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Soil physical properties, yield trends and economics after five years of conservation agriculture based rice-maize system in north-western India

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ABSTRACT

Rice-maize system (RMS) is emerging as dominant option for diversification of existing rice-wheat systems in Asia due to better suitability and higher yields of maize compared to wheat after long duration rice cultivars, and increasing demand of maize from poultry and fish industries. The conventional practice of cultivation of RMS is input intensive, deteriorates soil health and is less profitable. Conservation agriculture (CA) based management practices such as dry direct-seeded rice (DSR), zero tillage (ZT) and residue retention may hold potential to increase yields, reduce costs and increase farmers' profits in RMS. Therefore, replicated 5-year field study was conducted to evaluate the effects of six combinations of three tillage and crop establishment (TCE) techniques and two residue management options on soil physical properties, system productivity and economics of an irrigated RMS in north-west India. The TCE techniques consisted of transplanted puddled rice (TPR) followed by conventionally tilled maize (CTM); CTDSR followed by CTM; and ZTDSR followed by ZTM in main plots and two residue management options; removal of residues of both the crops (−R) and partial residue (5 t ha^{-1}) either retained at soil surface on ZT plots or incorporated into the soil in CT plots (+R) for both rice and maize in sub-plots. Compared with TPR/CTM-R, soil physical parameters such as water-stable aggregates >0.2 mm were 89% higher, and bulk density, penetrometer resistance and infiltration rate showed significant ($P < 0.05$) improvement in ZTDSR/ZTM (+R) treatment. Similarly, root mass density was 6 to 49% greater in rice and 21 to 53% in maize under ZTDSR/ZTM (+R) plots compared to conventional RMS in different soil layers to 60 cm depth. The total amount of soil organic carbon (SOC) in 0–30 cm layer increased by 2.86 Mg ha^{-1} in ZTDSR/ZTM (+R) over conventional practice. Grain yield of TPR was 5 –7% higher compared to CTDSR and ZTDSR, which was attributed to increased number of grains $panicle^{-1}$ and grain weight. Maize yield under ZTDSR/ZTM was significantly higher by 4.0% and 14.2% compared to CTDSR/CTM and TPR/CTM, respectively, due to increase in number of cobs $plant^{-1}$ and grain number cob^{-1}. Gradual improvement in soil physical health in ZTDSR/ZTM +R system resulted in higher and stable crop productivity (17.4–17.6 kg m^{-3}) with higher profitability in different years over conventional system. Our study demonstrates that CA based management practices can be adopted for RMS on sandy loam or similar soils for sustaining soil and crop productivity in South Asia.

Abbreviations: RMS, rice-maize systems; CA, conservation agriculture; DSR, dry direct seeded rice; ZT, zero till; CT, conventional till; TPR, transplanted puddled rice; CTM, conventional till maize; ZTM, zero till maize; CTDSR, conventional till dry direct seeded rice; ZTDSR, zero till dry direct seeded rice; SOC, soil organic carbon; IGP, Indo-Gangetic plain; UGP, Upper Gangetic Plain; SPR, soil penetrometer resistance; WSA, water stable aggregate; MWD, mean weight diameter; RMD, root weight density; VCC, variable cost of cultivation; GR, gross returns; MSP, minimum support price; NR, net returns; SREY, systems rice equivalent yield; TCE, tillage and crop establishment; RWS, rice-wheat system; +R, residue retention/incorporation; −R, residue removal; IR, infiltration rate; STR, soil thermal regime.

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1. Introduction

Rice (*Oryza sativa* L.)—maize (*Zea mays* L.) system (RMS) has emerged as a pre-dominant option for diversification of existing rice-based cropping systems in Asia. The RMS currently occupies approximately 3.5 m ha in Asia and about 1.31 m ha in South Asia, excluding Pakistan (Timsina et al., 2011). While RMS has emerged as highly productive and profitable cropping system in peninsular and eastern India, it may replace rice-wheat system in some niches of north-western India where wheat planting is delayed after rice, and faces terminal heat stress resulting in low productivity. The other drivers for replacing wheat or winter rice with maize in rice-based cropping systems include (a) better suitability of maize after harvest of long-duration rice cultivars, (b) increasing demand of maize in poultry sector, (c) tightening world export-import market (Pandey et al., 2008; Gill et al., 2008), (d) higher productivity and profitability of maize compared to the other crops (Ali et al., 2009). It is estimated that demand for maize by 2020 in developing countries will surpass the demand for both rice and wheat (Srinivasaran et al., 2002). Replacing second rice with less water requiring maize in the rice-rice system can also help in mitigation of arsenic (As) toxicity in eastern India and Bangladesh where plant uptake of As with water and its subsequent movement through food chain (soil-plant–animal continuum) is of great concern (Ravenscroft et al., 2005). Rice and maize grown in a sequence require contrasting soil hydrology because transplanted rice is grown under anaerobic flooded conditions but maize is highly sensitive to anaerobic environment. The contrasting growing environment and associated field operations leads to several chemical and electro-chemical transformations in soils (De Datta, 1981), and may cause deterioration of chemical and physical properties of soils (Dwivedi et al., 2003; Singh et al., 2005; Singh et al., 2006). Field preparation for conventional puddled transplanted rice is highly energy-intensive process (Dwivedi et al., 2011). Puddling results in formation of compacted soil layer below the puddled zone in which soil strength increases rapidly as the soil dries and restrict root proliferation of the subsequent crop (Dwivedi et al., 2003; 2011; Singh et al., 2005). However, several studies conducted in India and elsewhere indicate that puddling is not necessary in rice cultivation and it could be omitted without any significant yield loss (So and Kirchhoff, 2000; Gathala et al., 2011b; Jat et al., 2013). The effect of puddling in rice on the productivity of subsequent maize crop is rarely documented, but a reduction in wheat yield in post-rice fields and adverse changes in soil physical properties are reported by many researchers (Fujisaka et al., 1994; Dwivedi et al., 2011).

