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Optimizing dry and wet tillage for rice on a Gangetic alluvial soil: Effect on soil characteristics, water use efficiency and productivity of the rice–wheat system

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ABSTRACT

The effect of puddling in reducing water and nitrogen losses, and increasing rice (*Oryza sativa* L.) yields and N uptake depends on its intensity and also on the level of pre-puddling tillage, although an increase in the intensity of these operations involves excessive energy and may lead to a negative effect on the yield of succeeding wheat (*Triticum aestivum* L.) due to sub-soil compaction. A 3-year field experiment was conducted on a sandy loam (Typic Ustochrept) soil of Modipuram, India to study the interactive effects of pre-puddling tillage and puddling intensity on irrigation water productivity (IWP) in rice, the concentration of nitrate-N in the soil profile, and the performance of rice and wheat crops. Treatments included 3 levels of pre-puddling tillage – discing followed by a tine-cultivation and planking (T_1), discing followed by 2 tine-cultivations and planking (T_2), or discing followed by 4 tine-cultivations and planking (T_4); and 3 puddling intensities, i.e. 1, 2 or 4 passess of a puddler in ponded water (P_1, P_2 and P_4, respectively), each followed by planking. Increasing tillage levels from T_1P_1 to T_4P_4 decreased irrigation water requirement by 22–25%, and increased rice grain yield by 1.6–2.2 t ha^{-1} and IWP by 0.26–0.34 kg m^{-3} in different years. The post-rice nitrate-N concentration in the soil further indicated the advantage of puddling in retaining more nitrate-N in the upper profile, i.e. effective root zone. There was a significant ($p \leq 0.05$) interaction between pre-puddling tillage and puddling intensity on puddling index, which was the highest (0.63–0.65) under T_4P_4 during all years. Treatment T_4P_4 also increased bulk density over T_1P_1, especially at 28–33 cm depth. This sub-soil compaction led to decreased wheat root mass density and wheat grain yield; the adverse effect of excessive puddling on wheat yield increased with time. The present study indicated 2 pre-puddling tillage operations followed by 2 passes of puddler, i.e. T_2P_2 as the optimum tillage combination with respect to energy efficiency in rice, total annual productivity and economic returns of the rice–wheat system.

1. Introduction

Rice (*Oryza sativa* L.) is the most important and widely cultivated staple food crop in Asian countries, where it is grown mostly as a manually transplanted crop in puddled soil (Sanchez, 1976). Field preparation for transplanting rice is an energy-intensive process, and consists of two operations, i.e. pre-puddling tillage or dry tillage and puddling or wet tillage. Puddling, apart from lowering the percolation losses of water by reducing soil hydraulic conductivity, helps in weed control and creation of soft medium for easy transplanting rice seedlings (De-Datta, 1981; Sharma and De-Datta, 1986; So and Kirchhoff, 2000). The effect of puddling on puddle quality in terms of puddling depth and percolation rate, however, depends on the initial soil conditions created by pre-puddling tillage (Gajri et al., 1999). The impact of puddling on rice productivity varies in accordance with soil characteristics and climate (Kirchhof et al., 2000). The positive effects of puddling on the permeable (coarse-textured) soils of semi-arid regions of South Asia, particularly those of Indo-Gangetic Plain region (IGP), are frequently documented (Sharma and De-Datta, 1985; Yadav et al., 2000; Kukal and Aggarwal, 2003). On the other hand, 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). Puddling results in formation of compacted soil layers below the puddled zone on which soil strength increases rapidly as the soil dries, and limits the depth of root exploitation in subsequent crops (IRRI, 1986).

In the rice–wheat (*Triticum aestivum* L.) cropping system (RWS), which is the predominant annual crop rotation of South Asia occupying nearly 13.5 million ha area in the IGP of India, Pakistan,

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Bangladesh and Nepal, results are inconsistent regarding the effect of puddling in rice on the yield of a subsequent wheat crop. Whereas some studies suggested a reduction in wheat yields in post-rice soils due to puddling induced changes in soil physical properties (Boparai et al., 1992; Fujisaka et al., 1994; Dwivedi et al., 2003; Singh et al., 2005), others did not explicitly support this conclusion (Woodhead et al., 1994; Bhushan et al., 2007). Sharma et al. (2003) attempted to relate the impact of puddling on wheat yield with soil texture, stating that the same is more detrimental on medium- to fine-textured soils. However, results from field experiments in India and Nepal involving varying soil textural classes did not substantiate such relationships (Humphreys et al., 2005). It seems that the effects of puddling on subsequent wheat are more site-specific, and must be examined in relation to site history and nutrient availability in the root zone, along with the changes in soil physical properties.

Preliminary surveys in the Upper Gangetic Plain zone of the IGP undertaken by the authors indicated that the farmers have a tendency to create a very fine puddled top soil by applying 4–6 pre-puddling tillage operations including 1–2 discings and 2–4 harrowings. Other reports (Chatha et al., 1994; Sharma et al., 2004) even documented adoption of 4–8 pre-puddling tillage operations by the farmers in the IGP. This is followed by 3–4 wet tillage operations using a tractor-mounted puddler or a tine-cultivator plus wooden plank. In the absence of well-established site-specific recommendations on the extent of pre-puddling tillage and/or puddling, the field preparation by the farmers is usually dictated by the availability of a tractor and implements (Gajri et al., 1999), or by the conventional belief that repeated tillage would result in a favourable tilth. Thus, evaluation of different combinations of pre-puddling tillage and puddling in relation to changes in soil characteristics, nitrate-N distribution in the soil profile and productivity of the RWS assumes practical significance.

We, therefore, undertook field investigations to (i) study the interactive effects of pre-puddling tillage and puddling on important soil parameters, irrigation water requirement in rice and the yield of rice and subsequent wheat crop, and (ii) optimize these tillage operations with respect to productivity and economic returns of the RWS.

2. Materials and methods

2.1. The site

A field experiment was conducted for 3 consecutive years, i.e. 2000–2001, 2001–2002 and 2002–2003 on a Typic Ustochrept at the research farm of the Project Directorate for Farming Systems Research, Modipuram, Meerut, India. Meerut (29°4′N, 77°46′E, 237 m above mean sea level), located in the northwest India, represents an irrigated, mechanized and input-intensive cropping area of the Upper Gangetic Plain Zone of the IGP. The climate of Meerut is semi-arid subtropical, with dry hot summers and cool winters. The average monthly minimum and maximum temperatures in January (the coolest month) were 7.2 °C and 20.1 °C, respectively. The corresponding temperatures in May (the hottest month) were 24.2 °C and 39.8 °C, respectively. The 10-year average annual rainfall is 823 mm, and over 75% of this is received through the northwest monsoon during July–September. During the study period (2000–2001 to 2002–2003), average annual rainfall and PET were 825 and 1647 mm, respectively. Of the total annual rainfall, 76% was received during rice season (i.e. July to October), whereas PET during this period was 44% of the annual PET.

