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# Optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the northwestern Indo-Gangetic Plains of India

Mahesh K. Gathala[a,e], Virender Kumar[a,b], P.C. Sharma[c], Yashpal S. Saharawat[a,d], H.S. Jat[c], Mainpal Singh[c], Amit Kumar[c], M.L. Jat[b], E. Humphreys[f], D.K. Sharma[c], Sheetal Sharma[a], J.K. Ladha[a,*]

[a] International Rice Research Institute-India Office, NASC Complex, Pusa, New Delhi 110012, India
[b] International Maize and Wheat Improvement Center, NASC Complex, Pusa, New Delhi 110012, India
[c] Central Soil Salinity Research Institute, Karnal, Haryana 132001, India
[d] Indian Agricultural Research Institute, Pusa, New Delhi 132001, India
[e] International Maize and Wheat Improvement Center, Dhaka Office, Bangladesh
[f] International Rice Research Institute, Los Baños, Philippines

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ABSTRACT

Increasing scarcity of resources (labour, water, and energy) and cost of production, along with climate variability, are major challenges for the sustainability of rice–wheat system in the northwesten Indo-Gangetic Plains (IGP). We hypothesized that adopting the principles of conservation agriculture together with best crop management practices would improve system productivity and overall efficiency, resulting in a higher profitability. To test this hypothesis, we evaluated the performance of four cropping system scenarios (treatments), which were designed to be adapted to current and future drivers of agricultural changes. The treatments including farmers practices varied in tillage and crop establishment methods, residue management, crop sequence, and crop management. Zero-tillage direct-seeded rice (ZT-DSR) with residue retention and best management practices provided equivalent or higher yield and 30–50% lower irrigation water use than those of farmer-managed puddled transplanted rice (CT-TPR). Overall, net economic returns increased up to 79% with a net reduction in production cost of up to US$ 55 ha$^{-1}$ in ZT-DSR than CT-TPR. Substituting rice with ZT maize was equally profitable but with 88–95% less irrigation water use. Avoiding puddling in rice and dry tillage in maize with residue retention increased yield (by 0.5–1.2 t ha$^{-1}$) and net economic returns of the succeeding wheat crop. Inclusion of mungbean in the rotation further increased system productivity and economic returns. In summary, our initial results of 2-year field study showed positive effects of CA-based improved management practices on yield and system efficiencies with greater benefits in the second year. There is a need of longer term monitoring to quantify cumulative effects of various interventions and to eventually make recommendations for wider dissemination.



## 1. Introduction

The Indo-Gangetic Plains (IGP) of South Asia are home to nearly one billion people, about 40% of whom live in extreme poverty (Balasubramanian et al., 2012). In the Indian IGP, rice–wheat (R–W) is the dominant cropping system, occupying about 10.3 mha and accounts for 23% and 40% of India's total rice and wheat area, respectively (Ladha et al., 2003). In this system, rice is grown during the rainy summer season (*kharif*) from June to October and wheat during the dry winter season (*rabi*) from November to March/April. The land generally remains fallow between the harvest of wheat and planting of rice.

Rice is predominantly grown by transplanting seedlings into puddled (conventional wet-tillage) soil (CT-TPR) and is continuously flooded for much of the growing season. The soil is puddled to achieve good crop establishment, weed control, and to reduce deep percolation losses (Sanchez, 1973; Sharma et al., 2003). However, this requires large amounts of labour, water, and energy, which are gradually becoming scarce and more expensive, thus reducing the profitability and system sustainability. The CT-TPR is also a major contributor to global methane (a potent greenhouse gas) emissions (Mosier et al., 1998). Moreover, puddling has adverse effects on

* Corresponding author. Tel.: +91 11 25841292; fax: +91 11 25841801.
*E-mail address:* j.k.ladha@irri.org (J.K. Ladha).

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the productivity of the succeeding wheat crop through its negative impacts on soil structure for wheat (see for review Gathala et al., 2011b; Kumar and Ladha, 2011; Sharma et al., 2003). A yield decline of 8–9% has been observed in wheat when grown after puddled rice compared with non-puddled rice (Gathala et al., 2011a; Kumar and Ladha, 2011).

Similarly, conventional land preparation for wheat production is also intensive, involving several passes of discs and/or tine harrows and plankings to create a friable seedbed. Intensive tillage leads to a long turnaround period, often delaying wheat planting, with a yield loss of 15–60 kg $ha^{-1}$ $day^{-1}$ if delayed beyond mid-November (Pathak et al., 2003).

Rice and wheat in northwestern India is mostly harvested by large combine harvesters (Gajri et al., 2002). Following harvest, rice residue is partly or fully burnt to avoid incorporation which requires additional tillage. This results in 2–3 weeks delay in crop sowing to avoid N deficiency due to N immobilisation (Thuy et al., 2008; Singh et al., 2004). On the other hand, the wheat residue is removed to use as animal feed and sometimes partly burnt (Gajri et al., 2002). Residue burning results in (a) losses of C (almost 100%) and nutrients (90% N, 60% S and 25% of each of P and K) (Dobermann and Fairhurst, 2002), and (b) emissions of greenhouse gasess (annual emissions of 110, 2306, 2, and 84 Gg of $CH_4$, CO, $N_2O$, and $NO_x$, respectively; Gupta et al., 2004).

