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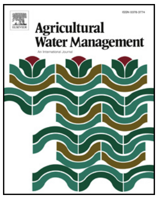

Developing soil matric potential based irrigation strategies of direct seeded rice for improving yield and water productivity

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ABSTRACT

Water and labour scarcity besides increasing cost of cultivation in transplanted puddle rice (TPR) warrants to develop and adopt input use efficient and cost effective direct seeded rice (DSR) method of cultivation. Though DSR saves substantial amount of irrigation but there are contradictory observations on yield realization. Therefore, a two year field study was undertaken with the aim to develop efficient irrigation strategy for maximizing tilled DSR yield with minimum irrigation input. Total 08 irrigation strategies, based on 03 soil matric potential (SMP) levels (−15, −30 and −45 kPa) and their combinations based on crop growth stages, were evaluated for fine grain aromatic (Basmati) rice variety 'CSR30'. Responses of respective irrigation strategies were evaluated on crop water use and its components, biometric parameters and yield attributes and yield of DSR. Performance of DSR was also compared with standard TPR practice. Soil profile moisture content ranged from 32 to 39, 27–39 and 22–39% in −15, −30 and −45 kPa irrigation regimes, respectively. Irrigation input in DSR method of cultivation varied between 709–1541 mm as compared to 1807 mm of TPR. With different irrigation strategies, DSR grain yield and irrigation water productivity (IWP) varied from 1.72 to 2.89 Mg/ha and 0.19–0.24 kg/m^3, respectively. Irrigation threshold −15 kPa at all stages in DSR produced the highest yield and crop water productivity (CWP; 0.48 kg/m^3), but with lowest IWP. Irrigations at or below −30 kPa during initial phase (< 90 DAS) and at −15 kPa during remaining period produced comparable yield with significantly higher IWP. Though TPR registered lower IWP (0.18 kg/m^3) as compared to the best DSR treatment but recorded about 11% higher grain yield with significantly higher crop water productivity (0.58 kg/m^3) than DSR. Water balance studies revealed better utilization of precipitation in DSR due to irrigations at more negative SMP. Overall, study suggests irrigation scheduling at $\leq$ −30 kPa during initial phase and −15 kPa during the remaining crop season proved to be the optimum irrigation threshold for maximizing DSR yield with limited irrigation input.

1. Introduction

Meeting the food demand, of a continuously increasing world population, has become a major challenge, especially in water scarce regions where water management in agriculture is often inefficient (Yao et al., 2012). It is more so in the most of resource poor communities in Asia including India. Nevertheless, the Asian region, which suffers the most from scarcity and uneven availability of water, has been identified as an area of high climate risk under projected global climate change scenarios (IPCC, 2013; Liu et al., 2015). India cultivates rice in > 4.34 Mha, the highest in the world, with the second largest production of 15.72 million Mg after China (FAOSTAT, 2014). The north-western region of India, comprising Punjab, Haryana and Western Uttar Pradesh, has played an important role in food and livelihood security of the country by contributing a major share to national food basket. The region produces ˜48% of the total rice production of the country (Rockström et al., 2007).

Transplanted puddled rice (TPR) followed by conventional tilled wheat (RW) is the dominant cropping system of this part of the country. The percolation and surface evaporation losses of water are very high from TPR fields (Farooq et al., 2011). The evaporation loss is estimated to be 30–40% of total evapotranspiration (Tabbal et al., 2002). Depending upon texture of soil, combine seepage and deep percolation losses vary between 25–85% of total water losses from the paddy field (Bouman et al., 2005). TPR is also labour intensive and requires 2–3 times more water, as compared to upland crops like maize (Bhushan et al., 2007), leading to overexploitation of groundwater and thus has become uneconomical (Kumar and Ladha, 2011). Under prevailing TPR-wheat cropping system, groundwater is depleting at a rate of about 0.33 m per year in north-west part of India (Narjary et al., 2014).

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Creating shallow hard pan through puddling is beneficial in TPR-TPR cropping system for reducing irrigation water demand by reducing deep percolation losses but, it adversely affects productivity of upland cropping systems (McDonald et al., 2006). The long term practice of TPR system has adverse effect on wheat yield due to sub-soil compaction and restricted root growth in the lower layers (Naresh et al., 2010). Negative impacts of conventional RW system are further aggravated in RW cropping system with fine grain aromatic rice (CSR 30) because of its long duration causing delay in wheat sowing and reduction in grain yield.

Water and labour scarcity and increasing cost of cultivation in TPR are forcing farmers to adopt input use efficient and cost effective direct seeded rice (DSR) technique (Dawe, 2005; Kakraliya et al., 2018). Establishment of crop by broadcasting/line drilling seed directly in the non puddle soil having optimum moisture is referred as direct seeded rice (Liu et al., 2015). DSR improves soil physical conditions. Adoption of zero tillage or minimum tillage operation in place of conventional agronomic practices improves water stable macro aggregates in surface soil (Choudhury et al., 2014). The soil penetration resistance (SPR) in direct seeded rice (DSR) is significantly lower at sub-surface soil layer as compared to puddled rice in north-west India (Jat et al., 2018). Research studies on DSR at various places revealed that though it saves substantial amount of irrigation water in addition to achieving higher water use efficiency and reducing greenhouse gases emission, but with contradictory observations on yield gains and losses (Bhushan et al., 2007; Saharawat et al., 2010; Zhang et al., 2017; Wang et al., 2017). It is an established fact that performance of crops is very sensitive to water stress. Rice being high water requiring crop is even more sensitive with DSR method of cultivation as compared to TPR. Though water stress tolerance level of crops varies with crop growth stages (Yadav et al., 2011) but despite of some published guidelines, systematic information on irrigation scheduling for DSR is lacking (Gopal et al., 2010). So far very limited systematic studies, that too with contradictory observations, have been conducted for optimizing irrigation schedules for DSR. Yadav et al. (2011) reported −20 kPa soil moisture potential (SMP) as safe limit while Mahajan et al. (2011) recorded contradictory observations. Hence, there is a great need to identify optimum irrigation schedules for getting the maximum benefit from DSR method of cultivation. Keeping above facts in view, the present study was undertaken with a hypothesis that water stress during vegetative phase reduces irrigation demand without compromising crop yield and to develop suitable irrigation strategies for higher input factor productivity and production of tilled DSR method of cultivation.

