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Effective management of irrigation water in citrus orchards under a water scarce hot sub-humid region

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ABSTRACT

Water scarcity is one of the major causes of low productivity and decline of citrus orchards. Deficit irrigation (DI) is a recently proposed water saving technique in irrigated agriculture. The impact DI versus full irrigation (FI: 100% crop water requirement) was evaluated in citrus orchards under a hot sub-humid climate of central India. Two DI strategies applied to citrus trees were DI$_1$: 20% FI during initial fruit growth period (IFGP) + 40% FI during final fruit growth period (FFGP) + FI during rest of the period, and DI$_2$: 70% FI during entire irrigation season. Fully irrigated trees had the highest vegetative growth. However, DI$_1$ produced 18% higher fruit yield with superior quality fruits, resulting 30% improvement in water productivity under this treatment compared to FI. Fruit yield prediction based on vegetative growth and leaf physiological parameters of the trees using principal component regression analysis technique was found reasonable accurate. These results suggest for adoption of DI$_1$ in citrus orchards of central India and elsewhere having similar agro-climate of this study region.

1. Introduction

Water scarcity is a major constraint in crop production. Efficient water supply through precise irrigation scheduling is one of the pathways to sustain crop production with higher water productivity. Deficit irrigation (DI) has been found as a potential water saving technique in some crops. DI is an irrigation strategy where the amount of water applied is less than the full water requirement of a crop to develop desirable stress that has minimal effects on crop yield (English, 1990). The correct application of DI requires the thorough understanding of the yield response of crops to water supply. In water scarce regions, DI can be more profitable for a farmer to maximize crop water productivity instead of maximizing the harvest per unit land (English, 1990). Citrus, a high water requiring evergreen perennial fruit crop is mainly grown in tropics. Irrigation water is a key input to success of citrus cultivation in tropical and sub-tropical regions of the world (Singh and Srivastava, 2004). The higher vegetative growth in bearing trees reduces the productivity of citrus (González-Altozano and Castel, 1999). Moreover, the water stress during certain crop growth stages enhances the yield and fruit quality of citrus (González-Altozano and Castel, 1999). However, the plants undergo severe stress when soil-water is very low and the water uptake by the roots fails to compensate the optimal evpotranspiration of the tree. Hence, the accurate and precise water application, creating a desirable stress is important for citrus production in water scarce regions.

Nagpur mandarin (*Citrus reticulata* Blanco), a loose skin citrus cultivar is commercially grown in around 0.20 million hectares of central India as an irrigated crop (Singh and Srivastava, 2004). Central India is globally the only commercially important citrus belt where soil water deficit stress is adopted in absence of low temperature stress for induction of flowering in citrus. The crop is mainly grown on smectite rich black clay soil with 35–60% clay content (Srivastava et al., 2001) in this region. The acreage under the crop is increasing exponentially each year due to its high production economics and cultivar suitability in this region. The irrigation water shortage is one of the major *abiotic* constraints for higher and quality production of citrus in central India. Earlier study reported that drip irrigation could save 30% irrigation water with enhancing fruit yield by 50% compared with basin irrigation in citrus of central India (Panigrahi et al., 2012). Further, it becomes a necessary to find a new irrigation strategy under drip irrigation to sustain crop productivity with less water expanse.

In recent years, several contributions have documented the advantages of DI in improving water use efficiency and fruit quality of different citrus cultivars in various regions of the world

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(González-Altozano and Castel, 1999; Pérez-Pérez et al., 2008; García-Tejero et al., 2010). However, pedo-climatic characteristics of the orchard and crop characteristics play a greater role in success of DI scheduling in fruit crops (Ginestar and Castel, 1996; García-Tejero et al., 2010). The most sensitive phenological stages of citrus to water stress are flowering, fruit set and fruit development (fruit enlargement) in which shortage of soil moisture in root-zone reduces yield drastically (Ginestar and Castel, 1996). The reduction of irrigation water quantity to certain level in non-critical growth stages (initial fruit growth period, final fruit growth period) is one of the options to sustain citrus production with higher water productivity in water scarce areas.

Imposition of desirable water stress on trees through DI in clay soils is difficult due to high buffering capacity and intrinsic water holding ability of these soils (Girona et al., 2002; Turner, 2004). Moreover, the information available on citrus production under DI in clay soils is very limited worldwide. Keeping this in view, a study was undertaken to evaluate the performance of various DI strategies in Nagpur mandarin on clay soil (Vertisol) in hot sub-humid tropical climate of central India. Moreover, the yield prediction based on vegetative and physiological parameters of the trees under DI, using principal component regression analysis (PCRA) has been tried. This can be helpful to forecast the yield under different water stress conditions in the crop.

