CSIRO PUBLISHING
Soil Research
http://dx.doi.org/10.1071/SR15346

Effect of different rice establishment methods on soil physical properties in drought-prone, rainfed lowlands of Bihar, India

Surajit Mondal[A,B], *Santosh Kumar*[A], *A. Abdul Haris*[A], *S. K. Dwivedi*[A], *B. P. Bhatt*[A], *and J. S. Mishra*[A]

[A]ICAR Research Complex for Eastern Region, Patna, Bihar, India.
[B]Corresponding author. Email: surajit.icar@gmail.com

Abstract. To enhance productivity, alleviate environmental and management constraints, and enhance farmers' incomes in the rice–wheat cropping system of the Indo Gangetic Plains, new approaches that are labour-saving, more productive and sustainable need to be developed. Most systems of rice cultivation use puddling to prepare the seedbed and control weeds in rice fields of rainfed, stress-prone environments. This practice might be helpful to reduce weed pressure and obtain slightly higher productivity, but might have negative impacts on soil physical properties. A better understanding is needed of the comparative advantage of unpuddled rice fields for maintaining good soil physical properties. To study the effect of different rice establishment methods on soil physical properties in a rice–wheat cropping system, we analysed soil samples in 2 years (2012–13 and 2013–14) from an experiment testing puddled and unpuddled rice-establishment methods. The treatments were: (*i*) puddled, transplanted with best management practices; (*ii*) puddled, transplanted with the system of rice intensification; (*iii*) unpuddled, transplanted; and (*iv*) unpuddled, direct-seeded. Omission of puddling improved soil physical properties such as bulk density, penetration resistance, aggregation stability and cracking behaviour. The absence of soil disturbance also improved soil aggregation, average mean-weight diameter and water-stable aggregates. Thus, unpuddled conditions increased the macro-aggregate fraction by 18–33%. By contrast, the higher frequency of smaller macro-aggregates (0.053–0.25 mm diameter) in puddled conditions clearly indicated the breakdown of larger macro-aggregates (>0.25 mm) into smaller size fractions. Puddled treatments were also characterised by a hard pan and wider, longer and deeper cracks, with a crack volume more than three times higher in puddled conditions. Unpuddled treatments recorded slightly higher nutrient contents in the topsoil. The study reveals that puddling deteriorates soil health. However, a long-term study is required for a better understanding of the soil changes related to different rice establishment technologies.

Additional keywords: crop establishment methods, productivity, rainfed drought-prone ecology, rice–wheat cropping system, soil physical properties, unpuddled transplanting.

Received 25 November 2015, accepted 9 February 2016, published online 13 July 2016

Introduction

Among countries growing rice (*Oryza sativa* L.), India has the largest area (42.5 Mha) producing 29% of the nation's calorie requirements, making it the most staple food crop of the country (IRRI 2014). Worldwide, rice feeds ~50% of the human population and provides 19% of its global calorie intake (IRRI 2014). Therefore, improving and sustaining the production of rice is essential for global food security. In India, rice is mainly grown by manual transplanting in puddled fields. Puddling (wet tillage) is done to reduce water infiltration and to maintain the standing water in the field, which helps in weed management and facilitates easier transplanting (Sharma and De Datta 1986). The impact of puddling on rice productivity varies according to soil characteristics and climate (Kirchhof *et al.* 2000). Field preparation for transplanting rice is an energy-intensive process and requires a considerable amount of water. Tillage also influences weed emergence because of changes in the mechanical characteristics (bulk density, penetration resistance, aggregate mean-weight diameter and surface roughness) of the seedbed (Carman 1996; Mohanty *et al.* 2004). In addition, puddled and flooded soils have many benefits such as neutralised soil pH, improved availability of plant nutrients (phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), and iron (Fe)), and accumulation of organic matter (Ponnamperuma 1972; Sahrawat 2005). An indirect increase in the availability of nutrients by puddling is due to a reduction in cation (e.g. NH_4^+) leaching (Aggarwal *et al.* 1995). There is also the potential for biological nitrogen fixation by blue-green algae and *Azolla* in the puddled-transplant system, which can save up to 20–30 kg nitrogen (N) ha^{-1} (Singh and Bisoyi 1989).

There are, however, some problems associated with puddling in rice, such as deterioration of soil structure and creation of a hardpan (Sharma and De Datta 1986; Thierfelder and Wall

2009), increased methane emissions and hydrogen sulfite formation (Ponnamperuma 1972), and increased bulk density and soil compaction (Kirchhof *et al.* 2000). Moreover, puddling and transplanting require large amounts of scarce water resources as well as labour (Kumar and Ladha 2011). Puddling operations consume ~25% of the total water required for rice during the growing season. Extensive field studies on fine-textured soils (clay content varying from 41% to 74%) in the Philippines and Indonesia revealed that puddling was not necessary, and could be omitted without any yield loss (So and Kirchhoff 2000). The destruction of soil aggregates (or soil structure) and formation of a hardpan during puddling have adverse effects on the yield of subsequent non-rice crops in rotation, and these crops also require more energy for field preparation (Fujisaka *et al.* 1994; Kumar and Ladha 2011). Another consequence is that the soil infiltration rates in the wheat season are less where the land had been puddled for rice than when the soil had been dry-drilled or kept under no-tillage (Singh *et al.* 2011).

Problems in the Eastern Indo Gangetic Plains (EIGP) include small farms, land fragmentation, inadequate irrigation infrastructure, weak institutions and markets, and poverty (Balasubramanian *et al.* 2012). Cereal production systems in these less favourable, rainfed and drought-prone areas often result in low yield and low farm income. Often, farmers delay wet tillage (puddling) of rice until after the onset of the monsoon, resulting in low rice yields and consequently low wheat yields due to delayed sowing as a result of the late rice harvest.

Rice can be grown under non-puddled and even no-tilled soil conditions by mechanical transplanting (Kamboj *et al.* 2013) or direct seeding (Yadav *et al.* 2009; Singh *et al.* 2011), sometimes even with yield advantages and/or overall increased profits compared with the traditional method of rice cultivation (puddling followed by manual transplanting), provided weeds are managed properly. Higher grain yields of rice have also been reported when grown with the system of rice intensification (SRI) method than conventional rice culture (Hugar *et al.* 2009; Thakur *et al.* 2010; Zhao *et al.* 2010). Therefore, conservation agriculture together with best management practices (BMP) used in other parts of the IGP offer potential to be extended to the EIGP. In light of these facts, the present study was undertaken with the aim of evaluating the effect of alternative rice establishment methods on soil physical properties and productivity of the rice–wheat cropping system in rainfed, drought-prone environments.

Materials and methods

Experimental site

Three sets of on-station field experiments were conducted in 2012–13 and 2013–14 at the experimental farm of the Indian Council of Agricultural Research Complex for the Eastern Region in Patna, Bihar, India (25°24.912′–25°25.971′N and 85°03.536′–85°03.624′E). Drought-tolerant rice varieties were evaluated using different rice-crop establishment methods in drought-prone, rainfed environments of Bihar, followed by no-tillage wheat (Table 1). The climate of Patna is subtropical humid (Fig. 1), with an average annual rainfall of 1130 mm (85–90% of which is received from June to September), daily minimum temperatures of 7−9°C in January, daily maximum temperatures of 36−41°C in May, and relative humidity of 60–90% throughout the year. The rice crop season in the region normally lasts from June to November (*kharif*), and wheat (*rabi*) from November to March. However, rice harvest in large areas commonly extends to late December, leading to delayed wheat sowing from mid-December to early January, and delayed harvest up to April.