2. Materials and methods

2.1. Description of experimental site

Present field study was carried out on the experimental farm of Central Soil Salinity Research Institute, Karnal, India (29° 42′ 20.6″ N, 76° 57′ 19.80″ E, 243 m AMSL) for two years during *Kharif* seasons of 2014 and 2015. The climate of the area is semi-arid to sub-humid with an average annual rainfall of 655 mm. About 486 and 386 mm rainfall was received during crop seasons of 2014 and 2015, respectively, which was only 58 and 53% of the evaporation occurred during respective seasons. Total 21 and 14 numbers of rainy days were recorded during crop seasons of 2014 and 2015, respectively. However, 10 and 9 numbers of rainy days were observed during July – August period of 2014 and 2015, respectively, which coincides with vegetative phase of rice.

Physio-chemical properties of the soil of experimental site are listed in Table 1. The soil was sodic (Alkali) prior to start of extensive cultivation about 40 years back. It was reclaimed using gypsum ‘a chemical amendment’. But pH of the soil, below 30 cm, is still in alkali range (> 8.5), which limits moisture movement through soil profile and nutrient availability. Soil texture in 0–120 cm soil depth is loam to sandy clay loam.

2.2. Experimental design and treatments

Considering previous observations, crop physiology and aim of reducing irrigation demand to maximize precipitation use; soil moisture potential (SMP; -15, -30 and -45 kPa) based irrigation scheduling treatments were planned and assessed, in this study, to develop suitable irrigation strategies for fine grain aromatic (CSR 30) tilled DSR. The treatments consisted of continuous irrigation scheduling at respective SMPs and their selected combinations (Table 2) imposed during establishment (10–30 DAS), vegetative (31–90 DAS), reproductive (91–120 DAS) and ripening (121–135 DAS) phases of crop growth, respectively. To test our hypothesis i.e. water stress during vegetative phase reduces irrigation demand without compromising crop yield, and proper implementation of treatments in field; a total of eight irrigation scheduling strategies were imposed in DSR. These comprised of continuous minimum (T1), mild (T2) and high (T3) stress, and mild to high stress except at reproductive phase (T4, T5, T6, T7 and T8). During first 10 days, all DSR plots received uniform irrigations for proper germination and establishment. Thereafter, to impose water stress, irrigations were applied at different crop growth stages as per pre-decided SMPs. SMP was monitored with irrometer (gauge-type soil tensiometer; made by IRROMETER, Riverside, CA) installed at 15 cm depth in every plot. While in TPR, 3–4 cm water depth was maintained continuously for first 20 days after transplanting (DAT). However, during remaining crop period, subsequent irrigations were applied at 2 days after water disappearance (DWD) from the surface of field. Irrigation was stopped 15 days prior to harvesting in each plot. The details of soil matric potential for imposing irrigation treatments at different crop stages is given in Table 2.

2.3. Agronomic practices

The field was ploughed and leveled with laser guided land leveler before laying out the experiment. In first year, field was prepared by 2 harrowings followed by planking. However, in second year, plots were prepared using power tiller. Pre-sowing irrigation was applied in each year and seeds placed at ˜3–4 cm below soil surface in DSR when soil moisture reached at the field capacity. While in TPR, prior to transplanting of seedlings, soil was puddled using power tiller. In DSR, seeds were sown on 15 and 14 June in 2014 and 2015, respectively keeping row to row spacing of 20 cm. Nursery for transplanted plots was sown on the same day during respective seasons and transplanting was done in puddle plots with 25 days old seedlings. About 20, 13, 25 and 10 kg/ha of N, P_2O_5, K_2O and $ZnSO_4$, respectively were applied as basal dose in both DSR and TPR. Remaining 40 kg N/ha was applied in two equal splits at 21–23 and 42–45 days after sowing (DAS)/transplanting. For controlling weeds, pre- and post-emergence herbicides were applied at 1 and 21 DAS, respectively in DSR; but in TPR, only post emergence herbicides were applied at 15 DAT.

2.4. Water balance

The water balance of each plot was computed by using the following relationship (Eq. 1)

$$R_c = (I + R) - R_o - (ET_c) \pm \theta_{smc} \tag{1}$$

where, R_c is Recharge component (mm); I, R, R_o and ET_c are irrigation applied (mm), rainfall (mm), Runoff (mm) and evapotranspiration (mm), respectively; while θ_{smc} is change in soil moisture storage in different depths (mm) in a given period. The proportion of input water moved beyond 1.2 m soil depth was considered as ground water recharge component (R_c). R_c was determined at weekly interval and summed up for the whole season. Among the water balance components, rainfall, irrigation amount, runoff and change in soil moisture

Table 1
Soil physiochemical properties of experimental field.