The soil of experimental site was a sandy loam of Gangetic alluvial origin, very deep (>2 m), flat (about 1% slope) and well-drained. Detailed soil characteristics up to a profile depth of 100 cm are given in Table 1. At the onset of the field experiment, the surface soil (0–20 cm) was mildly alkaline (pH 8.3), non-saline (EC 0.21 dS m^{-1}), low in organic C (0.41%), medium in available P and K (0.5 M $NaHCO_3$-extractable P 11 mg kg^{-1} and N NH_4OAc-extractable K 110 mg kg^{-1}) and low in available Zn (DTPA-extractable Zn 0.73 mg kg^{-1}). The values of pH, EC, organic C and available nutrients were decreased with increasing profile depth. The CEC of surface soil was 14.4 cmol (p^+) kg^{-1}, which decreased with an increase in profile depth. Prior to establishment of the experiment, the site was generally managed under puddled-transplanted rice (PTR) with 3–5 pre-puddling tillage and 3–4 puddling followed by wheat, although crops like maize or pearlmillet during monsoon and mustard during winter were also grown occasionally.

2.2. Treatments and crop management

The field experiment comprised 9 treatments, i.e. 3 pre-puddling tillage operations in main plots and 3 puddling intensities in sub-plots. Treatments were compared in a split-plot design with 4 replications, on a layout that remained undisturbed during the course of study, i.e. 3 years. The sub-plot size was 12 m × 12 m. The pre-puddling treatments were: (i) discing + 1 harrowing with a tine-cultivator (T_1); (ii) discing + 2 criss-cross harrowing operations with a tine-cultivator (T_2); and (iii) discing + 4 criss-cross harrowing operations with a tine-cultivator (T_4). Discing was done 1-week after an irrigation applied immediately after wheat harvesting.

Table 1
Initial soil characteristics measured at the commencement of field experiment (2001–2002) at Modipuram, India.

Parameters	Soil depth (cm)				
	0–20	20–40	40–60	60–80	80–100
pH	8.3	7.7	7.8	7.4	7.4
EC (dS m^{-1})	0.21	0.18	0.13	0.11	0.10
Clay (%)	16.5	17.2	18.0	18.0	15.1
Silt (%)	18.0	18.0	19.8	21.6	17.3
Sand (%)	65.5	64.8	62.2	60.4	67.6
Texture	SL	SL	SL	SL	SL
[a]Bulk density (Mg m^{-3})	1.49	1.50	1.56	1.57	1.67
Organic carbon (%)	0.41	0.36	0.31	0.21	0.28
0.5 M $NaHCO_3$-extractable P (mg kg^{-1})	11.0	8.5	6.9	6.5	6.0
N NH_4OAc-extractable K (mg kg^{-1})	110	89	76	67	72
0.05% $CaCl_2$-extractable S (mg kg^{-1})	27.8	21.0	21.0	13.5	12.2
DTPA-extractable Zn (mg kg^{-1})	0.73	0.56	0.56	0.40	0.48
CEC (cmol (p^+) kg^{-1})	14.4	12.1	10.6	11.1	9.3
Exchangeable Na^+ (% of CEC)	5.1	2.1	3.6	3.2	2.7

SL, sandy loam.

[a] Measured at 8–13, 28–33, 48–53, 68–73 and 88–93 cm soil depth.

Subsequent harrowing operations were carried out in June, i.e. 1 harrowing (T_1) in the last week of June, 2 harrowings (T_2) in second and fourth weeks, and 4 harrowings (T_4) at weekly intervals. The discing and harrowing operations were carried out using a tractor-mounted disc-harrow and tine-cultivator, respectively which are conventionally used by the farmers of the region. All harrowings were followed by a planking, i.e. one pass of a wooden plank for post-tillage packing and levelling of the soil. After completion of the pre-puddling tillage operations, each main plot was divided into 3 sub-plots, isolated from each other by a 1.5 m wide buffer channel to avoid lateral flow of irrigation water, and puddling treatments were imposed by passing a tractor-mounted puddler once (P_1), twice (P_2) or 4 times (P_4) in 8–10 cm standing water, followed by planking. The puddler was a rotavator used by the farmers to achieve a better puddle quality as compared to puddling with harrowing and planking in ponded water. All the cultivation tools were operated with a 60 bhp tractor. The depth of pre-puddling tillage was 20 cm, and that of puddling 10 cm across the treatments.

Twenty-five day old seedlings of rice (cv PR 106) were transplanted manually at 20 cm × 15 cm spacing (33 plants m^{-2}) during the first week of July. A uniform dose of 120 kg N, 26 kg P, 33 kg K and 5 kg Zn ha^{-1} was applied to rice by urea (46.4% N), single superphosphate (6.99% P), muriate of potash (49.8% K) and zinc sulphate (21% Zn). One-third of the N and all the P, K and Zn were applied before rice transplanting, and the remaining urea-N was top-dressed in two equal splits, 30 and 55 days after transplanting (DAT). For weed control in rice, Butachlor was mixed in sand and applied in standing water 4 DAT, followed by manual spot-weeding 35 DAT. This helped to maintain a weed-free condition in all treatments throughout the cropping seasons. After rice harvesting in the first week of November, the field was irrigated and a uniform tillage comprising 2 discings then 2 harrowings was carried out for seed bed preparation for wheat. Wheat (cv PBW 343) was sown in 20 cm rows, using 100 kg seed ha^{-1}. All plots received 120 kg N, 26 kg P and 33 kg K ha^{-1} through the above fertilizers. In wheat also, chemical weed control was applied using Bracket (sulfosulfuran + metsulfuran methyl) 35 days after seeding (DAS). Wheat was harvested in the third week of April each year.

Both crops were grown under assured irrigated conditions. In rice, continuous submergence was maintained for a period of 2 weeks after transplanting and thereafter irrigations with 7 cm standing water were applied at the appearance of hairline cracks on the soil surface. Wheat received 5 irrigations (5 cm each) at the key growth stages, viz., crown root initiation (21 DAS), tillering (45 DAS), jointing (60 DAS), ear emergence (85 DAS) and milking (105 DAS). At maturity, a 10 m × 10 m area of rice or wheat was harvested manually just aboveground level using sickles. After sun drying in the field the total biomass was weighed, threshed with a plot thresher, and grain weight was recorded. The aboveground biomass was removed from the plots and root/stubbles were disced into the soil.

2.3. Soil and plant analysis

Before the commencement of the experiment in 2000–2001, soil samples were collected from the 0–100 cm profile in 20 cm layers using a core sampler. The samples from each layer were mixed, bulked and sampled for chemical analysis. Post-rice soil samples (0–160 cm profile-depth at 20 cm intervals) were also drawn from all plots each year, following the same procedure. For the determination of nitrate-N content (Bremner and Keeney, 1965), the initial and post-rice soil samples were refrigerated immediately after collection from the plots and were extracted the next day. The soil bulk density (BD) before the start of the experiment was determined at 8–13, 28–33, 48–53, 68–73 and 88–93 cm depth using 5 cm high core sampler rings. After harvest of third rice crop, the BD was measured again at 5 cm interval up to a depth of 20 cm (i.e. 0–5, 5–10, 10–15 and 15–20 cm using the same 5 cm high rings), and then at 28–33, 48–53, 68–73 and 88–93 cm soil-depth as measured at the beginning of the experiment. The initial samples (0–100 cm profile-depth at 20 cm interval) were also analysed for organic carbon (Walkley and Black, 1934), pH and EC (1:2 soil water suspension), mechanical composition (Bouyoucos hydrometer method), cation exchange capacity, exchangeable Na^+, and available P, K, S and Zn content, following standard procedures (Page et al., 1982).