The soil physical and chemical properties in different experimental plots were similar because the trial plots of three sets of experiments were adjacent (they belonged to one big field plot). The soil at the experimental site had a loam texture, was of Gangetic alluvial origin, very deep (>2 m), flat (~1% slope) and well drained. Detailed soil characteristics to a profile depth of 30 cm were measured just before laying out the experiment and are presented in Table 2. At the onset of the field experiment, the surface soil (0–15 cm) was mildly alkaline (pH 7.7), non-saline (electrical conductivity 0.08 dS m^{-1}), low in organic carbon (OC, 0.48%), high in available P (0.5 M $NaHCO_3$-extractable P, 24.1 kg ha^{-1}), and medium in K (1 N NH_4OAc-extractable K, 216 kg ha^{-1}).

Treatments and crop management

The treatments from which soil samples were taken were: (*i*) puddled, transplanted with BMP (P-BMP); (*ii*) puddled, transplanted with SRI (P-SRI); (*iii*) unpuddled, transplanted (UP-TR); and (*iv*) unpuddled, direct-seeded (UP-DS). Particle density of the soil was 2.645 g cm^{-3}, and, sand, silt and clay contents were 42.2%, 35% and 22.8%, respectively. Puddled experimental plots (P-BMP and P-SRI) were dry-ploughed followed by deep harrowing (twice), levelling and proper puddling before rice transplantation. For unpuddled plots

Table 1. Details of field experiments conducted at ICAR-RECR, Research Station

SRI, System of rice intensification; CT, conventional transplanting; BMP, best management practices; NT, no-till

Expt no.	Experiments	Year	Treatment Rice	Treatment Wheat
1	Evaluation of drought-tolerant rice genotypes under SRI and CT using BMP in puddled condition followed by NT wheat in rainfed, drought-prone systems	2012–13, 2013–14	P-BMP, P-SRI	NT
2	Evaluation of drought-tolerant rice genotypes or lines in unpuddled transplanted conditions and NT wheat in rainfed, drought-prone systems	2012–13, 2013–14	UP-TR	NT
3	Evaluation of rice varieties or lines in unpuddled dry direct seeding and NT wheat in rainfed, drought-prone systems	2012–13, 2013–14	UP-DS	NT

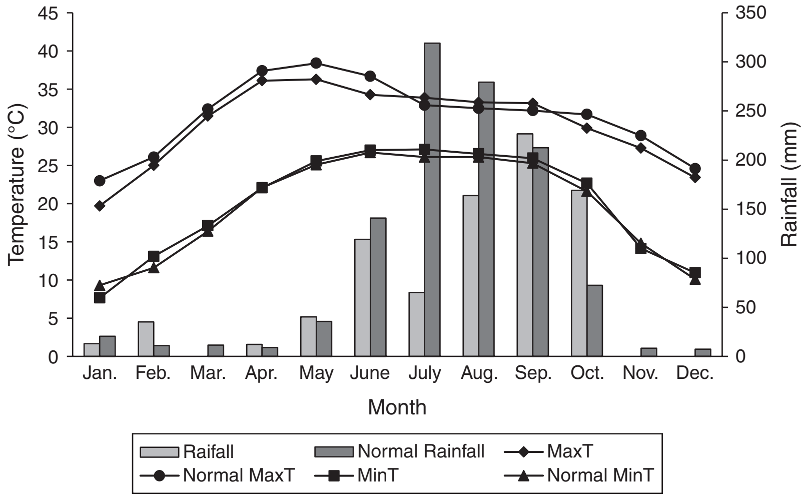

Fig. 1. Weather data from the experimental site during 2013.

Table 2. Soil physico-chemical properties before start of the experiment

Soil parameters	Soil layer (cm) 0–15	Soil layer (cm) 15–30	Soil parameters	Soil layer (cm) 0–15	Soil layer (cm) 15–30
Texture	Loam	Loam	Avail. N (kg ha^{-1})	225.8	194.4
Sand (%)	42.2	43.2	Avail. P (kg ha^{-1})	24.1	17.9
Silt (%)	35.0	29.8	Avail. K (kg ha^{-1})	216.2	224.5
Clay (%)	22.8	26.9	DTPA Fe (μg g^{-1})	29.7	31.2
pH	7.7	7.8	DTPA Mn (μg g^{-1})	28.1	26.3
Electrical conductivity (dS m^{-1})	0.08	0.09	DTPA Cu (μg g^{-1})	3.5	3.07
Organic C (g kg^{-1})	4.8	3.2	DTPA Zn (μg g^{-1})	0.7	0.6

(UP-TR and UP-DS), only one dry ploughing followed by harrowing and leveling was done before water ponding. No puddling was done and rice seedlings were transplanted into the saturated soil (UP-TR), or the seed was direct-seeded with a seeding machine (UP-DS). Seedlings of rice (21 days old) were transplanted in both puddled and unpuddled plots by using one seedling per hill at a spacing of 25 cm (row to row), with 15 cm between hills. In P-SRI, 12-day-old seedlings were transplanted in the first week of July. In each plot, the designated plant stand was maintained and standard agronomic practices were followed. Chemical and mechanical weed-control methods were employed. During the winter (*rabi*) season, no-tilled wheat was grown under rainfed conditions across all plots without disturbing the original layout. Recommended rates of fertiliser were uniformly applied in both rice and wheat crops during both years.

Soil sample collection, bulk density and penetration resistance

Composite soil samples from depths of 0–15 and 15–30 cm in each replicated plot were collected at wheat harvest in the second year for determination of aggregate size distribution. For bulk density analysis, undisturbed core samples were collected at wheat harvest. The undisturbed cores were further used for generating soil-water retention functions. For determination of soil chemical properties, triplicate disturbed samples were collected from each treatment after wheat harvest.

Bulk density of the samples (g cm^{-3}) was determined by core method (Blake and Hartge 1986). Fresh soil cores of known volume were processed in the laboratory, weighed and then dried at 105°C in the oven until they attained constant weight.

Soil penetration resistance was measured using a hand penetrometer (Eijkelkamp Soil & Water, Giesbeek, The Netherlands). It is an instrument for indicative measurement of maximal resistance to penetration. The base area of the cone was 2 cm^2. The maximum resistance that can be recorded by the instrument is 1000 N. For each depth, the probe attached with the instrument was inserted vertically and maximum reading was recorded. Before taking the second reading, the instrument was set back to zero. The cone resistance was calculated according to Eqn 1:

$$\text{Cone resistance} = \text{manometer reading} \div \text{base area of cone} \quad (1)$$

Soil aggregate analyses

Soil samples were prepared in the laboratory by carefully breaking larger clods (field-moist soil) by hand into smaller segments along natural cleavages and then air- dried. Air-dried samples were then passed through an 8-mm sieve and retained on a 6-mm sieve. The aggregates were then wet-sieved through a collection of six sieves (mesh sizes 4, 2, 0.5, 0.25, 0.12 and 0.0.53 mm), following the procedure described by Yoder (1936). A shaking operation was performed for 20 min with 35 cpm.