Depth (cm)	Texture			Texture class	Bulk density (kg/m^3)	EC$_e$ (dS/m)	pH$_e$
	Sand (%)	Silt (%)	Clay (%)				
0-15	43.50	31.24	25.26	Sandy Clay Loam	1.59	1.14	8.29
15-30	41.00	33.12	25.88	Loam	1.63	1.13	8.25
30-60	36.74	33.76	29.50	Clay Loam	1.68	1.10	8.71
60-90	38.36	29.84	31.80	Clay Loam	1.62	0.97	9.15
90-120	43.82	29.04	27.14	Clay Loam	1.58	1.21	9.20

Table 2
The detail of SMP based irrigation strategies implemented for DSR.

Treatment	Symb.	Establishment Phase (10-30 DAS)	Vegetative Phase (31-90 DAS)	Reproductive Phase (91-120 DAS)	Ripening phase (121-135) DAS)
		Soil matric potential/irrigation threshold			
15-15-15 – 15 kPa	T1	15 kPa	15 kPa	15 kPa	15 kPa
30-30-30 – 30 kPa	T2	30 kPa	30 kPa	30 kPa	30 kPa
45-45-45-45 kPa	T3	45 kPa	45 kPa	45 kPa	45 kPa
15-30-15-15kPa	T4	15 kPa	30 kPa	15 kPa	15 kPa
15-45-15-15kPa	T5	15 kPa	45 kPa	15 kPa	15 kPa
30-30-15 – 30 kPa	T6	30 kPa	30 kPa	15 kPa	30 kPa
45-45-15-45 kPa	T7	45 kPa	45 kPa	15 kPa	45 kPa
30-30-15 – 15 kPa	T8	30 kPa	30 kPa	15 kPa	15 kPa
Transplanted rice, 2 DWD	TPR	Irrigation after 2 days of disappearance of water from field surface			

were measured directly from the field and evapotranspiration was estimated using related weather parameters. A 50 cm wide uncultivated strip having bunds on both edges consisting 60 cm wide vertical plastic film, were used to minimize any possibility of lateral seepage. In addition to it, 2 m strip bordering inside of the plots was left and not considered for data collection including soil matric potential (SMP) observation. Hence, lateral seepage was considered zero for water balance study. With the help of water meter fitted on main outlet and pipe network, approximately, 5.5–6.0 cm water was applied directly to each of the plots. The volume of water applied was divided by plot size (10 m × 10 m) to convert irrigation (I) in mm for individual treatment plots. Daily weather parameters viz. temperature, relative humidity, wind speed, sunshine hours, rainfall etc. were collected from the weather station situated adjacent to the experimental area. Runoff was generated only when heavy rains took place. It was estimated as difference between height of bund, depth of ponded water before rainfall and amount of rainfall occurred (Yadav et al., 2011). The crop evapotranspiration for different treatments were estimated as (Eq.2)

$$ET_c = ET_0 \, x \, K_c \, x \, K_s \tag{2}$$

where ET_0 is potential evapotranspiration estimated with Penman-Montieth method according to FAO 56. Locally developed crop coefficient "K_c" by Choudhury et al. (2013) was adopted for crop ET_0 calculation. Water stress coefficient "K_s" was calculated on daily basis by using soil moisture content and following the procedure described in FAO 56. Estimated ET was partitioned, into evaporation (E) and transpiration (T), according to the relationship given by Belmans et al. (1983) as a function of crop growth. The evaporation and transpiration were calculated using following relationships, respectively, (Eqs. 3 and 4)

$$E_p = ET_c \, x \, e^{-K_{gr} x LAI} \tag{3}$$

$$T = ET_c - E_p \tag{4}$$

Where, K_{gr} is an extension coefficient. In order to estimate change in moisture storage in upper 120 cm soil depth, soil moisture content from different layers (0–15, 15–30, 30–60, 60–90 and 90–120 cm) was measured at weekly interval by using Neutron moisture probe (CPN 503 TDR Hydroprobe). For this purpose, aluminum access tubes were installed in each plot. TDR (Trime-PICO 64) was used to measure soil moisture from surface 15 cm soil layer.

2.5. Crop biometric observations and water productivity

Plant height, tillers/m row length (m.r.l.) and leaf area index were measured at 15 days interval as crop growth indicators. But, in this paper, the maximum values recorded at the end of vegetative phase were used for comparing treatments' effect. Ten plants from each plot were selected randomly and tagged at 15 DAS/DAT for determining plant height and plot wise heights averaged for representing respective treatments. In order to determine tillers in unit length of DSR, one m.r.l. was earmarked randomly at three places and used for counting tillers/m.r.l for respective plots. In TPR, 0.9 m.r.l. was used for counting tillers. Leaf area index (LAI) was measured by using canopy analyzer (SunScan, Delta-T Devices Ltd, UK). LAI was taken from 5 places in a plot and average value was used for comparing the treatments.

Panicle numbers were recorded by harvesting randomly selected five rows of 0.9 and 1.0 m length from TPR and DSR, respectively and averaged for representing panicles/m.r.l. in respective treatments. To determine grains/panicle, 15 panicles were randomly picked from harvested samples, grains separated manually and counted. An area of 36 m^2 was harvested from the middle of each plot and threshed manually for determining the grain yield. Representative grain samples from respective treatments were oven dried and total grain yield was expressed at 14% moisture content. Total grains produced in a hectare area were divided with volume of water applied for estimating irrigation water productivity (IWP). IWP was expressed as kilogram of grains produced for per m^3 of irrigation applied. The crop water productivity (CWP, kg/m^3) was estimated as crop yield per unit water consumed (Zwart and Bastiaanssen, 2004). The water consumed by the crop was taken equal to the crop evapotranspiration.

