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Deficit irrigation scheduling and yield prediction of 'Kinnow' mandarin (*Citrus reticulate* Blanco) in a semiarid region

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ABSTRACT

Scarcity of irrigation water in critical growth stages of the crop is one of the major causes of low productivity and decline of citrus orchards. Regulated deficit irrigation (RDI) is a recently proposed water saving technique in irrigated agriculture. The present study was planned with a hypothesis that the optimal RDI scheduling at early fruit growth period (EFGP), which coincides with summer months could save substantial amount of water, without significantly affecting the yield of 'Kinnow' mandarin (*Citrus reticulata* Blanco) plants. Two DI strategies: (a) withholding irrigation at EFGP (RDI_0) and (b) irrigation at 50% crop evapotranspiration (ET_c) at EFGP (RDI_{50}) were compared with full irrigation (FI, 100% ET_c) in relation to gas exchange, water relation and nutrient composition of leaves along with growth and yield of the plants. The greater plant growth with maximum fruit yield (61.9–63.2 t ha^{-1}) was recorded with fully-irrigated plants. However, the yield under RDI_{50} was statistically ($p > 0.05$) at par with that under FI. The reduction in water application of around 24% with RDI_{50} resulted in 30% improvement in irrigation water use efficiency with this treatment over that with FI. The maximum rate of net-photosynthesis, stomatal conductance and transpiration of leaves was recorded with fully-irrigated plants. However, the plants under RDI_{50} exhibited the highest leaf water use efficiency. The leaf nutrients (N, P, K, Fe, Mn, Cu and Zn) analysis revealed that RDI_0 produced significantly ($p < 0.05$) lower concentration of all the nutrients except P and Cu than that in other treatments. Relative leaf water content (RLWC), leaf water concentration (LWC) and mid-day stem water potential (Ψ) showed a decreasing trend, whereas water stress integral (S_Ψ) and plant canopy reflectance indices (water band index, WBI; normalised difference water index, NDWI; and moisture stress index, MSI) showed the reverse trend of RLWC with water stress. The prediction model formulated based on midday stem water stress integral, leaf N, leaf K, stomatal conductance and water stress index using Principal component regression technique during EFGP performed well with reasonably accuracy ($R^2 = 0.85$) to forecast annual fruit yield of the citrus plants. Overall, these results reveal that irrigation at 50% ET_c during EFGP could impose desirable water stress on 'Kinnow' mandarin plants, improving their water use efficiency, without significantly affecting the fruit yield under water scarce condition.

1. Introduction

Water availability becomes a major constraint to crop production in almost all regions of the world. In recent years, deficit irrigation (DI) has emerged as one of the potential tools to be used for sustainable crop production in water scarce regions. Reducing water supply to optimal level of crop water requirement in certain growth stages of the crop improves water use efficiency and quality of produces, without affecting the yield significantly (Panda et al., 2004). Therefore, the correct application of DI requires the thorough understanding of the yield response of crops to irrigation (English, 1990).

Citrus, an evergreen and high water requiring perennial fruit crop, is mainly grown in tropical and sub-tropical regions of the world. Irrigation water is a key input to successful cultivation of citrus (Singh and Srivastava, 2004). Drip irrigation is one of the potential water saving irrigation methods in citrus (Abu-Awwadm, 2001; Panigrahi et al., 2012a). In recent years, several research contributions have documented the advantages of DI in citrus in water

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scarce regions. Castel and Buj (1990) reported that 40% reduction in irrigation water supply during flowering and fruit set period did not reduce the fruit yield significantly in 'Salustiana' orange (*Citrus sinensis* Osbeck) trees in Spain. Gonzaalez-Altozano and Castel (1999) compared the 'Clementina de Nules' (*Citrus clementina* Hort. ex Tan.) tree performance under DI at 25% or 50% ETc during flowering and fruit set, initial fruit enlargement phase, and final fruit growth and maturation phases. They reported that water stress during flowering and fruit set period significantly reduced the fruit yield up to 62% over full irrigation. Pérez-Pérez et al. (2008b) observed that withholding irrigation at initial fruit growth period and final fruit growth period of 'Lane late' orange (*Citrus sinensis* Osbeck) reduced the yield significantly. DI scheduled with 40 and 60% reduction in irrigation water quantity at initial fruit enlargement stage of 'Navalina' sweet orange (*Citrus sinensis* Osbeck) in Spain did not affect the yield and fruit quality (Gasque et al., 2010). García-Tejero et al. (2010b) demonstrated that the irrigation applied at 55% crop water requirement during flowering and fruit growth in 'Navelina' sweet orange significantly reduced the fruit yield. However, irrigating the trees at 70% full irrigation at flowering and fruit-growth phases along with 55% FI at fruit maturity phase decreased the yield by 10–12% with 24% enhancement in water productivity. Panigrahi and Srivastava (2011) advocated for irrigation at 70% crop water requirement for 'Nagpur' mandarin (*Citrus reticulata* Blanco) grown in clay soil, which enhanced the water use efficiency substantially without affecting the yield significantly. Overall, the studies indicate that the level and time of water stress along with its duration are the main factors responsible for success of DI in citrus. Moreover, orchard and crop characteristics such as soil, climate, and cultivar also play a role in success of DI (Treeby et al., 2007; Panigrahi and Srivastava, 2011).

