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PJBS

ISSN 1028-8880

Pakistan
Journal of Biological Sciences

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Pakistan Journal of Biological Sciences, 2 (4): 1245-1251, 1999 *Research Article*

Soil Hydraulic Properties and Rice Root Development as Influenced by Tillage

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Abstract

Tillers number and paddy yield increased by 30 percent with deep tillage + puddling over deep tillage without puddling and conventional tillage. Root length and mass in the soil profile remained un-affected by the treatments but the depth wise distribution changed as in AB (12-20 cm) horizon both the parameters were greater in case of deep tilled plots than the conventional tillage plots. Bulk density (ρ_b) of 10 to 20 cm depth decreased due to the deep tillage. Saturated hydraulic conductivity of the 0-20 cm layer, which includes Ap (0-12 cm) and AB (12-20 cm) horizons, was 3.0 mm h^{-1} in the deep tillage, 1.0 mm h^{-1} in deep tillage + puddling and 0.1 mm h^{-1} in the conventional tillage. Puddling after deep tillage reduced K_{fs}. The deep tilled soil retained more water at -10 kPa and less at -1500 kPa metric potential suggesting a greater available water capacity than with the conventional tillage. Towards the end of the rice season, conventional tillage plots had greater total residual soil water than the moldboard plots suggesting that deep tillage can reduce the turn around time between rice harvesting and wheat planting.

Introduction

Land preparation practice for irrigated rice in Pakistan includes a combination of shallow dry cultivation and wet tillage operations (puddling). Puddling causes deterioration of soil structure (Prihar *et al.*, 1985; Zunpu, 1992) and decreases infiltration rate (Saroch and Thakur, 1991; Humphreys *et al.*, 1992; Wopereis *et al.*, 1992). Long-term puddling also forms a pan below the puddled layer due to physical compaction as indicated by an increase in soil bulk density and penetrometer resistance (Rahman, 1991). The decrease in hydraulic conductivity due to puddling was greater in sandy loam and clay loam soils than in clay soil (Mambani *et al.*, 1989). Thus, the benefits of puddling as well as the dynamics of pan formation are dependent on soil type (Lal, 1985; Mambani *et al.*, 1989; De Datta and Kerim, 1974).

Reduction in percolation due to puddling generally improves water use efficiency in rice. However, percolation of 5 to 20 mm water per day is necessary to regulate soil temperature and to leach away toxins produced by anaerobic decomposition of organic matter (Lal, 1985; Prihar *et al.*, 1985). Continuous puddling changes the soil water-relations for the upland crops following rice. Tillage of a puddled field causes the soil to break into hard, medium to large clods reducing sod-seed contact (Prihar *et al.*, 1985). Water transmission and root penetration characteristics of the rice soil are controlled by the high density layer in the puddled field. Consequently, the restricted drainage of the puddled layer increases the delay before the soil is dry enough to be cultivated for the wheat crop. Also, wheat roots were observed to spread horizontally below 10 cm depth after hitting a compact layer of >1.70 g cm^{-3} bulk density.

The relatively row bulk density resulting from tillage operations (Kar *et al.*, 1986) and incorporation of organic manures (Boparai *et al.*, 1992; Mbagwu, 1992) favors rice root growth and penetration. Enhanced root length and rooting density due to deep plowing produce higher grain yield than the restricted root growth in shallow tillage treatments (Sood and Acharya, 1991). In the rice-wheat system a complete soil inversion using a moldboard plow was shown to be a better tillage practice in terms of tillering and paddy yield than the partial soil inversion using a disc harrow and tine cultivation (Bhuiyan *et al.*, 1993; Razzaq and Karim, 1993a,b). Tillage has also been shown to improve nitrogen and water use efficiency in wheat (Gajri *et al.*, 1992) and total N, P and K uptake in rice (Sood and Acharya, 1991).

To increase crop production in the rice-wheat system, a suggested compromise is to break the pan by deep plowing for wheat and use shallow tillage and puddling for rice (Lal, 1994). As the benefits of deep tillage are associated with soil type (Lal, 1985).

Materials and Methods

The site consisted of deep, moderately well drained and moderately fine textured, saline-sodic, moderately calcareous soil having a Cambic horizon and classified as a Typic Camborthid. The soil developed in mixed calcareous silty alluvium derived from the Himalayas and deposited during the 'Late Pleistocene in a semiarid subtropical continental climate. The soil covers a large area and is suitable for irrigated rice production (Soil Survey of Pakistan, 1967). The experimental site was at 31°42'30" North and 73°54'42" East in the Punjab province of Pakistan.