The aggregates retained on each sieve were transferred to a set of pre-weighed beakers, oven-dried at 60°C for 48 h and weighed. The mean-weight diameter (MWD) was calculated as an index of aggregation (van Bavel 1950) along with other indices as follows. The line between macro- and micro-aggregates is commonly drawn at 0.25 mm (Edwards and Bremner 1967; Oades and Waters 1991). Therefore, the macro-aggregates were determined by adding the weight of the aggregates retained in the 4-, 2-, 0.5- and 0.25-mm sieves. Micro-aggregates were calculated by adding the weight of aggregates retained by the 0.12- and 0.053-mm sieves. The MWD and geometric mean diameter (GMD) of aggregates (Kemper and Roseneau 1986) were calculated according to Eqns 2 and 3:

$$MWD\,(mm) = \frac{\sum_{i=1}^{n} XiWi}{\sum_{i=1}^{n} Wi} \tag{2}$$

$$GMD\,(mm) = \exp\left[\frac{\sum_{i=1}^{n} Wi\,logXi}{\sum_{i=1}^{n} Wi}\right] \tag{3}$$

where *Wi* is the weight of aggregates retained over the particular sieve and *Xi* is the mean diameter of the size class (mm). The aggregate ratio (AR) of soils was computed according to Eqn 4:

$$\begin{aligned} \text{AR} &= \%\ \text{water-stable macro-aggregates} \\ &\quad \div \%\ \text{water-stable micro-aggregates} \end{aligned} \tag{4}$$

Water-retention curve and available water capacity

The pressure plate apparatus (Soil Moisture Equipment Corp., Goleta, CA, USA) method was used for obtaining the water-retention curve (Klute 1986). Water retention of undisturbed soil core samples was determined at 33, 50, 75, 100, 350 and 1500 kPa. The pressure plates were saturated overnight and undisturbed soil samples (cores) were placed on the plate in separate rubber rings. Then water was added to saturate the sample for 24 h until complete saturation. Saturated plates with the soil samples were placed in pressure chambers and desired pressures were applied. For attaining equilibrium, they were kept for 48 h at the specified pressure. Then, samples were taken out from the chambers and the weights of the soil core samples were recorded. After passing the highest pressure-step, the soil core samples were oven-dried at 105°C until constant weight and the dry weights were recorded. The moisture content retained by each sample at a specified potential was then calculated from the moist and dry weight recorded. Water-holding capacity of soil was determined by the Keen box method (Piper 1966).

Measurement of crack parameters

Each experimental plot was divided into four parts, and squares 1 m by 1 m were demarcated in each part. Within each of these squares, total crack length apparent on the soil surface was measured with a flexible twine run along the crack (Dasog and Shashidhara 1993). The average depth and width of cracks were based on measurements made at 0.5-m intervals along the course of the crack. The crack depth was measured with a 2-mm-diameter steel rod inserted until it offered resistance to further penetration, and the width was measured with an adjustable divider at 1 cm below the soil surface (Dasog *et al.* 1988). A depth of 1 cm was chosen to avoid exaggerated widths caused by surface disturbance. For measurement of crack parameters at different water potentials, one tensiometer was installed in each plot. Crack volume measurement was done at –60 kPa soil moisture potential with sand and measuring cylinder. An area of 0.5 m by 0.5 m was selected and sand was poured into the cracks until they were all filled. The measured volume was multiplied by four to express the volume per m^2 area.

Chemical analyses of soil

Prior to analysis, soil samples were air-dried and passed through a 2-mm sieve. The principal chemical properties of soil were determined by standard methods (Sparks *et al.* 1996). In particular, the pH and EC was measured for sample–water mixtures of 1 : 2.5, and the OC content was determined by dichromate oxidation of the sample and subsequent titration with ferrous ammonium sulfate (Walkley and Black 1934). The mineralisable N content was obtained by the Kjeldahl method followed by titration with diluted sulfuric acid (Subbiah and Asija 1956). Available P content was determined by the $NaHCO_3$-ascorbic acid method (Watanabe and Olsen 1965), and available K content with the ammonium acetate method using a flame photometer (Hanway and Heidel 1952). Physico-chemical properties of the experimental field from the composite soil samples taken from 0–15 and 15–30 cm were also determined at the beginning of experiment (Table 2). The measured available N, P and K were converted to kg ha^{-1} according to Eqn 5:

$$\begin{aligned} &\text{Available N, P or K}\ (\text{kg ha}^{-1}) \\ &\quad = \text{Measured value}\ (\text{mg kg}^{-1}) \times 2.24 \end{aligned} \tag{5}$$

Results

Bulk density

A noticeable difference in bulk density values was recorded for the various rice-crop establishment methods. In the 0–15 cm soil layer, significantly higher bulk density was found under puddled conditions than unpuddled conditions. It was highest in P-BMP (1.631 g cm^{-3}), followed by P-SRI (1.625 g cm^{-3}) and UP-TR (1.590 g cm^{-3}), and lowest bulk density was recorded in UP-DS (1.584 g cm^{-3}) (Fig. 2). A similar trend was observed in the second layer (15–30 cm). However, irrespective of the rice-crop establishment method, all treatments showed higher bulk density in the lower than the upper layer. Bulk density was similar in P-BMP and P-SRI, followed by UP-TR and lowest in UP-DS, which was significantly different from P-SRI. Further down the profile (30–45 cm layer), bulk density was again higher than in the layers above; however, no difference was observed among the various treatments.

Soil penetration resistance

The effect of puddling on soil penetration resistance was clear (Fig. 3). In the surface layer (0–10 cm), penetration resistance was highest in P-SRI (1.50 MPa) followed by P-BMP (1.49 MPa), UP-TR (1.47 MPa) and UP-DS (1.44 MPa). In the second layer (10–20 cm), penetration resistance was always higher than in the layer above. Again the highest resistances were recorded in puddled treatments (1.54 MPa in

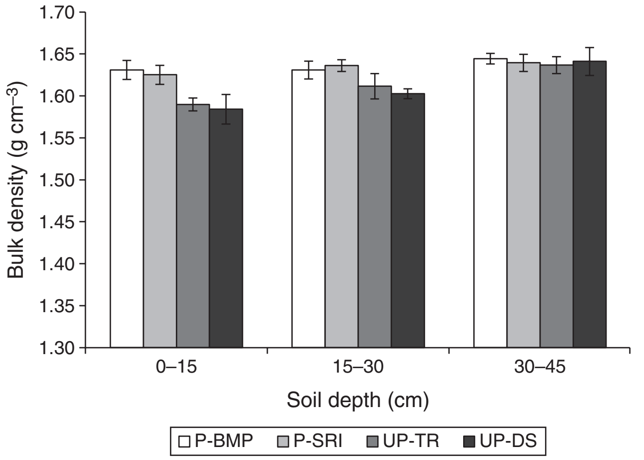

Fig. 2. Bulk density under different rice-crop establishment methods. Capped lines indicate standard errors of mean. P, Puddling; BMP, best management practices; SRI, system of rice intensification; UP, unpuddled; TR, transplanted; DS, direct-seeded.