'Kinnow' mandarin, a hybrid of 'King' mandarin (*Citrus nobilis* Loureiro) and 'Willow leaf' mandarin (*Citrus deliciosa* Ten), is a leading citrus cultivar in India. The cultivation of the crop is mainly confined to semiarid and arid environments of northern India, where more than 90% of annual rainfall (600 mm) is concentrated in 3–4 months (June–October) of a year. Irrigation is practised during January–June to improve the productivity of citrus orchards in this region. Water from ground water wells is the common source of irrigation for the crop. For last few years, the shortage of irrigation water caused by over exploitation of ground water has become a major threat to citrus production. On the other hand, the area under the crop has been exponentially increasing due to the cultivar suitability and its high production economics in this region (Bhat et al., 2011). Farmers are more concerned with the sustained production of 'Kinnow' mandarin using less water. Optimal DI scheduling under drip irrigation is one of the option for sustaining 'Kinnow' mandarin production in this region.

The earlier study by Hasan and Sirohi (2006) on 'Kinnow' mandarin indicated that the crop is most sensitive to water stress at flowering and fruit set stage which takes place during month of March in northern India. The water scarcity caused by low water level in the wells in summer months (March–June) has forced the orchard growers to opt for DI during this period. In absence of the information on the crop response to DI in early fruit growth period (EFGP, April–June), the orchard growers have adopted faulty irrigation strategy which has affected the yield drastically with inferior quality fruits. Moreover, the information on the responses of mandarin cultivars of citrus to water stress in summer months, which coincides with EFGP, is very limited worldwide. Further, the yield prediction under differential water stress condition is also limited in fruit crops. Since it has been recognised that the tree itself is the best indicator of water stress and yield (Braun et al., 1989; Goldhamer et al., 2003), a new methodology for forecasting yield using plant-based measurements in any growth stage of citrus could also benefit growers.

The present study was, therefore, carried out with following objectives: (i) to optimize the DI scheduling in EFGP in relation to yield, fruit quality, and water use efficiency of 'Kinnow' mandarin and (ii) to develop the plant parameter-based yield forecasting model for the crop under differential water stress conditions in EFGP using principal component regression (PCR) technique, in a semiarid subtropical climate of North India.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at the Research orchard of the Centre for Protective Cultivation Technology, Indian Agricultural Research Institute, New Delhi (latitude 28° 38′23″ N, longitudes 77° 09′27″ E and at an average elevation of 228.61 m above the mean sea level), India. The citrus plant used in the study was 'Kinnow' mandarin budded on rough lemon (*Citrus jambhiri* Lush) rootstock. The experiment was conducted for two consecutive years (2010 and 2011) with 10 year-old plants, which were drip-irrigated from initial year of planting. The plant to plant spacing in a row and within the row was 4 m and 5 m, respectively.

The texture of experimental soil was sandy loam with bulk density 1.54 g cm^{-3}. Taxonomically the soil belongs to Typic Haplustept. The field capacity (−0.033 MPa) and permanent wilting point (−1.50 MPa) of the soil were 24.0% and 8.5% on volume basis, respectively. The soil had almost neutral pH (7.2) with mild EC (0.15 dS m^{-1}). The mean available N, P, K, Fe, Mn, Cu, and Zn concentration in the soil was 63.6, 11.7, 85.7, 7.4, 10.0, 6.6 and 1.4 mg kg^{-1} soil, respectively. The irrigation water was free from salinity (EC, 1.15 dS m^{-1}), alkalinity (pH, 7.3) and sodicity (SAR, 4.4). The water level in the groundwater wells, situated at 20 m distance from the experimental plot, was around 17.0 m deep.

The climate of the experimental site is characterized as semiarid sub-tropical, with hot and dry summers. The mean annual rainfall is 600 mm, out of which around 90% is received during monsoon (June–October). The mean daily class-A pan evaporation rate varied from 1.6 mm in January to as high as 10.7 mm in June. The meteorological parameters during different growth stages of the crop are presented in Table 1. The rainfall amount in EFGP during 2010 (8.8 mm) was lower than that during 2011 (82.2 mm). However, the daily mean maximum temperature (40.7 °C), mean minimum temperature (25.4 °C) and pan evaporation (10.0 mm day^{-1}) in EFGP during 2010 were higher than the mean maximum temperature (38.9 °C), mean minimum temperature (23.3 °C) and pan evaporation (7.0 mm day^{-1}) in EFGP during 2011.

2.2. Treatments and layout

Two DI regimes: no irrigation (RDI_0) and 50% crop evapotranspiration (RDI_{50}) were applied at EFGP and their impact on crop performance was compared with that under full irrigation (FI: 100% crop evapotranspiration). The duration of EFGP was taken from mid-April to mid-June, as suggested by Dhillon (1986) and Singh et al. (1998) for 'Kinnow' mandarin in the study region. Irrigation was applied through drip system from mid-January to June and from October to December. Water supply was stopped during monsoon season (July–September) due to adequate rainfall fulfilling the crop water need during this period. The irrigation treatments were laid out in randomized complete block design with 7 replications. Each replicated plot having size 240 m^2 (15 m × 16 m) had 12 trees in 3 adjacent rows and two central trees of the rows were considered as experimental trees. All the measurements were taken from the experimental trees.

Table 1
Meteorological parameters during different growth stages of 'Kinnow' mandarin in the experimental site.

Year	Growth stages	Rainfall (mm)	Daily mean temperature (°C)		Pan evaporation (mm day^{-1})
			Maximum	Minimum	
2010	PFP[a]	13.0	24.6	9.9	3.2
	FFSP[b]	0	37.5	18.1	7.9
	EFGP[c]	8.8	40.7	25.4	10.0
	MFGP[d]	898.6	39.9	25.0	5.4
	FFGP[e]	33.3	25.3	11.3	1.8
2011					
	PFP[a]	52.5	22.9	8.9	3.4
	FFSP[b]	0	32.9	15.2	5.6
	EFGP[c]	82.2	38.9	23.3	7.0
	MFGP[d]	527.4	33.8	24.88	3.8
	FFGP[e]	0	23.4	12.0	1.7

[a] PFP: Pre-flowering period (February to mid-March).
[b] FFSP: Flowering and fruit setting period (mid-March to mid-April).
[c] EFGP: Early fruit growth period (mid-April to mid-June).
[d] MFGP: Mid-fruit growth period (mid-June to mid-October).
[e] FFGP: Final fruit growth period (mid-October to January).