After harvesting wheat in 1994, the field was irrigated to bring the water content to a level suitable for tillage operation level. The following tillage treatments: (1) moldboard plowing, (2) moldboard plowing and puddling and (3) conventional tillage were applied separately in a net plot size was of 35 x 70m. Each treatment was replicated three times in a randomized block design. The moldboard consisted of one moldboard plowing to 25 cm depth and two cultivator and planking to reduce the clod size. The conventional tillage consisted of four operations with a tine cultivator to 10 cm followed by two planking operations. Puddling was done by three to four planking operations in standing water after flooding the field for 10 days. Planking consisted of dragging a heavy plank (a 2 m long weighing about 100 kg) behind a tractor mounted cultivator. Rice (c.v. 385-Basmati) was transplanted on July 15, 1994 and grown to maturity under the farmer's management. The number of matured tillers per plant and grain yield was recorded at harvest.

Plant roots were extracted manually from soil monoliths, Soil monolith including a representative healthy plant was taken on October 15, 1994. Galvanized pipe of 18 cm diameter was hammered into the soil to the depth of 50 cm. The monolith was extracted by excavating soil around it and sectioned by 10 cm increments in laboratory. Roots were extracted manually by breaking the sections into <1 cm^3 size clods. Root mass was taken after washing with distilled water and oven drying at 65°C. Root length was measured by summing the lengths of individual root pieces. During the 3rd week of November 1994 undisturbed soil samples were taken to determine water retention characteristics of each plot at various depths immediately after harvesting rice. Soil cores were taken from the depth representing Ap (0-12 cm), AB (12-20 cm), Bw (20-35 cm) and BCk (35-75 cm). Soil water retention measurements were made at the -5, -10, -50, -200 and -1500 kPa matric suctions. The -10 and -1500 kPa matric suctions were taken as approximates of field capacity and permanent wilting point, respectively (Klute, 1986). The difference between field capacity and permanent wilting point was assumed to be "plant available water". Soil bulk density and residual soil water were determined using a Gamma probe CPN Model 501 with three replications in each plot. The radiation counts were taken at the center of each horizon using Polyvinyl Chloride (PVC) access tubes in each plot at 6, 16, 27, 35 and 55 cm depth representing Ap (0-12 cm), AB (12-20 cm), Bw (20-35 cm) and BCk (35-75 cm). respectively. Soil texture was determined by the modified hydrometer method (Gee and Bauder, 1986).

Saturated hydraulic conductivity (K_{fs}) was determined in the field by the in-hole Mariotte bottle-type constant-head well Guelph permeameter (Elrick *et al.*, 1984). In the field, after harvesting rice, a steady-state water in-take rate was taken at 10 cm for Ap + AB, 27.5 cm for Bw and 55 cm for BCk horizons at three locations in each plot. The measurement depths were based on the genetic horizination, except for the 0-20 cm layer which included the Ap and AB as an isolation of the 0 to 12 and 12-20 cm horizons was not possible. From the average rate of water in-take, as indicated by the rate drop in water level in the permeameter's reservoir, saturated hydraulic conductivity (K_{fs}) was calculated by the method of Reynolds and Elrick (1986) and Reynolds *et al.* (1985).

Variance analysis of the agronomic parameters and total depth of plant available and residual water in the profile was done by tillage treatment sampling. Variance analysis of bulk density; water contents at various matric potentials, root length, root mass were analyzed as the Split Plot Design with tillage as the main-plot treatment and the depth as sub-plot-treatment. The treatment and depth means were compared with Duncan's Multiple Range test. The statistical analysis was carried out using SAS release 6.10 (SAS Institute, 1992).

Results

Number of Tillers and Paddy Yield: Both the number of productive tillers and paddy yield increased significantly with the moldboard treatment as compared with conventional tillage (Table 1). A maximum number of tillers were observed in the moldboard - puddled plots followed by moldboard plowing without puddling and the conventional tillage. The numbers of tillers for rice from the moldboard plots with or without puddling did not differ significantly, yet, both had significantly greater number of tillers than rice with the conventional treatment ($P = 0.01$). Rice in moldboard plots had a greater biomass, which was attributed to increased number of tillers per plant.