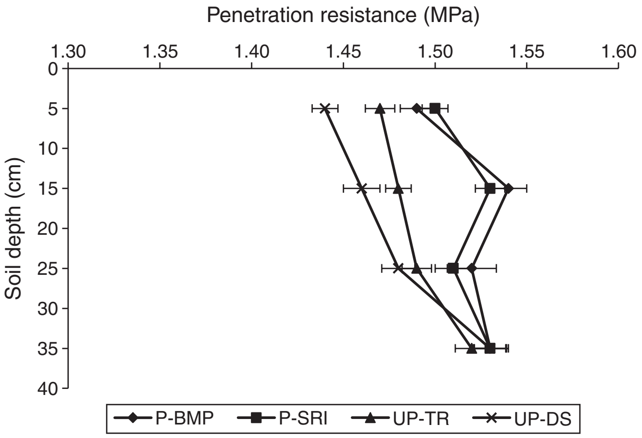

Fig. 3. Penetration resistance as affected by different rice-crop establishment methods. Capped horizontal bars indicate standard errors of mean. P, Puddling; BMP, best management practices; SRI, system of rice intensification; UP, unpuddled; TR, transplanted; DS, direct-seeded.

the P-BMP treatment), with unpuddled treatments recording lower resistances (1.46 MPa in the UP-DS). A similar trend was also observed in the next layer (20–30 cm) but the difference in penetration resistance among various treatments was small. Beyond 30 cm soil depth, no difference in penetration resistance was detected.

Soil aggregate size distribution

The effect of different rice-crop establishment methods on soil aggregate size distribution was prominent. For the surface 0–15 cm soil layer, the highest MWD was recorded in UP-DS (1.16 mm), followed by UP-TR (1.01 mm), P-SRI (0.94 mm) and UP-BMP (0.81 mm) (Table 3). Water-stable aggregates showed a similar trend. The lowest water-stable aggregate percentage was measured in P-BMP (89.5%), and the highest in UP-DS (94.6%). In the 15–30 cm soil layer, UP-DS again recorded the highest water-stable aggregate percentage.

Table 3. Aggregate-size distribution, mean-weight diameter (MWD), water-stable aggregates (WSA) and geometric mean diameter (GMD) as affected by different rice-crop establishment methods

Values are means ± standard error of mean. P, Puddling; BMP, best management practices; SRI, system of rice intensification; UP, unpuddled; TR, transplanted; DS, direct-seeded

Treatment	Aggregate-size distribution (%) by aggregate size group (mm): 8–4	4–2	2–0.5	0.5–0.25	0.25–0.12	0.12–0.053	<0.053	MWD (mm)	WSA (%)	GMD (mm)	Aggregates (%) Macro	Micro	Aggregate ratio
						0–15 cm							
P-BMP	1.17 ± 0.04	5.55 ± 0.20	16.77 ± 1.11	26.38 ± 1.03	29.74 ± 1.15	9.85 ± 0.17	10.54 ± 1.40	0.81 ± 0.02	89.46 ± 1.40	0.73 ± 0.01	49.87 ± 0.27	39.59 ± 1.19	1.26 ± 0.03
P-SRI	1.38 ± 0.14	4.74 ± 0.24	28.94 ± 1.29	26.97 ± 1.25	17.17 ± 0.40	11.35 ± 0.34	9.44 ± 1.88	0.94 ± 0.03	90.56 ± 1.88	0.78 ± 0.02	62.03 ± 2.45	28.53 ± 0.67	2.18 ± 0.13
UP-TR	1.32 ± 0.11	6.87 ± 0.43	29.55 ± 2.33	28.17 ± 1.67	12.01 ± 0.54	13.40 ± 0.45	8.69 ± 2.28	1.01 ± 0.03	91.31 ± 2.28	0.80 ± 0.03	65.91 ± 2.56	25.41 ± 0.50	2.60 ± 0.14
UP-DS	3.51 ± 0.29	7.59 ± 0.27	28.63 ± 0.77	28.61 ± 0.63	15.68 ± 0.32	10.55 ± 0.57	5.42 ± 1.48	1.16 ± 0.02	94.58 ± 1.48	0.86 ± 0.02	68.35 ± 1.21	26.23 ± 0.71	2.61 ± 0.08
						15–30 cm							
P-BMP	1.47 ± 0.08	5.05 ± 0.13	17.25 ± 0.20	31.07 ± 1.26	28.49 ± 0.56	10.89 ± 0.42	5.78 ± 1.88	0.85 ± 0.01	94.22 ± 1.88	0.77 ± 0.01	54.84 ± 1.28	39.38 ± 0.73	1.39 ± 0.02
P-SRI	1.65 ± 0.16	5.68 ± 0.48	17.63 ± 1.08	32.85 ± 0.83	29.11 ± 1.42	9.76 ± 0.40	3.31 ± 0.63	0.90 ± 0.02	96.69 ± 0.63	0.80 ± 0.01	57.82 ± 1.89	38.87 ± 1.30	1.49 ± 0.10
UP-TR	2.87 ± 0.24	7.86 ± 0.88	22.63 ± 1.81	30.56 ± 1.39	20.04 ± 0.80	10.43 ± 1.02	5.62 ± 2.19	1.06 ± 0.01	94.38 ± 2.19	0.83 ± 0.01	63.91 ± 0.91	30.47 ± 1.30	2.10 ± 0.06
UP-DS	3.92 ± 0.38	9.07 ± 0.76	26.21 ± 0.99	28.41 ± 0.71	18.49 ± 0.71	8.65 ± 0.45	5.25 ± 1.34	1.19 ± 0.01	97.04 ± 1.34	0.87 ± 0.01	67.62 ± 0.87	27.13 ± 1.16	2.50 ± 0.11

Irrespective of rice-crop establishment methods, all treatments except P-SRI showed higher MWD values in the second than in the upper layer. Maximum and minimum MWD values were recorded in UP-DS (1.19 mm) and P-BMP (0.85 mm), respectively.

Soil moisture content and water holding capacity

There were clear differences in soil moisture characteristics between the different rice-crop establishment methods (Table 4). Water-holding capacity, the maximum amount of water that a given soil can retain, is a function of volume and size of pores and was highest in UP-DS (0.346 cm^3 cm^{-3}), followed by UP-TR (0.331 cm^3 cm^{-3}) then P-BMP (0.327 cm^3 cm^{-3}), and lowest in P-SRI (0.305 cm^3 cm^{-3}). However, a different trend was observed for plant-available water. At low soil moisture potentials (at and close to saturation), soil water content was clearly higher in puddled soils than unpuddled soils. But with increasing soil moisture potential, the moisture content decreased faster in puddled soils and the difference between unpuddled and puddled soil diminished (Fig. 4). Therefore, the available water up to 1500 kPa was higher in puddled soils than in unpuddled soils.

Cracking behaviour

The cracking behaviour of soils was highly affected by different rice-crop establishment methods. Deeper and wider cracks were recorded throughout the whole range of soil moisture potential in puddled conditions. Initially (at –10 kPa), crack depth in puddled condition was 5.03 cm and in unpuddled condition 3.87 cm (Fig. 5). As the soil moisture potential increased, the difference in depth between puddled and unpuddled soils widened. The range of difference increased from 30% at –10 kPa to 78% at –60 kPa. A similar trend was observed for crack width. Crack width was always greater in

Table 4. Water-holding capacity (WHC), soil moisture retention at different potential, and available water (cm^3 cm^{-3}) under different treatments
Values are means ± standard error of mean. P, Puddling; BMP, best management practices; SRI, system of rice intensification; UP, unpuddled; TR, transplanted; DS, direct-seeded