2.3. Irrigation scheduling and crop management practices

Irrigation was imposed every other day through six on-line 8 l h^{-1} pressure compensated drip emitters (Jain Irrigation, India) per tree, fitted on 16 mm diameter lateral pipes. The emitters were placed at 1.0 m away from tree trunk with a hexagonal arrangement. The water quantity applied under FI was determined according to potential crop evapotranspiration (ET$_c$) which was estimated based on 100% class-A pan evaporation rate, as observed by Hasan and Sirohi (2006) for 'Kinnow' mandarin plants in the study region. ET$_c$ was worked out using the following formula:

$$ET_c = K_p \times K_c \times E_p \tag{1}$$

where ET$_c$ (mm); K_p, the pan coefficient (0.8), K_c, the crop-coefficient (0.85) for bearing 'Kinnow' plant as proposed by Hasan and Sirohi (2006) and Ep the 2-days cumulative pan evaporation (mm). The volume of water applied under FI was computed following the formula (Germanà et al., 1992):

$$V_{id} = \pi(D^2/4) \times (ET_c - R_e)/E_i \tag{2}$$

where, V_{id} is the irrigation volume applied in each irrigation (litre tree^{-1}), D the mean tree canopy spread diameter measured in N–S and E–W directions (m), R_e the effective rainfall depth (mm), and E_i the irrigation efficiency of drip system (90%). R_e was estimated as the summation of soil water content enhancement in root zone of the trees (mm) due to rainfall and ET$_c$ (mm) for the rainfall day (Dastane, 1978). The water supply in each treatment was regulated with the help of water meters and control valves provided at the inlet end of sub-main pipes.

The fertilizer (354 g N as both urea and urea-phosphate, 160 g P_2O_5 as urea-phosphate and 345 g K_2O as muriate of potash per plant) was applied 4 times (January, March, June and October) in a year, as recommended for bearing 'Kinnow' plants (Hasan and Sirohi, 2006). Ground floor of the experimental orchard was kept weed free and uniform plant protection measures against insect pests and diseases were adopted for all plants in the experimental block.

2.4. Measurements and analysis

Soil sampling was done at 0.3 m, 0.6 m, 0.9 m, 1.2 m, and 1.5 m distances from plant stem and at 0–0.2 m, 0.2–0.4 m, 0.4–0.6 m, 0.6–0.8 m, and 0.8–1.0 m depths at beginning and end of each experimental year. The samples were subjected to analysis for available nutrients (N, P, K, Fe, Mn, Cu and Zn). One plant basin from each replicated plot (7 experimental plants per treatment) was taken for soil sampling. Available nutrients were determined by following the standard procedures suggested by Tandon (2005). The depth wise mean values of available nutrients in different treatments were calculated and averaged for entire root zone depth.

Three- to five- months old leaf samples (3rd and 4th leaf from tip of non-fruiting branches) at a height of 1.5 m from ground surface surrounding the plant canopy were collected at end of October, as recommended by Chahill et al. (1988) and analysed for macronutrients (N, P, K) and micronutrients (Fe, Mn, Cu, and Zn) following the standard methods suggested by Tandon (2005).

The volumetric soil-water content (θv) at different soil depths (0.2 m, 0.4 m, 0.6 m and 1.0 m) was measured daily using a moisture meter (Profile Probe-PR2/6, Delta-T Devices, Cambridge, UK) in EFGP during 2010 and 2011. Seven plants per treatment were selected for the measurement and one access tube per plant was installed at 0.15 m distance from drip emitters. The depth wise mean soil water content for each fortnight was calculated.

Stem water potential measured at 12:00–13:00 hr (ψ) was determined fortnightly on a cloudless day using a Pressure chamber (Model-600, PMS instrument, Oregon, USA) in EFGP, following the procedure described by Turner (1988). Two leaves per plant near the trunk or a main scaffold branch were covered by both aluminium sheet and black polythene sheet before 2 h of measurement and their water potential represented the ψ (Pérez-Pérez et al., 2008a). Moreover, the water stress integral for each treatment was calculated using the midday stem water potential data, according to the equation defined by Myers (1988):

$$S_\psi = \sum_{i=0}^{i=1} \{(\psi i, i+1) - c\} n \tag{3}$$

where S_ψ is water stress integral (MPa day), $\psi_{i,\,i+1}$ is average midday stem water potential for any interval i and $i+1$ (MPa), c is maximum stem water potential measured during the study and n is number of days in the interval.

The net photosynthesis rate (P_n), stomatal conductance (g_s), and transpiration rate (T_r) of leaves were recorded fortnightly, in one hour interval from 9 am to 3pm on a clear-sky day by portable infrared gas-analyser (LI-COR-6400, Lincoln, Nebraska, USA) in EFGP. Four mature leaves per plant (3rd or 4th leaf from tip of shoot) from exterior canopy position (one leaf in each North, South, East and West direction), and two plants per treatment were sampled for these measurements. Leaf water use efficiency (LWUE) was calculated as the ratio of P_n to T_r of leaves (Ribeiro et al., 2009).