Paddy yield with the moldboard and moldboard-puddling treatments was significantly greater than with conventional tillage (Table 1). The yield increase for the moldboard treatments was 30 percent over the control, with no significant difference in rice yield with the moldboard and moldboard-puddling treatments.

Table 1: Agronomic parameters and residual soil water in the upper 75 cm profile depth after rice harvest

Tillage Treatment	Tiller per plant No	Yield Mg ha^{-1}	0(profile) cm
Moldboard	17.0a	3.51a	17.82ab
Moldboard-Pudding	18.8a	3. 64a	16.84b
Conventional Tillage	12.1b	2.63b	20.30a
LSD (0.05)	3.6	0.82	2.93

Soil Bulk Density : The tillage treatment effect of on ρ_b was significant ($P \leq 0.05$). Special interest was in any change in bulk density of Ap (0-12 cm) and AB (12-20 cm;) horizons, where it reduced due to the deep tillage but, when pooled over all the horizons, ρ_b remained unaffected by the tillage treatments. Bulk density of the AB horizon (12-20 cm) decreased from 1.68 Mg m^{-3} to 1.58 Mg m^{-3} with the moldboard treatment (Fig. 1). Puddling the moldboard plowed plots resulted in re-generation of the impervious layer toward end of the rice season, while, the moldboard but un-puddled plot remained previous (Fig. 1). The depth effect pooled over all the treatments was significant. The contrast of Ap vs. all other horizons suggested that Ap had the lowest ρ_b and a contrast of AB (12-20 cm) vs. all the horizons suggested that AB had the highest ρ_b in all the treatments.

Table 2: Water fraction retention and residual water distribution in the profile

Horizon	Depth	θv-5	θv-10	θv-50	θv-200	θv-1500	θv-avl	θv-rsi	θcm-rsi
	cm	---m^3/m^3---							---cm---
Ap	0-12	0.45a	0.41a	0.28a	0.22a	0.13c	0.28a	0.11c	1.27c
AB	12-20	0.45ab	0.42a	0.28a	0.22a	0.16b	0.27a	0.22b	1.68c
Bw	20-35	0.44ab	0.37a	0.27a	0.23a	0.16ab	0.21b	0.23b	3.47b
BCK	35-75	0.42b	0.37a	0.29a	0.24a	0.18a	0.20b	0.30a	11.90a
LSD (0.05)		0.06	0.11	0.06	0.03	0.02	0.07	0.02	0.52

θv-5, -10-, -50, -200, -1500, water fractions determined at matric suctions of -5, -10, -50, -200 and -1500 kPa, respectively; θv-avl, available water fraction, θv-rsi, residual water fraction, θcm-rsi, depth of residual water

Rice-Root Length and Distribution: Total rice root length and mass were not affected by tillage treatments, however, depth wise distribution of roots was affected by the treatments. Rice root length and mass at sub-surface layers were greater incase of the moldboard treatment than the root length and mass at corresponding depth incase of the conventional tillage (Fig. 2a,b). Although it was noted that the greatest root length and weight occurred with conventional tillage, the roots were limited only in the upper 12 cm. Therefore, differences in root length and mass data were due only to the 0 to 12 and 12 to 20 cm horizons.

Hydraulic Properties

Infiltration Rate: Saturated infiltration of the native profile at 35 cm depth, which included plow layer (Ap, 0-12 cm) and the impervious layer (AB, 12-20 cm) was about 5 cm per day and the underlying Bw (20.35 cm) had infiltration rate of 3.2 cm per day. The sub-soil composing of BCk (35-75 cm) had infiltration rate of about 1.7 cm per day. The moldboard treatment resulted in about three times increase in infiltration at 0 to 35 cm depth, which was moldboard plowing depth (Fig. 3a). Puddling the moldboard plowed plots decreased the infiltration rate to about 6.5 cm per day, which was only slightly greater than the conventional tillage treatment. The infiltration rate of moldboard plowed plots, especially at 20 to 35 cm profile depth was spatially variable as indicated by high standard deviation. This may be attributed to variable shattering of the impervious layer. It may be noted that 0-20 cm layer includes Ap (0-12 cm) and AB (12-20 cm) horizons. The term layer is used in text to denote a three dimensional soil, which is none genetic in character: Also, that permeability of a profile is controlled by the least permeable layer.

