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Soil physical responses to novel rice cultural practices in the rice–wheat system: Comparative evidence from a swelling soil in Nepal

A.J. McDonald [a,*], S.J. Riha [a], J.M. Duxbury [b], T.S. Steenhuis [c], J.G. Lauren [b]

[a] *Department of Earth and Atmospheric Sciences, Cornell University, 1121 Bradfield Hall, Ithaca, NY 14853, USA*
[b] *Department of Crop and Soil Sciences, Cornell University, Ithaca, NY 14853, USA*
[c] *Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA*

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Abstract

Soil puddling in advance of rice (*Oryza sativa* L.) transplanting disperses surface aggregates and generates compaction at depth. As a management scheme for rice, puddling is typically considered advantageous for maximizing resource availability and yield. However, some experimental findings suggest a conflict between edaphic conditions created by this establishment technique and the performance of subsequent non-rice crops like wheat (*Triticum aestivum* L.). At a site in the mid-hills region of Nepal on a silt loam soil with vertic characteristics, we compared the impact of six rice tillage (surface tillage—T_1, shank subsoiler—T_2, shank subsoiler + moldboard plough—T_3) and establishment (soil puddling + transplanting—TPR, direct seeding—DSR) combinations on soil physical properties over two cycles of the rice–wheat rotation. For the rice season, 0–20 cm saturated hydraulic conductivity (K_{sat}) in the DSR plots was 2.6 and 4.3 times higher than their TPR counterparts in the first (Y_1) and second (Y_2) years, respectively (TPR-Y_1 = 93 mm day^{-1}, DSR-Y_1 = 241 mm day^{-1}, TPR-Y_2 = 133 mm day^{-1}, DSR-Y_2 = 582 mm day^{-1}), whereas tillage method did not significantly influence K_{sat} in this soil layer. The impact of rice establishment method was reflected in higher TPR bulk densities in the 5–10 (DSR = 1.19 g cm^{-3}, TPR = 1.24 g cm^{-3}) and 10–15 cm (DSR = 1.24 g cm^{-3}, TPR = 1.29 g cm^{-3}) depth increments in the wet season. Although none of the treatments significantly influenced the position or thickness of the plough sole, penetration resistance profiles suggest that vertical fractures with reduced soil strength were created within the pan region by deep tillage (T_2 and T_3), although these features were not associated with higher hydraulic conductivities from 20 to 50 cm. As the soils dried at the end of the rice season, crack propagation in the deep tilled plots (T_2 and T_3) was more pervasive. During the wheat season, comparable bulk density profiles and soil moisture retention characteristics across the treatments suggest that many of the edaphic changes induced by contrasting rice tillage and establishment practices did not persist in the self-mulching, vertic soils at our site. Conversely, significant

* Corresponding author. Tel.: +1 607 279 6310; fax: +1 607 255 2106.
E-mail address: ajm9@cornell.edu (A.J. McDonald).

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increases in K_{sat} among the DSR plots from Y_1 to Y_2 (Y_1 = 241 mm day^{-1}, Y_2 = 582 mm day^{-1}) imply a temporal element to soil structural regeneration with adoption of direct seeding.

Keywords: Soil puddling; Direct seeding; Deep tillage; Hydraulic conductivity; Plot-scale permeameter; Bulk density; Penetration resistance; Soil cracking; Soil-water-holding capacity

1. Introduction

In Nepal, traditional paddy systems compose over 90% of the regional rice production (Upadhyaya, 1996). One month prior to the anticipated arrival of intense monsoon rains, rice is seeded in small nurseries. With the onset of heavy rains in early-June, land soaking of the main fields commences. Rainwater, often supplemented with irrigation, saturates the soil and reduces bond strength within and between aggregates. These inundated fields are subsequently worked with manual and/or mechanical implements (i.e. puddled) to remove emerged weeds, create water-conserving soil compaction, and soften the surface horizon. Three-week-old seedlings are then transplanted into the main fields.

As a management scheme for rice, soil puddling in advance of transplanting (i.e. paddy rice) is typically considered advantageous for achieving resource-use efficiency, yield stability, and high productivity, primarily by retaining water and nutrient resources while reducing weed pressure (e.g. DeDatta and Barker, 1978; Naklang et al., 1996; Surendra et al., 2001). Evidence from several rice-based crop rotations, however, suggests a putative conflict between soil conditions created by puddling and performance of subsequent non-rice crops (e.g. Meelu et al., 1979; Utomo et al., 1985; Sharma and DeDatta, 1985). Poor stand establishment due to low germination rates has been linked to inadequate seed–soil contact in cloddy, post-paddy soils (Rahmianna et al., 2000; Cook et al., 1995; Ringrose Voase et al., 2000). Data from rice-based systems in the Punjab (Sur et al., 1981; Aggarwal et al., 1995; Ishaq et al., 2001; Kukal and Aggarwal, 2003b) and from Australia (Kirchhof and So, 1996) suggest that subsurface compaction can amplify drought probability for subsequent dry season crops by limiting root development at depth. On the other hand, conflicts between puddled rice and succeeding crops are not consistently observed. Hobbs et al. (2002) report a 10% yield advantage for wheat on a silt loam soil following non-puddled rice, whereas no benefit was observed on a sandy loam. Kirchhof et al. (2000) note that puddling reduced soybean (*Glycine max* L.) yield but did not influence mungbean (*Vigna radiata* L.) or peanut (*Aracis hypogaea* L.) productivity. Other experiments document substantial soil physical changes from puddling that did not cause growth penalties for several cereal and legume crops (e.g. Humphreys et al., 1996; Singh et al., 1996; Tranggono and Djoyowasito, 1996). Much of this response inconsistency is likely related to the site-specific nature of soil puddling.