For determining relative water content (RLWC) and water concentration (LWC), two leaves per plant (7 plants per treatment) from the similar position of leaves taken for water potential measurement were detached once in a fortnight at midday in EFGP. The leaves were cut into small pieces (approximately 1 cm^2 area) and weight of the leaflets was measured (known as fresh weight, FW). Afterwards the leaflets were placed in distilled water (for 3–4 h) until they gained a constant weight (known as turgid weight, TW). The dry weight (DW) was determined by placing the leaflets in an oven at 60 °C (for 1–2 days) till a constant weight had been achieved. RLWC and LWC were estimated following the procedures suggested by Bowman (1989) using the formulae:

$$RLWC(\%) = \{(FW - DW)/(TW - DW)\}X100. \quad (4)$$

$$LWC(\%) = \{(FW - DW)/(FW)\}X100 \quad (5)$$

To study the reflectance behaviour of the mandarin plants, one plant per replicated block was selected and monitored fortnightly in EFGP. Canopy reflectance spectra in the range of 350–2500 nm with 1 nm bandwidth were measured at the top the trees around midday (12:00–13:00 hr) on cloudless days with the help of hand held ASD FieldSpec Spectroradiometer (Analytical Spectral Devices Inc., Boulder Co, USA). The spectroradiometer was deployed with the field of view (FOV) of 25° and the distance between the optical head of the spectroradiometer and the top of the tree canopy was kept at 1 m for all observations. Four readings (1–2 s each) per tree were taken at different position of tree canopy and averaged to calculate the plant reflectance. Resultant data afterwards were interpolated by the ASD software to produce values at each nanometre interval. The spectral reflectance indices related to water deficit conditions (water band index, WBI; normalized difference water index, NDWI; moisture stress index, MSI), which reflects the overall health and canopy water status of the plants, were calculated as: WBI = $(R_{900})/(R_{970})$ (Peñuelas et al., 1993); NDWI = $(R_{857} - R_{1241})/(R_{857} + R_{1241})$ (Gao, 1995) and MSI = $(R_{1599})/(R_{819})$ (Hunt and Rock, 1989), where R and the subscript numbers indicate the light reflectance at the specific wavelength (in nm). The lower values of the indices indicate the better health of the plants with higher greenness (chlorophyll content) and greater water content in canopy.

The plant height (PH, distance from ground surface to top of plant crown), stem height (SH, distance from ground surface to base of first branch on stem), canopy diameter (CD, mean of canopy spread diameter measured in N–S and E–W directions), stock girth diameter (STGD, stem diameter measured at 0.01 m above bud union), scion girth diameter (SGD, stem diameter measured at 0.1 m above bud union) were recorded annually by using a metric tape. Plant canopy volume (CV) was estimated using the following formula (Obreza, 1991):

$$CV = 0.5238\,H\,(CD)^2 \quad (6)$$

where CV is in m^3, H is the plant canopy height (difference between plant height and stem height) in meter and CD in meter.

Weekly fruit growth was recorded by using a digital slide caliper. Ten fruits per plant (7 plants per treatment) were tagged after completion of fruit setting (Mid-April), and their height and diameter were recorded. The rate of fruit growth (FGR, mm day^{-1}) was calculated based on the formula (Pérez-Pérez et al., 2008b):

$$FGR = (\ln D_2 - \ln D_1)/(T_2 - T_1) \quad (7)$$

Where D_2 and D_1 are the final and initial mean diameter (mean of polar and equatorial diameter) of fruits measured during a week. The difference of time (T_2–T_1) was 7 days

The number and weight of entire fruits harvested from each experimental plant were recorded and the mean yield per plant under various treatments was calculated. The fruit yield per hectare was estimated considering 500 plants per hectare. Irrigation water use efficiency (IWUE) was worked out as the fruit yield per unit quantity of irrigation water applied. Five fruits per plant were taken randomly for determination of fruit quality parameters (juice percent; titrable acidity, TA; total soluble solids, TSS and ascorbic acid content). All the quality parameters were determined following the standard procedures suggested by Ranganna (2001).

2.5. Statistical analysis

The fruit yield of a tree is the function of many plant-based factors such as nutrition, physiology, vegetative growth, etc. which are well correlated with each other and are affected by water stress. Determining the most dominating variables affecting fruit yield is the foremost step for predicting yield. PCR (Principal component analysis) is a standard statistical technique to predict any output from a number of inputs. The process involves two steps: PCA of the input variables and development of multi-linear regression equation taking output as dependent variables and principal components (PCs) as independent variables. PCs are the variables having maximum variability in the data set which can be derived by PCA. In principle, PCs with eigen values ≥1 have a significant contribution towards the explanation of total variation and thus retained for further analysis, as suggested by Jolliffe (1986) and Khattree and Naik (2000). PCA is commonly used when the number of predictor variables is large and/or when strong correlations exist among the predictor variables. The objective of PCA is to obtain linear combinations of representative variables that exhibit maximum variance for a multidimensional phenomenon and which are also uncorrelated. The wide application of PCA has been found in modelling. However, the use of PCA and/or PCR in forecasting yield of a crop is very limited.

Analysis of variance of main effects of macronutrients and micro-nutrients in soil and leaves, RLWC, LWC, Ψ, SΨ, P_n, g_s, T_r, LWUE, WBI, NDWI, MSI, vegetative growth parameters, yield and fruit quality parameters was performed using SAS procedures PROC ANOVA (SAS Institute, Inc., 2009). The multivariate analysis (correlation matrix and PCA) and multi-linear regression analysis, correlating fruit yield to other plant-based parameters were also performed using the software. Correlation matrix (using PROC CORR) was made to determine the strength of linear relationship among the variables, whereas regression analysis (using PROC REG) was done to establish the mathematical relation between the dependent variable (yield) with independent variables having maximum variability in the data set. PCA was performed using PROC PRINCOMP procedure to determine the variables with maximum variability. Data for different years were tested comparing treatment means using *t*-test.

3. Results and discussion

3.1. Water applied and soil water variation

The quantities of irrigation water applied under RDI_0, RDI_{50} and FI in 2010 were 434.7 mm, 641.1 mm and 847.5 mm, respectively, whereas in 2011 these quantities were 320.0 mm, 460.2 mm and 600.4 mm, respectively. The variation in water quantity between two years of observation was attributed to change in evaporation rate, rainfall and canopy diameter of the plants.