2.6. Statistical analysis

Eight DSR treatments and TPR (as control) were laid out in triplicate in randomized block design (RBD) and compared. Data on all crop biometric parameters were subjected to analysis of variance (ANOVA) test to confirm significance of variability among treatments. ANOVA analysis was performed online with SAS 9.2 version (http://stat.iasri.res.in/sscnarsportal). Treatment means of respective parameters were

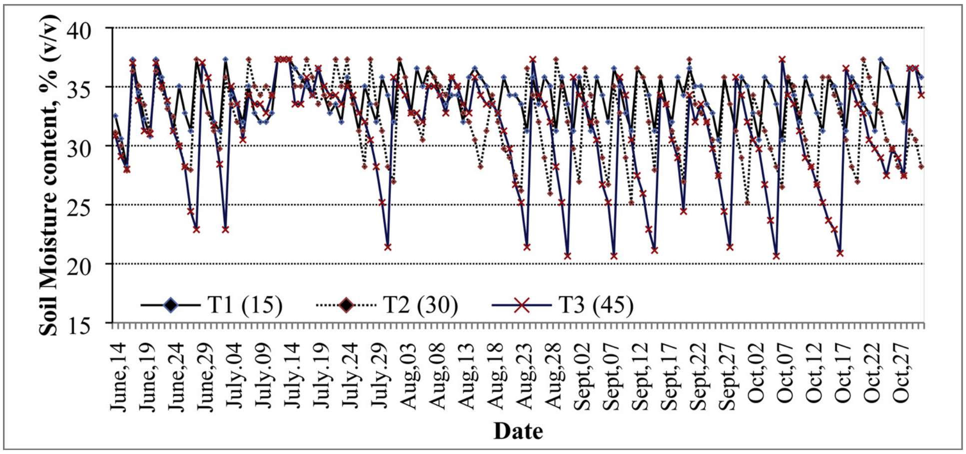

Fig. 1. Variation in soil moisture content in 0–15 cm soil layer under different SMP based irrigation strategies, T1:15-15-15-15 kPa; T2: 30-30-30-30 kPa; T3: 45-45-45-45 kPa.

compared using least significant difference (LSD) at 5% ($p = 0.05$) level of probability.

3. Results and discussion

3.1. Soil moisture content

The irrigation scheduling thresholds varied according to pre-decided soil matric potential of -15, − 30 and − 45 kPa adopted during different crop growth phases. However, to get a distinct information about the soil moisture fluctuation, soil moisture content of only three treatments providing irrigation continuously at − 15 kPa (T1), − 30 kPa (T2) and − 45 kPa (T3) during all crop growth phases are included here and presented in Fig. 1. Frequent peaks followed by declines were observed in soil moisture content in − 15 kPa (T1) treatment. In this treatment, soil moisture fluctuated between 32–39% and never dropped below the field capacity (FC; ˜31%) at any crop growth phase. In case of − 30 kPa (T2) treatment, soil moisture content varied between 27–39%. It decreased below FC for some time but rarely for more than one day. Contrary to these two treatments, the soil moisture dropped far below (i.e. 21%) FC and remained so continuously for 2–3 days between two irrigations in − 45 kPa (T3) irrigation regime. Nevertheless, though the soil moisture did not reach frequently to threshold of − 45 kPa during vegetative period, due to refilling of soil pores by rains (219 mm, mean of two consecutive seasons) received, but it decreased to this level more frequently during reproductive stage due to lesser rains.

3.2. Crop growth

The seed germination and crop stand in all plots were good during early period because irrigation treatments were imposed only at 10 DAS onwards. However, variation in crop growth was observed after introduction of treatments that became further conspicuous by the end of vegetative period (90 DAS). The plant height, number of tillers per m.r.l. and leaf area index (LAI) recorded at 90 DAS (Fig. 2a–c) served as growth indicators for comparing different irrigation strategies. The data presented in Fig. 2, shows that T1, DSR with irrigation threshold − 15 kPa at all stages, produced the maximum plant height (118.8 cm), number of tillers per m.r.l. (150.3) and LAI (4.9). Significantly lower values for plant growth indicators in T2 and T3 as compared to T1 revealed that further increase in SMP to − 30 kPa and − 45 kPa for scheduling irrigation, had detrimental effect on plant growth.

The best crop performance with irrigation regime of − 15 kPa at all stages was probably due to the maintenance of more conducive soil moisture as it always remained above the field capacity, which might have facilitated better nutrient uptake as also observed earlier (Yadav et al., 2011; Jat et al., 2018) and luxurious crop growth. However, performance in T4 was comparable with T1 in terms of plant height and no of tillers/ m.r.l., which means that mild stress only during vegetative phase, coinciding with monsoon season, did not cause adverse impact. But, LAI (4.65) differed significantly due to the combined effect of slightly lower number of tillers/ m.r.l. and crop growth in comparison to T1. Further increase in soil matric potential to -45 kPa during initial phase of 90 DAS (T7) resulted into lower values of plant growth indicators. The worst growth indicators were recorded in T3, probably due to the fact that irrigation threshold of -45 kPa at all stages led to sub-optimal soil moisture for 2–3 days between every cycle of two irrigations and consequently causing repeated water stress during crop season. This poor performance, observed with higher soil matric potential, confirmed that limited water supply adversely influenced morpho-physiological behavior of the crop as also reported earlier by Cheng and Song (2006); Yadav et al. (2011) also recorded lower tiller density and LAI in DSR, with irrigations scheduled at more negative soil matric potential of − 40 and − 70 kPa than − 20 kPa, because of water stress and deficiency of iron. Comparable crop growth performance in T2 with T6 and T3 with T7, also clearly indicated that frequent irrigations during reproductive stage did not have any positive impact on crop growth indicators. Our observations are in the line of the findings of Sarvestani et al. (2008), who reported that higher moisture regimes during reproductive stages of rice did not influence plant height significantly. Further, Pirdashti et al. (2004) observed that water stress imposed during reproductive stages produces at par plant height with well watered transplanted rice but significantly lower in those plots which experienced water stress during vegetative stage.