Treatment	WHC	Soil moisture potential (–kPa):						Available water
		33	50	75	100	350	1500	
P-BMP	0.327 ± 0.003	0.249 ± 0.004	0.214 ± 0.003	0.164 ± 0.004	0.122 ± 0.002	0.073 ± 0.002	0.050 ± 0.001	0.199 ± 0.005
P-SRI	0.305 ± 0.004	0.246 ± 0.003	0.224 ± 0.004	0.162 ± 0.003	0.110 ± 0.004	0.068 ± 0.003	0.052 ± 0.003	0.195 ± 0.006
UP-TR	0.331 ± 0.003	0.216 ± 0.004	0.208 ± 0.004	0.170 ± 0.004	0.129 ± 0.004	0.073 ± 0.004	0.052 ± 0.003	0.164 ± 0.006
UP-DS	0.346 ± 0.002	0.222 ± 0.003	0.202 ± 0.003	0.166 ± 0.005	0.147 ± 0.004	0.083 ± 0.003	0.052 ± 0.001	0.170 ± 0.004

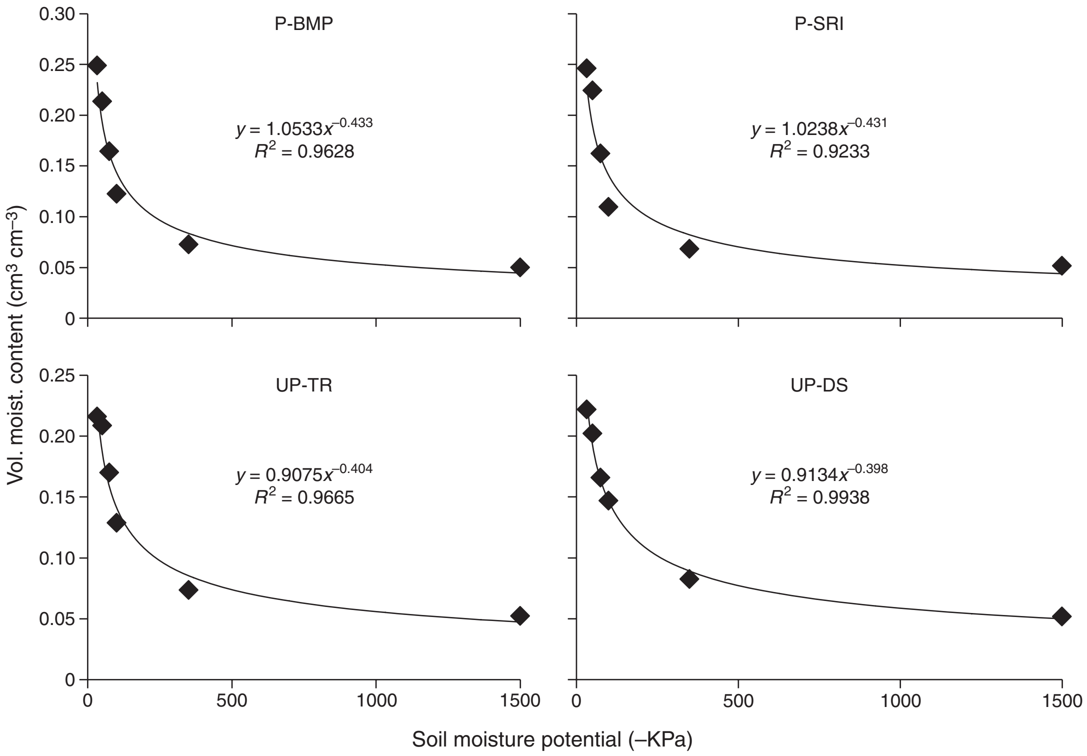

Fig. 4. Soil moisture characteristic curve under different treatments. P, Puddling; BMP, best management practices; SRI, system of rice intensification; UP, unpuddled; TR, transplanted; DS, direct-seeded.

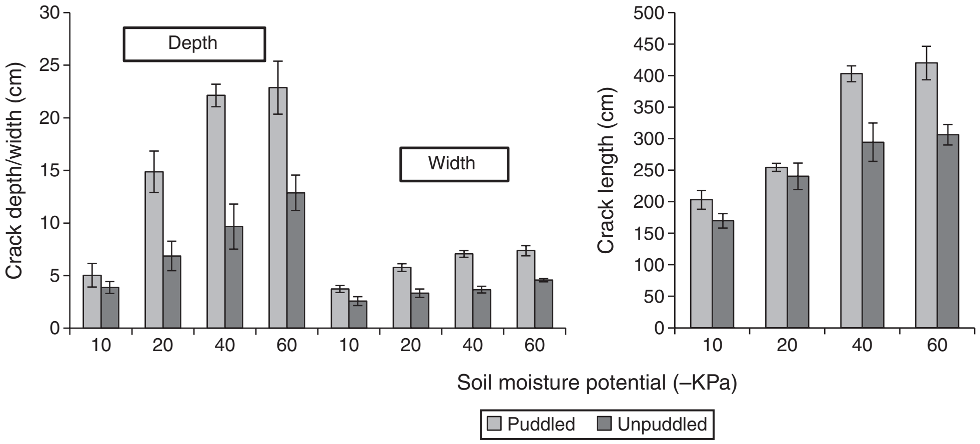

Fig. 5. Crack parameters (depth, width and length) under puddled and unpuddled conditions. Capped lines indicate standard errors of mean.

Table 5. Soil pH and electrical conductivity (EC, dS m^{-1}) and nutrient status (g kg^{-1}) after wheat harvest in 2014

Values are means ± standard error of mean. P, Puddling; BMP, best management practices; SRI, system of rice intensification; UP, unpuddled; TR, transplanted; DS, direct-seeded

Treatment	pH	EC	Org. carbon	Nitrogen	Phosphorus	Potassium
			0–15 cm			
P-BMP	7.82 ± 0.02	0.10 ± 0.01	4.4 ± 0.02	203.8 ± 5.4	23.9 ± 1.25	199.0 ± 9.2
P-SRI	7.76 ± 0.08	0.09 ± 0.01	4.5 ± 0.03	209.6 ± 9.5	23.0 ± 2.75	222.5 ± 6.1
UP-TR	7.75 ± 0.11	0.11 ± 0.01	4.6 ± 0.02	213.3 ± 9.6	29.7 ± 4.52	218.4 ± 15.7
UP-DS	7.82 ± 0.08	0.11 ± 0.01	4.8 ± 0.00	221.0 ± 10.9	27.5 ± 3.05	221.3 ± 24.0
			15–30 cm			
P-BMP	7.77 ± 0.07	0.10 ± 0.01	3.5 ± 0.01	187.9 ± 2.3	15.7 ± 0.92	220.9 ± 6.5
P-SRI	7.81 ± 0.11	0.09 ± 0.01	3.8 ± 0.01	183.1 ± 9.1	16.1 ± 0.86	231.6 ± 8.5
UP-TR	7.77 ± 0.11	0.11 ± 0.01	3.8 ± 0.03	192.8 ± 21.8	17.5 ± 3.76	231.5 ± 10.2
UP-DS	7.76 ± 0.06	0.10 ± 0.01	3.6 ± 0.05	172.5 ± 5.0	18.2 ± 1.61	226.9 ± 13.8

puddled condition. Crack width varied from 3.73 to 7.37 cm in puddled soils, whereas it ranged between 2.57 and 4.57 cm in unpuddled conditions. Crack length reflected the same trend as crack width and crack depth. Crack volume was more than three times higher in puddled soils. It was estimated at 8.82 and 2.85 L m^{-2} area in puddled and unpuddled soils, respectively.