The mean fortnightly volumetric water contents (θv) observed at different soil depths (0.2, 0.4, 0.6 and 1.0 m) in EFGP during 2010 and 2011 are presented in Fig. 1a and b. The θv decreased progressively from the day after onset of stress (DAOS) to end of stress period (60 DAOS) in both the years of experiment, except at 0.2 m depth at 30 DAOS in 2010 and at 0.2 m and 0.4 m depths at 45 DAOS in 2011. The increase in θv at 30 DAOS in 2010 and 45 DAOS in 2011 was due to rain (8.8 mm and 33 mm in respective years)

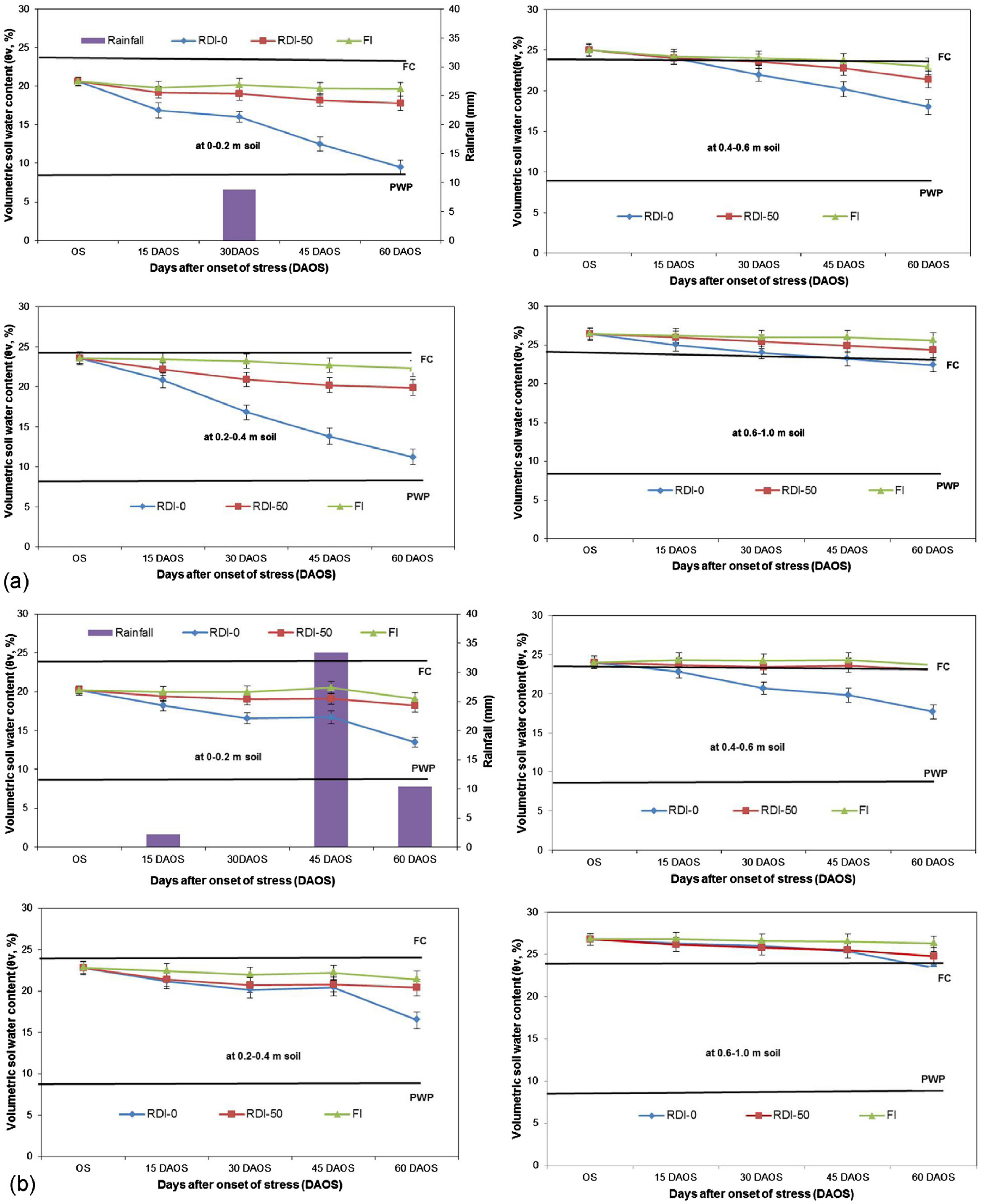

Fig. 1. Soil water content variations at different depths at early fruit growth period (EFGP) of 'Kinnow' mandarin plants under RDI_0 (no irrigation), RDI_{50} (irrigation at 50% crop evapotranspiration) and FI (Full irrigation: 100% crop evapotranspiration) (a) in 2010 and (b) in 2011. FC: field capacity and PWP: permanent wilting point of soil. The vertical bar at each data point represents the standard error of mean.

during EFGP. The fortnightly estimated soil water depletion (SWD) was greatest with RDI_0 (4.4–12.4% in 2010 and 3.4–9.0% in 2011), followed by RDI_{50} (2.0–3.7% in 2010 and 1.0–2.4% in 2011) at different soil depths. The SWD was greater in 2010 compared with that in 2011, in spite of higher rainfall in 2011 at EFGP. This was due to higher evaporative demand of the plants in 2010 (mean daily pan evaporation, 10.01 mm) compared with that in 2011 (mean daily pan evaporation, 6.95 mm) in this period. However, the SWD at top 0.4 m soil between 2 observations in a week was observed to be greater with FI than that with other treatments, reflecting the higher evapotranspiration of the trees under increased soil water regime in this treatment (Fig. 1a and b).