3.3. Yield contributing attributes and grain yield

Variable irrigation thresholds adopted during different crop growth phases had significant effect on yield contributing attributes like number of panicles/m.r.l., grains/panicle and 1000-grain weight. The most of DSR treatments produced more than 130 tillers/m.r.l. Interestingly about 20–30% less number of panicles/m.r.l. was recorded at the time of harvest than at 90 DAS but reduction was not similar in all treatments. Among different irrigation strategies, T1 with irrigation threshold of − 15 kPa at all stages produced the highest number of panicles/m.r.l as well as grains/panicle (Table 3). Further stress due to increase in irrigation threshold to − 30 kPa (T2) and − 45 kPa (T3) at all stages, significantly reduced number of panicles/m.r.l and grains/panicle. However, T4 and T8 produced relatively higher grains/panicle with lower number of panicles/m.r.l as compared to T1. This suggests that mild stress only during vegetative phase though reduced panicles/m.r.l but produced more number of grains/panicle than T1. This was

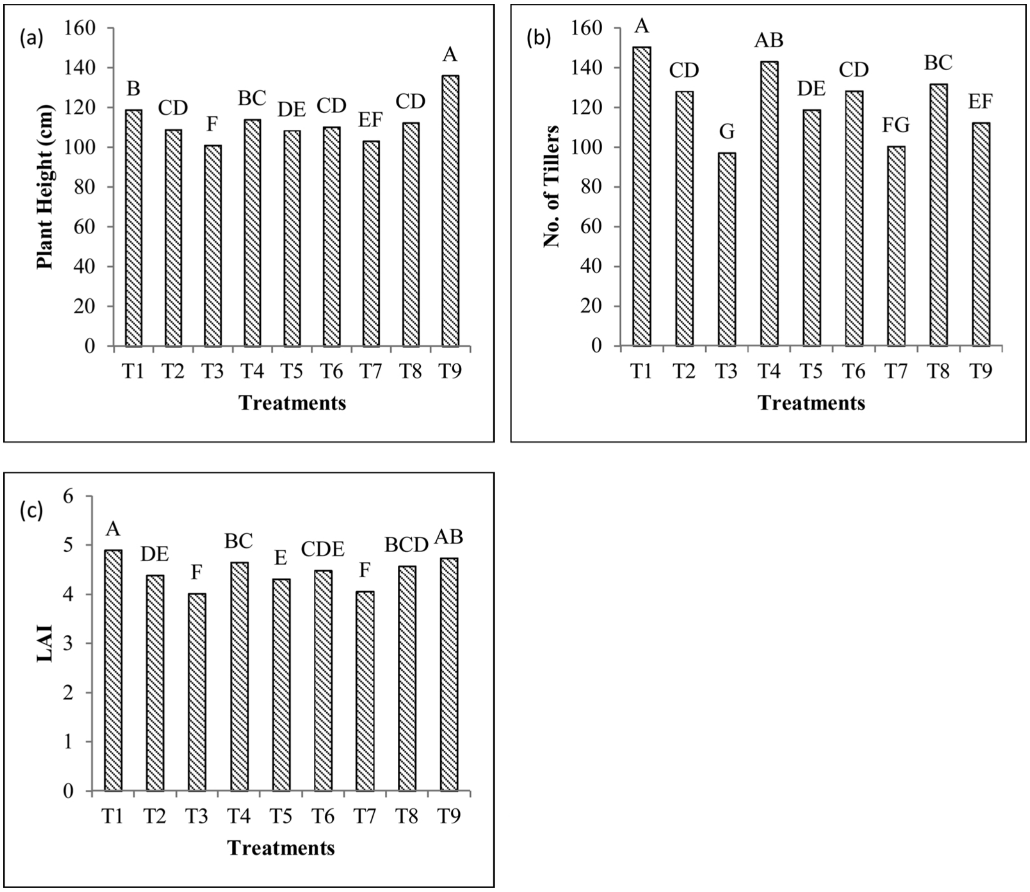

Fig. 2. Effect of different irrigation treatments on a) plant height, b) tillers/m.r.l. and c) leaf area index (LAI) (mean represented by bars having similar letter are not different at the 0.05 level of probability.

probably due to lesser competition for water and nutrients at later crop growth stages under lower plant population. Liu et al. (2015) also observed a reciprocal relationship between spikelets/panicle and plant population and attributed it to more competition for production factor inputs. T3 produced the lowest (61.4) grains/panicle as well as number of panicles/m.r.l among all DSR irrigation strategies. It might be due to the fact that crop experienced repeated water shortage under −45 kPa irrigation schedule at all stages. Slight improvement in grains/panicle in T7 than T3 shows the importance of frequent irrigations at reproductive stage, but, that was not sufficient to compensate significant reduction in grains/panicle and number of panicles/m.r.l. Similarly, the best performance in terms of 1000 grain weight was recorded in T1, while T3 produced the lowest 1000 grains weight. This variation was directly associated with water availability and crop vigour (Table 3). T4, T6 and T8 produced grains weight statistically at par with T1. This indicates that irrigation threshold at or below −30 kPa during initial phase (< 90 DAS) and −15 kPa during remaining period was able to create conducive soil moisture regimes for producing vigorous grains in DSR. Significantly higher 1000 grains weight in T7 than T3 but lower than the other treatments, indicates that irrigations at −15 kPa during reproductive stage alone had very little influence on grains weight when irrigation is applied at −45 kPa during the remaining period. But higher 1000 grains weight in T8 than T6 indicates that frequent irrigations at ripening stage improved grains weight further.