Nutrient status in soils

The nutrient status of soils mainly depends on the input used, through both organic and inorganic sources, and the cropping system followed. Only small variations in nutrient concentrations were found among the different treatments (Table 5). In the topsoil (0–15 cm), OC concentration was marginally higher in unpuddled soils than in puddled treatments. The highest OC concentration was recorded in UP-DS (4.8 g kg^{-1}) and the lowest value in P-BMP (4.4 g kg^{-1}). A similar trend was observed for the three major nutrients (N, P, K. Unpuddled treatments recorded higher nutrient content than puddled treatments. In the next layer (15–30 cm), N and P but not K recorded lower values than in the topsoil. Within the same layer, variations among treatments were not great.

Rice and wheat yield

Yield data of rice and wheat are presented in Fig. 6. In case of rice, highest yield was produced by the P-BMP treatment (3412 kg ha^{-1}), followed by P-SRI (3187 kg ha^{-1}), UP-TR (3062 kg ha^{-1}) and UP-DS (2062 kg ha^{-1}). For the wheat crop, highest and lowest yields were recorded in P-SRI (3133 kg ha^{-1}) and P-BMP (2680 kg ha^{-1}), respectively.

Discussion

Soil physical properties

Differences in bulk density values under various rice-crop establishment methods were clearly caused by puddling and non-puddling before transplanting. Puddled conditions under P-BMP and P-SRI showed higher bulk density, which can be attributed to the smearing action of puddling, resulting in the breakdown of aggregates and more compaction of soil aggregates after drying. Sharma and De-Datta (1985) also reported higher bulk density in puddled soils upon drying of the soil after rice harvest. The lower bulk density values in unpuddled conditions were therefore due to better (and maintained) aggregation of soil particles. The higher bulk density in the second soil layer can be explained by

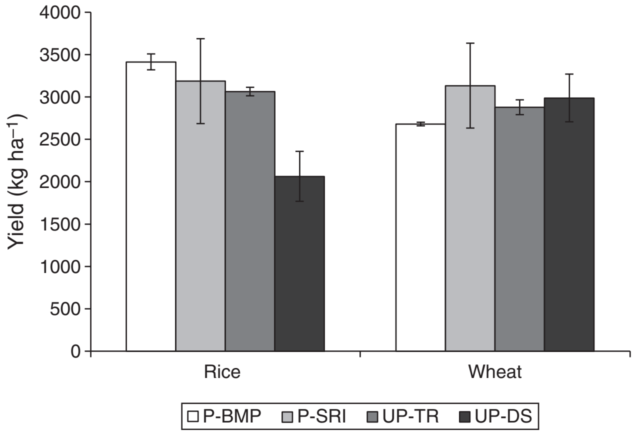

Fig. 6. Yield data of rice and wheat in 2013–14. Capped lines indicate standard errors of mean. P, Puddling; BMP, best management practices; SRI, system of rice intensification; UP, unpuddled; TR, transplanted; DS, direct-seeded.

eluviation of fine soil particles from the top layer into the layer below due to puddling (Aggarwal *et al.* 1995; Hobbs and Gupta 2000). In addition, the puddling operation does compress the layer below. No difference in bulk density values among the various treatments could be observed in the 30–45 cm layer, indicating that the tillage and puddling effect was limited to the upper 30 cm.

No data on the critical soil strength at which root growth could be hampered are available for the present soil. However, based on the limited information available in literature, 1.54 MPa (the maximum range of values in P-BMP at 10–20 cm depth) appears not to be a limiting value. In our study, penetration values never exceeded 2 MPa, at which root elongation was also not likely to be restricted. However, root growth can be hampered by reduced gas exchange and oxygen supply to the roots, which affects wheat roots more than rice roots. The higher penetration resistance in puddled conditions than unpuddled conditions will have been caused by the breakdown of soil aggregates, which in turn leads to a more compact arrangement of soil particles. A comparatively hard layer was clearly observable from penetration resistance values in puddled soils (both P-BMP and P-SRI) at 10–20 cm depth. Creation of a hardpan and compaction due to puddling were also reported by Sharma and De Datta (1986) and Kirchhof *et al.* (2000). The difference in penetration resistance between puddled and unpuddled conditions was reduced in the deeper soil layers.

The aggregation index and MWD of aggregates could clearly differentiate the puddled and unpuddled treatments in both 0–15 and 15–30 cm layers. More of the smaller macro-aggregates with an average diameter of 0.053–0.25 mm in puddled soils clearly demonstrated the breakdown of larger macro-aggregates (>0.25 mm) into smaller size fractions. Similarly, Chaudhary and Ghildhyal (1969) and Painuli (1993) reported a decrease in aggregate size due to puddling. Thus, less disturbance of soils without puddling resulted in significantly higher macro-aggregates in these unpuddled conditions (UP-TR and UP-DS). The results for unpuddled treatments, showing an improvement in soil aggregation, average MWD and water-stable aggregates, proved the interactive effect of the absence of soil disturbance. Similar results were presented by Singh and Malhi (2006), whose data on aggregate-size distribution indicated a larger effect of no-tillage on soil structure. The size distribution of aggregates is intimately linked to soil quality in relation to water stability of aggregates and soil carbon accumulation (Saha *et al.* 2011, 2014). The positive effect of no puddling in UP-TR and UP-DS was clearly reflected in terms of MWD, proving again that this structural index might be a valuable parameter for soil quality indices.

Higher water-holding capacity in unpuddled conditions will be closely related to better soil aggregation and the presence of more macropores, which can be drained at lower soil water tensions. Therefore, moisture content at field capacity under puddled condition was lower despite higher water-holding capacity. The greater moisture retention at higher potentials indicated the possibility of a greater number of medium-sized pores under unpuddled condition, enabling the soil to retain more moisture, which is available to plants at these potentials. Puddling resulted in breaking down of aggregates and therefore, reduced the number of macropores.

Cracks play an important role in physical processes of soil. The frequency, size and rate of development of cracks influence water, air, solute and heat dynamics in soils, and hence influence crop productivity and the potential for groundwater pollution. Our results indicated that wider, deeper and longer cracks could be attributed to the puddling operation. This finding is in agreement with the study of Flowers and Lal (1999), who reported an increase in the area and volume of cracks with a decrease in the soil-water content. Puddling resulted in breaking down of larger aggregates into smaller aggregates, which in turn helped the crack-development process. Sudhir-Yadav *et al.* (2011) showed that there was greater cracking on puddled soils than on non-puddled soils during soil drying, and that this was associated with a faster rate of drying in the puddled soil. Mohanty *et al.* (2006) also found that the surface area of cracks was larger in puddled soils than in non-puddled soils.

Soil nutrient status at the end of the experiment

Minor improvements or no significant differences in the soil nutrient status after a period of only 2 years could well be expected in the present study. However, even the little improvement observed under unpuddled conditions (UP-TR and UP-DS) was encouraging and this could be expected to improve the soil health further in the longer term.

Yield of rice and wheat

The effect of different crop-establishment methods on yield of rice was prominent; however, the carryover impact on the succeeding wheat crop was not yet significant. Significantly lower rice yield in UP-DS than in the P-BMP treatment could be partly attributed to suboptimal management and higher weed infestation. Lower yield in direct-seeded rice, mainly due to greater infestation of weeds, has been reported by many researchers elsewhere (Bhushan *et al.* 2007; Ladha *et al.* 2009; Yadav *et al.* 2009; Singh *et al.* 2011). Puddling in rice did not bring about any significant adverse effect on the productivity of wheat, although the trends did indicate a negative effect on wheat in the P-BMP treatment. Longer experiments would probably be needed to clarify the effect of slow changes in soil quality. Otherwise, puddling has already been extensively reported to be detrimental not only to soil health but also to non-rice upland crops in rotation (Sharma *et al.* 2003; Gathala *et al.* 2011; Laik *et al.* 2014). Also, there were inconsistent results elsewhere with regard to effect of puddling on the performance of wheat (Kirchhof *et al.* 2000; Mousavi *et al.* 2009). This could also indicate that the effect of puddling and its impact on crop growth may vary depending on intensity of puddling, soil type and crop grown, but no meta-study on this topic is currently available.

