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Effect of Puddling and Direct Sowing of Rice on Soil Physical Health and Water Productivity of Rice-Wheat Cropping System under Different Irrigation Regimes

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A field experiment was conducted during 2012-13 to 2013-14 at the research farm of ICAR-Indian Agricultural Research Institute, New Delhi to study the effect of three rice cultivation methods, *viz*., direct seeded rice (DSR), system of rice intensification (SRI) and conventional puddled transplanted rice (PTR) under adequate and deficit irrigation on soil structure and the water productivity of rice-wheat cropping system (RWCS). Results showed that mean weight diameter and percentage of macro-aggregate stability decreased under PTR (0.86 mm and 71.8%) and SRI (0.85 mm and 74.2%) compared with DSR (1.00 mm and 79.5%) method. The SRI method resulted in significantly higher yield of rice than PTR and DSR by 15.9 and 42.6 per cent, respectively. Water productivity of rice under SRI and DSR was significantly higher than PTR by 41.1 and 34.1 per cent, respectively. The grain yield and water productivity of wheat following DSR were significantly higher than those following PTR by 23.7 and 11.8 per cent, respectively. Moreover, considering RWCS as a whole, DSR resulted in significantly higher system water productivity (7.01 kg ha-mm^{-1}) and significantly lower water use (1390 mm) compared with PTR and SRI methods.

Key words: Water productivity, rice-wheat cropping system, puddled transplanted rice, direct seeded rice, system of rice intensification, soil structure

Rice-wheat cropping system (RWCS) is critical to food security and livelihood, which covers about 10.5 million hectare (Mha) in the Indo-Gangetic Plain (IGP) of India (Bouman *et al*. 2007) and contributes to 26% of the total cereal production and 60% of the total calorie intake (Gupta *et al*. 2003; Chahal *et al*. 2007). However the area under RWCS is static and the productivity and sustainability of this cropping system is at stake because of the inefficiency of the current production practices, shortage of water resources and labour besides socio-economic changes (Ladha *et al*. 2003). Growing scarcity of water is the biggest threat for sustaining and increasing productivity of this region. The projected per capita water availability by the year 2025 will lead the IGP to a water-stressed area if the current water use practices continue (Sikka and Gichuki 2003). The global average water footprints of rice and wheat crops are 2291 and 1334 L kg^{-1} with a global water share of 21.4 and 12.4%, respectively. Such a high water footprint and share of water for rice and wheat crops need to be reduced because of competing demands for water from other agricultural and non-agricultural sectors, which would help in achieving sustainable and equitable use of water. This can be accomplished by enhancing water productivity (WP), nutrient use efficiency, and soil and water health in RWCS. The decreased availability of water is a challenge to develop novel technologies that can produce higher yields of these crops with less water. Need is being felt to increase grain yield and water productivity of these crops through different methods of crop establishment and cultivar selection under adequate and deficit irrigation regimes.

Rice is traditionally grown by transplanting seedlings in puddled soil (PTR). Puddling causes breakdown of soil aggregates, leads to formation of hard pan at shallow depths, which causes deterioration of soil physical health leading to yield reduction of the post rice crops (Boparai *et al*. 1992). Kassam *et al*. (2011) reported that system of rice intensification (SRI) involving transplanting of single young seedling per hill at shallow depth, wider spacing, moist and

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non-flooded water management regime, inter-cultivation to control weeds and increased use of organic manures, can raise substantially the productivity of land, water, seeds and capital used in irrigated rice environment. However, according to De Datta (1986), direct seeded rice (DSR) offers the advantage of faster and easier planting, proper plant population, reduced labour demand, earlier crop maturity, efficient water use, higher tolerance to water deficit, and high profit in areas having assured water supply. The DSR method taken-up in non-puddled soils on flat or raised beds showed saving of water by 15-30 per cent compared with traditional PTR (Sharma *et al*. 2002; Singh *et al*. 2002).

A field experiment was therefore, conducted in irrigated RWCS in a silty loam soil of the experimental farm of ICAR-Indian Agricultural Research Institute during 2012-13 and 2013-14 with the objectives to study the interaction of three rice establishment methods (*i.e.* PTR, SRI and DSR), irrigation regimes and cultivars on soil physical health, yield, water use and water productivity.

Materials and Methods

Soil and Climate

The field experiment was carried out during 2012-13 to 2013-14 at the research farm of ICAR-Indian Agricultural Research Institute, New Delhi located at 28°37' and 28°39' N latitude, 77°90' and 77°11' E longitude and at 228.7 m above mean sea level. This region is characterized by extreme temperatures with the annual maximum temperature touching as high as 45 °C in summer, whereas the minimum temperature dip to as low as 1 °C in winter. Summers are long (early April-August) with the monsoon months from July to September. The daily weather during rice and wheat growth period is depicted in fig. 1. The surface soil (Typic Haplustept) is silty loam in texture (% sand, silt and clay being 13.3, 66.7 and 20.1, respectively) with medium to angular blocky structure, non-calcareous and slightly alkaline in reaction. The soil was medium in organic carbon (OC), and available nitrogen (N), phosphorus (P) and potassium (K) content. The bulk density varied from 1.46 Mg m^{-3} in the 0-15 cm layer to 1.63 Mg m^{-3} in the 60-90 cm layer. Available soil moisture ranged from 31-37% (0.033 MPa) to 13-20% (1.5 MPa) in five different layers up to 90 cm soil depth.

Experimental details

The experiment was laid out in a split split-plot design with three replications, and the size of the sub sub-plot was 5 m × 4 m. Rice was grown in the *kharif* season under three establishment methods *viz*., (i) direct seeded rice (DSR), (ii) system of rice