2.4. Root studies

In the last year (2002–2003), wheat root samples were collected at the maximum flowering stage, in 20 cm layers down to 100 cm, using a core sampler with 7.5 cm internal diameter. Four representative plants with 5–7 tillers were selected from each plot. The core sampler was placed over a plant in such a way that the plant was in the centre. These samples were soaked in water overnight and washed with a gentle spray of water over a 2-mm sieve. Washed roots were picked up by forceps and dried at 60 °C. Root mass density (RMD) was expressed as the weight of dry roots per unit volume of soil.

2.5. Other field measurements and computations

The puddle quality of soil was measured as puddling index (Sinha, 1964). For determining puddling index (PI), samples of the soil–water suspension were collected in 1 l measuring cylinders immediately after puddling. The volume of suspended sediments at zero (initial, I) and after 48 h (final, F) of settling was used to compute the PI as following:

$$PI = FI^{-1} \quad (1)$$

The amount of irrigation water applied to rice was measured using a Parshall flume with 15 cm throat width. The discharge of flume was in a free flow condition (0.6, Hb/Ha) during all irrigations. The amount of water applied at each irrigation, and the total irrigation water use (IWU, m^3) were calculated. The irrigation water productivity (IWP, kg m^{-3}) was computed as:

$$IWP = Y_R IWU^{-1} \quad (2)$$

where Y_R is the grain yield of rice (kg ha^{-1}).

To compare the treatments in terms of energy used for rice production, the specific energy requirement (SE_R, MJ kg^{-1}) was computed using the following formula:

$$SE_R = IE_R Y_R^{-1} \quad (3)$$

where IE_R is the input energy requirement (MJ ha^{-1}) for rice grain production and Y_R is the rice yield (kg ha^{-1}). The assumptions on input energy equivalents as proposed by Mittal et al. (1985) for different cultural operations in rice production (Table 2) were used for computing the IE_R.

Annual net returns (US dollars, USD ha^{-1}) of the RWS under different tillage options were also computed. The total cost of cultivation (TCC) of rice and wheat was calculated on the basis of different operations performed and materials used for raising the crops, including the cost of pre-puddling tillage and puddling intensity. For rice, the operations and inputs included were seed, nursery raising and its maintenance, transplanting, weeding and herbicide application, fertilizer application, irrigation, harvesting and threshing. For wheat, the operations and materials used were seed, seedbed preparation, sowing, fertilizer application, irrigation, herbicide application, harvesting and threshing. The costs (USD 1 = Indian rupees, Rs. 40) incurred were: USD 1 kg^{-1} of rice seed, USD 0.59 kg^{-1} of wheat seed, USD 0.26 kg^{-1} of N, USD 0.41 kg^{-1} of

Table 2
Assumptions on input energy equivalents (Mittal et al., 1985) used for computation of energy requirements for rice cultivation.

S. no.	Particulars	Unit	Energy equivalent (MJ)
1.	Human labour		
	a. Adult men	man-hour	1.96
	b. Adult women	woman-hour	1.57
2.	Tractor	hour	332
3.	Diesel	litre	56.31
4.	Electricity used	kWh	11.93
5.	Chemical fertilizers		
	a. Nitrogen (N)	kg	60.6
	b. Phosphorus (P)	kg	11.1
	c. Potassium (K)	kg	6.7
	d. Zinc sulphate	kg	20.9
6.	Herbicides	kg or litre	120
7.	Rice seed	kg	14.7

P, USD 0.22 kg^{-1} of K, USD 2.50 kg^{-1} of Zn, USD 3.50 l^{-1} of Butachlor, and USD 12.50 packet (16 g)$^{-1}$ of Bracket. Among the field operations, the cost of irrigation was taken as USD 1.25 h^{-1}, labour USD 2.50 unit^{-1} day^{-1}, discing USD 21.25 ha^{-1} operation^{-1}, harrowing USD 12.50 ha^{-1} operation^{-1}, puddling USD 18.75 ha^{-1} operation^{-1} and planking USD 6.25 ha^{-1} operation^{-1}.

Gross returns (GR) were calculated by multiplying grain and straw yield (t ha^{-1}) by price, i.e. USD 212.50 t^{-1} and 12.50 t^{-1} for rice grain and straw, and USD 250 t^{-1} and USD 50 t^{-1} for wheat grain and straw, respectively. Net returns of rice or wheat ($NR_{R\ or\ W}$) were calculated as:

$$NR_{R\ or\ W} = GR - TCC \tag{4}$$

The NR of rice were added to the NR of wheat in respective treatments to compute the cropping system's annual net return (ANR, USD ha^{-1}) as:

$$ANR = NR_R + NR_W \tag{5}$$

where NR_R and NR_W are the net returns (USD ha^{-1}) of rice and wheat, respectively.

2.6. Statistical analysis

For treatment comparisons in the field experiment, the '*F* test' was used following the procedure of split-plot design (Cochran and Cox, 1957). The LSD (least significant difference), was computed to determine statistically significant treatment differences in Tables 3–7 and Figs. 1–4.

In order to quantify the relationship of soil BD with wheat yield and that of BD with RMD, coefficients of correlation (*r*-value) were computed. Quadratic functions were fitted to express the relationship between PI and rice yield. The nitrate-N, RMD and BD data were subjected to log-transformation, prior to LSD computation.

3. Results

3.1. Rice yield

The grain yield of rice increased significantly ($p \leq 0.05$) with increasing levels of pre-puddling tillage up to T_4 (discing + 4 harrowings) and puddling intensity up to P_2 (2 passes of the puddler) each year (Table 3). The interaction between pre-puddling tillage and puddling intensity on yield was significant ($p \leq 0.05$) during the last year only, with T_4P_2 and T_4P_4 giving significantly higher yield than all other treatment combinations except T_2P_4.

Table 3
Effect of pre-puddling tillage and puddling intensity on the yield (t ha^{-1}) of rice on a sandy loam soil.

[a]Pre-puddling tillage	[a]Puddling intensity (passes of puddler)			Mean
	P_1	P_2	P_4	
2000–2001				
T_1	4.69	5.18	5.54	5.14
T_2	4.82	5.68	6.07	5.52
T_4	5.34	6.10	6.26	5.90
Mean	4.95	5.65	5.96	–
2001–2002				
T_1	3.66	4.52	4.75	4.31
T_2	4.21	4.92	5.22	4.78
T_4	4.54	5.18	5.30	5.01
Mean	4.14	4.87	5.09	–
2002–2003				
T_1	3.76	4.85	5.30	4.64
T_2	4.47	5.37	5.49	5.11
T_4	4.81	5.91	5.97	5.56
Mean	4.35	5.38	5.59	–

Year	Puddling intensity (P)	Pre-puddling tillage (T)	P × T
LSD ($p \leq 0.05$)			
2000–2001	0.42	0.37	NS
2001–2002	0.38	0.22	NS
2002–2003	0.38	0.32	0.48

NS, non-significant.
[a] For treatment details, see Section 2.2.

3.2. Puddling index

The puddling index (PI) ranged between 0.31 and 0.63 in the initial year, 0.32 and 0.65 in the second year and 0.35 and 0.71 in the terminal year (Table 4). In general, PI increased progressively with increasing levels of pre-puddling tillage or puddling intensity. Averaging across the pre-puddling tillage treatments, PI values were higher by 41, 42 and 34% under P_2, and by 68, 61 and 63% under P_4 compared with those under P_1 during 2000–2001, 2001–2002 and 2002–2003, respectively. Similarly, an increase in pre-puddling tillage from T_1 to T_4 raised the PI values by 36–38% in different years. Also, the PI values showed a general increase from the initial to the terminal year, in respective treatments.