2. Materials and methods

The field experiment was conducted for 3 consecutive years during 2007–2009 at experimental farm of Central Citrus Research Institute, Nagpur (21°08′45″N, 79°02′15″E and 340 m above mean see level) with 12 year-old Nagpur mandarin (*Citrus reticulata* Blanco) plants budded on rough lemon (*Citrus jambhiri* Lush) rootstock with spacing of 6 × 6 m. The experimental soil was clay. The physic-chemical properties of experimental soil are presented in Table S1. The mean daily USWB Class-A pan evaporation rate varied from 2.0 mm in month of December to as high as 12.0 mm in May at the experimental site. The mean monthly weather parameters during the experimental years are presented in Table S2. The irrigation water was free from salinity (EC, 0.12–0.32 $dS\,m^{-1}$) and alkalinity (pH, 6.8–7.2). The ground water level in the well near to the experimental field was at 17–19 m depth from land surface.

Two deficit irrigation (DI) schemes i.e. 20% of full irrigation (FI) during initial fruit growth period + 40% FI during final fruit growth period + FI during rest irrigation season (DI_1), and 70% FI during entire irrigation season (DI_2) were evaluated against FI imposed throughout the irrigation season. The initial fruit growth period (IFGP) and final fruit growth period (FFGP) were taken from mid-February to mid-March and mid-October to November, respectively (Srivastava et al., 1998; Huchche et al., 1999). The orchard having area 2.72 ha with 756 trees was selected for the study. The experimental design was a randomised complete block, with seven replicates per treatment. The selected orchard was divided into 3 equal size plots (252 m × 36 m) and each plot was further divided into 7 sub-plots (36 m × 36 m) with 36 trees per sub-plot in six rows (6 trees per row). Sixteen trees in the four mid-rows of each sub-plot were taken for experimental observations, so called experimental-trees. Each tree was irrigated by four number of pressure compensated on-line drip emitter ($8\,L\,h^{-1}$) placed at 1.0 m away from tree trunk as suggested by Panigrahi et al. (2008) for the crop. The volume of irrigation water (V) required under FI was computed by using following equation:

$$V = 0.8 \times S \times Kp \times K_C \times (Ep - ER)/r \quad (1)$$

where, V is the irrigation volume (litre day^{-1} $tree^{-1}$), S the tree canopy area (m^2), Kp the pan factor (0.7), Kc the crop factor (0.7) as suggested by Autkar et al. (1989), Ep the daily Class-A pan evaporation (mm), ER the effective rainfall (mm), and r the water application efficiency of irrigation system (≈90%). The amount of effective rainfall during the irrigation seasons (January–June, October–15th December) was equal to total rainfall, as runoff observed in the experimental sub-plots was negligible during these periods (Panigrahi et al., 2009). The irrigation water quantities in different DI treatments were estimated as fractions of FI. Water meters were used to regulate the water supply to various treatments. All the experimental trees were grown under uniform cultural and management practices.

The soil water content was monitored at 0–0.20 m, 0.20–0.40 m, 0.40–0.70 m and 0.70–1.0 m depths daily in morning before initiation of irrigation by neutron moisture meter (Troxler model-4300, USA). As the roots of Nagpur mandarin trees goes up to 1.0 m soil depth, this depth was taken for soil moisture study (Autkar et al., 1989). Four ceramic cup tensiometers per tree (5 trees per treatment) were placed at 0.20 m, 0.40 m, 0.70 m and 1.2 m depths of soil to measure soil water suction. The daily (ith day) water used (WU_i) by the trees was determined by using the water balance equation:

$$WU_i = P_i + I_i + C_i - D_{pi} - R_{fi} - \Delta S_{(i+1,i)} \quad (2)$$

where, P_i is effective rainfall on ith day (≈rainfall) as discussed earlier, I_i is depth of irrigation water applied on ith day, C_i is contribution through capillary rise from ground water table on ith day, D_{pi} is deep percolation loss on ith day, R_{fi} is surface water runoff on ith day and $\Delta S_{(i+1,i)}$ is sum of daily change in moisture storage (difference between moisture content on i + 1th and ith days) in the soil profiles to a depth of 1.0 m. All units are in millimetres. Since no enhancement of water potential was observed at 1.2 m depth during irrigation seasons, deep percolation loss (Dp) was assumed negligible. C was ignored as the water table was below 15 m throughout the growing seasons. As C, Dp, and R_f were negligible, water used was calculated as the difference between rainfall plus irrigation and changes in total moisture content in the soil profiles.

The leaf physiological parameters (net photosynthesis rate, transpiration rate and stomatal conductance) were recorded fortnightly on a clear day by CO_2 gas analyser (model—301PS, CID Bio-Science, USA) during November to June from 9 am to 5pm in one hour interval. Four leaves per plant (one leaf in each direction: North, South, East and West) and two plants per treatment were considered for these measurements. Overall, seventy two observations were taken in each treatment to estimate the leaf physiological parameters fortnightly. Leaf water use efficiency (LWUE) is calculated as the ratio of net photosynthesis rate to transpiration rate of leaves (García-Sánchez et al., 2007).