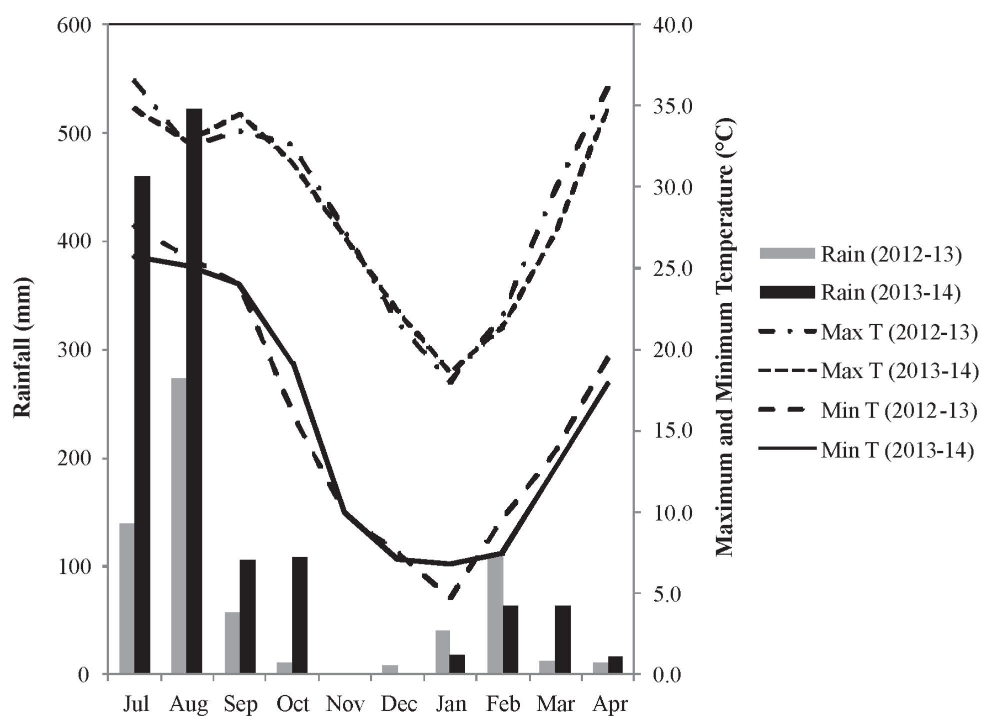

Fig. 1. Variation in rainfall, and maximum and minimum temperature during growing periods of rice and wheat during 2012-13 and 2013-14

intensification (SRI) and (iii) conventional puddled transplanted rice (PTR) as main-plot factor, two irrigation methods *viz.* (i) adequate irrigation and (ii) deficit irrigation as sub-plot factor and two cultivars (*i.e.* PRH 10 and Pusa 1460) as sub sub-plot factor. In case of PTR and SRI, the field was puddled using a tractor drawn puddler. In PTR, 21 days-old seedlings were transplanted, whereas in SRI 14 days-old seedlings were transplanted as per principle of SRI. In DSR, dry sowing of rice seed was done using a tractor-drawn seed drill. Adequate irrigation in case of puddling corresponded to continuous submergence to a depth of 5 cm and the deficit irrigation corresponded to alternate wetting and drying. Adequate irrigation in case of SRI corresponded to saturated moisture content and deficit irrigation meant 25% less irrigation than that supplied to bring the moisture to saturation level. Adequate irrigation in DSR corresponded to irrigation to keep the soil at field capacity moisture content and deficit irrigation meant 25% deficit irrigation than the adequate irrigation. In the *rabi* season, wheat was grown in these fixed plots with residual effect of three rice establishment methods as main plot factor, two irrigation regimes (adequate and deficit) as sub-plot factor and two cultivars (*i.e.* DBW 17 and HD 2967) as sub sub-plot factor. Adequate irrigation in wheat corresponded to irrigation to bring the moisture content of soil to field capacity and deficit irrigation corresponded to 25% less irrigation than the adequate irrigation. The irrigation water depth supplied to each experimental plot was measured using a digital water flow meter. Effective rainfall depths were estimated using the standard formulae (USDA method), and the total water used for different cultivation methods was estimated. The hypothesis behind taking different varieties was to evaluate them on the basis of their water productivity. In rice, PRH 10 is a hybrid (non-*basmati*) whereas Pusa 1460 is a long duration (*basmati*) rice variety. In wheat, variety HD 2967 is more sensitive to water stress compared with DBW 17. The duration of DBW-17 is 20 days less than that of HD 2967.

Irrigation scheduling, water use and water productivity

Surface irrigation with measured depth of water was applied during each irrigation event in all experimental plots. The irrigation water depth applied to each plot was measured, on an average, four times using a digital velocity meter and the wetted area of the field channel. At the start of the experiment, a rating curve was generated showing the relationship between flow depth and discharge in the main channel, and then an exponential equation was developed. Afterwards, during each irrigation, only flow depth was measured in the channel and corresponding discharge was determined using either the rating curve or the exponential equation developed. Moreover, the depth of irrigation water was estimated based on the soil moisture deficit (SMD) protocol for each treatment. The calculation was as per the Eq.1 given below:

$$SMD = (\theta_{FC}-\theta_i) \times D_{RZ} \times BD \times f \qquad \ldots(1)$$

where, SMD: soil moisture deficit (mm); θ_{FC}: gravimetric soil water content at field capacity; θ_i: gravimetric soil water content before irrigation (weight basis in g g^{-1}); D_{RZ}: depth of root development (mm); BD: bulk density of the given soil layer (Mg m^{-3}); and f: coefficient of each treatment.

The root depth of rice and wheat was measured by uprooting the seedlings carefully in well-watered condition and measuring the root depth by a scale. The dates of irrigation were determined based on the root zone soil moisture content approaching 50% of total available water (TAW) and was considered as the manageable allowable deficit (MAD), which did not cause any stress to the plant. Further, the measured quantity of irrigation was applied for a depth from the existing moisture level up to the field capacity using Eq.1 to ensure that there is no loss of water. Thus, the depth of irrigation water was estimated for the full irrigation treatment for a given date based on the existing soil moisture. Subsequently, the deficit irrigation treatments with 25% deficit levels were estimated by multiplying the coefficient "f" of 0.75 with the depth estimated for full irrigation treatment and the value of "f" was 1 for full irrigation. All irrigation treatments were applied on same day during the crop growth period.

Rainfall data were recorded using a rain gauge. The effective rainfall was computed using USDA approach:

$$Pe = Pt/125(125-0.2Pt), \text{ when } Pt < 250 \text{ mm} \qquad \ldots(2)$$

$$Pe = 125 + 0.1Pt, \text{ when } Pt > 250 \text{ mm} \qquad \ldots(3)$$

where, Pe = monthly effective rainfall (mm) and Pt monthly total rainfall (mm).

Further, the water use (WU) was computed as the sum of water applied through irrigation and estimated effective rainfall. Subsequently, the water productivity (WP_{I+R}) (kg grain/ha-mm of water) was computed using Eq. 4 (Humphreys *et al*. 2006):

$$WP_{I+ER} = \frac{\text{Grain yield, kg ha}^{-1}}{\text{Total water use (I+ER), mm}} \qquad \ldots(4)$$

Determination of physical properties of soil

Soil samples were collected from the surface layer (0-15 cm) after the harvest of rice and wheat crops in each year. The soil OC content was determined by modified Walkley and Black rapid titration method (Nelson and Sommers 1975). The BD of soil was determined up to a depth of 30 cm in triplicate from each replication by a core sampler with cores of 5 cm height and 5 cm diameter. Undisturbed core samples were also collected in triplicate from 0 to 30 cm soil depth at 7.5 cm intervals for determination of saturated hydraulic conductivity. The saturated hydraulic conductivity was determined by constant head method using a closed permeameter (Klute and Dirksen 1986).

The C pool of the soil was computed using the following equation (Lal *et al*. 1998):

$$\mathrm{C\,pool}\left(\frac{\mathrm{Mg}}{\mathrm{ha}}\right) = A \times D \times \rho_b \times C \times 10^{-3} \qquad \ldots(5)$$

where, A = area (ha, 10^4 m^2); D = depth of soil (m), ρ_b = bulk density (Mg m^{-3}); and C = concentration of C (g kg^{-1} soil).