Table 4
Puddling index in rice as affected by pre-puddling tillage and puddling intensity.

[a]Pre-puddling tillage	[a]Puddling intensity (passes of puddler)			Mean
	P_1	P_2	P_4	
2000–2001				
T_1	0.31	0.39	0.48	0.39
T_2	0.33	0.49	0.59	0.47
T_4	0.39	0.56	0.63	0.53
Mean	0.34	0.48	0.57	–
2001–2002				
T_1	0.32	0.41	0.48	0.40
T_2	0.36	0.52	0.60	0.49
T_4	0.41	0.59	0.65	0.55
Mean	0.36	0.51	0.58	–
2002–2003				
T_1	0.35	0.42	0.50	0.42
T_2	0.38	0.50	0.64	0.51
T_4	0.42	0.62	0.71	0.58
Mean	0.38	0.51	0.62	–

Year	Puddling intensity (P)	Pre-puddling tillage (T)	P × T
LSD ($p \leq 0.05$)			
2000–2001	0.032	0.017	NS
2001–2002	0.017	0.019	0.028
2002–2003	0.013	0.016	0.019

NS, not significant.
[a] For treatment details, see Section 2.2.

Table 5
Effect of pre-puddling tillage and puddling intensity on irrigation water use and irrigation water productivity in rice.

[a]Pre-puddling tillage	2000–2001 [a]Puddling intensity (passes of puddler)			Mean	2001–2002 [a]Puddling intensity (passes of puddler)			Mean	2002–2003 [a]Puddling intensity (passes of puddler)			Mean
	P_1	P_2	P_4		P_1	P_2	P_4		P_1	P_2	P_4	
Irrigation water use (100 m^3)												
T_1	105	104	99	102.7	123	119	113	118.3	132	121	118	123.7
T_2	105	98	89	97.4	122	116	106	114.7	130	117	111	119.3
T_4	102	90	79	90.3	118	108	94	106.7	126	107	103	112.0
Mean	104.0	97.3	89.0	–	121.0	114.3	104.3	–	129.3	115.0	110.7	–
Irrigation water productivity (kg m^{-3})												
T_1	0.45	0.50	0.56	0.50	0.30	0.38	0.42	0.37	0.29	0.40	0.45	0.38
T_2	0.46	0.58	0.68	0.57	0.35	0.42	0.49	0.42	0.34	0.46	0.50	0.43
T_4	0.52	0.68	0.79	0.66	0.39	0.48	0.56	0.48	0.38	0.55	0.58	0.51
Mean	0.48	0.59	0.68	–	0.34	0.43	0.49	–	0.34	0.47	0.51	–

Year	Irrigation water use (100 m^3) Puddling intensity (P)	Puddling intensity (T)	P × T	Irrigation water productivity (kg m^{-3}) Puddling intensity (P)	Puddling intensity (T)	P × T
LSD ($p \leq 0.05$)						
2000–2001	1.47	2.98	2.54	0.05	0.05	0.08
2001–2002	1.78	2.71	3.09	0.01	0.02	0.03
2002–2003	1.44	2.28	2.49	0.03	0.03	0.06

[a] For treatment details, see Section 2.2.

The pre-puddling tillage and puddling interaction was significant ($p \leq 0.05$) during 2001–2002 and 2002–2003, and treatment T_4P_4 had significantly greater PI than all other treatments, and was double that of T_1P_1 (Table 4).

3.3. Irrigation water input and water use efficiency in rice

There was a significant interaction between pre-puddling tillage and puddling intensity on irrigation water input each year (Table 5).

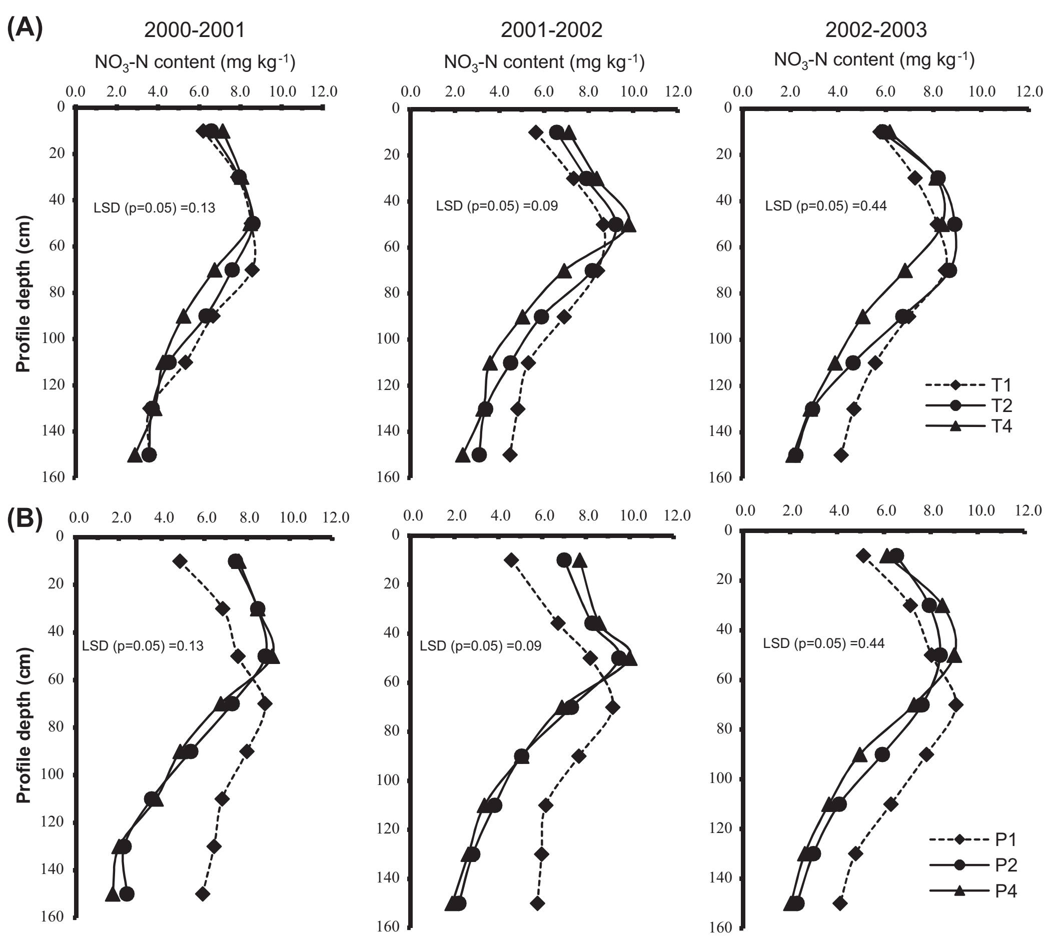

Fig. 1. Effect of (A) pre-puddling tillage and (B) puddling intensity on distribution of nitrate-N in soil profile after rice harvest. LSD ($p \leq 0.05$) values in (A and B) are for T × profile depth and P × profile depth interaction, respectively.

Table 6
Specific energy requirements ($MJ\,kg^{-1}$) in rice as influenced by number of pre-puddling tillage and puddling intensity.