Saturated Hydraulic Conductivity (K_{fs}): The variation in saturated hydraulic conductivity determined in the K_{fs} was due to tillage, the horizon associated and the interaction of both the factors. The effect of treatment on hydraulic conductivity was depth-specific, while, when pooled over all the horizons, the treatment effect was non-significant ($P \leq 0.12$). The deep tillage effect on K_{fs} was significant for the 0-20 cm layer ($P \leq 0.05$) but non-significant for the deeper horizons as the moldboard tillage treatment changed only the upper 25-30 cm profile depth. Comparison of the horizons done by constructing contrasts suggested that the 0 to 20 cm layer had larger K_{fs} as compared to both 20 to 35 cm and 35 to 75 cm horizons, The K_{fs} values were similar for lower two horizons. Saturated hydraulic conductivity was the highest with the moldboard treatment followed by that with the moldboard+puddled and conventional tillage treatments (Fig. 3b). Saturated hydraulic conductivity of the native profile, which represented by the conventional tillage plots was 3.0 cm day^{-1} in the 0-20 cm layer (Ap+AB horizons), 1.2 cm day^{-1} in the 20 to 35 cm horizon and 0.7 cm day^{-1} in the 35 to 75 cm horizon. K_{fs} in deep tilled plots was 7.6 cm day^{-1} in the 0-20 cm layer (Ap+AB horizons), 4.1 cm day^{-1} in the 20 to 35 cm horizon and 1.4 cm day^{-1} in the 35 to 75 cm horizon. Puddling after moldboard resulted in reduction in K_{fs} to the level of conventional tillage (Fig. 3b). Similar trend in matrix flux potential was observed (dated not prested).

Water Retention Characteristics: Water retention characteristics of the soil were analyzed for the tillage treatments (Fig. 4a,b). Volumetric water fraction (θv) held at -10 kPa increased by the moldboard treatments, but treatment effects were inconsistent at -50 and -200 kPa matric suctions, while reverse was true at -1500 kPa matric suctions (Fig. 4a,b). This lead to the significant differences in the available water fraction due to the tillage treatments. Moldboard plowing resulted in significantly greater available water followed by moldboard+puddling and conventional tillage treatments (Table 2), The available water fraction was 0.33 with the moldboard treatment and 0.19 with the conventional treatment. The moldboard plots contained more water at field capacity, which increased their available water capacity.

Except at -5 and -1500 kPa potentials, depth effect on θv determined at various matric suctions was non-significant. Similarly, the depth*treatment effect was non-significant at all the matric suctions. Also, depth *treatment interaction on available water capacity was not statistically significant. Water content retained at -5 and -1500 kPa matric potential were influenced by the tillage treatment at 12-20 cm horizon (Table 2). Soil water content retained at -5 kPa was highest in the Ap horizon (0-12 cm) and lowest in BCk horizon (35-75 cm) whereas the AB (12-20 cm) and Bw (20-35 cm) horizons did not differ significantly in water content (Table 2). Water fraction retained at -10, -50, -200 kPa was similar at different depths. At -1500 kPa the BCK

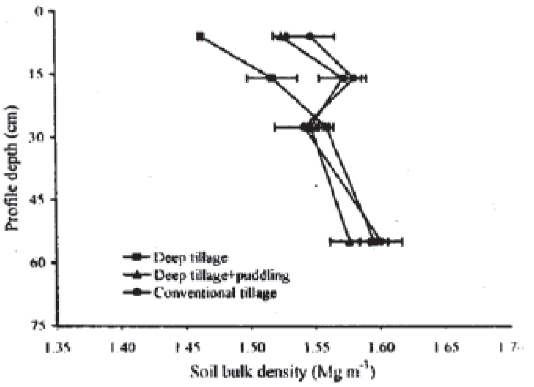

Fig.1: Soil bulk density as affected by the tillage treatments

horizon retained the greatest and the Ap horizon retained the least water. Available water capacity in the profile was 0.27 to 0.28 in the surface horizons and 0.20 to 0.21 in the sub-surface horizons (Table 2).