The vegetative growth parameters (tree height, stem height, canopy spread, stock and scion girth diameter) were measured for all experimental trees and their pooled annual incremental magnitudes were compared. The canopy volume (Vc) was calculated based on the formulae (Obreza, 1991):

$$Vc = 0.5238\,H\,W^2 \quad (3)$$

where Vc is the canopy volume (m^3), H the difference between tree height and stem height (m) and W the mean canopy width measured in North-South and East-West directions (m). The fruits were harvested by mid of December. The number and weight of total fruits from each experimental-tree under various treatments was recorded and the mean yield per tree was estimated. The total yield was computed considering 278 trees per hectare. The water productivity (WP) was calculated as the ratio of annual fruit yield ($t\,ha^{-1}$) to total water used (mm) and irrigation water productivity (IWP) was the ratio of annual fruit yield ($t\,ha^{-1}$) to total irrigation water used (mm) for Nagpur mandarin. At the harvest, five fruits per experimental tree were taken randomly for determination of

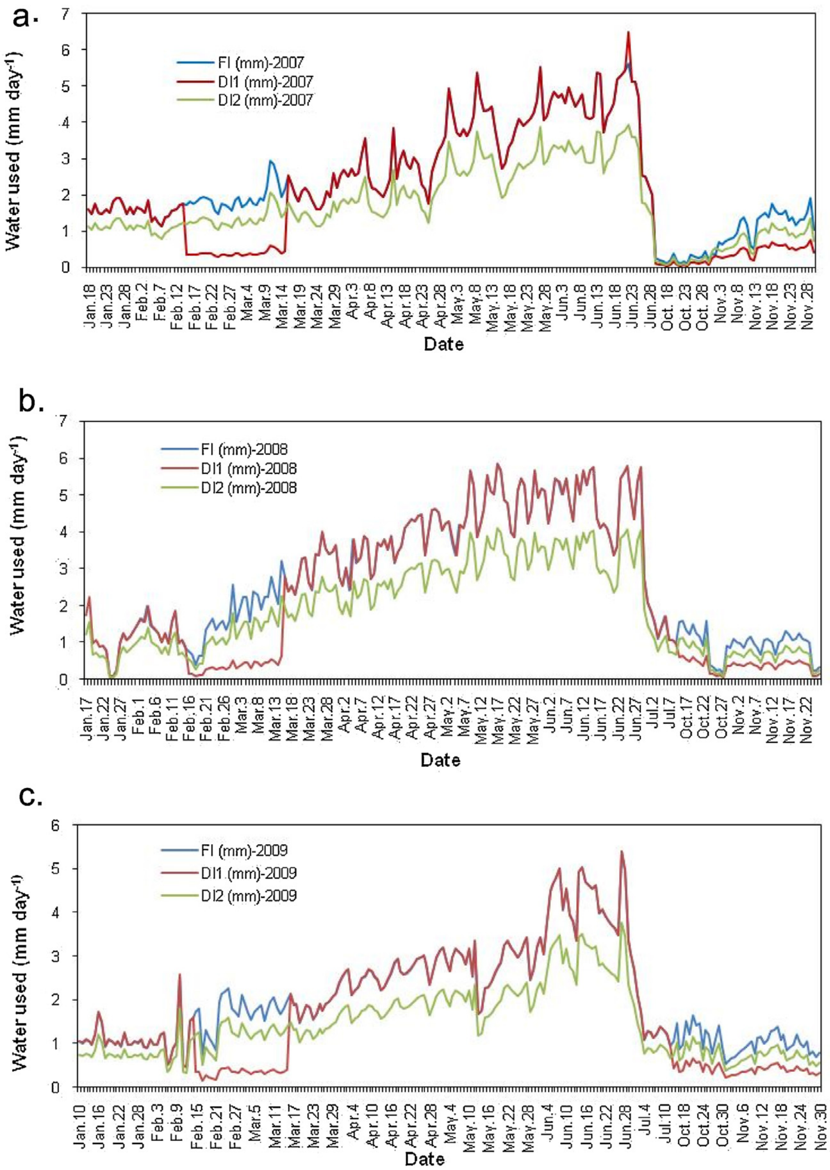


Fig. 1. (a), (b) & (c). Daily water used (mm) in Nagpur mandarin orchard during irrigation season (Nov.–Jun.) during 2007–2009.
Note: DI1: Deficit irrigation at 20% full irrigation (FI) in initial fruit growth period; DI2: Deficit irrigation at 70% FI throughout the crop growing season; FI: Full irrigation (irrigation at 80% of class-A pan evaporation rate).

fruit quality parameters (fruit weight, fruit diameter, juice percent, acidity, total soluble solids). Fruit diameter was calculated as the geometric mean diameter of the fruits measured by 'Vernier' calliper along the three co-ordinates i.e. X, Y and Z using following equation:

$$D = (A \times B \times C)^{1/3} \tag{4}$$

where D is the mean fruit diameter, A the diameter along X-axis (mm), B the diameter along Y-axis (mm) and C the diameter along Z axis (mm).