[a]Pre-puddling tillage	[a]Puddling intensity (passes of puddler)			Mean
	P_1	P_2	P_4	
2000–2001				
T_1	4.24	4.04	4.11	4.13
T_2	4.20	3.73	3.78	3.89
T_4	3.92	3.57	3.75	3.74
Mean	4.11	3.76	3.86	–
2001–2002				
T_1	5.53	4.68	4.88	5.00
T_2	4.88	4.37	4.49	4.56
T_4	4.67	4.26	4.51	4.47
Mean	5.00	4.44	4.66	–
2002–2003				
T_1	5.58	4.31	4.29	4.68
T_2	4.76	3.94	4.17	4.26
T_4	4.56	3.68	3.93	4.02
Mean	4.92	3.96	4.12	–

Year	Puddling intensity (P)	Pre-puddling tillage (T)	P × T
LSD ($p \le 0.05$)			
2000–2001	0.21	0.21	0.30
2001–2002	0.28	0.28	0.38
2002–2003	0.24	0.24	0.37

NS, not significant.
[a] For treatment details, see Section 2.2.

The effect of pre-puddling tillage was greater at higher levels of puddling, and the effect of puddling was greater at higher levels of pre-puddling tillage. Irrigation water use was significantly lower in T_4P_4 than all other treatments each year.

The interactive effect of pre-puddling tillage and puddling on irrigation water productivity (IWP) was also significant ($p \le 0.05$) each year (Table 5). The IWP increased with increasing pre-puddling tillage or puddling intensity, and it was significantly higher in T_4P_4 than in all other treatments in the first two years, and than all treatments except T_4P_2 in the third year. Compared with T_1P_1, IWP values under T_4P_4 were higher by 78–103%. Like irrigation water use, the extent of increase in IWP due to increasing puddling intensity from P_1 to P_4 was greater (42–51%) than that (30–34%) due to increments in pre-puddling tillage levels.

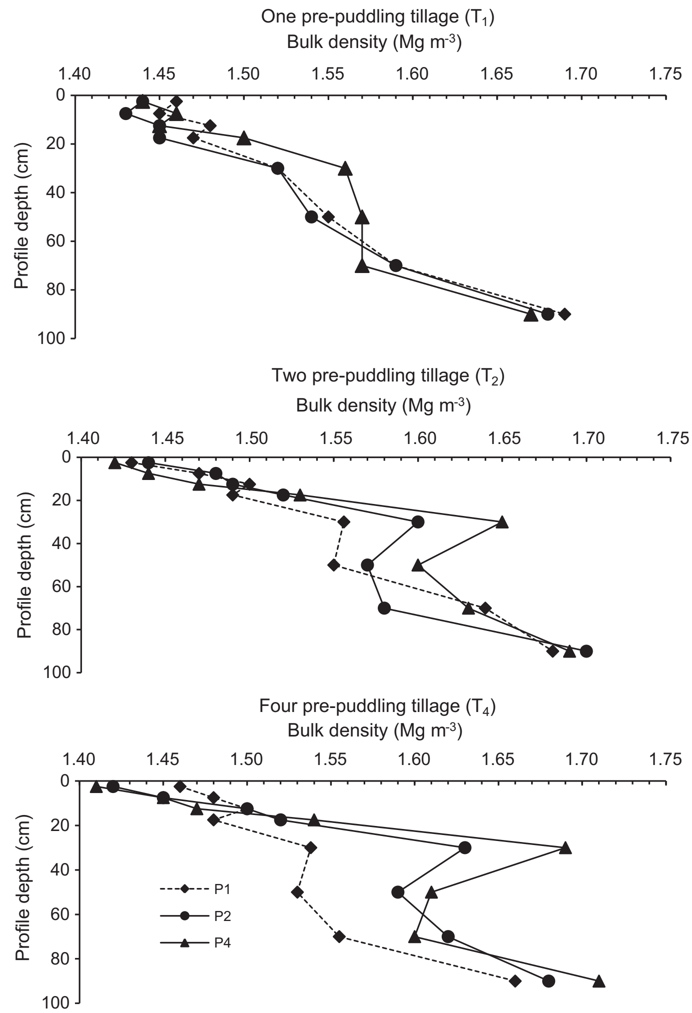

Fig. 2. Effect of dry tillage and pudding levels on the bulk density of soil profile after rice harvest. LSD ($p \le 0.05$) for P × T is 0.096, T × profile depth (D) or P × D is 0.104, and not significant for P × T × D.

Table 7
Effect of pre-puddling tillage and puddling intensity applied to rice on the yield ($t\,ha^{-1}$) of succeeding wheat.

[a]Pre-puddling tillage	[a]Puddling intensity (passes of puddler)			Mean
	P_1	P_2	P_4	
2000–2001				
T_1	4.47	4.38	4.51	4.45
T_2	4.70	4.40	4.46	4.52
T_4	4.68	4.63	4.51	4.61
Mean	4.62	4.47	4.49	–
2001–2002				
T_1	4.53	4.49	4.32	4.45
T_2	4.50	4.35	4.16	4.34
T_4	4.44	4.29	4.07	4.27
Mean	4.49	4.38	4.18	–
2002–2003				
T_1	4.76	4.58	4.29	4.54
T_2	4.64	4.43	4.01	4.36
T_4	4.59	4.31	3.72	4.24
Mean	4.66	4.44	4.04	–

Year	Puddling intensity (P)	Pre-puddling tillage (T)	P × T
LSD ($p \le 0.05$)			
2000–2001	NS	NS	NS
2001–2002	0.17	NS	NS
2002–2003	0.18	0.18	0.23

NS, not significant.
[a] For treatment details, see Section 2.2.

3.4. Nitrate-N distribution in soil profile

In the post-rice soil samples, the effect of pre-puddling tillage on nitrate-N concentration was generally inconsistent up to 60 cm profile-depth, but the nitrate-N beyond this depth was significantly greater under T_1 than that under T_4 in the second and terminal years (Fig. 1). On the other hand, nitrate-N concentration in P_1 treatments was highest at 60–80 cm profile-depth, whereas in P_2 or P_4 it was highest at 40–60 cm soil profile depth. The strikingly higher nitrate-N concentrations at depths beyond 60 cm in the least-puddled treatments indicate greater leaching losses. An increase in puddling intensity resulted in greater retention of nitrate-N in the effective root zone (0–20 cm for rice and 0–45 cm for wheat), and the effect was magnified with increasing pre-puddling tillage operations.

When compared with the initial nitrate-N concentration ($6.6\,mg\,kg^{-1}$) of the top soil (0–20 cm), treatments receiving 2 or 4 passes of puddler showed higher NO_3-N by $0.4–1.1\,mg\,kg^{-1}$ at rice harvest in the terminal year. On the other hand, raising the rice crop with 1 pass of the puddler depleted the nitrate-N concentration by $2.0\,mg\,kg^{-1}$.