The physical manipulation of saturated soil (i.e. puddling) disperses surface aggregates and compresses the subsoil. A portion of the clay fraction from the surface horizon is deposited as clay-skins along pore surfaces at the top fringe of the compacted layer (Koenings, 1950; Grant, 1964; Hobbs et al., 1994). These processes reduce macropore volume in the upper portion of the soil profile while increasing bulk density in the compacted, anthropogenic horizon that is alternately termed the plough sole or tillage pan (Ghildyal, 1978; Sharma and DeDatta, 1985; Adachi, 1990; Aggarwal et al., 1995; Bhagat et al., 1999). Physical transformations induced by wet cultivation are influenced by intrinsic soil characteristics, paddy frequency within the overall field history, plus the intensity and type of tillage employed (Singh and Ladha, 2004). Silty loam soils can be more susceptible to prominent physical changes from puddling than well-structured clays or disaggregated sands (Hobbs et al., 1994; Kirchhof and So, 1996). Hobbs et al. (1994) report that deep ploughing prior to puddling shifts the pan to deeper in the soil profile, while other studies note a decrease in pan bulk density with similar deep tillage methods (Akhtar and Quereshi, 1999). Aggarwal et al. (1995) and Kukal and Aggarwal (2003a) found that pan bulk density increased with puddling intensity, while Kirchhof et al. (2000)

document a positive relationship between tillage intensity and depth to the start of the tillage pan.

The implications of soil puddling for crop growth and resource utilization can be extensive. Puddling typically lowers soil hydraulic conductivity and diminishes the water required to maintain flooding (Koenings, 1963; Sanchez, 1973; DeDatta and Kerim, 1974; Naklang et al., 1996). Alteration of the pore size distribution by puddling can increase plant available water (i.e. $\theta_{PAW} = \theta_{FC} - \theta_{PWP}$) within the root zone (Jamison, 1953; IRRI, 1975). After drying, the structure of puddled soils is usually massive, which limits the effectiveness – and increases the cost – of tillage for seedbed preparation (So and Woodhead, 1987). When crop-specific strength thresholds are exceeded, penetration resistance within the plough sole limits deep root development (Barley et al., 1965; Hasegawa et al., 1985; Pagliai and Painuli, 1988; Oussible et al., 1992). Loss of macropore volume reduces air-filled porosity at matric potentials below saturation, compromising gas exchange with the soil surface (Hobbs et al., 1994). On balance these changes are considered favorable for rice and detrimental to subsequent dry season crops. In Nepal, average productivity from rice is nearly 1 mt ha^{-1} higher than that achieved for wheat (FAO, 2002). Hence, the challenge is to devise management schemes that maintain rice yield and yield stability while improving soil physical conditions for ensuing crops.

Deep tillage following rice can improve wheat productivity (Sur et al., 1981; Prihar et al., 1985; Hobbs et al., 1994), presumably by fracturing the plough sole and thereby promoting deep root development. Nevertheless, the timely completion of cultural operations between rice harvest and wheat planting is a significant management challenge. Some evidence suggests that deep tillage must be conducted with multiple passes to adequately breech the tillage pan (Fujisaka et al., 1994). With the massive structure commonly encountered in many soil types after paddy rice, extensive tillage can be expensive and wasteful in terms of soil moisture losses to evaporation (Gomez and Zandstra, 1976; Zandstra, 1982). Moreover, there is a limited range of water contents that are sufficiently dry to permit field access for tillage yet moist enough to allow seed germination and emergence (Rahmianna et al., 2000). Late planting is the principal limitation to wheat productivity in many areas of South Asia (Hobbs et al., 1994; Ahmed and Meisner, 1996). At best, post-rice deep tillage is a partial solution for physical constraints to wheat performance because it does not alleviate poor tilth in the surface horizon.

Temporal and efficacy limitations to tillage following rice suggest that practical management alternatives must address the problem of soil physical quality for subsequent crops by devising new methods for rice cultivation. For most regions that utilize the rice–wheat cropping pattern, there is general consensus that wheat yields will increase if puddling operations for rice establishment are reduced or eliminated (Fujisaka et al., 1994; Hobbs et al., 1994; Timsina and Connor, 2001); deep tillage for rice also offers scope for remediating existing plough soles or for fostering their formation at deeper depths in the soil profile when coupled with puddling (Hobbs et al., 1994). However, the enduring influence these rice management alternatives is difficult to predict in agroecosystems with marked climatic seasonality, high activity clays, and non-rigid soil structure. All these conditions occur in the Kathmandu Valley and create immense temporal variation of several fundamental soil properties. Hydric land units are commonly flooded from June onward during the monsoon season and reduced forms of iron impart the soil with a bluish-gray cast. Concurrently, bonding forces weaken and clay interlayers hydrate. At our site, the resulting volume expansion increases soil porosity from 50% to ca. 70%. By October, drained and oxidized conditions prevail and large desiccation cracks propagate from the soil surface. Most significantly, clay interlayers contract and the solid matrix experiences a substantial increase in bulk density.