The θv value increased with depth under each treatment. However, the maximum SWD was found at 0.4 m soil depth, followed by 0.2 m depth, indicating the existence of the most active roots (effective root depth) of mandarin trees at 0.2–0.4 m depth. The earlier findings showed a shallow active rootzone of 0.15 m for drip-irrigated 'Nagpur' mandarin budded on Rangpur lime grown in vertisol of central India (Autkar et al., 1988; Panigrahi et al., 2008) and of 0.3 m for Sweet orange budded on Rangpur lime on red sandy-clay loam soil in South India (Iyengar and Shivananda, 1990). This difference in rooting is due to the variation of citrus cultivars and root stock used in varied pedo-climatic conditions. However, the active root depth observed in 'Kinnow' mandarin in this study is strongly supported by the earlier observation of Bhambota et al. (1977) which showed that the active root zone of Jatti Khatti, the citrus cultivar used as a rootstock for Kinnow mandarin, exists within the top 0.4 m soil. The root stock is mostly responsible for root development of a budded tree in citrus (Bielorai, 1982; Treeby et al., 2007). The SWD value at 0.6 m depth under RDI_0 was significantly increased compared with that under RDI_{50} and FI. This happened due to the higher root activity which was probably caused due to extension of roots in 0.6 m soil under water stress condition in RDI_0 treatment. However, the lower soil water depletion at 1.0 m depth even under FI indicated the lower concentration of roots in this soil layer.

3.2. Variation in available soil nutrients

The changes in available macronutrients (N, P and K) in root zone of the plants under various irrigation treatments show that the nutritional status of the soil improved in both the years of experiment (Table 2). This happened due to the application of NPK-based fertilizers to the plants during irrigation seasons. The maximum increase in the soil available N, P and K was observed with FI, followed by RDI_{50}. The greater nutrients availability with FI was probably caused by higher microbial activities which resulted in higher mineralisation and transformation of nutrients with optimum soil-water regime prevailed in root zone of the plants in this treatment compared with other treatments (Amberger, 2006). However, the effect of irrigation on available-P was statistically insignificant, due to low solubility and slow movement of P in soil water continuum (Amberger, 2006). The increase in available nutrient amount was higher in 2010 than 2011, indicating higher nutrients uptake by plants in the latter year.

The magnitudes of available micronutrients (Fe, Cu, Zn, Mn and Cu) in the soil decreased, irrespective of irrigation treatments (Table 2). The maximum decrease in concentration of available micronutrients was observed under FI and the minimum was with RDI_0. The greater loss of micronutrients in soil under FI might be caused due to higher plant uptake of these nutrients under increased soil water content in this treatment. However, the effect of irrigation on available Cu was insignificant. The consistent amount of Cu maintained in soil under different treatments was due to the application of Cu-based fungicides which is a common recommendation against *Phytopthora* disease in the crop. The consistent reduction of micronutrients (except Cu) in soil suggests a need for application of appropriate quantity of micronutrients-based fertilizers to mandarin plants to improve the efficiency and longevity of the orchards.

3.3. Changes in leaf nutrient composition

The macronutrients (N, P and K) concentration in leaves showed a differential response to irrigation treatments (Table 3). FI treatment produced the higher concentrations of N, P and K in leaves compared with that in leaves in DI treatments. The greater N, P and K content in leaves of fully-irrigated trees was caused by increased availability of such nutrients in soil under FI. The concentration of nutrients in leaves decreased with decrease in irrigation regime. However, the amount of N, P and K in leaves was adequate with both FI and RDI_{50}, when compared to the foliar diagnostic chart (2.50–2.93% N, 0.17–0.28% P and 1.63–1.89% K) developed for optimum 'Kinnow' mandarin productivity in North India condition (Srivastava, 2011). The sub-optimum leaf nutrient concentration with RDI_0 indicates that withholding irrigation in EFGP is not suitable for balanced nutrition of 'Kinnow' mandarin plants, which is a prerequisite for higher productive life of the orchards (Hundal and Arora, 2001; Srivastava, 2011). The trend of leaf nutrients observed in this study was reflective of the observations made by Shirgure et al. (2000) in acid lime and Panigrahi et al. (2012b) in 'Nagpur' mandarin, which stated that the leaf nutrient composition is affected by water stress in citrus. In contrast, Romero et al. (2006) observed that mineral (N, P, and K) nutrition of 'Clemenules' mandarin budded on 'Cleopatra' mandarin in Spain was not affected by water stress which was imposed by stopping irrigation in both initial fruit growth period and final fruit growth period. This variation was attributed to the higher nutrients concentration in soil, better soil water availability due to intermittent rainfall, and higher capability of the rootstock plant ('Cleopatra' mandarin) for mineral uptake due to its superior root morphology (higher specific root length and higher root fineness) in the study site as compared with 'Kinnow' mandarin in the present study.

The micronutrient (Fe, Mn, Cu and Zn) concentration in leaves except Cu followed the same trend of N and K under different irrigation treatments (Table 3). Overall, in all irrigation treatments except RDI_0, the leaf micronutrients (Fe, Mn and Zn) content was higher than their threshold values (57.8–69.4 ppm Fe, 52.7–76.3 ppm Mn and 25.9–28.5 ppm Zn) required for optimum productivity of 'Kinnow' mandarin (Srivastava, 2011). Similar trend of micronutrient concentration in leaves was observed with acid lime (Shirgure et al., 2000) and 'Nagpur' mandarin (Panigrahi et al., 2008) under DI. However, Romero et al. (2006) concluded that water stress has no significant affect on Fe, Mn, Cu and Zn concentration of leaves in citrus. This difference from the present observation might be due to higher micro-nutrients concentration in their soil that supported the availability of the nutrients to plants even under water stress condition, as compared to the soil in the present study. Moreover, the concentration of micronutrients in leaves decreased from 2010 to 2011 due to their reduced availability in soil over time.