Residual Water: Residual soil water after harvesting cioe was significantly affected by the tillage treatment ($P \leq 0.002$). Residual soil water was greater in conventional tillage plots than in moldboard plots (Fig. 5). In the 75 cm deep profile the total residual water was 203 mm with conventional tillage, 170 mm with moldboard and 161 mm with moldboard and puddled treatment. Puddling of the moldboard soil did not affect residual soil water and residual water content was same as for un-puddled moldboard soils. All the treatments resulted in similar water content at the surface as indicated by the non-significant differences in the Ap horizon (Fig. 5). The conventional tillage resulted in more residual soil water at the lower horizons. The volumetric water content was the greatest in the BCk horizon (35-75 cm) and the least in the Ap horizon. The tillage effects on water content were statistically significant ($P \leq 0.05$) for the AB and Bw horizons.

Discussion

Rice development benefited from the deep tillage on this soil as both the number of productive tillers and paddy yield increased with the moldboard treatment. Rice plants from moldboard treatment plots also had greater biomass. Similarly, the deep tillage with or without puddling treatment resulted in greater paddy yield than the farmer practice. The beneficial effect of the moldboard treatment was attributed to deeper root development and hence better nutrient utilization (Gajri *et al.*, 1992; Rahman, 1991; Razzaq and Karim, 1993a,b; Sood and Acharya, 1991).

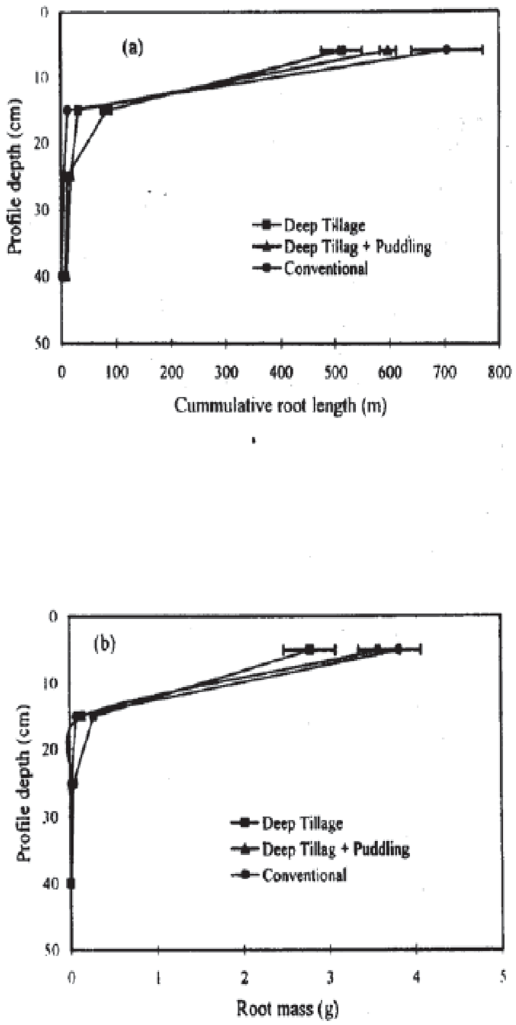

Fig. 2: Rice root distribution in the soil as affected by the tillage treatment: (a) cumulative root length and (b) total root mass

Overall, in the moldboard plots soil ρ_b after rice harvest was not different from the conventional tillage plots. Since the soil was saline-sodic, clay dispersion under high electrolyte condition and the mechanical action of puddling resulted in collapse of structure during the rice season. However, the moldboard tillage resulted in disrupting the previously formed pan. The AB horizon (12-20 cm) had the highest ρ_b and the Ap (0-12 cm) had the lowest ρ_b. The cultivation pan, which is represented by the AB horizon (12-20 cm) under conventional tillage, had the greatest ρ_b and this was significantly reduced by deep plowing. The bulk density