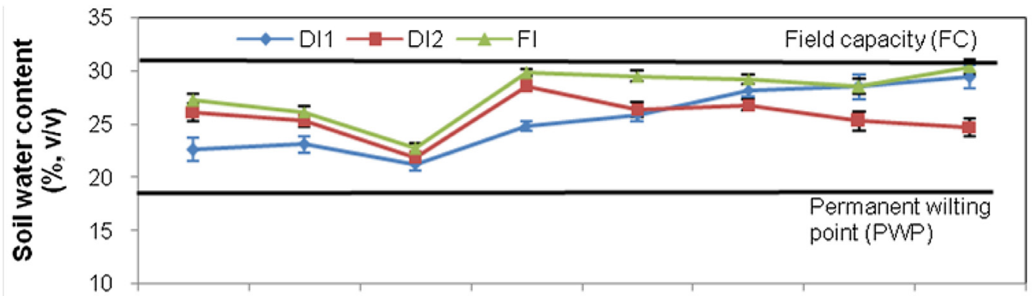
Juice was extracted manually by juice extractor and its percent was estimated on weight basis with respect to fruit weight. The total soluble solid (TSS) was determined by digital refractometer (Atago model-PAL 1, Japan) and acidity was measured by volumetric titration with standardized sodium hydroxide, using phenolphthalein as an internal indicator (Ranganna, 2001).

All the data generated were subjected to analysis of variance (ANOVA) and the least significant difference (LSD) at 5% probability level was obtained. Principal component analysis (PCA) and development of regression equation for prediction of fruit yield were done using SAS statistical software.

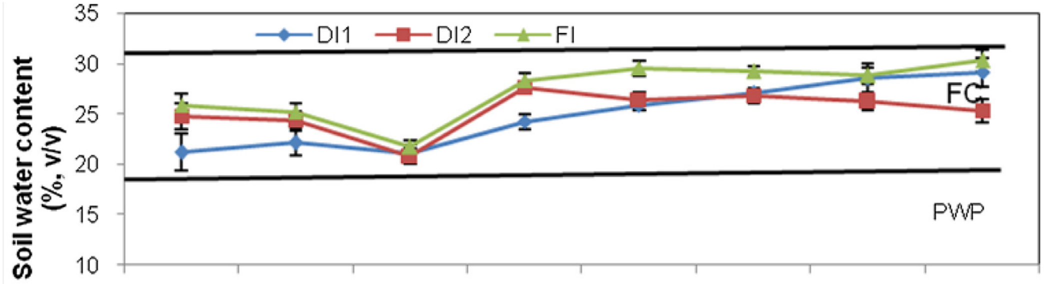
3. Results and discussion

3.1. Water use

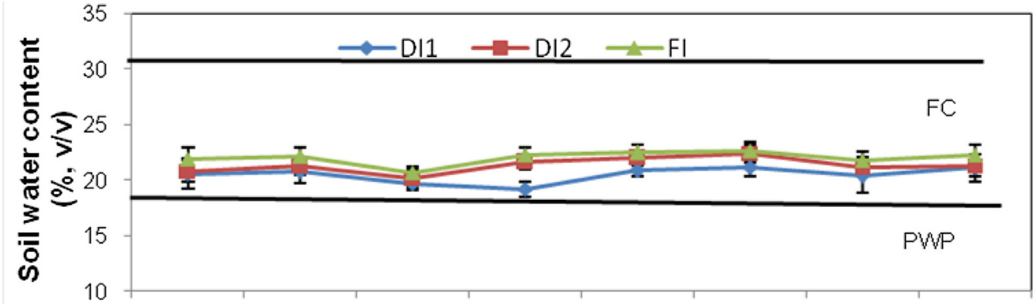
The daily water use of mandarin trees in various irrigation treatments (except DI_1) showed an increasing trend from October–November (0.3–1.9 mm day^{-1}) to May–June (2.8–6.5 mm day^{-1}) (Fig. 1). Higher water use is attributed to higher evapo-transpiration rate of the trees, caused by increasing atmospheric water demand evident from evaporation rate during this period (Table S2). However, the lowest rate of daily water use of the trees during mid-February to mid-March (0.3–0.5 mm day^{-1}) and mid-October to November (0.2–0.6 mm day^{-1}) was recorded under DI_1. This was due to reduced soil-water availability caused by under irrigation in this treatment during these periods. The water used for citrus trees in this study under full irrigation