Conclusions

Cereal production systems in the EIGP are traditional, with low yield and low farm income, and they have largely missed out on the benefits of the Green Revolution. Traditional systems of rice cultivation use puddling to increase water availability and control weeds in rainfed, stress-prone environments. This practice has a significant impact on soil physical properties. It was found that omission of puddling (UP-TR and UP-DS) quickly improved the physical properties of soil, such as bulk density, penetration resistance, aggregation stability and cracking behaviour. In addition, there was an improvement in soil aggregation, average MWD and water-stable aggregates under non-puddled conditions. Unpuddled conditions increased macro-aggregates by 18–33%. Later, a hard layer was noticed in puddled conditions (P-BMP and P-SRI). Wider, longer and deeper cracks developed in the plots that were subjected to puddling, and unpuddled treatments recorded slightly higher nutrient contents than puddled treatments. Therefore, the present study clearly showed that puddling deteriorates soil health. Based on the present study, it can be concluded that not puddling can create conditions that are more favourable for soil health, including improvement in bulk density, aggregation stability, pore size distribution and penetration resistance, which in the longer term should improve crop growth. Productivity and profitability of rice-based systems in unpuddled, transplanted conditions may become the better options, because these conditions help to improve soil health, reduce the energy required and costs for soil preparation, and require less labour. However, long-term research is needed for better understanding of the impact of such practices on the productivity of rice and succeeding dry-season crops. The results of this study can form the basis of further long-term experiments in the IGP and in mega-deltas comprising parts of India, Bangladesh and Myanmar.

Acknowledgements

We are most grateful to the International Rice Research Institute in Los Baños, Philippines, and the Bill and Melinda Gates Foundation (BMGF) for rendering the financial assistance through the IRRAS project in Bihar. Authors thank Dr S. Singh, Dr Ashok Yadav, Dr Stephan M. Haefele, Dr S. S. Singh, Dr Bikash Sarkar and two anonymous reviewers for suggesting improvements in the manuscript.

References

Aggarwal GC, Sidhu AS, Sekhon NK, Sandhu KS, Sur HS (1995) Puddling and N management effects on crop response in a rice-wheat cropping system. *Soil & Tillage Research* **36**, 129–139. doi:10.1016/0167-1987(95)00504-8

Balasubramanian V, Adhya TK, Ladha JK (2012) Enhancing eco-efficiency in the intensive cereal-based systems of the Indo-Gangetic plains. In ‘Issues in tropical agriculture-eco-efficiency: from vision to reality’. pp. 1–7. (CIAT Publication: Cali, Colombia)

Bhushan L, Ladha JK, Gupta RK, Singh S, Tirole-Padre A, Saharawat YS, Gathala M, Pathak H (2007) Saving of water and labor in rice-wheat system with no-tillage and direct seeding technologies. *Agronomy Journal* **99**, 1288–1296. doi:10.2134/agronj2006.0227

Blake GR, Hartge KH (1986) Bulk density. In ‘Methods of soil analysis. Part 1. Physical and mineralogical methods’. Agronomy Monograph No. 9. 2nd edn (Ed. A Klute) pp. 363–375. (Soil Science Society of America Inc.: Madison, WI, USA)

Carman K (1996) Effect of different tillage systems on soil properties and wheat yield in middle Anatolia. *Soil & Tillage Research* **40**, 204–207.

Chaudhary TN, Ghildhyal BP (1969) Aggregate stability of puddled soil during rice growth. *Journal of the Indian Society of Soil Science* **17**, 261–265.

Dasog GS, Shashidhara GB (1993) Dimension and volume of cracks under different crop covers. *Soil Science* **156**, 424–428. doi:10.1097/00010694-199312000-00007

Dasog GS, Acton DI, Mermut AR, de Jong E (1988) Shrink-swell potential and cracking in clay soils of Saskatchewan. *Canadian Journal of Soil Science* **68**, 251–260. doi:10.4141/cjss88-025

Edwards AP, Bremner JM (1967) Microaggregates in soils. *Journal of Soil Science* **18**, 64–73. doi:10.1111/j.1365-2389.1967.tb01488.x

Flowers M, Lal R (1999) Axle load and tillage effects on shrinkage. Characteristics of a Mollic Ochraqualf in northwest Ohio. *Soil & Tillage Research* **50**, 251–258. doi:10.1016/S0167-1987(99)00009-4

Fujisaka SL, Harrington L, Hobbs PR (1994) Rice-wheat in South Asia Systems and long-term properties established through diagnostic research. *Agricultural Systems* **46**, 169–187. doi:10.1016/0308-521X(94)90096-X

Gathala M, Ladha JK, Balyan V, Saharawat YS, Kumar V, Sharma PK, Sharma S, Pathak H (2011) Tillage and crop establishment affects sustainability of South Asia rice–wheat system. *Agronomy Journal* **103**, 961–971. doi:10.2134/agronj2010.0394

Hanway JJ, Heidel H (1952) Soil analysis methods as used in Iowa state college, soil testing laboratory. *Iowa Agriculture* **54**, 1–31.

Hobbs PR, Gupta RK (2000) Sustainable resource management in intensively cultivated irrigated rice–wheat cropping systems of the Indo-Gangetic Plains of South Asia: strategies and options. In ‘Proceedings International Conference on Managing Natural Resources for Sustainable Production in 21st Century’. New Delhi, India, 14–18 February. pp. 584–592. (Indian Council of Agricultural Research: New Delhi)

Hugar AY, Chandrappa H, Jayadeva HM, Sathish A, Mallikarjun GB (2009) Influence of different establishment methods on yield and economics of rice. *Agricultural Science Digest* **29**, 202–205.

IRRI (2014) World Rice Statistics Online Query Facility. International Rice Research Institute. Available at: http://ricestat.irri.org:8080/wrsv3/entrypoint.htm (accessed 21 April 2014)

Kamboj BR, Yadav DB, Yadav A, Goel NK, Gill G, Malik RK, Chauhan BS (2013) Mechanized transplanting of rice (*Oryza sativa* L.) in non-puddled and no-till conditions in the rice-wheat cropping system in Haryana, India. *American Journal of Plant Science* **4**, 2409–2413. doi:10.4236/ajps.2013.412298

Kemper WD, Roseneau RC (1986) Aggregate stability and size distribution. In ‘Methods of soil analysis. Part I. Physical and mineralogical methods’.