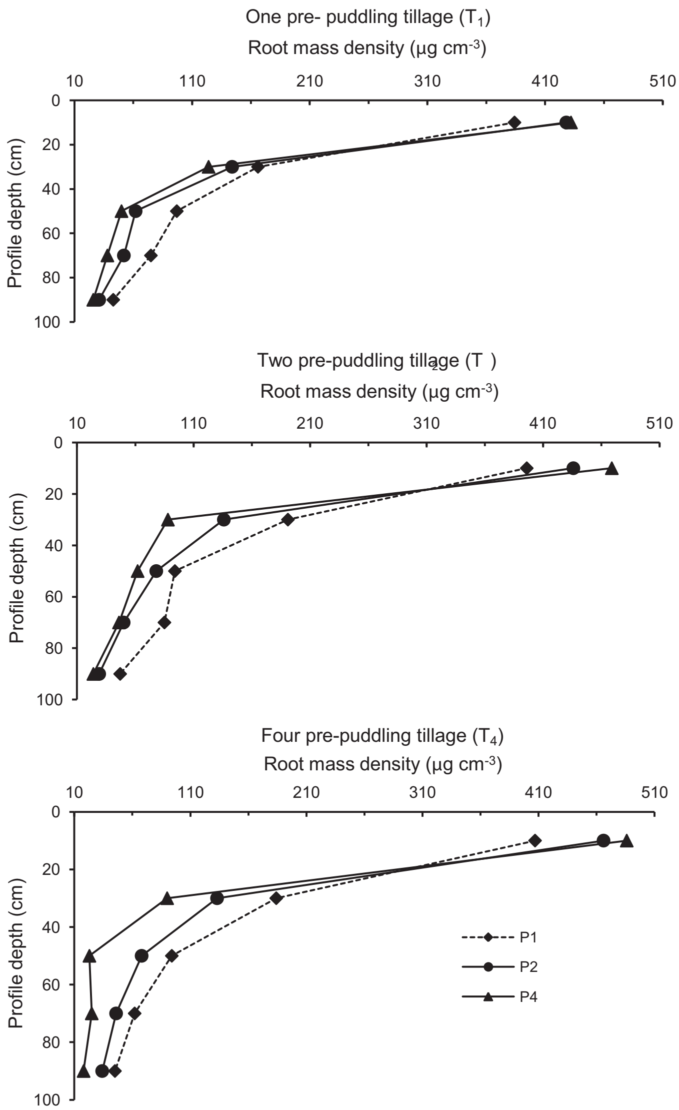

Fig. 3. Effect of pre-puddling tillage and pudding intensity on wheat root mass density in different soil profile during 2002–2003. LSD ($p \leq 0.05$) for P × T is 42.0, for T × profile depth (D) or P × D is 58.1, and for P × T × D is 70.4.

3.5. Specific energy requirement in rice

The SE_R for rice grain production decreased with increasing pre-puddling tillage and with puddling intensity up to T_2 or P_2 (Table 6). The P × T interaction was significant each year. SE_R in T_2P_2, T_4P_2 and T_4P_4 was significantly lower than all other treatment combinations in each year. Treatments T_2P_2, T_4P_2 and T_4P_4, however, did not differ significantly among themselves.

3.6. Wheat yield

The tillage treatments applied to rice did not influence wheat grain yield in the initial year, i.e. 2000–2001 (Table 7). In the second year, there was a significant decline in wheat yield as puddling intensity increased from 1 to 4 passes. In the third year, there was a significant interaction between pre-puddling tillage and puddling intensity. There was no effect of pre-puddling tillage at low levels of puddling intensity, but at higher levels of puddling intensity there was a significant decline in wheat yield as the number of pre-puddling tillage increased. The yield of T_4P_4 was significantly lower than that in all other treatments.

3.7. Soil bulk density

The bulk density (BD) of soil at the start of the experiment increased progressively with profile depth, with a value of 1.49 Mg m^{-3} at 8–13 cm to 1.67 Mg m^{-3} at 88–93 cm depth (Table 1), however, the density from 13 to 28 cm was not measured, so it is unknown whether there was a hard pan. Given that history of puddling at this site, it is likely that there was a hard pan which our initial sampling did not detect. In the post-rice soil (2002–2003), measurement of BD at 5 cm interval up to a depth of 20 cm revealed that intensive puddling resulted in a decrease in the BD of top soil layers (0–5, 5–10 and 10–15 cm) and a subsequent increase in the BD at 15–20 cm depth across the pre-puddling tillage treatments, although the differences were not significant. There was a consistent trend for higher BD at 28–33 cm depth with increasing puddling intensity, and the magnitude of increase was greater in treatments with more pre-puddling tillage (Fig. 2). For instance, soil BD at 28–33 cm depth under T_1 was 1.54, 1.55 and 1.57 Mg m^{-3} with P_1, P_2 and P_4, respectively. The corresponding BD values at T_4 were 1.54, 1.63 and 1.69 Mg m^{-3}, respectively. There was a significant interaction between pre-puddling tillage and puddling, and the soil BD under T_4P_4 was significantly greater than T_4P_1 indicating clearly that puddling-induced sub-soil compaction in RWS increases with the amount of pre-puddling tillage.

3.8. Root mass density in wheat

An increase in soil profile depth brought a large decrease in the root mass density (RMD) of wheat irrespective of treatments, and an average of 41% of the total wheat root mass was concentrated in the 0–20 cm profile depth (Fig. 3). The interaction between pre-puddling tillage, puddling intensity and profile depth was significant, and the RMD under T_4P_4 was significantly smaller than T_4P_2 and T_4P_1 in 20–40 and 40–60 cm profile depths. The RMD in 0–20 cm was increased ($p \leq 0.05$) by 11% and 17% under P_2 and P_4, respectively compared to P_1. The reverse was, however, true for sub-surface profile layers, where P_4 caused a significant lowering of RMD by 34–53% compared with P_1 to a depth of 20–100 cm across the pre-puddling treatments. Pre-puddling tillage operations did not affect RMD significantly at 0–20 cm profile depth.

3.9. Economic returns

Annual net returns (ANR) for the rice–wheat system ranged between USD 1439 and 1721 ha^{-1} during 2000–2001, USD 1225 and 1408 ha^{-1} during 2001–2002, and between USD 1323 and 1580 ha^{-1} during 2002–2003 (Fig. 4). In general, the effect of puddling intensity on ANR was more pronounced than that of pre-puddling tillage, more so in the second and the terminal year. Averaged across the pre-puddling tillage levels, treatment P_2 resulted in an additional ANR of USD 86 ha^{-1} over P_1, while a further increase in puddling intensity gave a smaller additional increase of USD 39 ha^{-1} in 2000–2001. In subsequent years, particularly the terminal year, ANR under intensive puddling (P_4) was similar to ANR of P_1, and smaller by about USD 113 ha^{-1} compared with those under P_2. The P × T interaction was significant during 2001–2002 and 2002–2003, when treatment T_4P_2 gave the maximum ANR.