The response of various irrigation strategies to grain yield was similar to that observed for yield contributing traits. For different irrigation strategies of DSR, grain yield varied from 1.72 to 2.89 Mg/ha. Higher frequency of irrigation with SMP −15 kPa throughout the season (T1) produced the maximum grain yield in DSR. Further increase in SMP to −30 kPa (T2) and −45 kPa (T3) recorded significant

Table 3
Effect of different irrigation treatments on yield attributes, total grain yield and water productivity.

Treatment	Symb.	No. of panicle/m	No of grains/panicle	Total grain Yield (Mg/ha)	1000_grains weight (gm)	Irrigation Water Productivity (kg/m^3)	Crop Water Productivity (kg/m^3)
15-15-15 − 15 kPa	T1	104.6^{A}	69.7^{BCD}	2.89^{B}	21.67^{BC}	0.19^{BC}	0.48^{B}
30-30-30 − 30 kPa	T2	91.4^{CD}	67.4^{E}	2.42^{DE}	20.50^{DE}	0.24^{A}	0.43^{C}
45-45-45-45 kPa	T3	80.2^{F}	61.4^{F}	1.72^{F}	18.15^{F}	0.24^{A}	0.37^{D}
15-30-15 − 15 kPa	T4	96.3^{B}	70.8^{B}	2.72^{BC}	21.91^{B}	0.21^{AB}	0.47^{B}
15-45-15 − 15 kPa	T5	89.2^{D}	69.1^{CDE}	2.29^{DE}	20.90^{CD}	0.21^{ABC}	0.43^{C}
30-30-15 − 30 kPa	T6	93.1^{BCD}	68.4^{DE}	2.53^{CD}	21.56^{BC}	0.22^{AB}	0.43^{C}
45-45-15-45 kPa	T7	84.7^{E}	62.3^{F}	2.19^{E}	19.75^{E}	0.24^{A}	0.44^{C}
30-30-15 − 15 kPa	T8	94.8^{BC}	70.7^{BC}	2.76^{BC}	22.34^{B}	0.22^{A}	0.47^{B}
Transplanted rice, (2 DWD)	TPR	94.1^{BC}	73.5^{A}	3.25^{A}	24.06^{A}	0.18^{C}	0.58^{A}

Note: Means in the columns followed by common letters are statistically at par at the $P < 0.05$ level.

reduction due to poor yield contributing parameters. The yield reduction in T2 and T3 as compared to T1 was about 16 and 40%, respectively. Higher yield in −15 kPa irrigation threshold was the combined positive effect of higher number of panicles/m.r.l., grains/panicle and 1000 grains weight. Our finding of higher yield in irrigation at −15 kPa throughout the season is in line with the observations of Yadav et al. (2011), who reported that in DSR, irrigations scheduled at −20 kPa and daily irrigation produced comparable grain yield. The lowest grain yield recorded in T3 was due to dropping of soil moisture far below the field capacity between every cycle of two irrigations which might have led to insufficient water availability for full development of crop reproductive primordia and optimum yield realization. Earlier Mostajean and Eichi (2009) also reported that water shortage in rice significantly affected photosynthetic rate thereby reduction in production of assimilates for panicle growth and grain filling and ultimately total grain yield. However, T7 with irrigations at −15 kPa during reproductive stage and at -45 kPa during the remaining period produced significantly higher grain yield than T3. It confirms the positive impact of frequent irrigations during reproductive phase (Table 3), however, insufficient to match the yield level of still better performing irrigation strategies. T4 and T8 produced numerically lower but statistically at par grain yield to T1. Since vegetative growth stage of rice coincides with active period of south-west monsoon in Indo-Gangetic Plains of South Asia, so any mild water stress imposed during this phase had no or very little adverse effect on crop growth. Further, mild stress during early stage of CSR-30 prevents luxurious growth and crop lodging and thus higher grain yield (Jabran et al., 2017). Thus mild water stress, as a result of irrigations at −30 kPa during first 90 DAS, probably did not prove detrimental to good grain yield. Further, lower yield of T2 than T8 indicated that even mild stress (−30 kPa) during reproductive and ripening stages adversely affected 1000 grains weight and grain yield. Lower 1000 grains weight was probably due to the fact that irrigation at SMP more than −15 kPa during latter stage might have caused decreased translocation of assimilates to the grains as also observed earlier by Rahman et al. (2002). Overall, it can be summarized that irrigation threshold of −30 kPa during initial phase (up to 90 DAS) and at −15 kPa during remaining crop season saves significant irrigation input without adverse effect on grain yield.

3.4. Water productivity

3.4.1. Irrigation water productivity

Variable irrigation frequency under different irrigation strategies registered a wide range of irrigation water productivity (IWP). For different irrigation strategies of DSR, IWP ranged from 0.18-0.24 kg/m^3 (Table 3). Despite of the highest grain yield, T1 registered the lowest IWP among all DSR treatments. The highest (0.24 kg/m^3) but identical IWP was recorded for T2, T3 and T7 which indicates that crop response in terms of grain yield for unit amount of water applied was better than the other DSR treatments. T6 and T8 produced the second best IWP (0.22 kg/m^3) among all DSR treatments. Numerically lower IWP was found in T4 and T5 than T2, but difference was non-significant. Among the treatments registering identical IWP, T2 produced the highest grain yield. It indicates that mild stress (−30 kPa) at all crop growth stages could be a good option for maximizing DSR yield per unit water applied under limited water supply.