For aggregate analysis, surface soil samples (0-15 cm) were collected in cores at field capacity. After drying in shade, the soil in the cores were broken by giving gentle strokes of a wooden hammer and only aggregates of 4-8 mm size was used for analysis. The aggregate size distribution of soil was determined by wet sieving method using Yodder's apparatus (Yodder 1936). For this purpose, after capillary rewetting, 100 g of soil aggregates (4-8 mm size) were kept on the top of 4 mm size sieve and shaken through a series of seven sieves *i.e.* 4, 2, 1, 0.5, 0.25, 0.125 and 0.053 mm, in a water drum for a period of 10 min approximately 3 cm up and down with the frequency of 50 times during 2 min. Further, soil samples from each sieve and also from the drum were collected. This resulted in distributing the aggregates into the following size classes *viz.*, (i) >4000 µm, (ii) 2000-4000 µm (iii) 1000-2000 µm (iv) 500 to 1000 µm, (v) 250-500 µm, (vi) 125-250 µm, (vii) 53-125 µm, and (viii) <53 µm. Subsequently, these samples were dried in oven and the dry weight was recorded. To determine the percentage of sand free mass in the size classes, soil from each of the size classes were shaken overnight with 1% (w/v) sodium hexametaphosphate solution and sieved through the 53 µm sieve (Elliott 1986). After rinsing several times with deionized water, the sand fraction retained in the sieve was oven-dried at 105 °C and the dry weight was recorded. Water stable aggregation was expressed as the percentage of sand free aggregates greater than 250 µm diameter. Mean weight diameter (MWD) was calculated following Van Bavel (1949) from the weighted mean of the aggregate retained in each sieve using the following formula (Eq 6):

$$\mathrm{MWD(mm)} = \sum_{i}^{n} x_i \times w_i \qquad \ldots(6)$$

where, x_i is the mean diameter of the sieve (mm) and w_i is the proportion of the weight of soil retained in each sieve.

Statistical analysis

The data pertaining to the crop and soil properties were analyzed by analysis of variance as outlined by Gomez and Gomez (1984). The significance of the treatment effect was determined using F-test, and to determine the significance of difference between the means of two treatments, least significant differences (LSD) at 5% probability level and Duncan's multiple range tests were undertaken.

Results and Discussion

Soil aggregation as influenced by rice establishment methods

There was significant decrease in the MWD of soil at 0-15 and 15-30 cm depths under PTR by 16.3 and 30.8 per cent than DSR after harvest of rice (Table 1). Such decrease in MWD could be attributed to the breakdown of soil aggregates due to puddling. The MWD of soil under SRI was at par with the PTR after rice harvest. The water stable aggregate (WSA)

Table 1. Mean weight diameter and water stable aggregate percentage of soil after rice harvest

Treatment	Mean weight diameter (mm)		Water stable aggregates (%)	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Rice establishment				
DSR	1.00a*	1.02a	79.5a	76.0a
SRI	0.85b	0.74b	74.2b	69.9b
PTR	0.86b	0.78b	71.8b	74.5b
Irrigation levels				
Adequate	0.92a	0.82a	76.6a	73.9a
Deficit	0.89a	0.87a	73.7a	73.0a
Cultivars				
PRH 10 and DBW 17	0.83b	0.91a	71.8a	71.1a
Pusa 1460 and HD 2967	0.98a	0.79b	78.5a	75.8a

*Numbers followed by same letters are not significantly different at $p<0.05$ as per DMRT

percentage also showed the similar trend as that of the MWD. The WSA percentage under DSR, SRI and PTR was 79.5, 74.2 and 71.8 at 0-15 cm and 76.0, 69.9 and 74.5 at 15-30 cm soil depths, respectively. These results were in agreement with Mondal *et al*. (2016), who reported that non-puddled conditions increased the macro-aggregate fraction by 18–33 per cent, whereas, the higher frequency of micro-aggregates (0.053–0.25 mm diameter) in puddled conditions clearly indicated the breakdown of larger macro-aggregates (>0.25 mm) into smaller size fractions.

Bulk density and hydraulic conductivity of soil under different rice establishment methods

After wheat harvest, BD of soil under PTR was higher than DSR by 5.6 per cent at 0-15 cm soil depth (Table 2). This finding was in agreement with McDonald *et al*. (2006). The BD of soil under SRI was at par with PTR, but was higher than DSR by 3.3 per cent. However, there was no significant difference in the BD of soil due to different rice establishment methods at 15-30 cm soil depth.

The saturated hydraulic conductivity of soil after wheat harvest under DSR was significantly higher than PTR and SRI at both 0-15 and 15-30 cm soil depths (Table 2). This could be attributed to lower BD and higher WSA and MWD of soil under DSR than that under SRI and PTR. This finding was also in agreement with McDonald *et al*. (2006). However, there was no significant difference between the SRI and PTR methods with respect to saturated hydraulic conductivity of soil at 0-15 and 15-30 cm soil depths. Irrespective of the treatments, there was an increase in BD and decrease in saturated hydraulic conductivity at 15-30 cm compared with 0-15 cm soil depth.

Soil organic carbon concentration as influenced by rice establishment methods

Irrespective of the treatments, soil OC content decreased with increase in soil depth (Table 3). The OC concentration was not influenced by irrigation or

Table 2. Bulk density and saturated hydraulic conductivity of soil after rice harvest

Treatment	Bulk density ($Mg\ m^{-3}$)		Saturated hydraulic conductivity ($m\ sec^{-1}$)	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Rice establishment				
DSR	1.76b*	1.86a	7.63E-06a	4.23E-06a
SRI	1.85a	1.88a	2.24E-06b	1.59E-06b
PTR	1.85a	1.89a	2.04E-06b	1.56E-06b
Irrigation levels				
Adequate	1.81a	1.87a	3.76E-06a	2.23E-06a
Deficit	1.83a	1.88a	4.19E-06a	2.69E-06a
Cultivar				
PRH 10 and DBW 17	1.81a	1.87a	4.09E-06a	2.65E-06a
Pusa 1460 and HD 2967	1.83a	1.88a	3.85E-06a	2.28E-06a

* Numbers followed by same letters are not significantly different at $p<0.05$ as per DMRT

Table 3. Effect of crop establishment, irrigation and cultivars on soil organic carbon content after wheat harvest in a rice-wheat cropping system