Over two cycles of the rice–wheat rotation, this experiment evaluated soil physical properties for two types of rice establishment practices (direct seeding, transplanting w/puddling) coupled with either conventional (i.e. shallow) tillage or two different methods of deep tillage (i.e. chisel, moldboard + chisel). Two deep tillage regimes were tested to determine if the soil inversion aspect of moldboard ploughing enhanced pan disruption from chiseling. We anticipated that direct seeding, especially in tandem with deep tillage, would result in lower bulk densities and elevated hydraulic conductivities in the plough sole relative to the transplanted plots and that these soil physical differences would persist through the wheat season. We also hypothesized that combining deep tillage with transplanted rice (TPR) would shift plough sole position to deeper in the soil profile without significantly modifying the hydraulic conductivity of the most limiting soil layer for floodwater transmission.

2. Materials and methods

2.1. Site and treatment description

This experiment was conducted over two cycles of the rice–wheat rotation (Y_1: May 1999–May 2000; Y_2: May 2000–May 2001) at the Nepal Agricultural Research Council (NARC) experimental farm in Khumultar, Lalipur District, Nepal (27°N, 85°E) on a parcel that has been cropped with this system for more than 20 years. Situated in the bottomlands of the Kathmandu Valley (1350 masl), the area has a geomorphology typical of mountain valleys found in the mid-hills physiographic region of Nepal. Thick lacustrine sediments deposited during the last glacial period mantle the valley floor. Texturally, soils of the valley range from clay loam to silty loam and are classified primarily as Haplaquepts or Haplaquents with near-neutral pH and exhibit significant vertic characteristics that derive from the dominance of 2:1 clays in the fine fraction. At our site, silt loams predominate (ca. 22% sand, 58% silt, 20% clay). Kathmandu receives 1197 mm of precipitation per year compared to 1212 mm of potential evapotranspiration (PET). Although balanced on an annual basis, the ratio of precipitation to PET demonstrates conspicuous seasonality with the summer monsoon months (June–September) having a ratio in excess of 1, May and October near unity values, and November to April substantially in deficit. This experiment straddled the central and near edge positions of a broad terrace, which are common landscape features in the valley bottomlands of Nepal. Cropping system elements evaluated in this balanced factorial trial were tillage (surface—T_1, shank subsoiler—T_2, shank subsoiler + moldboard plow—T_3) and establishment method (transplanting with soil puddling (TPR) and direct seeding without soil puddling (DSR)), which were tested in two adjacent landscape positions (terrace edge *upland* and central terrace *lowland*). Within each landscape position, the six tillage and establishment combinations were replicated three times for a total of 36 plots. Plot dimensions were 3.7 m × 7.5 m (27.75 m^2), with 0.5 m bunds isolating all plots. This experiment followed a semi-randomized strip (tillage)–split (landscape)–split (establishment) design.

2.2. Plot preparation

Tillage operations for rice were initiated soon after wheat harvest in mid-May, prior to the arrival of intense monsoon rains when the soil was moist but below field capacity. First, 24 plots were tilled to an approximate depth of 50 cm with a single-shank chisel implement (T_2, subsoiler tillage) at 40-cm intervals. Then, soil in 12 of the chiseled plots was inverted to a depth of 30 cm with a moldboard plough (T_3, subsoiler + moldboard tillage). Lastly, all 36 plots were shallow tilled with a rotary plough to a depth of 10 cm (T_1, conventional tillage). Conducting water balance studies on small, adjacent rice plots can pose challenges to the elucidation of treatment-based differences because of lateral water movement (e.g. Bouman et al., 1994). To mitigate the lack of hydrological independence between neighboring areas, each plot perimeter was surrounded by 50 cm (height and width) bunds constructed with tightly compacted soil. Plastic barriers were installed on the boundaries of each plot to a depth of 30 cm to further minimize edge interactions. Prior to wheat sowing, all plots were tilled to 10 cm with a single pass from a rotary plough.

2.3. Rice establishment and management

In the direct seeded (DSR) plots, rice was line-sown into moist but unsaturated soil. Preceding transplanting in the remaining plots (TPR), soil inundated with a combination of rainfall and surface irrigation (ca. 10 cm standing water) was puddled by human traffic and manipulation with hoes and spades. This method of field preparation is the norm for paddy rice cultivation in the mid-hills region. After establishment, all plots were irrigated on mornings when standing water did not exceed the bund height and water supplies were available. Irrigation was accomplished through small breeches in the bunds that allow entry of floodwater from a channel adjacent to the experimental area. Bunds were re-sealed when ca.

10 cm of standing water was achieved. Some evidence suggests that field traffic from weeding operations in saturated soils can generate significant soil compaction (Wickham and Singh, 1978; Wopereis et al., 1992). To eliminate weeding as a potential source of soil physical change in the DSR treatments, these plots were drained to field capacity prior to weeding.

2.4. Soil water dynamics

Piezometers and time domain reflectometry (TDR) were utilized to study subsurface water dynamics. During the rice season, piezometer tubes (5 cm diameter, PVC) were installed to monitor pressure head at two depths (20 and 50 cm) on a daily basis (see Wopereis et al., 1994), while a tube-access TDR system (TRIME-FM, IMKO Corporation) tracked volumetric moisture contents twice weekly to a depth of 63 cm in both the rice and wheat crop. A sloping gauge was employed to measure standing surface water in the rice plots. Potential evapotranspiration rates were estimated on-site with an atmometer (MEASURET, Aquaterr Instruments Corporation), and daily precipitation recorded with a manual raingauge accurate to 0.2 mm (Tenite Corporation).