3.4.2. Crop water productivity

Crop water productivity (CWP) i.e. yield response to ET under different irrigation strategies ranged from 0.37-0.48 kg/m3 in DSR (Table 3). The variation in CWP was mainly due to yield variation with almost similar ET or vice versa. The well watered DSR irrigation threshold (−15 kPa) at all stages recorded the highest CWP value (0.48 kg/m3). T4 and T8 irrigation strategies recorded statistically at par CWP (0.47 kg/m^3) with T1 which clearly indicates that crop did not experience water stress much during vegetative phase despite of lesser and very little reduction in yield was in proportion of the ET. That shows effective contribution of rains towards crop ET and yield. This suggests that, under limited water resources, mild water stress ($\leq$ −30 kPa) can be imposed during early phase (till the end of vegetative stage). However, irrigation threshold of −30 kPa (T2) and −45 kPa (T3) at all growth stages recorded significantly lower CWP as compared to other irrigation strategies. The lowest CWP (0.37 kg/m3) in T3 shows that −45 kPa irrigation threshold reduced crop yield drastically than ET. Though, frequent irrigation during reproductive stage (T7) improved CWP significantly (0.43 kg/m3) as compared to T3 because of greater proportional improvement in yield than ET.

3.5. DSR vs TPR

Despite of higher tiller density and LAI, even the best DSR treatment (T1) did not match TPR yield (Fig. 2 and Table 3). TPR, with 15% more irrigation input, produced significantly higher grain yield and at par IWP than T1. However, T4 and T8 saved substantial irrigation input with significantly higher IWP in comparison of TPR. But, the significantly higher CWP (0.58 kg/m^3) in TPR than all irrigation strategies of DSR clearly affirm the superiority of TPR for achieving higher yield with per unit crop water use. The higher yield (3.25 Mg/ha) in TPR, despite less tillers/m.r.l., was due to significantly higher number of grains/panicle (73.5) and 1000- grains weight than DSR. Competition for soil moisture by more tilleres/m.r.l., particularly during reproductive and ripening might had led to unfertile and/or partially filled spiklets and grains leading to lower number of grains/panicle and 1000-grains weight and ultimately lower yield in DSR. Liu et al. (2015) also recorded lower spikelets/panicle in DSR than TPR and established a reciprocal relationship between spikelets/panicle and plant population. Relatively more yield reduction in DSR than TPR, as observed in our study, is consistent with 27% lower yield of DSR when irrigated at field capacity (Choudhury et al., 2007) and in reduced or zero till DSR at farmers field (Ladha et al., 2009). However, contrary to above findings, Yadav et al. (2011) reported comparable yield of DSR irrigated at −20 kPa and TPR. Likewise Singh et al. (2005); Bhushan et al. (2007) and Saharawat et al. (2010) have also reported similar yield of DSR and TPR. Relatively inconsistent performance of DSR was probably due to poor understanding of crop response to soil moisture at different growth stages, site-specific soil conditions and no standard plant population guidelines for DSR. At seed rate of 25 kg/ha, higher plant population/m^2 with excellent growth was recorded in DSR during vegetative phase but that did not convert into good yield. The dense population led to lower number of panicles/m.r.l., grains/panicle and 1000 grain weight and thus ultimately lower yield. Further, there is chance of reaching predefined SMP earlier in top 10 cm layer than the depth of tensiometer installed (˜15 cm depth). The porous cup depth of tensiometer was decided by keeping the fact in view that it will be an average representation of SMP of 30 cm effective root zone of the rice crop. But, the yield gap between well watered DSR and TPR warrants further more systematic field investigations on placement depth of tensiometers for precise representation of available soil moisture in the effective root zone of DSR. Also there is a need for further studies to optimize plant density for ensuring better moisture, nutrients and other production factors availability. These two factors seem mainly responsible for lower yield in DSR in comparison to TPR.

3.6. Water balance

In DSR, irrigation input varied (between 709.5–1540.5 mm) with frequency and number of irrigations depending on SMP adopted during different crop growth stages (Table 4). T1, adopting −15 kPa SMP based continuous irrigations, received the maximum irrigation (1541 mm). Increase in irrigation threshold to −30 kPa (T2) and further to −45 kPa (T3) at all stages saved about 35 and 54% irrigation water, respectively.

Table 4
Water balance components of rice recorded with different irrigation strategies.

Treatment	Symb.	Irrigation (mm)	Rainfall (mm)	Ep[a] (mm)	Tp[a] (mm)	Runoff (mm)	ΔSWC[b] (0-1.2 m) mm	Recharge component (mm)
15-15-15−15 kPa	T1	1540.5	431.6	253.2	388.3	10.5	74.6	1245.5
30-30-30−30 kPa	T2	1007.0	431.6	271.8	333.4	7.5	18.7	807.2
45-45-45-45 kPa	T3	709.5	431.6	285.6	274.2	5.5	14.1	561.7
15-30-15−15 kPa	T4	1243.0	431.6	251.5	361.3	9.0	40.3	1012.5
15-45-15−15 kPa	T5	1097.0	431.6	260.2	333.2	9.0	49.0	877.2
30-30-15−30 kPa	T6	1131.0	431.6	264.2	355.5	5.1	22.4	915.4
45-45-15-45 kPa	T7	908.0	431.6	264.8	303.8	6.5	12.2	752.3
30-30-15−15 kPa	T8	1192.5	431.6	255.9	367.6	7.0	38.1	955.5
Transplanted rice, (2 DWD)	TPR	1806.5	409.2	239.6	353.2	74.8	34.0	1514.1

[a] Ep&Tp – Evaporation & transpiration.