Treatment	Soil organic carbon concentration ($g\ kg^{-1}$)		Soil organic carbon pool ($Mg\ ha^{-1}$)		
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-30 cm
Rice establishment					
DSR	8.87a*	7.30a	23.3a	20.3a	43.7a
SRI	8.07b	6.38b	22.4b	18.0b	40.4b
Transplanted	7.99b	6.40b	22.2b	18.1b	40.3b
Irrigation levels					
Adequate	8.18a	6.53a	22.2a	18.3a	40.4a
Deficit	8.40a	6.92a	23.1a	19.5a	42.6a
Cultivars					
PRH 10 and DBW 17	8.43a	6.58a	22.9a	18.4a	41.3a
Pusa 1460 and HD 2967	8.15a	6.87a	22.4a	19.4a	41.7a

* Numbers followed by same letters are not significantly different at $p<0.05$ as per DMRT

crop cultivars. However, different rice establishment methods significantly influenced both OC concentration and pool. The OC concentration and pool under DSR was significantly higher than the PTR and SRI methods of rice establishment at 0-15 and 15-30 cm soil depths (Table 3). This was mainly attributed to the breakdown of aggregates and thus decomposition of aggregate-protected OC under puddling. Paudel *et al*. (2014) also reported higher OC under DSR than that of PTR establishment method. There was no significant difference in the OC concentration at 0-15 and 15-30 cm soil depths due to SRI and PTR as puddling was done in both cases. The OC pool at 0-30 cm soil depth under DSR (43.7 Mg ha^{-1}) was significantly higher than that under SRI (40.4 Mg ha^{-1}), and PTR (40.3 Mg ha^{-1}), but there was no significant difference in the OC pools between the SRI and PTR methods.

Rooting depth of wheat as influenced by rice establishment methods

The rooting depth of wheat grown after DSR was higher than that after SRI or PTR (Fig. 2). Lower BD and higher aggregation under DSR might have promoted better root growth over other methods. Bajpai and Tripathi (2000) reported that puddling in rice enhanced the root length density of rice by 12 per cent but decreased the root length density of subsequent wheat by 28 per cent. Rooting depth under deficit irrigation was higher than that of adequate irrigation. Tendency of the plants to search for moisture to meet evapo-transpirative requirement might be the reason for better root growth under deficit irrigation levels. Wheat cultivar DBW 17 exhibited better root growth than HD 2967.

Grain yield, water use and water productivity of rice

Grain yield of cultivar PRH 10 ranged from 3.88 t ha^{-1} (DSR with deficit irrigation) to 5.93 t ha^{-1} (SRI with adequate irrigation) and that of Pusa 1460 ranged from 2.37 t ha^{-1} (DSR with deficit irrigation) to 3.67 t ha^{-1} (SRI with adequate irrigation) during 2012 (Fig. 3). During 2013, grain yield of cultivar PRH 10 ranged from 3.75 t ha^{-1} (DSR with deficit irrigation) to 5.72 t ha^{-1} (SRI with adequate irrigation) and that of Pusa 1460 ranged from 2.87 t ha^{-1} (DSR with deficit irrigation) to 4.82 t ha^{-1} (SRI with adequate irrigation) (Fig. 4). Lower yield of rice during 2012 was due to lower rainfall received during 2012 than that in 2013 (Fig. 1). Averaged over irrigation and cultivars, grain yield under SRI method of establishment was significantly higher than under PTR and DSR by 16.3 and 38.6 per cent during 2012 and by 15.6 and 46.6 per cent during 2013, respectively. Grain yield under PTR was significantly higher than DSR by 19.1 and 26.7 per cent during 2012 and 2013, respectively

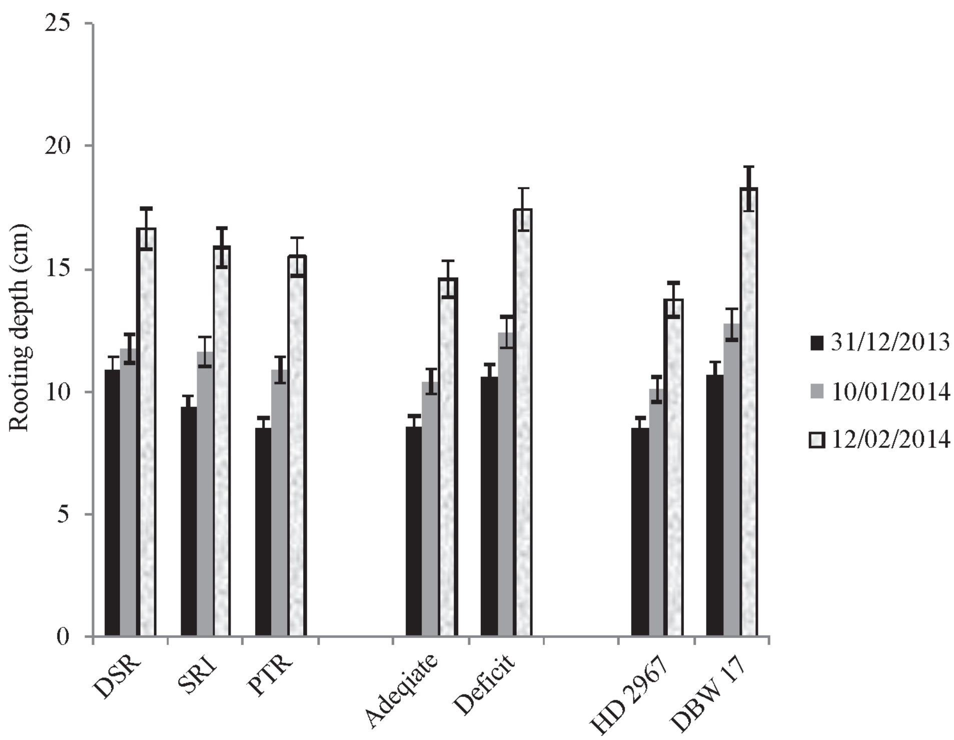

Fig. 2. Rooting depth of wheat as influenced by rice establishment methods, irrigation levels and cultivars