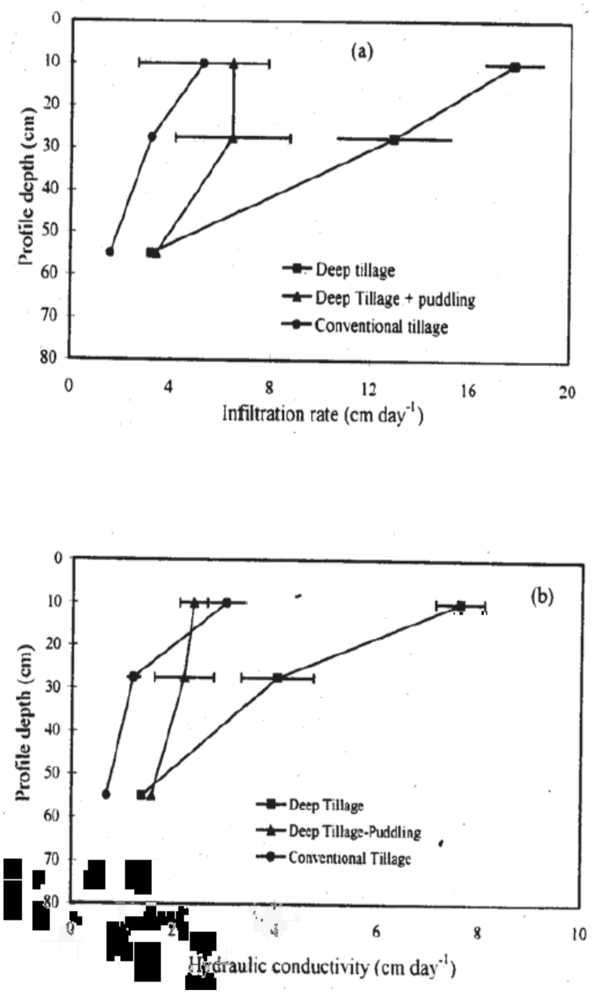

Fig. 3: Soil profile infiltration characteristics as affected by the tillage treatment: (a) saturated infiltration and (b) hydraulic conductivity

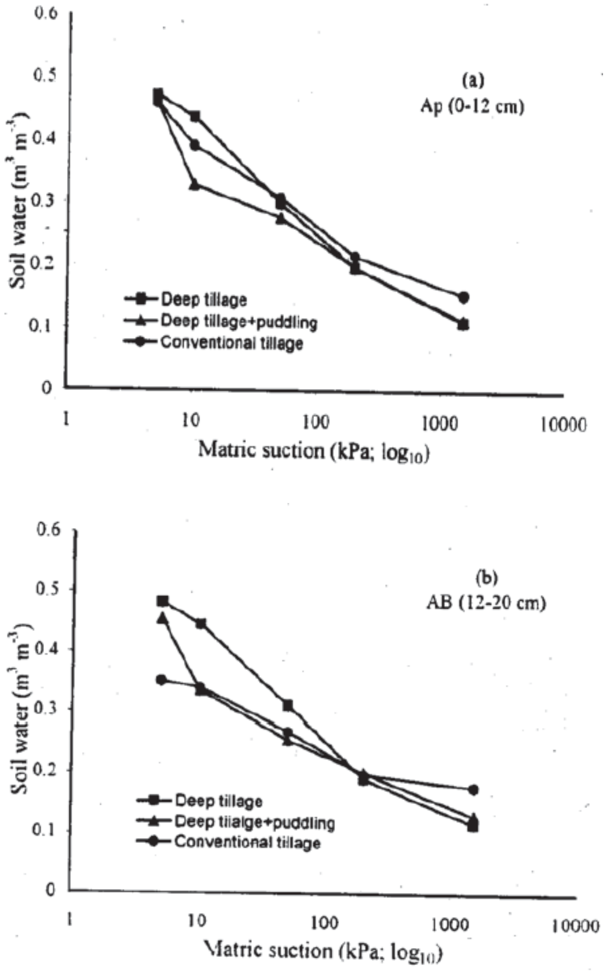

Fig. 4: Water retention characteristics as affected by the tillage treatment: (a) Ap (0-12 cm) and (b) AB horizon (12-20 cm)

profile is typical of the rice soils in Pakistan (Islam *et al.*, 1990; Matin and Uddin, 1994; Hassan and Gregory, 1999).

Growth and penetration of rice roots are favored by relatively low bulk density resulting from tillage operations (Kar *et al.*, 1986; Acharya and Sood, 1992). In this study, the distribution of rice roots down the profile was affected by the tillage treatments, although, the total rice-root length and mass remained unaffected. Matin and Uddin (1994) reported similar results for a silty loam soil. Rice root length and mass with the moldboard treatment were greater at 12-20 cm as compared to that with the conventional tillage. Although, it was noted that root length was the greatest with the conventional tillage treatment but roots were concentrated only in the upper 12 cm. Thus the high-density layer controlled root penetration characteristics of the rice soil. The moldboard plowing resulted in better penetration of rice roots. However deep plowing with even one year puddling inhibited root penetration. However, it is evident that deep plowing resulted in improved paddy yield than conventional shallow tillage for rice.