[b] Soil water content.

The significant saving in water in −30 kPa (534 mm) and −45 kPa (831 mm) as compared to −15 kPa irrigation threshold at all stages was recorded due to longer irrigation interval and lesser number of irrigations. However, the saving in water simultaneously reduced yield. It implied that both higher yield and water saving should be considered while deciding irrigation scheduling threshold in DSR. Treatments T4 and T5 also saved 19 and 29% irrigation water, respectively over T1. Likewise mild stress (−30 kPa) during initial stages and frequent irrigation during the reproductive season also saved 23 % irrigation water than T1.

Estimated evapotranspiration (ET) in different irrigation strategies of DSR differed with variation in soil moisture availability. The most frequently irrigated (−15 kPa) DSR plots (T1) registered the highest ET, while irrigations at threshold −45 kPa at all stages (T3) recorded the lowest value. Bifurcation of ET into evaporation and transpiration using LAI revealed that the maximum evaporation was measured in T3 while minimum in T1 followed by T4 (Table 4). However, transpiration was the highest in T1 followed by T8 with lowest being in T3. Lower transpiration in T2 and T3 as compared to T1 indicates that more negative irrigation threshold of −30 kPa (T2) and −45 kPa (T3) at all stages had adverse effect on crop transpiration. Four days prolonged heavy rain generated about 5.5–10.5 mm runoff from different DSR treatments (Table 4). It was also noticed that well watered TPR plots, due to shorter duration in the field, registered lower evaporation as well as ET values than the most of DSR treatments, however, transpiration/day was significantly higher. Similarly, higher irrigation and low infiltration rate resulted in substantially higher runoff in TPR in comparison to DSR plots. About 74.4 mm runoff was measured from TPR plots. It implies that DSR plots had better rain water storage capacity than TPR which ultimately led to reduced irrigation input. Maintenance of either water ponding and/or continuous saturation in soil profile in TPR reduced the possibility of on farm rain water storage and thereby led to relatively more runoff. The higher infiltration rate in DSR probably percolated water at faster rate and reduced the possibility of runoff. These were the main reasons behind higher runoff from TPR field.

The recharge (water reaching groundwater aquifer) component (RC) from a cropped land depends on irrigation, rainfall, evapotranspiration, and runoff volume. In DSR, the highest RC was registered in T1 due to the highest irrigation amount while the minimum (561.7 mm) recorded in T3 with the lowest irrigation input of 709.5 mm (Table 4). The reduction in RC with T4 was about 19% over T1. Among all DSR treatments, percent contribution of total water input (irrigation + precipitation) to RC was the highest in T1 and the lowest in T3. This implies that irrigation at more negative SMP utilized the most of water input and contributed least to groundwater. This was probably due to longer irrigation interval in -45 kPa threshold than −15 and −30 kPa leading to better use of rainfall. Higher RC was measured in TPR receiving more irrigation input. Though TPR generated more runoff than DSR but it might be recycled in region itself due flat topography of the area. Thus, the real loss of irrigation input is in terms of ET, which was the lowest in TPR. DSR being longer duration, that too the extra duration coinciding with high evaporative demand period of the year, in the field results in slightly higher water loss (ET) than TPR.

3.7. Irrigation strategy for higher water productivity and yield of DSR

Two years field study indicated that DSR is very sensitive to available soil moisture. Irrigation thresholds, varying with crop growth stages, caused variable effect on crop growth, yield and water productivity. The duration of the period, with irrigations scheduled at higher SMP, also had significant effect on yield and irrigation water saving. Irrigations at −15 kPa during all stages in DSR produced the highest yield but with the highest irrigation input. Mild water stress (−30 kPa) during initial stages and −15 kPa during reproductive phase resulted in at par 1000-grains weight and yield with that of −15 kPa at all stages, but amount of irrigation water reduced by 21%. The higher yield with lower irrigation amount indicates better utilization of applied water. Further, increase in irrigation threshold to −45 kPa resulted into significant reduction in irrigation input but with proportionate simultaneous yield reduction. The present study suggests that adopting optimal irrigation schedules based on varying SMP according to growth stages can reduce irrigation input with higher IWP and good yield of DSR. As such, the study infers that irrigations at −30 kPa during initial phase (< 90 DAS) and at −15 kPa during later stages would be safer irrigation schedule for DSR.

4. Conclusion

Variable SMP based irrigation schedules imposed on different crop stages had significant influence on crop growth, yield contributing attributes, total grain yield and water balance components of DSR. Frequent irrigations (−15 kPa) throughout the crop season though registered the highest total grain yield and CWP, but simultaneously consumed the maximum irrigation water with the lowest IWP. However, mild water stress (−30 kPa) during initial phase and frequent irrigations (−15 kPa) during reproductive stages proved the best option because it saved significant (21%) irrigation input and produced comparable grain yield and CWP to −15 kPa irrigation threshold throughout the season.

The DSR method of cultivation, due to longer duration in the field than TPR, recorded higher water loss in terms of ET but lower CWP. Despite of lower tiller density, TPR recorded better yield contributing attributes and produced significantly higher total grain yield than best DSR irrigation strategy. The denser plant stand in DSR proved detrimental for yield contributing attributes and crop yield. Comparatively lower yield of DSR than TPR suggests that further studies are needed to optimize plant population in DSR and depth of installation of tensiometer for standardizing irrigation scheduling thresholds to achieve potential yield with higher water productivity and substantial water saving.

Conflict of interest

The authors declare that they have no conflict of interest in this publication.

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