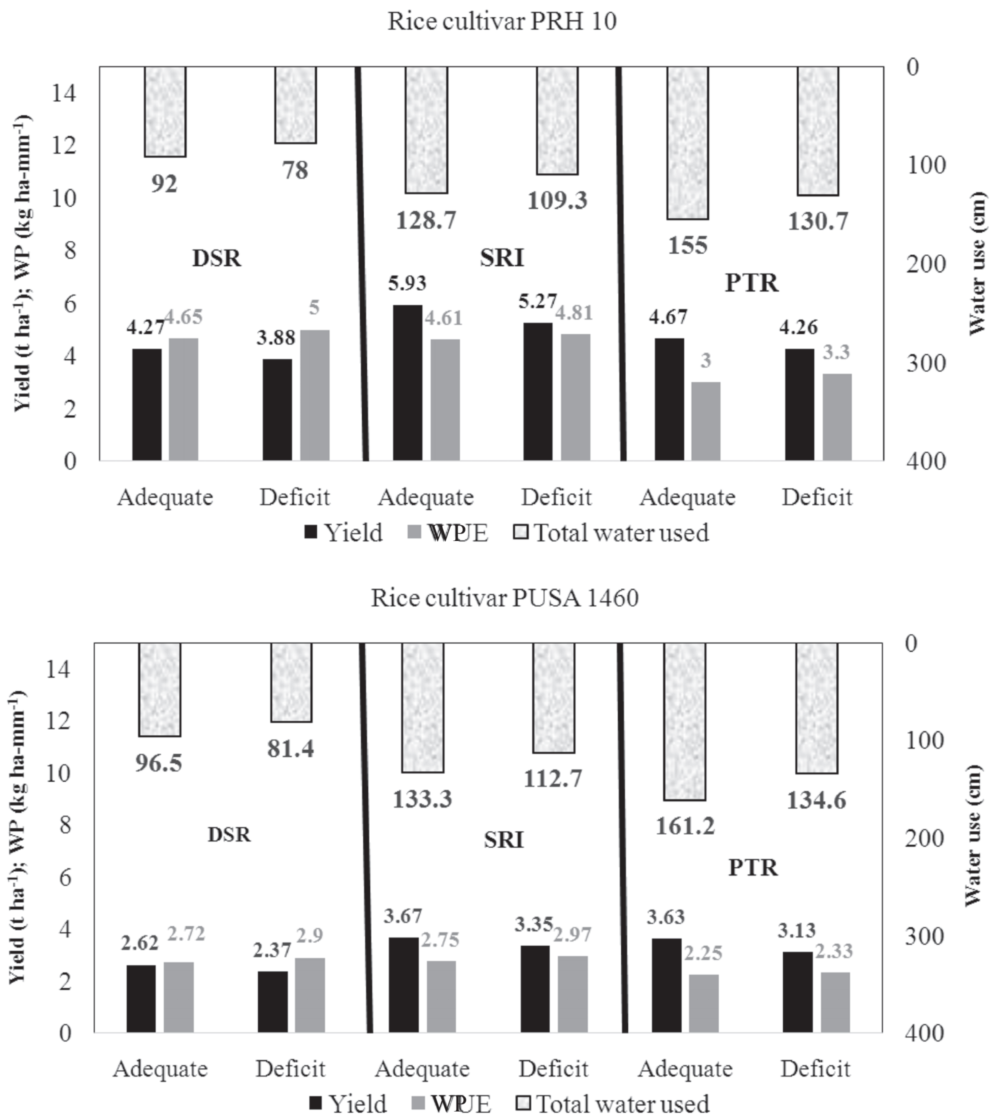

Fig. 3. Grain yield, water use and water productivity of rice cultivars as influenced by rice establishment method and irrigation during *kharif* 2012

(Table 4). Averaged over establishment methods and cultivars, adequate irrigation levels as per plant requirement significantly increased the grain yield of rice compared with that under deficit irrigation by 11.3 and 7.4 per cent during 2012 and 2013, respectively. Averaged over establishment methods and irrigation levels, PRH 10 registered significantly higher grain yield than Pusa 1460 (Table 4).

Water used by cultivar PRH 10 ranged from 780 mm (DSR with deficit irrigation) to 1550 mm (transplanted with adequate irrigation) and that by Pusa 1460 ranged from 814 mm (DSR with deficit irrigation) to 1612 mm (transplanted with adequate irrigation) during the year 2012 (Fig. 3). The water used by these cultivars was relatively greater during 2013 (Fig. 4). Averaged over irrigation levels and cultivars, water use by rice under PTR (1454-1786 mm in 2013) was significantly higher than under SRI (1210-1449 mm) and DSR (870-1103 mm) during different years (Table 4). Higher water use under PTR was quite obvious as the crop was grown under standing water condition in this treatment. Also, water use was greater under adequate irrigation compared with deficit irrigation, and that under Pusa 1460 compared with PRH 10 during both the years.

Water productivity (WP) of PRH 10 ranged from 3.0 (PTR with adequate irrigation) to 5.93 kg ha-mm^{-1} (SRI with adequate irrigation) and that of Pusa 1460 ranged from 2.25 (PTR with adequate irrigation) to 2.97 kg ha-mm^{-1} (SRI with deficit irrigation) during