This study and some other works suggested that moldboard plowing resulted beneficial effects on rice establishment and yield due to deeper root penetration (Majid *et al.*, 1988). However, for a rice-wheat system moldboard plowing is not generally recommended because a plow-pan is considered necessary for saving rice field water, as the water transmission characteristics of the rice soils are controlled by the high density layer. The study indicated that although conventional shallow tillage resulted in minimum saturated infiltration and breaking of the impervious pan caused increased infiltration, significant saving of water can be achieved by the subsequent puddling the moldboard plowed soils.

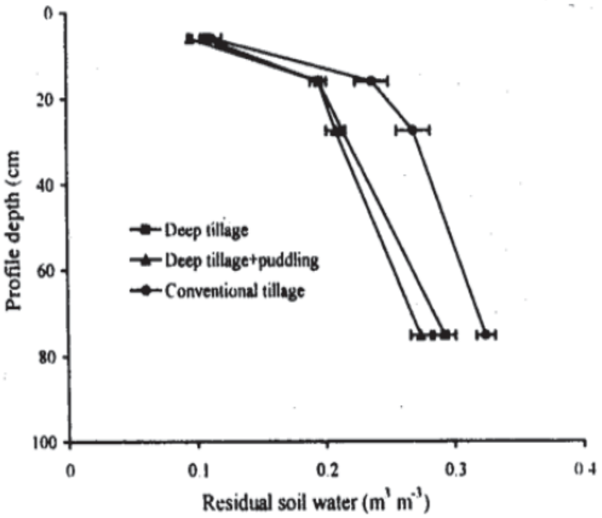

Fig. 5: Residual water fraction in the soil profile after harvesting rice

Tillage effects on K_{fs}, were significant at the 0-20 cm depth, which includes the plow-pan and Ap At this depth, K_{fs} was greatest in the moldboard plowed soil and the least in the conventional tillage treatments indicating the effects of disruption of the impermeable plow pan. Hydraulic conductivity of a soil. is a measure of its ability to transmit water, which depends on the geometry of the pores. The decrease in K_{fs}, due to the puddling of moldboard plowed plots to values similar to conventional tillage treatment was probably due to plugging of macro-pores by dispersed clay particles.

Moldboard plowing was shown to increase the available water capacity, which is a beneficial effect. With the moldboard treatment water fraction increased at lower matric suction; remained unaffected at -50 and -200 kPa; and decreased at -1500 kPa which resulted in significantly greater available water retention with the moldboard than with the conventional tillage treatment. In general, reduction in P_b increases soil water retention at low matric suctions and decreases it at high matric suction due to change in pore size distribution (Lal, 1992). The change in water retention characteristics may also be due to bringing more clay to the surface by the inversion effect of moldboard plowing.

The water content retained at -5 kPa was the highest in the Ap horizon (0-12 cm) and lowest in BCk horizon (35-75 cm) while water retained at -10, -50, -200 kPa was similar at different depths. In contrast to the -5 kPa, the BCk horizon retained the greatest and the Ap horizon retained the least water at -1500 kPa. These differences in water retention were due to varying organic matter and clay content among the horizons. The Ap horizon had more organic matter and lesser clay content than the BCk. Therefore, the available water fraction in the profile was higher in surface horizons and lesser in the sub-surface horizons.

The deep tillage treatment helped the rice field to drain faster as. the deep tillage plots had less residual soil water after harvesting rice. The conventional tillage plots had greater total residual soil water content than the moldboard plots. Puddling the moldboard plowed soil did not affect residual soil water content. Conventional tillage had a residual soil water content of 0.30 in the 35-75 cm horizon, which was close to the saturation point of 0,38 for the soil. Although, all the treatments resulted in similar water content in the Ap horizon (0-12 cm) but workability of soil for tillage operations are also controlled by subsurface water content. In the rice-wheat system, the tillage for wheat sowing is delayed by a period seven to ten days. A practical benefit of the improved drainage would be a 700 to 1000 kg grain yield increase due to early wheat sowing as each day late sowing decreases yield by about 100 kg ha^{-1}. Therefore, agronomic benefit lies in the moldboard tillage and water saving for rice field can be achieved by subsequent puddling after moldboard.

Acknowledgements

We acknowledge the technical and editorial help of Mr. Allen Stapleton, Consultant Hunting Technical Services, UK and financial assistance provided under World Bank Agricultural Research Program Phase-II.

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