Agronomy Monograph No. 9. (Ed. A Klute) pp. 425–442. (Soil Science Society of America Inc.: Madison, WI, USA)

Kirchhof G, Priyono S, Utomo WH, Adisarwanto T, Dacannay EV, So HB (2000) The effect of soil puddling on the soil physical properties and the growth of rice and post-rice crops. *Soil & Tillage Research* **56**, 37–50. doi:10.1016/S0167-1987(00)00121-5

Klute A (1986) Water retention: Laboratory methods. In 'Methods of soil analysis. Part I. Physical and mineralogical methods'. Agronomy Monograph No. 9. (Ed. A. Klute) pp. 635–662. (Soil Science Society of America Inc.: Madison, WI, USA)

Kumar V, Ladha JK (2011) Direct seeding of rice: recent developments and future research needs. *Advances in Agronomy* **111**, 297–413. doi:10.1016/B978-0-12-387689-8.00001-1

Ladha JK, Kumar V, Alam M, Sharma S, Gathala M, Chandna P, Saharawat YS, Balasubramanian V 2009. Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice-wheat system in South Asia. In 'Integrated crop and resource management in the rice–wheat system of South Asia'. (Ed. JK Ladha) pp. 69–108. (International Rice Research Institute: Los Baños, Philippines)

Laik R, Sharma S, Idris M, Singh AK, Singh SS, Bhatt BP, Saharawat Y, Humphreys E, Ladha JK (2014) Integration of conservation agriculture with best management practices for improving system performance of the rice-wheat rotation in the Eastern Indo-Gangetic Plains of India. *Agriculture, Ecosystems & Environment* **195**, 68–82. doi:10.1016/j.agee.2014.06.001

Mohanty M, Painuli DK, Mandal KG (2004) Effect of puddling intensity on temporal variation in soil physical conditions and yield of rice (*Oryza sativa* L.) in a Vertisol of central India. *Soil & Tillage Research* **76**, 83–94. doi:10.1016/j.still.2003.08.006

Mohanty M, Painuli DK, Mandal KG, Pachlaniya NK, Misra AK (2006) Cracking of a vertisol as influenced by puddling and residue management under rice–wheat cropping system. *Journal of the Indian Society of Soil Science* **54**, 452–460.

Mousavi SF, Yousefi-Moghadam S, Mostafazadeh-Fard B, Hemmat A, Yazdani R (2009) Effect of puddling intensity on physical properties of a silty clay soil under laboratory and field conditions. *Paddy Water Environment* **7**, 45–54. doi:10.1007/s10333-008-0148-4

Oades JM, Waters AG (1991) Aggregate hierarchy in soils. *Australian Journal of Soil Research* **29**, 815–828. doi:10.1071/SR9910815

Painuli DK (1993) The effect on some physical properties of a vertic tropaquept soil of the number of cultivations after applying different quantities of water and after different soaking periods. *Soil Technology* **6**, 173–181. doi:10.1016/0933-3630(93)90006-Z

Piper CS (1966) 'Soil and plant analysis.' (Hans Publishers: Bombay. India)

Ponnamperuma FN (1972) The chemistry of submerged soils. *Advances in Agronomy* **24**, 29–96. doi:10.1016/S0065-2113(08)60633-1

Saha D, Kukal SS, Sharma S (2011) Land use impacts on SOC fractions and aggregate stability in Typic Ustochrepts of Northwest India. *Plant and Soil* **339**, 457–470. doi:10.1007/s11104-010-0602-0

Saha D, Kukal SS, Bawa SS (2014) Soil organic carbon stock and fractions in relation to land use and soil depth in the degraded Shiwaliks hills of lower Himalayas. *Land Degradation & Development* **25**, 407–416. doi:10.1002/ldr.2151

Sahrawat KL (2005) Fertility and organic matter in submerged rice soils. *Current Science* **88**, 735–739.

Sharma PK, De-Datta SK (1985) Puddling influence on soil rice development and yield. *Soil Science Society of America Journal* **49**, 1451–1457. doi:10.2136/sssaj1985.03615995004900060024x

Sharma PK, De Datta SK (1986) Physical properties and processes of puddle rice soils. *Advances in Soil Science* **5**, 139–178. doi:10.1007/978-1-4613-8660-5_3

Sharma PK, Ladha JK, Bhushan L (2003) Soil physical effects of puddling in rice-wheat cropping systems. In 'Improving the productivity and sustainability of rice–wheat systems: issues and impacts'. ASA Special Publication No. 65. (Eds JK Ladha, *et al*.) pp. 97–114. (ASA, CSSA, SSA: Madison, WI, USA)

Singh PK, Bisoyi RN (1989) Blue green algae in rice fields. *Phykos* **28**, 181–195.

Singh B, Malhi SS (2006) Response of soil physical properties to tillage and residue management on two soils in a cool temperate environment. *Soil & Tillage Research* **85**, 143–153. doi:10.1016/j.still.2004.12.005

Singh Y, Singh VP, Singh G, Yadav DS, Sinha RKP, Johnson DE, Mortimer AM (2011) The implication of land preparation, crop establishment method and weed management on rice yield variation in the rice–wheat system in the Indo-Gangetic Plains. *Field Crops Research* **121**, 64–74. doi:10.1016/j.fcr.2010.11.012

So HB, Kirchhoff G (2000) Editorial: management of clay soils for rainfed lowland rice-based cropping systems. *Soil & Tillage Research* **56**, 1–2. doi:10.1016/S0167-1987(00)00118-5

Sparks DL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, Sumner ME (1996) 'Methods of soil analysis. Part 3: Chemical methods.' (Soil Science Society of America Inc.: Madison, WI, USA)

Subbiah BV, Asija GL (1956) A rapid procedure for the estimation of available nitrogen in soils. *Current Science* **25**, 259–260.

Sudhir-Yadav , Humphreys E, Kukal SS, Gill G, Rangarajan R (2011) Effect of water management on dry seeded and puddled transplanted rice. Part 2: water balance and water productivity. *Field Crops Research* **120**, 123–132. doi:10.1016/j.fcr.2010.09.003

Thakur AK, Uphoff N, Anthony E (2010) An assessment of physiological effects of system of rice intensification (SRI) practices compared with recommended rice cultivation practices in India. *Experimental Agriculture* **46**, 77–98. doi:10.1017/S0014479709990548

Thierfelder C, Wall PC (2009) Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil & Tillage Research* **105**, 217–227. doi:10.1016/j.still.2009.07.007

van Bavel CHM (1950) Mean weight diameter of soil aggregates as a statistical index of aggregation. *Soil Science Society of America Proceedings* **14**, 20–23. doi:10.2136/sssaj1950.036159950014000C0005x

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining organic carbon in soils: Effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science* **63**, 251–263. doi:10.1097/00010694-194704000-00001

Watanabe FS, Olsen SR (1965) Test of ascorbic acid method for determining phosphorus in water and sodium bicarbonate extracts of soil. *Soil Science Society of America Proceedings* **29**, 677–678. doi:10.2136/sssaj1965.03615995002900060025x

Yadav A, Dharam Bir, Gill G, Kamboj BR, Dahiya S, Lathwal OP, Garg RB (2009) Scope of direct seeded rice in Haryana. In 'Proceedings National Workshop on Scope and Problems of Direct Seeded Rice'. 16 September 2009, Ludhiana. pp. 26–37. (Punjab Agricultural University: Ludhiana, Punjab, India)

Yoder RE (1936) A direct method of aggregate analysis and study of the physical nature of erosion losses. *Journal – American Society of Agronomy* **28**, 337–351. doi:10.2134/agronj1936.00021962002800050001x

Zhao L, Wu L, Li Y, Sarkar A, Zhu D, Uphoff N (2010) Comparison of yield, water use efficiency and soil microbial biomass as affected by the system of rice intensification. *Communications in Soil Science and Plant Analysis* **41**, 1–12. doi:10.1080/00103620903360247