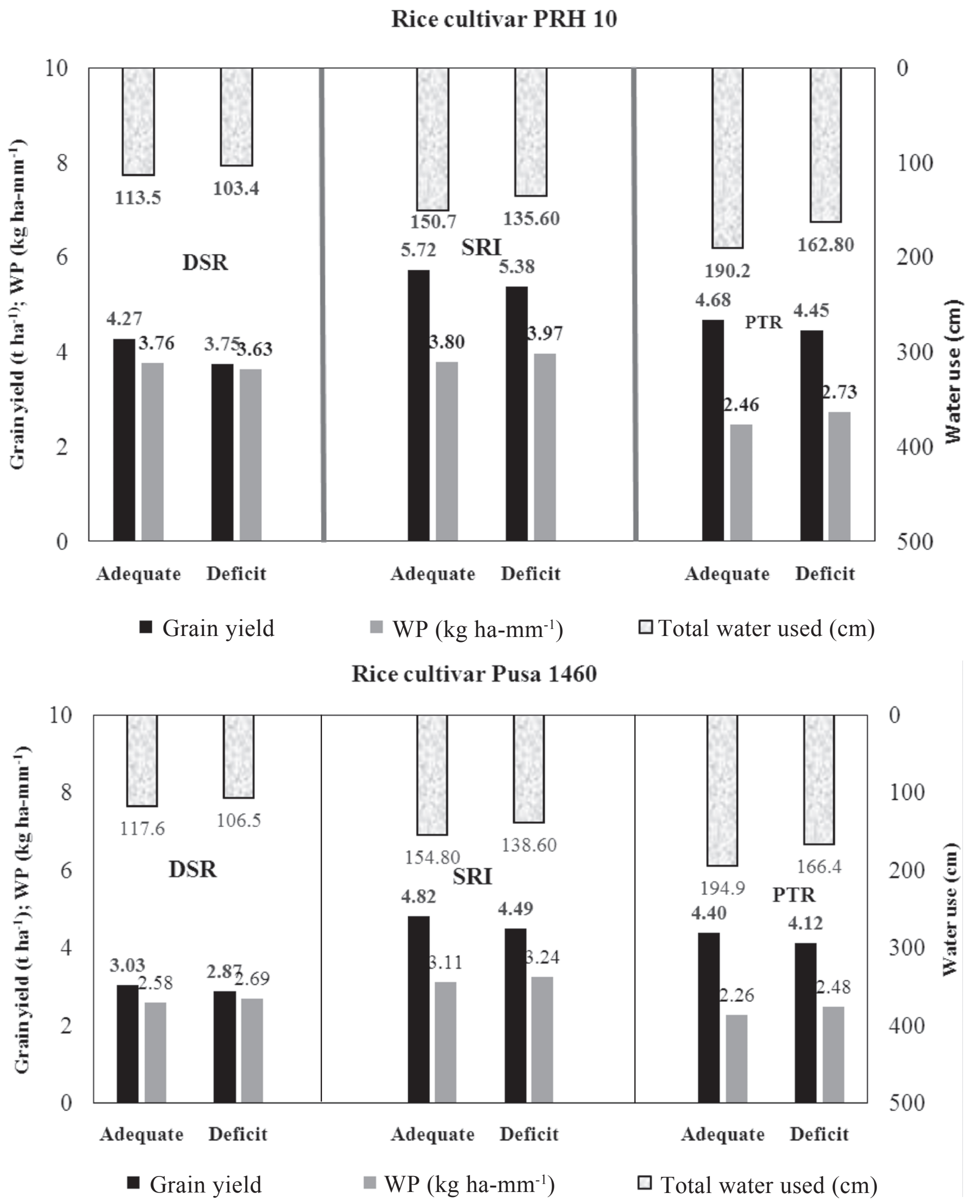

Fig. 4. Grain yield, water use and water productivity of rice cultivars as influenced by rice establishment methods and irrigation during *kharif* 2013

Table 4. Grain yield and water productivity of rice as influenced by crop establishment, irrigation and cultivars

Treatment	Grain yield (t ha^{-1})		Water use (mm)		Water productivity (kg ha-mm^{-1})	
	2012	2013	2012	2013	2012	2013
Rice establishment						
DSR	3.29c*	3.48c	870c	1103c	3.82a	3.16a
SRI	4.56a	5.10a	1210b	1449b	3.79a	3.53a
PTR	3.92b	4.41b	1454a	1786a	2.71b	2.48b
Irrigation levels						
Adequate	4.13a	4.49a	1278	1536a	3.33a	2.99a
Deficit	3.71b	4.18b	1078b	1356b	3.55a	3.12a
Cultivars						
PRH 10	4.71a	4.71a	1156b	1427b	4.23a	3.39a
Pusa 1460	3.13b	3.96b	1200a	1465a	2.65b	2.73b

*Numbers followed by same letters are not significantly different at $p<0.05$ as per DMRT

2012 (Fig. 3). Whereas, during 2013, WP of PRH 10 ranged from 2.46 (PTR with adequate irrigation) to 3.97 kg ha-mm^{-1} (SRI with deficit irrigation) and that of Pusa 1460 ranged from 2.26 (PTR with adequate irrigation) to 3.24 kg ha-mm^{-1} (SRI with deficit irrigation) (Fig. 4). Averaged over irrigation levels and cultivars, DSR registered significantly higher WP than PTR during both the years (Table 4). Higher WP of DSR (3.49 kg ha-mm^{-1}) than that under PTR (2.60 kg ha-mm^{-1}) could be attributed to lower water use under DSR (987 mm) than that under PTR (1620 mm), and the yield increase in the PTR was not in proportion to increased water use than the DSR. These findings were in agreement with Yadav *et al*. (2011). There was no significant difference between the SRI and the DSR methods with respect to WP. The effect of irrigation levels on WP of rice was statistically at par. Averaged over the establishment methods and irrigation levels, cultivar PRH 10 registered significantly higher WP than Pusa 1460 during both the years due to higher grain yield and lower water use in the former cultivar (Table 4). Results revealed that the non-basmati cultivar PRH 10 exhibited higher WP than the basmati cultivar Pusa 1460 under DSR method of rice establishment.

Grain yield, water use and water productivity of wheat

Grain yield of wheat was significantly influenced by the residual effect of rice establishment methods. Grain yield of cultivar DBW 17 ranged from 4.7 t ha^{-1} (PTR and deficit irrigation in wheat) to 6.63 t ha^{-1} (DSR and adequate irrigation in wheat) and that of HD 2967 ranged from 4.96 t ha^{-1} (PTR and deficit irrigation in wheat) to 6.85 t ha^{-1} (DSR and adequate irrigation in wheat) during the year 2012-13 (Fig. 5). Similar treatment behaviour was recorded during 2013-14 (Fig. 6). Averaged over irrigation levels and cultivars, grain yields of wheat following DSR were significantly higher by 7.9 to 11.4 per cent than those after SRI and 16.4 to 31 per cent than those after PTR during the study period (Table 5). Higher grain yield of wheat following DSR than that of PTR was mainly attributed to better soil physical conditions as evidenced by better soil aggregation, lower BD, higher hydraulic conductivity and OC pool under DSR (Jat *et al*. 2009). Averaged over rice establishment methods and cultivars, adequate irrigation in wheat increased the grain yield significantly over deficit irrigation by 6.2 and 11 per cent during 2012-13 and 2013-14, respectively. Averaged over rice establishment and irrigation levels, HD 2967 cultivar registered significantly higher grain yield than that of DBW 17 by 5.7 and 10.5 per cent during the year 2012-13 and 2013-14, respectively (Table 5).

Total water used by wheat cultivars was also significantly influenced by the rice establishment methods. The total water use of wheat cultivar DBW 17 ranged from 326-334 mm (PTR and deficit irrigation in wheat) to 435-439 mm (DSR and adequate irrigation in wheat) and that of HD 2967 ranged from 326-339 mm (PTR and deficit irrigation in wheat) to 448-469 mm (DSR and adequate irrigation in wheat) during both the years (Fig. 5 and 6). Averaged over irrigation levels and cultivars, water use by wheat after DSR was significantly higher than that after SRI and PTR (Table 5). Higher water use by wheat after DSR than that after PTR may be attributed to higher water loss due to deep percolation in DSR plots owing to lower BD and higher hydraulic conductivity than that in PTR plots (Table 2). Water use under adequate irrigation was significantly higher than deficit irrigation by 33.2 and 25.7 per cent during 2012-13 and 2013-14, respectively. Wheat cultivars DBW 17 and HD 2967 did not differ significantly with respect to the total water use.