4. Discussion

4.1. Increased puddling reduced percolation and N leaching

The necessity of puddling (wet tillage) in transplanted rice is often debated. Whereas a large number of reports indicate its advantage in terms of increase in rice yields (Ghildyal, 1978; Pandey et al., 1992; Timsina and Connor, 2001), some other reports have

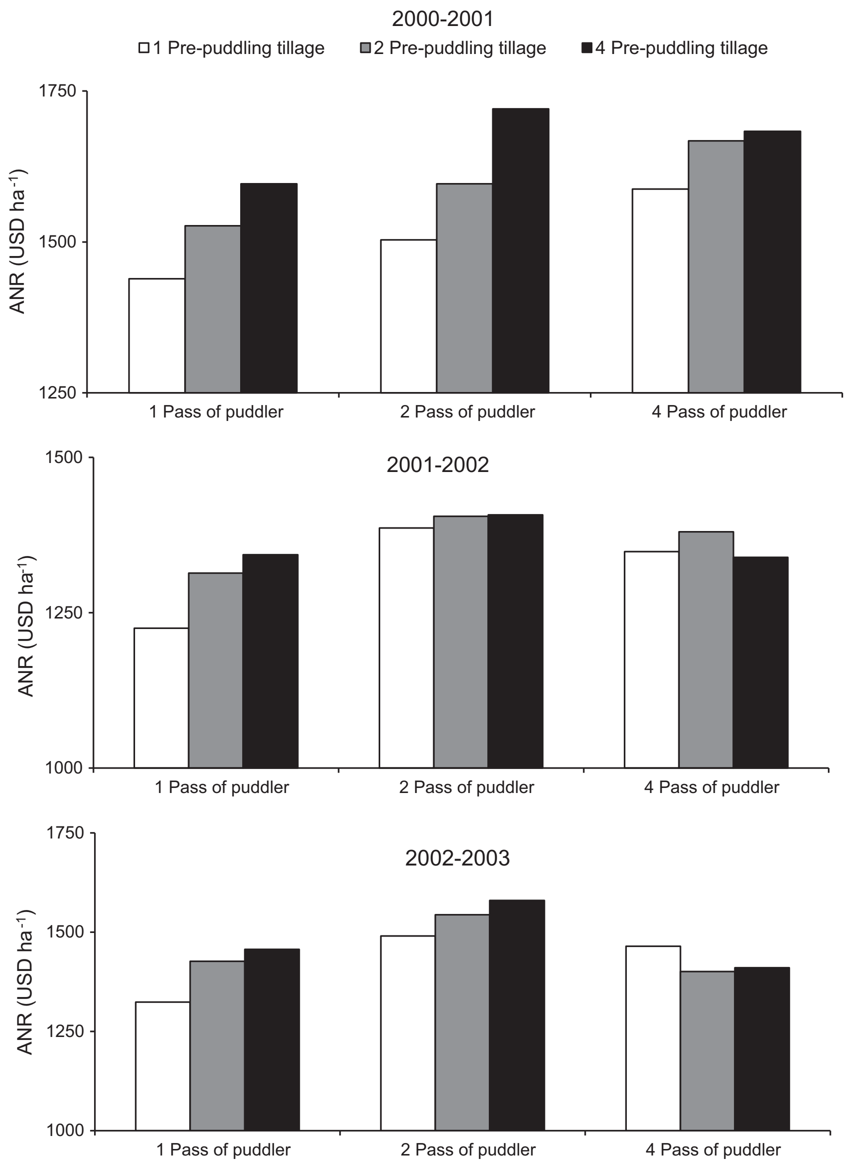

Fig. 4. Effect of pre-puddling tillage and puddling intensity on annual net returns (ANR) of RWCS. LSD ($p \leq 0.05$) values for T × P are not significant for 2000–2001, 106 for 2001–2002, and 154 for 2002–2003.

shown that puddling may not be necessary as it did not affect rice yields (Scheltema, 1974; Utomo et al., 1985). We are of the opinion that the impact of pre-puddling tillage or puddling should essentially be evaluated in a holistic manner taking into account the growing conditions (particularly soil type, climate and site history), annual productivity of the system, economic returns, and nutrient and water use efficiency, along with the changes in soil physical properties. Puddling may not be very useful on clayey soils, but would be necessary on permeable soils, where water table remains well below the soil surface and rainfall is inadequate (Kirchhof et al., 2000). It implies that in the coarse-textured soils of northwest India – the high productivity zone of RWS, where rainfall is only half of the annual PET (Velayutham et al., 1999) and receding groundwater table is one of the major concerns of researchers and planners (Yadav et al., 2000), the practice of puddling is something beyond a cultural habit for the rice farmers.

In the present study, rice yield increased significantly with increasing levels of pre-puddling tillage and puddling intensity, with T_4P_2 and T_4P_4 out-yielding all other tillage combinations (Table 3). These tillage operations appeared to benefit rice yield on the coarse-textured soil of the experimental field mainly through an improvement in puddle quality, i.e. increased puddling index and consequent reduction in percolation losses, and also by minimizing downward movement of nitrate-N beyond root zone. In fact, relatively greater churning of the soil owing to higher levels of pre-puddling tillage followed by puddling and planking resulted in more dispersion of soil particles, which ultimately led to a higher puddling index (Table 4). Findings of this study revealed a positive relationship between rice yield and puddling index (PI) corroborating well with earlier work on sandy loam soils of Punjab (Kukal and Sidhu, 2004), wherein pre-puddling tillage and puddling intensity had significant positive effect on PI.

Percolation loss of water is one of the major factors responsible for low irrigation water use efficiency in irrigated rice (Kukal and Aggarwal, 2002). Although the effect of different dry and wet tillage operations on the changes in percolation loss was not measured in this study, an increase in PI values with increasing T and/or P levels indicated enhanced aggregate destruction. The higher the aggregate destruction the higher is the reduction in water transmission in the pores, leading to significant reduction in percolation loss of water (Sur et al., 1981; Arora et al., 2006). These changes in soil physical properties could explain the saving of irrigation water and increase in IWP, and also the decrease in nitrate-N leaching at higher T and/or P levels (Fig. 1). In the present study, the IWP under T_4P_4 was greater by 78–103% compared with T_1P_1 (Table 5). Some other studies, however, reported that puddling does not necessarily reduce the total water input in rice despite reducing percolation losses (Tuong et al., 1996; Tabbal et al., 2002).

Restricted water movement to the lower profile under intensive puddling could have helped minimizing the nitrate-N leaching losses in the present study. Thus, greater retention of nitrate-N in upper profile, as was observed under the intensively puddled plots (Fig. 1), and consequently greater N availability to rice could be the reasons for the higher rice yields in these treatments over the less-puddled ones. Smaller RMD at lower profile depths under P_4 revealed that the lower values of nitrate-N at these depths were possibly not associated with N uptake by roots, and the distribution of nitrate-N in soil profile actually indicated variable effect of treatments on nitrate-N leaching. Measurement of other nutrients like sulphur and potassium that are also prone to leaching losses (Yadav et al., 2000) would have further supported this hypothesis. Unfortunately in the majority of the experiments evaluating tillage and crop establishment options in RWS, nutrient retention in the root zone and nutrient distribution in soil profile generally go unnoticed. Measuring nutrient availability in the tillage experiments would, however, not only add to our understanding of the RWS, but may also help resolving some of the existing controversies pertaining to the utility of puddling. This is of particular significance in the IGP, where widespread multi-nutrient deficiencies in the soils are considered to be one of the major constraints for sustaining high productivity (Tiwari et al., 2006; Dwivedi and Dwivedi, 2007).