Percolation refers to vertical water loss in a system, whereas seepage quantifies lateral movement. In practice, it is extremely difficult to separate these terms and they are usually combined in a single composite parameter (i.e. SP) (Wickham and Singh, 1978; Bouman et al., 1994). SP rates (i.e. cm day^{-1}) can be determined by calculating the residual of the readily measured or estimate components of the soil water balance. In a system with no irrigation or overbund flow, SP (positive values indicate loss) can be calculated with:

$$\mathrm{SP} = \Delta W + R - \mathrm{ET} \tag{1}$$

where ΔW is the change in ponded water depth (Start$_{\text{depth}}$ − Finish$_{\text{depth}}$, cm), R the rainfall (cm), and ET (cm) the water lost to the atmosphere as evaporation or transpiration. Each calculation is adjusted to express SP on a daily basis (i.e. cm day^{-1}).

In this study, changes in water depth (ΔW) were monitored at approximately 24-h intervals. Rainfall and PET were recorded for the same period. Since there was a free water surface in the paddy for the duration of these measurements, we estimated that actual ET approached the potential rate and, therefore, did not employ a crop coefficient to modify actual ET with crop growth stage.

2.5. Soil physical properties

2.5.1. Saturated hydraulic conductivity

During the rice season when the soil was flooded, SP rate calculations were used in conjunction with simultaneous measurements of standing water depth and pressure head (Ψ_p) at 20 cm (Y_1 and Y_2) and 50 cm (Y_2) to estimate saturated hydraulic conductivity (K_{sat}). This method is equivalent to constructing a falling-head permeameter on a plot scale. Most conceptual renderings of paddy rice systems envision a perched water table above a low-permeability plough sole with unsaturated subsoil at depth. In these cases, it is common to consider the plough sole – subsoil interface at atmospheric pressure ($\Psi_m = 0$) for the purpose of hydraulic conductivity calculations. When there was standing water at the soil surface at our site, the entire profile was saturated in both DSR and TPR plots; hence, piezometric surface values were indispensable for determining K_{sat}.

In saturated soils, gravitational and positive pressure head potentials govern the movement of water. It is convenient to express these potentials as energy per unit weight, which simplifies to the height of a water column or distance between two points, length units in either case (e.g. cm). The gravitational potential (Ψ_z) is the difference in elevation between a given location and a reference location, with points above the reference assigned positive values. The pressure head (Ψ_p) at a specific depth is equivalent to water rise in a piezometric tube inserted to that depth. At the soil surface, the pressure head (Ψ_p) is approximated by the standing water depth and was assumed to be the average flood depth over the measurement period. The gravitational potential is set equal to the distance between the soil surface and the reference point at depth (e.g. for 0–20 K_{sat}, $\Psi_z = 20$ cm). The total hydraulic head (Ψ_{total}) comprises both terms:

$$\Psi_{\text{total}}\text{Surface} = \text{Average flood depth}, \Psi_p\ (\text{cm}) + \text{Distance from reference}, \Psi_z\ (\text{cm}) \tag{2}$$

At depth, the total hydraulic head (Ψ_{total} Depth) is equivalent to the vertical rise of the piezometric surface (Ψ_p) and has no gravitational potential as it serves as the reference elevation ($\Psi_z = 0$).

For saturated rice soils, Darcy's equation can be inverted in the following form to calculate K_{sat}:

$$K_{sat} = (qz/(\Psi_{total}\text{Surface} - \Psi_{total}\text{Depth})) \quad (3)$$

where q (cm day^{-1}) is paddy water loss (i.e. SP), Ψ_{total}Surface is a combination of the pressure and gravitational potential energy (cm) at the soil surface, Ψ_{total}Depth is the pressure potential (cm) at a specific soil depth, and z (cm) is the linear distance between the two points. We used this form of Darcy's equation with averaged total pressure values for the measurement timeframe to calculate K_{sat}. Point-based methods (e.g. vacuum water evacuation from augered holes) can be used in saturated soils, but these techniques are destructive and can alter plot hydrology and therefore were avoided. Moreover, our method had the additional advantage of providing an integrated conductivity measure for the entire plot region.

2.5.2. Bulk density

To account for seasonal differences, bulk density samples were collected before soil shrinkage near the end of the rice season (Y_1) and again at the termination of the wheat season (Y_2) when the soils were near wilting point. We used a double-cylinder, hammer-driven core sampler (AMS Instruments) to acquire soil samples from the top 45 cm of the soil profile in 5 cm increments. During the wheat seasons, we avoided sampling in obviously cracked regions of the soil and the bulk density estimates reflect the solid matrix, exclusive of the macro-crack volume. Dry mass values were obtained by holding the samples in an oven at 105 °C for 3 days.

2.5.3. Penetration resistance

Penetrometers register the force required to insert an object into the soil. Penetration resistance is an important characteristic for plant growth; several studies have negatively correlated root development with increasing resistance (e.g. Hasegawa et al., 1985; Martino and Shaykewich, 1994; Busscher et al., 2000). Caution must be exercised when interpreting resistance measurements because values change with soil moisture status. Moreover, roots tend to develop along pre-existing cracks or biopores and resistance measurements often fail to capture soil differences in these types of features. Nevertheless, field-based penetration measurements are a useful tool for identifying zones of increased strength relative to other layers in the soil profile (e.g. the plough sole). We used a spring penetrometer to determine unconfined compressive strength (kg cm^{-2}). One pit per plot was excavated to a depth of 60 cm near the end of the rice season in Y_1. On each pit face, 10 depth-wise transects were conducted. Moisture content was uniform (near field capacity) for all soil layers. Results were averaged for each tillage-establishment combination to discern the uniformity, position, and maximum resistance of the plough sole region.