3.4. Leaf water content and stem water potential

The mean RLWC and LWC in EFGP were significantly affected under various irrigation treatments (Table 4). The maximum values for RLWC and LWC were observed with FI, whereas the minimum values were observed with RDI_0. The higher values for RLWC and LWC under increased irrigation regime were earlier observed in citrus (Maotani and Machida, 1980 and Ray et al., 1990).

Irrigation treatments affected ψ and S_ψ of the plants significantly in EFGP (Table 4). The greater values of ψ with lower

Table 2
Annual changes in available macronutrients (N, P and K) and micronutrients (Fe, Mn, Cu and Zn) concentration in soil under Regulated deficit irrigation (RDI) and full irrigation (FI) in 'Kinnow' mandarin in 2010 and 2011.

Treatments	Macronutrients (mg kg^{-1} soil)					
	2010			2011		
	N	P	K	N	P	K
RDI$_0$	$+2.94^{cA}$	$+0.85^{aA}$	$+3.85^{cA}$	$+0.70^{cB}$	$+0.35^{aB}$	$+1.48^{cB}$
RDI$_{50}$	$+3.45^{bA}$	$+0.87^{aA}$	$+4.21^{bA}$	$+1.10^{bB}$	$+0.48^{aB}$	$+1.71^{bB}$
FI	$+4.29^{aA}$	$+0.93^{aA}$	$+4.65^{aA}$	$+1.78^{aB}$	$+0.51^{aB}$	$+1.93^{aB}$

	Micronutrients (mg kg^{-1} soil)							
	Fe	Mn	Cu	Zn	Fe	Mn	Cu	Zn
RDI$_0$	-0.72^{bA}	-0.53^{bA}	-0.21^{aA}	-0.12^{bA}	-0.78^{bB}	-0.60^{bB}	-0.24^{aB}	-0.14^{bB}
RDI$_{50}$	-0.97^{aA}	-0.89^{aA}	-0.26^{aA}	-0.18^{aA}	-0.99^{aB}	-0.92^{aB}	-0.28^{aB}	-0.21^{aB}
FI	-1.19^{aA}	-1.06^{aA}	-0.27^{aA}	-0.23^{aA}	-1.24^{aB}	-1.11^{aB}	-0.31^{aB}	-0.27^{aB}

'+' sign indicates the increase and '–' sign indicates decrease in the magnitude of the variables.
Data in one column followed by different small letters are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test and data in different years for each variable with same irrigation treatment followed by different capital letters are significantly different at $P < 0.05$.
RDI$_0$: no irrigation at early fruit growth period (EFGP); RDI$_{50}$: irrigation at 50% crop evapotranspiration at EFGP.

Table 3
Macronutrients (N, P and K) and micronutrients (Fe, Mn, Cu and Zn) content in leaves of 'Kinnow' mandarin as affected by various Regulated deficit irrigation (RDI) and full irrigation (FI) annually in 2010 and 2011.

Treatments	Macronutrients (%)					
	2010			2011		
	N	P	K	N	P	K
RDI$_0$	2.34^{cB}	0.13^{aB}	1.58^{cB}	2.38^{cA}	0.15^{aA}	1.60^{cA}
RDI$_{50}$	2.52^{bB}	0.18^{aB}	1.60^{bB}	2.57^{bA}	0.21^{aA}	1.63^{bA}
FI	2.69^{aB}	0.22^{aB}	1.64^{aB}	2.71^{aA}	0.24^{aA}	1.66^{aA}

	Micronutrients (ppm)							
	Fe	Mn	Cu	Zn	Fe	Mn	Cu	Zn
RDI$_0$	55.6^{bA}	46.2^{bA}	7.2^{aA}	24.2^{bA}	54.4^{bB}	46.0^{bB}	7.0^{aB}	24.0^{bB}
RDI$_{50}$	59.7^{aA}	55.6^{aA}	7.6^{aA}	26.3^{aA}	58.8^{aB}	54.2^{aB}	7.3^{aB}	26.0^{aB}
FI	62.6^{aA}	61.5^{aA}	8.2^{aA}	27.1^{aA}	61.3^{aB}	61.0^{aB}	8.0^{aB}	26.9^{aB}

Data in one column followed by different small letters are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test and data in different years for each variable with same irrigation treatment followed by different capital letters are significantly different at $P < 0.05$.
RDI$_0$: no irrigation at early fruit growth period (EFGP); RDI$_{50}$: irrigation at 50% crop evapotranspiration at EFGP.

S_ψ in 2011 than that in 2010 was caused by higher amount of rainfall (82.2 mm), and lower temperature (mean, 31 °C) in conjunction with lower evaporation rate (6.95 mm day^{-1}) during EFGP in 2011 compared with rainfall (8.8 mm), mean temperature (33 °C) and evaporation rate (10.01 mm day^{-1}) in 2010. The trees with FI exhibited the highest ψ with lowest S_ψ, whereas the trees with RDI$_0$ exhibited the lowest values. However, the magnitude of S_ψ (17.6 MPa day) estimated with 'Kinnow' mandarin plants in this study differed from that observed by Ginestar and Castel (1996) with 'Clementine de Nules' (40 MPa day) and by Pérez-Pérez et al. (2008a) in Lane late' (9.0 MPa day), due to the differences in environmental factors, cultivars used and irrigation regime imposed.