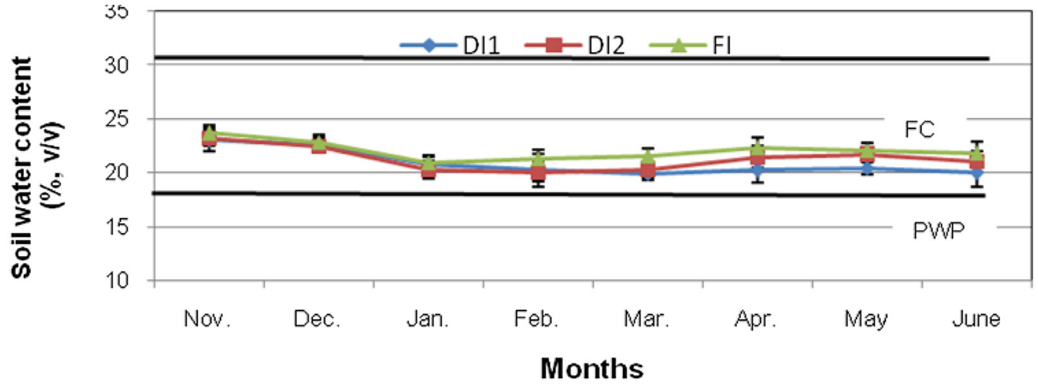
a.Soil water content at 0.20 m depth



b.Soil water content at 0.40 m depth



c.Soil water content at 0.70 m depth



d. Soil water content at 1.0 m depth

Fig. 2. (a), (b) & (c). Mean monthly soil water content (%, volume basis) at 0.20 m, 0.40 m, 0.70 m and 1.00 m during irrigation season (Nov.–Jun.) under various irrigation treatments in Nagpur mandarin during 2007–2009.

Note: DI1: Deficit irrigation at 20% full irrigation (FI) in initial fruit growth period; DI2: Deficit irrigation at 70% FI throughout the crop growing season; FI: Full irrigation (irrigation at 80% of class-A pan evaporation rate).

Table 1
Water used, rainfall and irrigation applied during irrigation season (October–June) for different years (2007–2009).

Year	Water used (mm)			Rainfall (mm)	Irrigation (mm)		
	DI_1	DI_2	FI		DI_1	DI_2	FI
2007	565	463	608	12	485	379	541
2008	562	468	603	40	460	360	513
2009	594	493	636	15	500	408	576
Mean	574	475	616	–	481	382	543

DI1: Deficit irrigation at 20% full irrigation (FI) in initial fruit growth period DI2: Deficit irrigation at 70% FI throughout the crop growing season FI: Full irrigation (irrigation at 80% of class-A pan evaporation rate).

(0.3–6.5 mm day^{-1}) deviated from the water use of citrus measured by Fares and Alva (1999) in Florida, USA (0.4–4.8 mm day^{-1}); Castel et al. (1987) in Valencia, Spain (1.3 and 5.5 mm day^{-1}) and Martin et al. (1997) in Arizona, USA (1.1–10.6 mm day^{-1}). These variations are due to the age and nature of citrus cultivars used in the studies under varied soil-climate, and methods of irrigation scheduling adopted.

The total water used and total water applied in irrigation seasons varied from 463 to 636 mm and 379 to 576 mm, respectively, under different treatments (Table 1). The higher water used by the trees compared to water applied was due to the utilization of stored soil water in the root-zone under drip irrigation. However, the mean water use by trees under FI was 7.3–29.6% higher, despite 10–42% increase in water supply under this treatment over DI treatments. This indicated that the deficit-irrigated trees used some higher quantity of stored soil moisture (6–20 mm/year) from root-zone than that used by fully-irrigated trees.

3.2. *Soil water variation*

The mean monthly soil water content (SWC) observed at 0.20 m, 0.40 m, 0.70 m and 1.0 m depths during irrigation seasons (November–June) indicates that FI resulted in significantly higher SWC (23.0–30.5%, v/v) compared to DI treatments (21.6–28.0%, v/v) at both 0.20 and 0.40 m depths (Fig. 2). The mean soil water fluctuation between two consecutive measurements under FI (2.0–6.5 mm) was observed to be higher than that under DI treatments (0.3–3.0 mm). This was due to higher evapo-transpiration rate of the trees under increased soil water availability under FI as compared with DI. However, the soil water fluctuations under different irrigation treatments were negligibly affected at both 0.70 m and 1.00 m depths, indicating that the effective root-zone of mandarin trees is confined within top 0.40 m soil profile. The finding of this study marginally differs from earlier observation of Autkar et al. (1989) which concluded that the maximum concentration of roots of basin-irrigated Nagpur mandarin trees exists in top 0.60 m soil depth. The shallow rooting system of mandarin trees is probably due to the moisture availability in upper soil profiles under frequent water application through drip irrigation in this study. The similar result of development of shallow rooting under drip irrigation was earlier reported with apple trees (Sokalska et al., 2009). The fluctuation of soil water content at 0.20 m and 0.40 m depths in all irrigation treatments was relatively higher during April–June than November–March. Higher fluctuation of soil water content during April–June could be attributed to higher evapotranspiration demand of trees during this period.