2.5.4. Soil cracking

Desiccation cracks are common features of the shrink-swell lacustrine soils in the Kathmandu Valley, especially between the massive structural units formed when rice soils dry. These cracks are a major conduit for water infiltration and may also provide access channels for deep root development that would otherwise be limited due to the presence of a restrictive horizon. Soil dyeing methods are frequently used to investigate crack propagation from the soil surface, but these methods require substantial excavation and plot disruption (Wopereis et al., 1994). To minimize disturbance, we utilized a flexible (<1 mm) ruler to assess cracking depth following rice harvest (Y_1 and Y_2) when the soils were below field capacity. The ruler was inserted to the crack terminus at 10 randomly selected locations in each plot.

2.6. Statistical analysis

Point and time-series data were analyzed with mixed-effects analysis of variance (ANOVA) models. Saturated conductivity and SP data were log-transformed prior to analysis to achieve normal distribution. Main experimental effects were tested for significance at the 95% confidence level ($p = 0.05$) along with two- and three-way interaction terms. Separation of treatment means was accomplished with a least-squares procedure using the Tukey–Kramer adjustment, also at $p = 0.05$. Linear and nonlinear regression techniques were used for trend investiga-

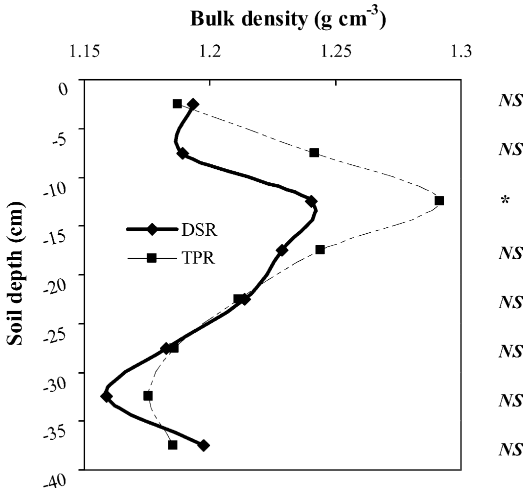

Fig. 1. Rice season (Y_1) soil bulk density profiles for direct seeding (DSR) and transplanted (TPR) establishment methods. The asterisk denotes statistically significance at $p < 0.05$.

tion. Analysis was performed with SAS, v.8 and Minitab, v13.1 statistical software packages.

3. Results

3.1. Rice season soil bulk density and saturated hydraulic conductivity

Bulk densities in the puddled treatments (TPR) were notably higher than the direct seeded plots (DSR) in the 5–10 and 10–15 cm depth increments (Fig. 1). Rice establishment method was a statistically significant factor in the 10–15 cm region (TPR = 1.29 g cm^{-3}, DSR = 1.24 g cm^{-3}) where, among the TPR plots, bulk densities attained their highest value within the surface 50 cm of the soil. Values for each tillage-establishment treatment combination are given in Table 1. In tandem with direct seeding, the soil inversion element of moldboard tillage (T_3) significantly reduced compaction from 10 to 15 cm (ca. 0.05 g cm^{-3}). We did not discern an impact of subsoiler tillage (T_2) on bulk density in the top 15 cm of soil when coupled with either establishment method. However, this tillage regime tended to reduce bulk density at 15–20 cm in both DSR and TPR plots, though the differences were not significant; the shallow till treatments (T_1) exhibited the highest mean densities for the 15–20 cm zone. Bulk densities were very similar for all tillage and establishment practices below 20 cm depth.

Table 1
Soil bulk density (g cm^{-3}) during the rice (Y_1) and wheat (Y_2) seasons

Bulk density	Conventional till (T_1)		Subsoiler till (T_2)		Subsoiler + moldboard till (T_3)	
	DSR	TPR	DSR	TPR	DSR	TPR
Rice season						
0–5 cm	1.17 a	1.16 a	1.21 a	1.20 a	1.19 a	1.21 a
5–10 cm	1.19 ab	1.24 ab	1.20 ab	1.24 ab	1.18 a	1.25 b
10–15 cm	1.26 ab	1.30 a	1.25 ab	1.28 ab	1.21 b	1.30 a
15–20 cm	1.26 a	1.25 a	1.22 a	1.23 a	1.21 a	1.25 a
20–25 cm	1.24 a	1.18 a	1.18 a	1.20 a	1.24 a	1.23 a
25–30 cm	1.19 a	1.20 a	1.17 a	1.16 a	1.20 a	1.19 a
Wheat season						
0–5 cm	1.19 a	1.14 a	1.21 a	1.15 a	1.17 a	1.17 a
5–10 cm	1.27 a	1.23 a	1.30 a	1.28 a	1.27 a	1.30 a
10–15 cm	1.32 a	1.33 a	1.32 a	1.35 a	1.35 a	1.31 a
15–20 cm	1.30 a	1.28 a	1.22 a	1.27 a	1.29 a	1.27 a
20–25 cm	1.28 a	1.25 a	1.23 a	1.20 a	1.24 a	1.25 a
25–30 cm	1.28 a	1.25 a	1.29 a	1.27 a	1.29 a	1.29 a

Different letters indicate statistical significance ($p < 0.05$) for row-wise comparisons.