4.2. Effect of pre-puddling tillage and puddling on wheat yields

Contrary to all positive effects of puddling in rice, puddling intensity beyond 2 passes of the puddler decreased significantly ($p \leq 0.05$) the grain yield of wheat in the second and last years. The BD and soil penetration resistance of excessively puddled soils increases upon drying of the soil after rice harvest (Sharma and De-Datta, 1985), leading to a soil condition that is less favourable for establishment of wheat. The decline in wheat yields over time under intensive puddling are explainable in the light of changes in soil BD and root mass density (RMD). Increased sub-surface soil compaction as indicated by increased BD particularly at 28–33 cm profile depth (Fig. 2) under intensive puddling resulted in restricted growth and penetration of wheat roots. Impaired soil structure of puddled and compacted sub-soil in rice–wheat system is the major impediment for establishment and growth of wheat (Gajri et al., 1992; Oussible et al., 1992; Unger and Kaspar, 1994; Aggarwal et al., 1995; Hobbs et al., 2002). In the present case, a highly significant ($p \leq 0.01$) negative correlation between wheat RMD (20–40 cm) and BD at 28–33 cm depth ($r = -0.76$), and between wheat RMD (40–60 cm) and BD at 48–53 cm depth ($r = -0.65$) was observed (Table 8). Oussible et al. (1992) also found a negative correlation ($r = -0.93$) between root length density of wheat and soil mechanical impedance. In our study, RMD of wheat in 0–20 cm profile measured during 2002–2003 under P_4 was greater by 17% compared with that under P_1, whereas the RMD under P_4 was drastically reduced in sub-surface soil layers. The wheat root system, on the other hand, was relatively better-distributed throughout soil profile under P_1 treatment. High BD at 28–33 cm soil depth under P_4 apparently restricted the downward penetration of wheat roots, causing their confinement to top soil layer. The adverse effect of sub-soil compaction on plant root growth has also been reported elsewhere (Unger and Kaspar, 1994; Jorajuria et al., 1997; Ishaq et al., 2001).

Table 8
Relationship of bulk density with root mass density and grain yield of wheat ($n = 36$).

Parameters	Soil depth (cm)	Correlation coefficient (r)
Bulk density vs. root mass density[a]	0–20[b]	0.08 NS
	28–33	−0.76**
	48–53	−0.65**
	68–73	0.15 NS
	88–93	−0.40*
Bulk density vs. wheat grain yield	0–20[b]	0.26 NS
	28–33	−0.79**
	48–53	−0.89**
	68–73	−0.13 NS
	88–93	−0.42**

NS, not significant ($p \geq 0.05$).
[a] Root mass density measured at 0–20, 20–40, 40–60, 60–80 and 80–100 cm depth.
[b] Bulk density averaged over 0–5, 5–10, 10–15 and 15–20 cm depth.
* Significant ($p \leq 0.05$).
** Significant ($p \leq 0.01$).

Earlier experiments on similar soils at Modipuram revealed that a deep and extensive root system of wheat helps to capture N and P from the deeper profile and ensures an increase in wheat productivity (Dwivedi et al., 2003; Singh et al., 2005; Singh and Dwivedi, 2006). Although the wheat yield was not supposed to be influenced adversely due to nutrient stress *per se* as the fertilizers were applied at soil test-based recommended rate, the relatively greater wheat yields under less-puddled treatments could also be explained in the light of greater contact between the absorbing root surface and available nutrient pool under an extensive root system (Tisdale et al., 1993). A decline in wheat yield due to restricted root growth in intensively puddled treatments ultimately decreased total annual (rice + wheat) grain productivity with the passage of time, which in the last year was smaller by 0.43 t ha^{-1} under T_4P_4 as compared to that (10.22 t ha^{-1}) under T_2P_2.

4.3. Alternative crop establishment options for RWS in the IGP

In recent past, there has been a lot of interest in alternative rice establishment options, like direct seeding under unpuddled or zero-till conditions, which are not so detrimental to soil physical properties for upland crops grown in rotation with rice, and which involve less water and energy input (Bhushan et al., 2007; Malik and Yadav, 2008). Although these tillage and crop establishment practices were not evaluated in the present case, results of the studies undertaken elsewhere in the IGP are of interest to the researchers as also to the rice–wheat growers. The results of the farmer-participatory trials in northwest India suggested a small increase or 10% decline in the yield of direct-seeded rice (DSR) compared with puddled-transplanted rice (PTR), and around 20% reduction in irrigation time or water use (Gupta et al., 2003). On the other hand, experiments in northwest India revealed input water savings of 35–57% for DSR sown on unpuddled soil compared with continuously flooded PTR (Singh et al., 2002; Sharma et al., 2002), although rice yields in these experiments were also reduced by similar amounts due to iron or zinc deficiencies and increased incidence of nematodes (Humphreys et al., 2005).

Farmers in this part of the IGP may be keen to grow DSR under zero-till or unpuddled conditions provided yields are close to those with PTR (Malik and Yadav, 2008). In fact, enumerating a number of water-saving technologies for the RWS, Humphreys et al. (2005) cautioned that moving away from the conventional ponded to aerobic rice culture on the highly permeable soils, such as those that predominate in the Trans- and Upper Gangetic Plain zones of the IGP, may bring a suite of new problems including weeds, micronutrient deficiencies, pests and diseases affecting long-term crop productivity and input use efficiency. Effective management of these problems would actually decide the success and adoption of the alternative rice establishment options, particularly DSR (Malik and Yadav, 2008). In PTR, however, preparatory tillage operations (involving puddling and pre-puddling tillage) need to be essentially optimized taking in to account yields of all crops, profitability and energy consumption.

4.4. Tillage combinations vis-à-vis energy requirements and financial return

Explaining the treatment effect in terms of SE_R further underlined the need for optimizing T and P combinations. The values of SE_R were lowest (3.57–4.26 MJ kg^{-1}) under T_4P_2, which were in fact statistically similar to T_2P_2 (3.73–4.37 MJ kg^{-1}) during all years of experimentation. The increase in tillage (dry or wet) beyond T_2P_2 was thus not advantageous with energy efficiency viewpoint. As the researchers rarely compared tillage combinations in terms of SE_R in RWS particularly in the IGP, it is difficult to discuss our findings vis-à-vis other studies. Nonetheless, our results indicated T_2P_2 as the optimum tillage combination to maximize grain yields and profits with minimum specific energy requirement, because increasing tillage levels beyond T_2P_2 did not bring a significant change in these parameters. On the other hand, T_4P_2 could be considered optimum where irrigation water economy is the major concern. Tripathi (1992) reviewing the tillage requirements for RWS concluded that 1–2 harrowings under dry condition followed by 2 puddlings along with planking were generally optimum on clay loam to silty clay loam soils. In economic terms also, T_2P_2 produced additional net returns of USD 134 ha^{-1} compared with those under T_4P_4 during the last year of the experiment. At present, reports on profit comparisons under different tillage options are scarce, although the same need to be invariably included as the profitability could be the major decisive factor for adoption of a tillage combination. We also recommend that the energy requirement protocols could be used effectively in the future studies to evaluate the tillage options for RWS.

5. Conclusion

Increasing both pre-puddling tillage and puddling intensity played a significant role in increasing irrigation water saving, reducing nitrate-N leaching and increasing rice yield. However, this comes at increasing energy and economic cost, and at the expense of wheat yield as tillage intensity increases. Optimization of pre-puddling tillage and puddling is, therefore, essential in rice–wheat systems to increase yield of the total rice–wheat system while saving energy and increasing profitability. The present study suggested 2 pre-puddling tillage operations followed by 2 passes of the puddler as the optimum tillage combination for rice on the coarse-textured (sandy loam) soils to achieve high productivity and greater annual economic returns from RWS. This study also underlined the significance of optimizing the preparatory tillage for RWS under different soil and climatic conditions. Multi-location (preferably on-farm) studies with a uniform set of observations would be of great relevance in this regard.

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