3.3. *Leaf physiological parameters*

The mean leaf physiological parameters such as photosynthesis rate (P_n), stomatal conductance (g_s) and transpiration rate (T_r) observed under different irrigation treatments were significantly affected (Fig. 3). The P_n was marginally higher in FI (3.923 μmol m^{-2} s^{-1}) followed by DI_1 (3.893 μmol m^{-2} s^{-1}). The decrease in P_n of deficit-irrigated trees was caused by soil water deficit in these treatments during irrigation seasons (Vu and Yelenosky, 1988). Both g_s (57.6–77.4 mmol m^{-2} s^{-1}) and T_r (2.018–2.739 mmol m^{-2} s^{-1}) followed the similar trend of P_n. The higher g_s and T_r were attributed to consistently higher available soil water content in the effective root zone of the fully irrigated trees. The leaf water use efficiency (LWUE: μmol CO_2 fixed per mmol H_2O transpired) under DI_1 was 65% and 16% higher over that under DI_2 and FI, respectively. Higher LWUE was due to marginal decrease in P_n associated with the higher decrease in T_r of trees under DI_1 over other treatments. These results are in concurrence with the findings of Vu and Yelenosky (1988) in 'Valencia' Orange and Ribeiro et al. (2009) in Satsuma mandarin.

3.4. *Leaf nutrients composition*

The leaf nutrient (N, P, K, Fe, Mn, Cu and Zn) analysis shows that all the nutrients except P and Cu were significantly affected

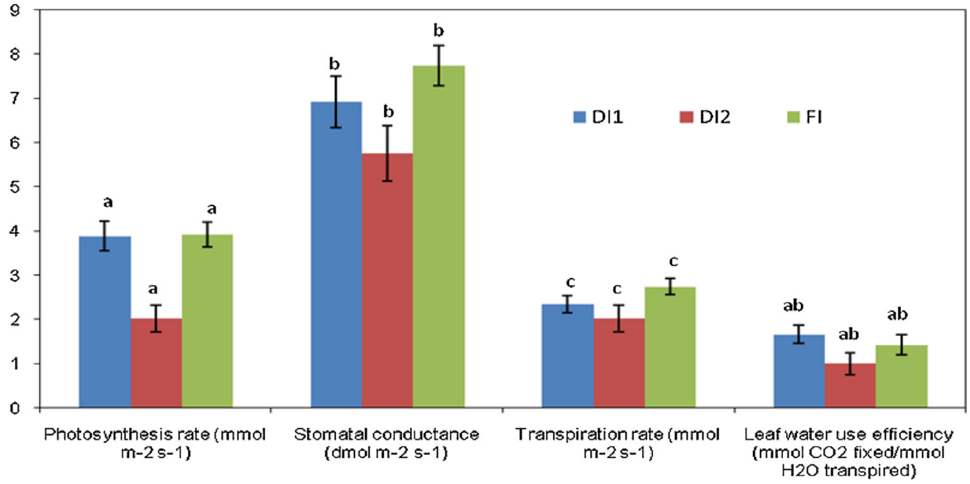


Fig. 3. Leaf physiological parameters (mean ± standard error) of Nagpur mandarin trees during 2007–2009 in different irrigation treatments. Vertical bars represent the standard deviation (n = 72). Values with different letters for each variable are significantly different among the treatments at $p < 0.05$ by Duncan's multiple range tests.
Note: DI1: Deficit irrigation at 20% full irrigation (FI) in initial fruit growth period; DI2: Deficit irrigation at 70% FI throughout the crop growing season; FI: Full irrigation (irrigation at 80% of class-A pan evaporation rate).

Table 2
Macronutrients (N, P, K) and micronutrients (Fe, Mn, Cu and Zn) in leafs of Nagpur mandarin under various irrigation treatments[a].

Treatments	Macronutrients (%)			Micronutrients (ppm)			
	N	P	K	Fe	Mn	Cu	Zn
DI_1	2.46	0.19	1.54	58.4	57.8	7.4	25.6
DI_2	2.31	0.15	1.41	54.0	56.6	7.3	24.7
FI_{100}	2.69	0.22	1.64	62.6	61.5	8.2	26.9
$LSD_{0.05}$	0.07	NS	0.04	2.16	2.4	NS	0.87

NS: not significant.

[a] Average of 3 years.

by irrigation treatments (Table 2). The highest concentration of the nutrients was registered with FI, followed by DI_1. The higher concentration of nutrients in leaves of fully-irrigated trees was due to higher plant uptake with increased availability of such nutrients in root zone under FI. The concentration of micronutrients (Fe, Mn, Cu and Zn) in leaves was also higher in FI. DI_1 and DI_2 resulted statistically similar concentrations of micronutrients in leaves. However, in all the treatments, the leaf micronutrient contents were higher than the optimum quantity required for sustainable production of citrus in central India (Srivastava et al., 2001).

3.5. *Vegetative growth*

Among various growth parameters of the trees (tree height, canopy volume, stock girth diameter, scion girth diameter), only tree height and canopy volume were significantly influenced by irrigation treatments (Fig. S1). The maximum increase in tree height (0.39 m) and canopy volume (9.42 m^3) was observed in FI followed by DI_1 (0.24 m and 7.23 m^3, respectively). The higher vegetative growth was probably due to higher leaf photosynthesis rate and better metabolic activities of fully-irrigated trees under favourable soil water condition in the root-zone. Earlier study taken by García-Tejero et al. (2010) showed the similar findings of decrease in vegetative growth of deficit-irrigated 'Salustiano' orange trees in Spain.