The influence of rice establishment method on soil structural properties was also apparent in the saturated hydraulic conductivity (K_{sat}) values for the surface 20 cm of the soil. In the Y_1 and Y_2 rice seasons, K_{sat} in the DSR treatments was significantly ($p < 0.01$) higher than in the TPR treatments (Fig. 2). TPR

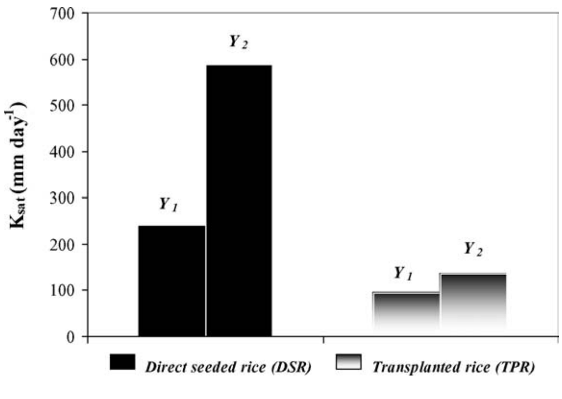

Fig. 2. Mean rice season saturated hydraulic conductivity (K_{sat}, mm day^{-1}) for the top 20 cm of the soil as influenced by rice establishment practice in Y_1 and Y_2.

establishment generated similar conductivities in both years (Y_1 = 93 mm day^{-1}, Y_2 = 133 mm day^{-1}), 1), whereas mean values in the direct seeded plots (i.e. DSR) more than doubled from the first to the second year (Y_1 = 241 mm day^{-1}, Y_2 = 582 mm day^{-1}), likely reflecting the cumulative impact of two rice seasons without soil puddling. Differences in conditioning events such as desiccation cracking may have also contributed to the second year increase in DSR hydraulic conductivity. In Y_2 when piezometers were installed at 50 cm, K_{sat} values for the 20–50 cm depth increment were not influenced by rice establishment method (experiment-wide mean = 224 mm day^{-1}). Neither tillage regime nor tillage interactions with rice establishment method appreciably affected K_{sat} in the top 50 cm of the soil (Fig. 3).

Desiccation cracking along with other transient phenomena such as pore clogging from microbial activity can induce shifts in hydraulic conductance within a single rice season. Temporal trends in K_{sat} were not evident during the summer monsoon (data not shown); while water supplies were sufficient to periodically achieve standing water in the field, conductivities for both years of the experiment were essentially constant in time, suggesting that fundamental post-establishment changes to the soil's hydraulic properties did not occur within the rice season.

3.2. Plough sole characteristics

At rice harvest in Y_1, we characterized the average maximum penetration resistance within the region of increased soil strength (i.e. the plough sole) and also the proportion of the vertical sampling planes that lacked plough sole formation (i.e. areas of structural weakness). These methods assess comparative soil strength within the most restrictive region of the soil for root growth and the horizontal continuity of the pan layer, respectively. Significant differences for maximum penetration resistance within areas identified as the plough sole were not evident. There were, however, noteworthy changes to plough sole uniformity among the treatment combinations (Fig. 4). When coupled with DSR, subsoiler tillage (T_2 and T_3) eliminated the plough sole in approximately 30% of the vertical sampling transects with or without

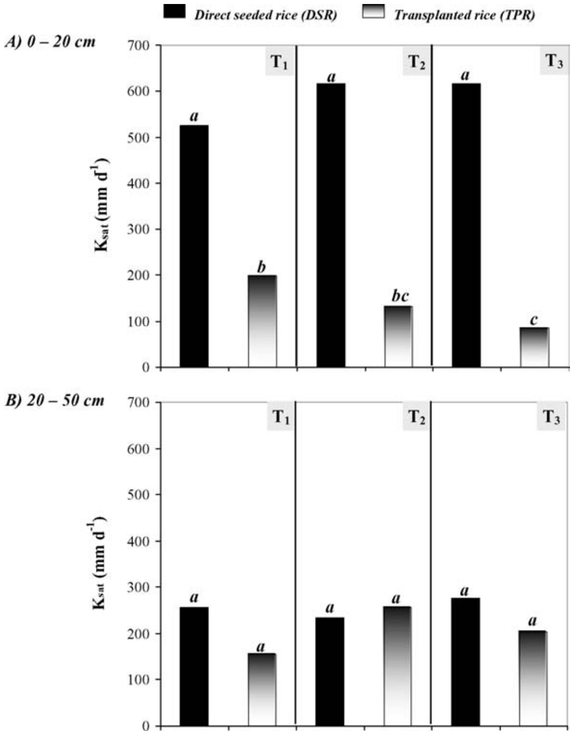

Fig. 3. Mean rice season saturated hydraulic conductivity (K_{sat}, mm day^{-1}) for 0–20 cm (A) and 20–50 cm (B) soil depths as a function of rice tillage (T_1 = shallow till, T_2 = subsoiler till, T_3 = subsoiler + moldboard till) and establishment practice (DSR, TPR) in Y_2. Different letters signify statistical significance at $p < 0.05$.