Conventional maize planting involves repeated dry tillage (6–8 tillage operations) to prepare the field resulting in excessive use of energy, which may constitute 25–30% of total energy use in maize cultivation (Sidhu et al., 2004). High energy costs and labour shortages in India further add to the complexity of challenges in conventional rice-based production systems. Therefore, farmers are in the search of alternate crop establishment options that have twin benefits of reducing production cost while enhancing productivity on a sustainable basis. Conservation agriculture (CA) practices, such as dry direct-seeding of rice (DSR) and zero-till planting of crops combined with straw mulching that may offset the production costs and other constraints associated with land preparation is getting momentum in recent years (Gupta and Seth, 2007; Hobbs, 2007). Moreover, DSR system not only requires less water than the conventional transplanting of rice but may also prevent As accumulation in plants (Ravenscroft et al., 2005; Norton et al., 2009). Wheat yields are reduced by 8-9% after puddled transplanted rice compared to that grown after DSR (Kumar and Ladha, 2011).

In northwestern India, farmers have no alternate uses for rice straw produced in large amounts, which are usually disposed of by burning causing intense air pollution. Crop residues are the main source of organic C input in the rice-based cropping systems and are often attributed to the increase in soil organic carbon (SOC) concentration, and improvement of the hydrothermal regime and soil physical conditions (Yadvinder-Singh et al., 2005; Jat et al., 2009). Experimental evidences from rice-wheat and maize-wheat systems suggest that CA based alternative tillage and crop establishment methods can produce both immediate e.g. reduced production cost, stabilized crop yields, and improved water productivity (Hobbs, 2007; Jat et al., 2009; 2013; Ladha et al., 2009; Ram et al., 2012), and long-term benefits like improved soil quality (Gathala et al., 2011a; Kienzler et al., 2012). From a recent study in Bangladesh, Gathala et al. (2014) reported significant advantages in terms of increased yields and higher income from the permanent beds over the conventional tillage in RMS. However, precise information on the long-term effects of different tillage and planting systems, and straw retention on productivity and profitability of the RMS in the Indo-Gangetic plains (IGP) of South Asia is lacking. The present study was therefore, planned to assess the effect of different tillage, crop establishment and residue management options on system productivity, economics and soil properties of an irrigated RMS under the climatic conditions of north-west India. The information generated in this study is unique and will provide a basis for diversification opportunities in the IGP of South Asia.

2. Materials and methods

2.1. Site description

A 5-year study (2006–2011) on RMS was conducted at the research farm of the ICAR-Indian Institute of Farming System Research, Modipuram, Meerut (29°4′ N, 77°46′ E and 237 m amsl), Uttar Pradesh, India. The study area represents irrigated and input-intensive region of the Upper Gangetic Plain (UGP) zone of the Indo-Gangetic plain of India. The soil of the experimental field was very deep (>20 m), well-drained sandy loam (158 g clay and 657 g sand kg^{-1}) with 1% slope and classified as Typic Ustochrept. The top-soil (0–15 cm layer) at the start of experiment was non-saline (electrical conductivity 0.35 dS m^{-1}) with pH 8.10, and contained 4.61 g kg^{-1} Walkley-Black carbon, 76.9 mg kg^{-1} available N (Subbiah and Asija, 1956), 7.72 mg kg^{-1} 0.5 *M* $NaHCO_3$-extractable P (Olsen et al., 1954) and 111 mg kg^{-1} 1 *N* NH_4OAc-extractable K.

2.2. Weather information

The decennial monthly minimum temperature fluctuates from 6.9 to 21.8 °C and maximum temperature from 23.7 to 42.6 °C at the experimental site. The average annual rainfall is 831 mm, and over 75% of this is received through northwest monsoon during July to September.

2.2.1. Rice season

The weather conditions at the experimental location during rice growing seasons (June-October) were quite variable in all the five years of experimentation. This showed uncertainty of weather in the Western IGP and hence climate resilient management practices are very crucial for sustainable production. The rainfall during rice was maximum in 2010 (718 mm) followed by 2008 (480 mm) and 2006 (452 mm) whereas 2009 rice season received the lowest rainfall of 210 mm (Table 1). Total monthly rainfall in June alone ranged from as low as 3–4 mm in 2009 and 2010 to as high as 86 mm in 2007, and total rainfall in July ranged from about 76 mm in 2009 to about 315 mm in 2010. June rainfall is important for