3.6. *Fruit yield, water productivity and fruit quality*

Table 3 presents the fruit yield (number of fruits/tree, average fruit weight and total fruit yield), water productivity and fruit quality parameters (juice content, TSS and acidity) under different treatments. The maximum number of fruits was harvested from fully-irrigated trees (515) followed by DI_1 (505). However, the heavier fruits were recorded in DI_1 (118.4 g $fruit^{-1}$). The final fruit size observed in different treatments (mean diameter: 70–82 mm) followed the similar trend as fruit weight (Fig. S2a). The enhancement of fruit size under DI_1 was due to the higher increase in fruit growth rate (0.5–3.0 mm per 15 days) after the relief of water stress under this treatment from mid-March (Fig. S2b). Earlier studies on DI in the initial growth stages of peach and pear also showed the similar trend of fruit growth which was considered as the compensatory effects of relieving water stress on fruit enlargement in the crops (Chalmers and Bvanden, 1975; Caspari et al., 1994). Secondly, the increased number of fruits with fully-irrigated trees could be a cause of smaller fruits in this treatment. The similar results of smaller fruits produced under DI were also reported by Pérez-Pérez et al. (2008) in 'Lane late' orange and García-Tejero et al. (2010) in 'Salustiano' orange.

The highest fruit yield was recorded in DI_1 followed by FI. The possible reasons for this may be that the water deficit during IFGP and FFGP in DI_1 suppressed the tree vegetative growth without much effect on leaf photosynthesis and the citrus trees invested higher quantity of photosynthates towards reproductive growth (fruiting) than vegetative growth under this treatment. However, the yield obtained in DI_2 was significantly lower over yield recorded in other treatments. This could be happened due to lower photosynthesis rate of leaves under continuous deficit water supply under DI_2.

The water productivity (WP) and irrigation water productivity (IWP) were computed to be maximum under DI_1 (0.029 t ha^{-1} mm^{-1} and 0.034 t ha^{-1} mm^{-1}, respectively), followed by DI_2 (0.025 t ha^{-1} mm^{-1} and 0.032 t ha^{-1} mm^{-1}, respectively). The higher water productivity under DI_1 was attributed to higher increase in fruit yield with comparatively less water supply over other treatments. An improvement in WP in response to DI over FI was also reported earlier in citrus (Pérez-Pérez et al., 2008; García-Tejero et al., 2010).

FI produced the fruits having highest juice content (40.4%) which was at par with that in DI_1 (40.2%). However, DI_1 produced the fruits with highest TSS (10.4 ^{0}Brix) and lowest acidity (0.83%), followed by DI_2 (TSS: 10.2 ^{0}Brix, acidity: 0.85). The reduction in juice content is one of the reasons for enhancement of soluble solids concentrations in fruits under DI treatments. Secondly, the higher TSS and lower acidity of fruits under mild water-stress (DI_1 and DI_2) was probably due to the enhanced transformation of acids to sugars in dehydrated juice sacs which is required to maintain the osmotic pressure of fruit cells under water deficit condition (Huang et al., 2000). Earlier studies also demonstrated the higher TSS of citrus fruits under soil water deficit condition in root-zone of trees (García-Tejero et al., 2010).

3.7. *Yield prediction*

The correlation matrix between fruit yield and other plant-based variables (SD, stem diameter; CV, canopy volume; leaf-N, leaf nitrogen content; leaf-K, leaf potassium content; Leaf- Fe, leaf iron content; Leaf-Zn, leaf zinc content; RLWC, relative leaf water content; LWC, leaf water concentration; Pn, net leaf photosynthesis rate; Tr, leaf transpiration rate; gs, leaf stomatal conductance; LWUE, leaf water use efficiency) presents that yield is highly correlated with gs, T_r, Leaf-K, Leaf-N, Leaf-Fe, Leaf-Zn, Pn, CV and SD under DI (Table 4). Similar pattern of correlations of fruit yield with

Table 3
Fruit yield, water productivity and fruit quality affected by various irrigation treatments in Nagpur mandarin.[a]

Treatment	Yield parameters			Water productivity (t ha^{-1} mm^{-1})	Irrigation water productivity (t ha^{-1} mm^{-1})	Quality parameters[a]		
	No. of fruits $tree^{-1}$	Average fruit weight (g)	Total yield (t ha^{-1})			Juice (%)	TSS(^{0}Brix)	Acidity (%)
DI_1	505	118.4	16.62	0.029	0.034	40.2	10.4	0.83
DI_2	468	92.5	12.04	0.025	0.032	39.4	10.2	0.85
FI	515	98.5	14.10	0.023	0.026	40.4	9.7	0.86
$LSD_{0.05}$	6.5	2.6	2.80	0.001	0.003	0.3	0.06	0.004

[a] Average of 3 years.

Table 4
Correlation matrix (Pearson's) for plant-based observations under DI treatments during 2007 and 2008.