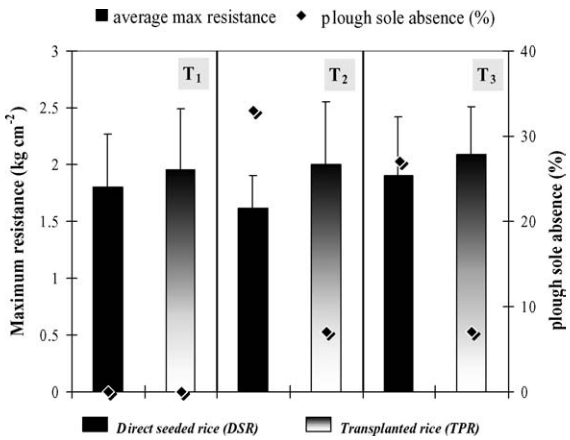

Fig. 4. Maximum penetration resistance within the plough sole (bar series, first y-axis) and the percentage of vertical sampling planes where the plough sole was absent (diamond series, second y-axis) – rice season (Y_1).

moldboard plowing. In tandem with soil puddling and rice transplanting, this fraction dropped below 10% for both deep tillage regimes. In contrast, among the shallow till plots (T_1) the plough sole was present in all sampling locations irrespective of rice establishment method. From the penetration resistance transects, the depth-wise position and extent of the plough sole was documented. The subsoiler + moldboard plough tillage treatments (T_3) caused a slight downward displacement of the plough sole, though the thickness of the region was unaffected. On average, the plough sole occurred between 16 and 28 cm depth in the T_3 plots, whereas placement for the other tillage practices were 2 cm shallower, but differences were not statistically significant.

3.3. Post-rice cracking

When the rice crop was active in both years of the experiment, small cracks periodically developed at the soil surface during low rainfall periods but never propagated beyond ca. 2–3 cm. Near crop maturity, major cracks formed at regular intervals at the soil surface as the monsoon rains diminished; cracking depth was assessed immediately following rice harvest. In Y_1, tillage method was a significant ($p = 0.02$) source of variation for crack propagation depth (Table 2). Deep till plots had deeper crack propagation ($T_2 = 23.1$ cm, $T_3 = 24.7$ cm) than shallow tilled plots ($T_1 = 18.2$ cm). Also, plots in the drier, upland setting tended to crack to a greater depth than their lowland counterparts, but this development was not statistically significant ($p = 0.065$) in our data set.

Table 2
Cracking depth (cm from soil surface) after rice harvest

	Conventional till (T_1)		Subsoiler till (T_2)		Subsoiler + moldboard till (T_3)	
	DSR	TPR	DSR	TPR	DSR	TPR
Y_1						
Lowland	15.4 a	17.2 a	18.2 a	21.2 a	20.9 a	24.5 a
Upland	21.1 a	19.0 a	26.4 b	26.4 b	26.8 b	26.4 b
Y_2						
Lowland	20.1 a	19.8 a	21.0 a	23.2 a	24.5 a	24.5 a
Upland	17.0 a	19.7 ab	21.9 ab	21.7 ab	19.0 ab	24.5 b

Different letters indicate statistical significance ($p < 0.05$) for row-wise comparisons.

Similar trends with tillage method were evident in Y_2, though the differences were not significant. Rice establishment practice did not influence cracking behavior in either year.

3.4. Wheat season soil physical characteristics

The observed trends in rice season saturated conductivity and bulk density suggest that rice cultural practices influence the pore size distribution and total porosity of the solum. By extension, these changes may affect the moisture retention characteristics of the soil profile during the wheat season. Volumetric water content data were utilized to make an in situ determination of profile water contents at presumptive field capacity (θ_{fc}) and near wilting point (θ_{pwp}) during the wheat season. Since saturated conductivity differences between DSR and TPR were larger in the second year, measurements from this period were evaluated. The same analysis was repeated for each tillage and tillage-establishment combination.

Field capacity (FC), operationally defined as the water content of a previously saturated soil after 2 days of unimpeded drainage, occurs when unsaturated hydraulic conductivity drops to levels that limit rapid water efflux. Water contents for FC were estimated 2 days following full irrigation during the wheat season. Parity in the water content data between the DSR and TPR plots both at the soil surface and at depth suggests that rice establishment method did not significantly modify the moisture retention properties of the soil at field capacity. Except the surface horizons that were depleted by evapotranspiration, volumetric moisture content values were approximately 47% at FC. Parity in moisture contents across treatments was also noted at the end to the wheat season after a long period without rain or irrigation (i.e. θ_{pwp}). Near the soil surface (0–36 cm) where root activities were highest, water content values were consistently around 16% in all plots. Hence plant available water – the volume of water stored in the soil between FC and PWP – was unmodified by rice season tillage practice, establishment method, or their interactions.

As a consequence of sustained drainage between the terminus of the primary monsoon rains and initiation of wheat planting, the soils at our site undergo pronounced physical and chemical transformations. The most evident of these are the appearance

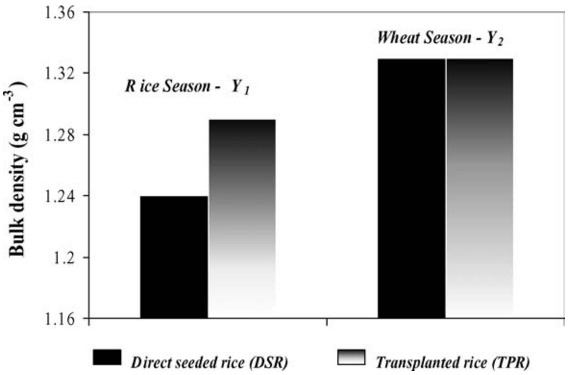

Fig. 5. Soil bulk density from 10 to 15 cm for the rice (Y_1) and wheat (Y_2) seasons as influenced by rice establishment (DSR, TPR) method.

of prominent desiccation cracks that form at regular intervals at the soil surface and the return of brownish hues indicative of fully oxidized conditions. Less visually apparent are the related increases in soil bulk density as hydrated clay interlayers contract with soil drying. Aside from the surface 5 cm that was essentially unchanged from the wet season, we observed a substantial increase in BD for the wheat season in all depth increments to 30 cm (5–15 cm: 0.06 g cm^{-3}; 15–25 cm: 0.03 g cm^{-3}; 25–30 cm: 0.09 g cm^{-3}). Cultural practice influences on BD evident during the rice season did not persist into the wheat season. The region from 10 to 15 cm had the highest bulk density, and there were no apparent differences between the establishment treatments (Fig. 5).