In addition to the large inefficiencies, the conventional rice–wheat system is faced with widespread yield stagnation or decline which resulting in a serious threat to the sustainability of this important crop rotation (Ladha et al., 2003). Projections indicate that production of rice, wheat, and maize will have to increase by about 1.1%, 1.7%, and 2.9% per annum, respectively, over the next four decades to ensure food security in South Asia. To meet the increasing cereal demand, there is a need of crop intensification while increasing resource-use efficiency and reducing the environmental footprint, or 'ecological intensification' (Cassman, 1999; Ladha et al., 2009). Achieving this will require a holistic system approach, incorporating the principles of conservation agriculture (CA), and judicious crop rotation (Balasubramanian et al., 2012).

During the last few years, several component technologies of CA such as reduced or zero tillage (ZT), dry drill seeding of rice (DSR), and rice residue retention have been evaluated in cereal systems (Gathala et al., 2011a,b; Ladha et al., 2009; Kumar et al., 2013b). Zero-till wheat has been adopted on a significant area in the R–W system in the northwestern IGP (Harrington and Hobbs, 2009) with positive impacts on wheat yield, profitability, and resource-use efficiency (Erenstein and Laxmi, 2008; Ladha et al., 2009). Unlike wheat, rice continues to be almost entirely grown by the conventional practice of CT-TPR. Also, crop residues continue to be either burned or removed both in rice and wheat. To harness the full potential of CA, not only residue will have to be used as soil surface mulch but also rice will have to be brought under zero tillage. Surface residue retention provides multiple benefits, including soil moisture conservation, suppression of weeds, and improvement in soil organic matter and soil structure (Singh et al., 2011a; Kumar et al., 2013a; Verhulst et al., 2011; Singh et al., 2005). The development of the "Happy Seeder" has now made it possible to sow wheat successfully into heavy loads of loose and anchored rice residues (Sidhu et al., 2008). Recently, interest has been rapidly increasing in non-ponded direct seeded rice (dry-DSR), due to increasing labor scarcity, energy constraint, and rising input costs (Kumar et al., 2013a; Kumar and Ladha, 2011).

In the future, in addition to shifting to CA based improved practices, there is a need to explore other crops in the traditional cereal based rotation. For example, if labour and water continue to become scarcer, a maize–wheat cropping system could be a potential alternative to the rice–wheat rotation. Likewise, driven by the need to maximise land and water productivity, other changes such as superior management practices and inclusion of legumes in the cropping system will be needed.

**Table 1**
Initial soil characteristics (0–15-cm soil depth) of CSISA Research Platform site, CSSRI, Karnal, India.

| Soil properties | Soil sampling depth Mean ± SE |
|---|---|
| Clay (%) | 19.89 ± 0.50 |
| Silt (%) | 46.07 ± 0.76 |
| Sand (%) | 34.03 ± 0.77 |
| Soil texture | Loam |
| pH (1:1 soil:water) | 8.00 ± 0.02 |
| EC (dS $m^{-1}$) (1:1 soil:water) | 0.37 ± 0.02 |
| Total carbon (%) | 0.56 ± 0.01 |
| Available P (mg $kg^{-1}$) | 5.74 ± 0.29 |
| Exchangeable K (mg $kg^{-1}$) | 130 ± 1.73 |
| TN (%) | 0.06 ± 0.002 |
| Particle density (g $cm^{-3}$) | 2.57 ± 0.01 |

Therefore, we designed and established large-scale production-level experimental research platforms to (1) assess the performance (short- to long-term) of different cereal-based cropping systems within key scenarios of agricultural change, using a wide range of indicators (e.g. yield; resource-use efficiency; crop, soil, and environmental health; economics; and energy), and (2) refine and parameterise simulation models for assessing key future cropping system scenarios and technology options. The platforms were established at four locations in India and Bangladesh as part of the comprehensive Cereal Systems Initiative for South Asia (CSISA) project. This paper presents the performance of four cereal cropping systems during the first two years at Karnal, northwestern India, in relation to yield, water use, water productivity, and economics.

## 2. Materials and methods

### 2.1. Experimental site

The study was conducted at the CSISA experimental research platform located at the Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, India (29°70′N, 76°96′E). A production-scale long-term trial with cropping systems adapted to four different scenarios was established in 2009 with an expected time frame of at least 10 years. The climate of the area is semi-arid, with average annual rainfall of 700 mm (75–80% of which is received during June–September), daily minimum temperature of 0–4 °C in January, daily maximum temperature of 41–44 °C in June, and relative humidity of 50–90% throughout the year. Seasonal weather data including rainfall, evaporation rate, minimum and maximum temperature, and solar radiation during the first two years are presented in Fig. 1. The site was under a continuous R–W system for many years before the establishment of the experimental platform. The experimental site is a reclaimed alkali loam soil. The initial soil characteristics of the site are given in Table 1.

In May 2009, before the start of the experiment, the entire experimental area was leveled (zero gradient) using a laser-equipped drag scraper (Trimble$^{TM}$, USA) with an automatic hydraulic system powered by a 60-HP tractor. After levelling, the experimental area was divided into 12 permanent plots separated by earthen bunds about 1.0 m wide and 0.20 m high. Puddled transplanted rice (as a uniformity crop) was grown in all plots during July–October 2009 to check for and promote site uniformity. The crop was very even across the entire 2.4-ha site. The cropping system treatments commenced with the 2009–2010 wheat season after harvest of the uniformity rice crop.