The WP of wheat cultivar DBW 17 ranged from 12.2 (PTR and adequate irrigation in wheat) to 17.4 kg ha-mm^{-1} (DSR and deficit irrigation in wheat) and that of HD 2967 ranged from 12.7 (PTR and adequate irrigation in wheat) to 17.4 kg ha-mm^{-1} (SRI and deficit irrigation in wheat) during the year 2012-13 (Fig. 5). During 2013-14, WP of cultivar DBW 17 ranged from 12.85 (PTR and adequate irrigation in wheat) to 16.01 kg ha-mm^{-1} (DSR and deficit irrigation in wheat) and that of HD 2967 ranged from 14.24 (SRI and adequate irrigation in wheat) to 16.42 kg ha-mm^{-1} (PTR and deficit irrigation in wheat) (Fig. 6). Averaged over irrigation levels and cultivars, WP of wheat after DSR was significantly higher than that after PTR by 19.8 per cent during 2012-13 and 3.7 per cent during 2013-14 (Table 5).This could mainly be attributed to the higher grain yield of wheat after DSR than that after PTR because of relatively better physical properties of soil after DSR (Jat *et al*. 2009). Averaged over rice establishment methods and cultivars, WP of wheat under deficit irrigation was significantly higher (13.2-16.0%) than that under adequate irrigation, owing to lower water use under deficit irrigation treatments. Also, the yield increase under adequate irrigation was not proportionate to water use compared to deficit irrigation. Wheat cultivars DBW 17 and HD 2967 did not differ significantly with respect to WP during both years (Table 5). A decrease in WUE with increasing

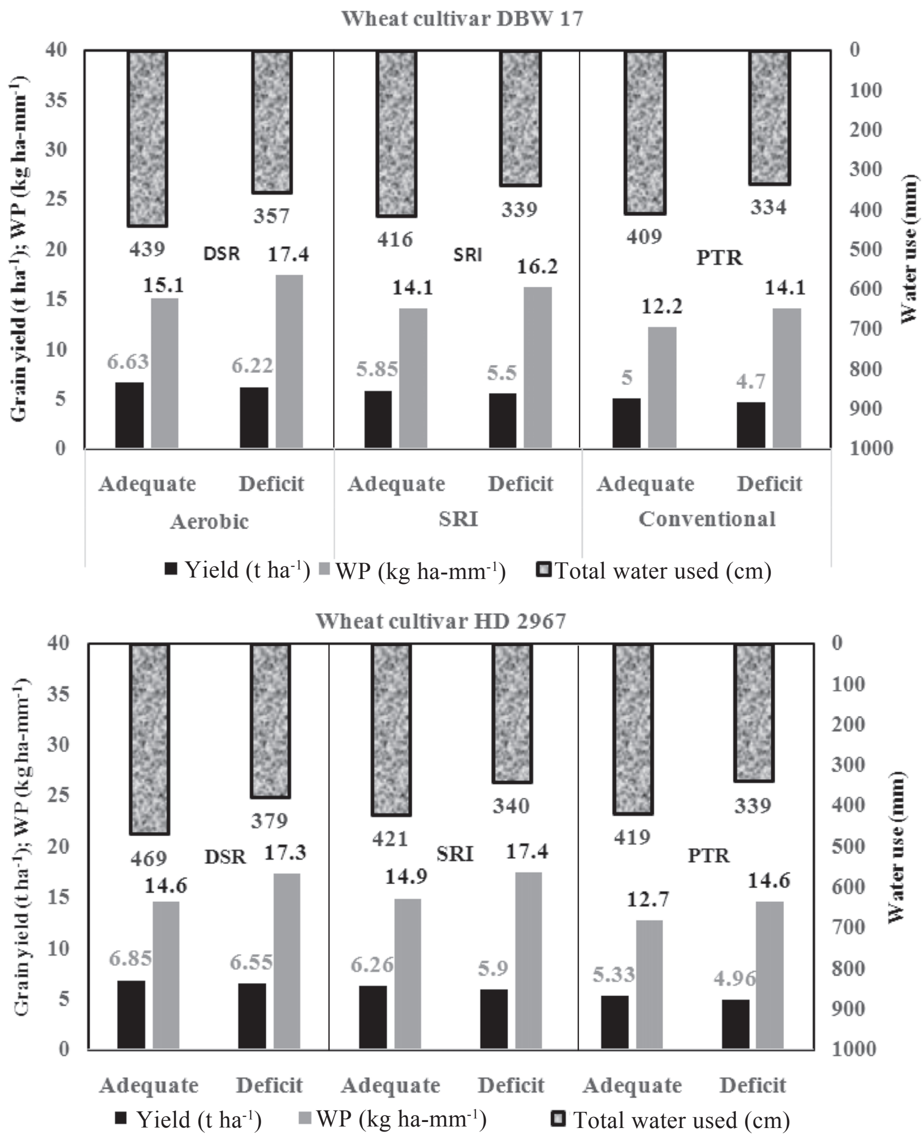

Fig.5. Grain yield, water use and water productivity of wheat cultivars as influenced by residual effect of rice establishment methods, and irrigation during *rabi* 2012-13

Table 5. Grain yield and water productivity of wheat as influenced by crop establishment (rice), irrigation and cultivars

Treatment	Grain yield (t ha^{-1})		Water use (mm)		Water productivity (kg ha-mm^{-1})	
	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
Rice establishment						
DSR	6.55a*	6.02a	411a	398a	16.1a	15.2a
SRI	5.88b	5.58b	379b	379b	15.6a	14.9b
PTR	5.00c	5.17c	375b	368b	13.4b	14.7b
Irrigation levels						
Adequate	5.99a	5.95a	429a	425a	13.9b	14.0b
Deficit	5.64b	5.36b	348b	338b	16.2a	15.8a
Cultivars						
DBW 17	5.65b	5.41b	382a	379a	15.3a	15.5a
HD 2967	5.97a	5.98a	395a	384a	14.9a	14.4a

*Numbers followed by same letters are not significantly different at $p<0.05$ as per DMRT

