggregates and more soil organic carbon (SOC) in Brazil. Roldan et al. (2003) found that after 5 years of ZT maize in Mexico, soil wet aggregate stability increased over traditional tillage. Water stable aggregates in the upper soil layer may improve the germination and seedling establishment by reducing crusting and erosion and by allowing water and air to enter the soil. Better aggregation (Lal, 1992) and lower soil BD (Bhattacharyya et al., 2006, 2009a,b) was observed by the adoption of ZT. Aquino (1998) observed that wheat on beds resulted in 8% higher yield, used ~25% less irrigation water, and encountered at least 25% less operational costs compared with conventionally tilled wheat using flood irrigation. Permanent raised beds with residue retention improved aggregation compared to conventionally tilled raised beds (Bhattacharyya et al., 2013a).

The integrated effect of soil water, soil air and soil strength on plant growth could be described by a single parameter called non-limiting water range or least limiting water range (LLWR) (Letey, 1985; Topp et al., 1994; da Silva et al., 1994). In this study, the soil moisture content value at −33 kPa (−0.033 MPa) or moisture content at 10% aeration porosity whichever was lower was considered as the upper limit of LLWR. A critical aeration limit is often assumed to occur at an air-filled porosity (AFP) of approximately 10% (v/v) for most agricultural crops (Glinski and Stepniewski, 1985). The SWC at permanent wilting point (PWP, *i.e.* SWC at approximately −1.5 MPa) or SWC at a threshold soil strength value (generally taken as 2 MPa) whichever was higher, was considered the lower water content limit in the LLWR (Thompson, 2001).

Although CA has the potential to improve soil physical properties (Saharawat et al., 2010; Bhattacharyya et al., 2012a, b, 2013b), information on the effects of short-to medium-term adoption of different CA practices in different cropping systems on LLWR in a semi-arid climate of the IGP is very limited. Hence, experiments were conducted to investigate the effects of different emerging CA practices on LLWR under both rice–wheat and cotton–wheat systems. Our hypothesis was that adoption of CA will reduce soil BD and increase the LLWR, thus, creating a better soil physical environment for crop growth. The reason behind this hypothesis was that using continuous ZT (almost no use of heavy machinery) and residue retention would reduce soil BD of the sub-surface layer. Renovation of beds under CA would also burry the retained residues and increase the soil organic matter (SOM) content. This would further help in reducing soil compaction.

2. Materials and methods

2.1. Soil and climatic conditions

This study was carried out at the Indian Agricultural Research Institute (IARI) experimental farm near New Delhi, which is located at 28°35′N latitude, longitude of 77°12′E and at an altitude of 228.16 m above mean sea level. The climate of the research farm is semi-arid with dry hot summer and cold winters. May and June are the hottest months with mean daily maximum temperature varying from 40 to 46 °C, while January is the coldest month with mean daily minimum temperature ranging from 6 to 8 °C. The mean (>30 years) annual rainfall is 710 mm, of which 80% is received during southwest monsoon from July to September and the rest is mainly received from December to February. Mean daily values for the meteorological parameters recorded at the adjacent IARI meteorological observatory during the Kharif (rainy) and Rabi (winter) seasons of 2012–2013 are presented in Fig. 1a and b. Prior to initiating the cropping system study, the entire site was laser levelled.

Soils at the experimental site belong to the major IGP alluvium group. They are classified as fine loamy, illitic, Typic Haplustept, with a sandy clay loam texture and medium to weak angular blocky structure. Surface (0–15 cm) soil in the cotton–wheat system had a pH of 7.7 and Walkley–Black C (Walkley and Black, 1934) content of 5.2 g kg^{-1}. For the rice–wheat system, the surface soil had a pH of 8.3 and Walkley–Black C content of 6.0 g kg^{-1}. Prior to conducting the study, the sites were both managed in an irrigated rice–wheat rotation with conventional tillage and recommended mineral fertilization for several years.

2.2. Details of field experimentation

2.2.1. Treatment details

Two CA experiments were initiated in May 2010, one in a cotton–wheat rotation and the other in a rice–wheat cropping system. First year (2010–2011), experimental treatments for the cotton–wheat system were: conventional tillage (CT), permanent narrow-bed (one row of cotton within 40 cm wide bed and 30 cm wide furrow) (PNB), permanent broad-bed (two rows of cotton within 100 cm wide bed and 40 cm wide furrow) (PBB), PBB with residue (PBB + R) and PNB with residue (PNB + R). Two additional treatments (zero tillage; ZT and ZT with residue retention; ZT + R) were introduced from the second year onwards. Thus, seven treatments were replicated thrice under a randomized complete block design. Treatment details, management practices, and crop productivity are given in Das et al. (2014). For the rice–wheat system, the treatments were: farmers' practice (conventional puddled transplanted rice–conventionally tilled wheat) (PTR–CTW), direct seeded rice–zero tilled wheat (DSR–ZTW) and DSR + brown manuring (BM)–ZTW (DSR + BM–ZTW). These treatments were imposed using a randomized complete block design with three replications in 2010. Treatment details are given in Table 1, but in general, all crop residues were removed and only the stubble was left. For the DSR + BM–ZTW treatment, about 3.5 Mg dry biomass ha^{-1} was surface retained each year. The plot size for the rice–wheat system was 14.0 m × 9.0 m and that for the cotton–wheat was 8.4 m × 10 m.

2.2.2. Preparation of seed bed and rice nursery

For the cotton–wheat system, fresh raised-beds were prepared for PBB and PNB treatments in 2010 using a bed planter. Subsequently, the beds were reshaped once in a year before sowing cotton with the same planter between 26 and 28 May of 2010–2012. In all three years, wheat was sown after rice in the middle of November and wheat was sown after cotton during the second week of December. Residue treatments included retention of cotton leaves and tender twigs along with boll husks (about 20% of the stover yield of cotton) and about 40% of the wheat residues. Thus, apart from stubble biomass, all residues were removed from the CT, PNB, PBB and ZT plots. For the PNB + R, PBB + R and ZT + R plots, about 20% of aboveground cotton biomass and 40% of the wheat residues were retained. A rice nursery (in which rice seeds were sown on the same day as the DSR plots were sown) was used to produce plants for the PTR treatment. Direct seeding and nursery sowing of rice for PTR were done on 18/06/2010, 14/06/2011 and 15/6/2012, respectively, and transplanting was done on 18/07/2010, 14/07/2011 and 15/6/2012, respectively, in 2010–2012. The rice nursery area was 10% of the total cropped area. The 25-day old seedlings were uprooted and transplanted in the main field at 20 cm × 20 cm spacing with 2–3 seedlings per hill.