Variables	Fruit yield	SD	CV	Leaf-N	Leaf-K	Leaf- Fe	Leaf- Zn	RLWC	LWC	P_n	T_r	g_s
SD	0.65^*											
CV	0.79^*	0.59^*										
Leaf-N	0.77^+	0.68^*	0.29^*									
Leaf-K	0.75^+	NS	0.41^*	0.43^*								
Leaf- Fe	0.42^*	NS	NS	NS	NS							
Leaf-Zn	0.58^*	NS	NS	NS	NS	0.41^*						
RLWC	0.55^+	0.20^*	0.17^*	0.32	0.32^*	NS	NS					
LWC	0.53^+	NS	NS	0.30	0.25^*	NS	NS	0.84^+				
P_n	0.75^+	NS	0.73^*	0.75^+	0.34^*	0.68^+	0.36^*	0.56^+	0.45^+			
T_r	0.77^+	NS	0.54^*	0.59^*	0.71^+	0.33^*	0.29^*	0.61^+	0.59^+	0.51^+		
g_s	0.80^+	NS	0.62^*	0.48^*	0.72^+	0.35^*	0.28^*	0.65^+	0.56^+	0.69^+	0.71^+	
LWUE	0.51^+	NS	NS	0.37^*	0.36^*	0.32^*	0.21^*	0.49^+	0.38^+	0.39^+	0.59^+	0.47^*

Data followed by "*" indicates their significant correlation at $P < 5\%$ probability level and data followed by " + " indicate their significant correlation at $P < 1\%$.

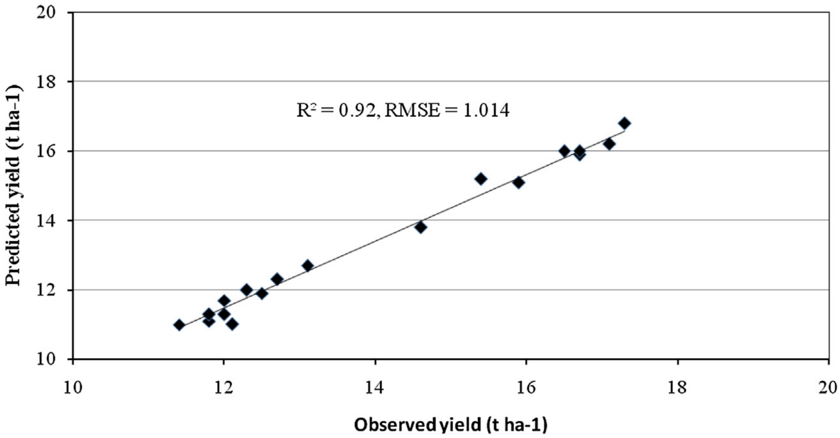


Fig. 4. Predicted fruit yield versus observed fruit yield of Nagpur mandarin under deficit irrigation during 2009.

Table 5
Principal components (PCs) with eigen values and variances under DI treatments.

PCs	Variables	Eigen value	% variance	Cumulative% of variance
1	g_s, Tr, Leaf-K	6.964	40.20	40.20
2	P_n, CV	3.716	33.54	73.74
3	Leaf-N, SD	2.449	15.28	89.02

Tr and gs was also observed by Dzikiti et al. (2010) in citrus under differential irrigation.

PCA for 12 variables indicates that the first 3 PCs explained 89% variability of data set under DI (Table 5). Therefore, the variables involved in these 3 PCs were considered for further analysis. The variables from PC1 (g_s, Tr, Leaf-K), PC2 (P_n, CV) and PC3 (Leaf-N, SD) were retained for interpretation, as their eigenvalues > 1. However, due to the stronger correlations among g_s, T_r and leaf-K; between P_n and CV ($r = 0.87–0.89$), and between leaf-N and SD as evident from Table 4, T_r, Leaf-K, P_n, SD were not considered for PCRA. A multi-regression model developed between fruit yields and other selected plant variables (g_s, CV, Leaf-N) for DI in 2007 and 2008 was:

$$\text{Fruit yield} = -0.957(\text{Leaf-N}) + 0.138(\text{gs}) + 17.510(\text{CV}) - 17.630 (P < 0.05;\ R^2 = 0.98;\ \text{RMSE} = 0.30\%) \tag{5}$$

The above model forecasted the fruit yield using the proposed plant-based variables with reasonable accuracy ($R^2 = 0.92$ and $\text{RMSE} = 1.014$) under DI in 2011 (Fig. 4).

4. Conclusions

Deficit irrigation is found as a productive and water saving technique in drip-irrigated Nagpur mandarin. This study demonstrated that 50–60% soil water deficit in effective root zone (0–0.40 m) during both initial fruit growth period and final fruit growth period could impose desirable water stress on the citrus plants, resulting bigger fruit size with improved internal fruit qualities (total soluble solids and acidity) in the crop. Principal component regression involving the plant vegetative growth parameters, leaf nutrient contents and leaf physiological parameters has been found as potential technique to predict fruit yield under differential water stress conditions. Overall, the study warrants the adoption of deficit irrigation in citrus orchards of central India, which will help in bringing more area under irrigation, resulting in large increase in production of citrus.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.scienta.2016.07.008.

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