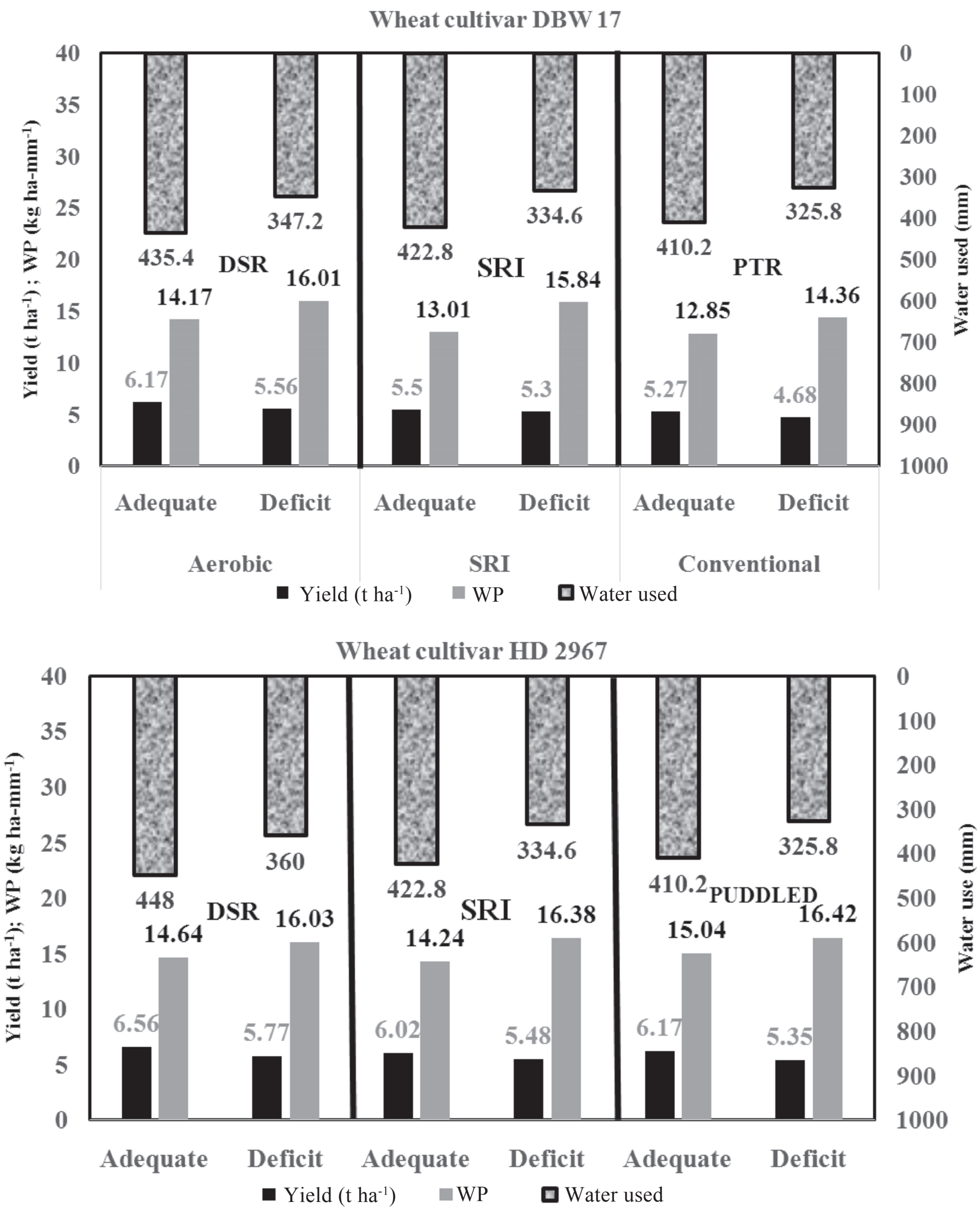

Fig. 6. Grain yield, water use and water productivity of wheat cultivars as influenced by residual effect of rice establishment methods, and irrigation during *rabi* 2013-14

irrigation level has also been reported earlier (Bandyopadhyay *et al*. 2009; Pradhan *et al*. 2014).

Grain yield, water use and water productivity of rice-wheat cropping system

Rice establishment methods significantly influenced the productivity of rice-wheat cropping system (RWCS). Averaged over irrigation levels and cultivars, the system productivity under SRI was significantly higher than DSR and PTR establishment methods by 5.9 and 16.9 per cent during 2012-13, and by 12.5 and 9.2 per cent during 2013-14, respectively (Table 6). There was no significant difference between the DSR and PTR establishment methods with respect to system productivity of RWCS. This was due to the fact that though rice yield

Table 6. Effect of crop establishment, irrigation and cultivars on system productivity, water use and water productivity of rice-wheat cropping system

Treatment	System productivity (t ha^{-1})		Water use (mm)		Water productivity (kg ha-mm^{-1})	
	2012-13	2013-14	2012-13	2013-14	2012-13	2013-14
Rice establishment						
DSR	9.85b*	9.49b	1281c	1500c	7.69a	6.33a
SRI	10.43a	10.68a	1589b	1828b	6.57b	5.84b
PTR	8.92b	9.78b	1829a	2154a	4.88c	4.54c
Irrigation levels						
Adequate	10.12a	10.44a	1707a	1961a	5.93b	5.32a
Deficit	9.35b	9.53b	1426b	1694b	6.56a	5.63a
Cultivars						
PRH 10 and DBW 17	10.36a	10.12a	1539a	1806a	6.74a	5.60a
Pusa 1460 and HD 2967	9.10b	9.85a	1594a	1848a	5.71b	5.33a

*Numbers followed by same letters are not significantly different at $p<0.05$ as per DMRT

was less under DSR system than that of PTR system, it was compensated by higher yield of subsequent wheat after DSR than that after PTR. Averaged over rice establishment methods and cultivars, the system productivity under adequate irrigation was significantly higher than that under deficit irrigation. The cultivar combination PRH 10 (rice) and DBW 17 (wheat) registered significantly higher system productivity (13.8%) than the cultivar combination Pusa 1460 (rice) and HD 2967 (wheat) during 2012-13. However, the difference in productivity of RWCS due to cultivars was not significant during 2013-14.

Averaged over irrigation levels and cultivars, the system water use under transplanted rice (1829 mm in 2012-13 and 2154 mm in 2013-14) was significantly higher than the SRI and DSR establishment methods by 15.1-17.8 per cent and 42.8-43.6 per cent, respectively during the years under study (Table 6). Water use by RWCS under adequate irrigation was significantly higher than deficit irrigation although the effect of cultivars was not significant (Table 6).

Water productivity (WP) of RWCS under DSR, SRI and PTR establishment methods was 7.69, 6.57 and 4.88 kg ha-mm^{-1}, respectively during 2012-13 and 6.33, 5.84 and 4.54 kg ha-mm^{-1}, respectively during 2013-14 (Table 6). Thus, averaged over irrigation levels and cultivars, the WP of RWCS under DSR was significantly higher than that under SRI and PTR establishment methods by 17 and 57.6 per cent during the year 2012-13 and by 8.4 and 39.4 per cent during the year 2013-14, respectively. These findings corroborated Jat *et al*. (2009). The system WP under deficit irrigation was significantly higher than that under adequate irrigation by 10.6 and 5.8 per cent during 2012-13 and 2013-14, respectively. Further, the system water productivity due to cultivar combinations followed the trends similar to RWCS production (Table 6).

Conclusions

The study revealed that there was deterioration of soil physical health under PTR compared with DSR as evidenced by decrease in MWD and percentage of water stable aggregates, and hydraulic conductivity, and increase in soil BD under PTR. However, the grain yield of rice under PTR was higher than DSR but lower than SRI method of rice establishment. But, the total water use under DSR was less than that of PTR and SRI whereas the WP under DSR was at par with SRI but significantly higher than PTR. In the subsequent wheat crop, the yield, water use and WP under DSR was higher than that under PTR. Considering the RWCS as a whole, the system productivity under SRI was significantly higher than DSR and PTR establishment methods whereas the water use under PTR was significantly higher than SRI and DSR rice establishment methods. The system WP under DSR was significantly higher than SRI and PTR rice establishment methods. In general, under adequate irrigation the WP was less than deficit irrigation both for the rice and wheat crops and RWCS. The averaged data of establishment methods and irrigation levels showed that rice cultivar PRH 10 registered significantly higher WP than Pusa 1460, whereas wheat cultivars DBW 17 and HD 2967 did not differ with respect to WP. Nonetheless, this study revealed that judicious selection of rice establishment methods, cultivars and appropriate irrigation strategy would not only enhance the WP but also restore soil health under RWCS.

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