Qualitative assessment of soil surface condition at rice harvest indicated that soil structure in the DSR plots was less massive and, consequently, possessing better tilth than the TPR plots. Wheat tillage operations eliminated any visual differences in structure at the soil surface.

4. Discussion

Saturated hydraulic conductivity differences in the surface soil layers (i.e. 0–20 cm) clearly demonstrate that the process of puddling and transplanting for rice establishment alters soil physical properties during the monsoon season at our site (TPR-Y_1 = 93 mm day^{-1}, DSR-Y_1 = 241 mm day^{-1}, TPR-Y_2 = 135 mm day^{-1}, DSR-Y_2 = 582 mm day^{-1}). Edaphic modification from rice establishment technique was also reflected in higher TPR bulk densities in the 5–10 (DSR = 1.19 g cm^{-3}, TPR = 1.24 g cm^{-3}) and 10–15 cm (DSR = 1.24 g cm^{-3}, TPR = 1.29 g cm^{-3}) depth increments relative to the direct seeded plots. Evidence from other rice-based systems documents similar changes to hydraulic properties and bulk density with DSR adoption (e.g. Sanchez, 1973; Bhagat et al., 1999). In contrast, tillage regime had no impact on K_{sat} from 0 to 20 cm and differences in hydraulic conductance were not observed in the subsoil (20–50 cm) as a function of establishment method, tillage, or their interactions. Since major differences were documented in floodwater export rates between DSR and TPR plots (not presented), these data suggest that near-surface (5–15 cm) soil physical properties largely govern the retention of floodwater at our site.

Interestingly, the starting depth of the region identified from penetration resistance criteria as the plough sole was approximately 15 cm, directly below the zone of maximum TPR bulk density (i.e. 10–15 cm); there was no apparent influence of rice establishment practice on maximum penetration resistance within the plough sole. In contrast to the observations reported by Hobbs et al. (1994), deep tillage (T_2 and T_3) did not change pan position or thickness. Subsoil tillage did, however, create vertical fracture zones of low soil strength within the plough sole region; these findings are consistent with results from other cropping systems (e.g. Busscher et al., 2000). Nevertheless, plough sole continuity did not modify hydraulic conductivity in the top 50 cm of the soil profile. These findings suggest that simple, field-based soil assessments of the plough sole horizon are inadequate for inferring comparative hydraulic behavior among different rice cultural practices.

Despite substantial changes to bulk density and hydraulic conductance from soil puddling, it is not clear that management-induced physical modifications persist through the wheat season and carryover to subsequent rice crops. Equivalent wheat season bulk densities (Y_2 averages: TPR = 1.33 g cm^{-3}, DSR = 1.33 g cm^{-3}) from 10 to 15 cm imply they do not. Unlike Jamison (1953) and IRRI (1975), we found no evidence that rice cultural practices influence wheat season water retention properties in the soil. On the other hand, dissimilar cracking depths among the tillage treatments (Y_1 averages: T_I = 18.2 cm, T_2 and T_3 = 23.9 cm) will likely remain through wheat harvest until clay interlayers re-hydrate and the soil swells with the arrival of inundating monsoon rains. Additionally, saturated hydraulic conductivity in the DSR plots was substantially higher in the second year of the experiment (Y_1 = 241 mm day^{-1}, Y_2 = 582 mm day^{-1}), suggesting a cumulative influence of direct seeding on soil structural regeneration. Aggarwal et al. (1995) report that benefits from low-intensity puddling did not accrue to the wheat crop until the second year.

Patterns of wheat establishment, resource capture, and productivity were not affected by rice cultural practices in either year of this experiment (see McDonald et al., in preparation). These results contrast with positive yield responses reported by Aggarwal et al. (1995), Bajpai and Tripathi (2000), and Hobbs et al. (2002) for other locations in South Asia, but are consistent with findings from other regions where substantial soil physical changes from puddling were yield neutral for several cereal and legume crops on fine textured soils (e.g. Tranggono and Djoyowasito, 1996; Singh et al., 1996; Humphreys et al., 1996). Despite the generation of significant soil physical differences in the rice season, the absence of wheat growth responses to no-puddle and deep tillage practices for rice are not surprising given the uniformity observed in soil water retention and bulk density characteristics across all treatments in the dry season.

5. Conclusions

The need for recurrent puddling to maximize floodwater retention is apparent at this site, even with its long-term history of transplanted rice cultivation. Saturated conductivity values from 0 to 20 cm in the first wet season more than doubled with adoption of no-puddle rice establishment methods. As the soils shift from dominantly anaerobic to aerobic with the cessation of the monsoon rains, the processes of soil shrinkage, cracking, and re-aggregation apparently overwhelmed soil physical changes created by puddled rice cultivation. This finding is consistent with experimental results on other soils with vertic, shrink-swell characteristics (Moormann and van Breeman, 1978). Hydraulic conductivity appears insensitive to deep tillage practices preceding rice establishment. Hence, deep tillage may prove useful for creating zones of low penetration resistance for root development without compromising the water-conserving elements of soil puddling.

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