3.5. Leaf physiological parameters

The P_n, g_s and Ts_r of leaves during EFGP was significantly influenced by irrigation treatments (Table 5). The greater values of P_n in 2011 were probably due to lower temperature in this period which favoured the better photosynthesis rate of mandarin plants in comparison to that in 2010 (Bhatnagar et al., 2011). Earlier, it was reported that citrus trees could attend maximum P_n value with ambient air temperature of 30 °C and then this parameter drastically decreases with increase in air temperature (Vu and Yelenosky, 1988; Romero et al., 2006). In this study, even with air temperature of 35 °C, there was no marked difference in photosynthesis rate,

Table 4
Relative leaf water content (RLWC), leaf water concentration (LWC), mid-day stem water potential (Ψ) and water stress integral (S_Ψ) of 'Kinnow' mandarin under Regulated deficit irrigation (RDI) and full irrigation (FI) during EFGP in 2010 and 2011.

Treatments	Leaf water relation factors							
	2010				2011			
	RLWC (%)	LWC (%)	Ψ (MPa)	SΨ (MPa day)	RLWC (%)	LWC (%)	Ψ (MPa)	S_Ψ (MPa day)
RDI$_0$	75.6^{cB}	66.8^{cB}	-1.4^{cB}	45.8^{aB}	78.2^{cA}	68.2^{cA}	-1.1^{cA}	39.2^{aA}
RDI$_{50}$	83.5^{bB}	70.6^{bB}	-1.2^{bB}	29.3^{bB}	84.6^{bA}	73.7^{bA}	-0.8^{bA}	24.1^{bA}
FI	93.7^{aB}	78.4^{aB}	-0.8^{aB}	18.9^{cB}	94.2^{aA}	79.6^{aA}	-0.7^{aA}	16.2^{cA}

Data in one column followed by different small letters are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test and data in different years for each variable with same irrigation treatment followed by different capital letters are significantly different at $P < 0.05$.
RDI$_0$: no irrigation at early fruit growth period (EFGP); RDI$_{50}$: irrigation at 50% crop evapotranspiration at EFGP.

Table 5
Photosynthesis rate (P_n, μmol m^{-2} s^{-1}), stomatal conductance (g_s, mmol m^{-2} s^{-1}), transpiration rate (T_r, mmol m^{-2} s^{-1}) and leaf water use efficiency (LWUE) of 'Kinnow' mandarin under Regulated deficit irrigation (RDI) and full irrigation (FI) during EFGP in 2010 and 2011.

Treatments	Leaf physiological parameters							
	2010				2011			
	P_n	g_s	T_r	LWUE	P_n	g_s	T_r	LWUE
RDI$_0$	3.03^{cB}	29.13^{cB}	1.73^{cB}	1.75^{c}	3.61^{cA}	28.48^{cA}	1.51^{cA}	2.39^{cA}
RDI$_{50}$	3.59^{bB}	31.01^{bB}	1.82^{bB}	1.97^{a}	4.16^{bA}	30.47^{bA}	1.57^{bA}	2.64^{aA}
FI	3.88^{aB}	37.78^{aB}	2.08^{aB}	1.86^{b}	4.37^{aA}	37.37^{aA}	1.74^{aA}	2.51^{bA}

Data in one column followed by different small letters are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test and data in different years for each variable with same irrigation treatment followed by different capital letters are significantly different at $P < 0.05$.
RDI$_0$: no irrigation at early fruit growth period (EFGP); RDI$_{50}$: irrigation at 50% crop evapotranspiration at EFGP.

indicating the well acclimatised character of 'Kinnow' mandarin to higher temperature and higher light intensity for attending saturated P_n. However, the P_n started to decrease when air temperature became more than 35 °C, probably due to the partial damage of photosynthetic system with high temperature in this cultivar, as found in other citrus cultivars (Vu and Yelenosky, 1988; Pérez-Pérez et al., 2008a).

The higher values of P_n with fully-irrigated trees compared with that with RDI$_0$ and RDI$_{50}$ indicated the negative effect of soil water deficit on P_n in citrus trees. However, the greatest reduction in P_n was observed in between RDI$_{50}$ and RDI$_0$ (14.5%) compared with that between any other two treatments, indicating the existence of its threshold limit with RDI$_{50.}$ In other way, it can be expressed that the mandarin plants could sustain their photosynthesis rate with 50% reduction of water supply, which is called as the photosynthetic acclimatisation nature of citrus (Tomar and Singh, 1986; Vu and Yelenosky, 1988; Zhihui et al., 1990). The g_s and T_r values followed the same trend of P_n in different irrigation treatments. However, the highest reduction in g_s (18.2%) and T_r (11.0%) was observed between FI and RDI$_{50}$ in comparison with that between irrigation at RDI$_{50}$ and RDI$_0$ (g_s, 6.3%; T$_r$, 4.7%), reflecting the existence of critical soil water regime in relation to transpirational water loss with RDI$_{50}$. The maximum reduction in g_s and T_r compared to that in P_n at RDI$_{50}$ reflects the less sensitivity of the trees to soil water deficit in irrigation at 50% ETc to produce higher water use efficiency in leaf level. Moreover, the reduction of g_s was greater than that of T_r under RDI$_0$ and RDI$_{50}$ compared to FI. The lower reduction of T_r could be probably due to the contribution of residual or mesophyll conductance (movement of water through intercellular spaces and mesophyll cells of leaves) to transpiration of leaves (Davies and Albrigo, 1994). Leaf transpiration depends on total conductance (stomatal conductance + mesophyll conductance) of leaf. As water stress occurs, the stomatal closure restricts the entry of both CO$_2$ and water fluxes from surrounding atmosphere to leaf, but mesophyll conductance remains same and transpiration reduces disproportionately to stomatal conductance.

The magnitude of LWUE (μmol CO$_2$ fixed per mmol H$_2$O transpired) increased from RDI$_0$ to RDI$_{50}$ and then decreased at FI. The higher LWUE was with RDI$_{50}$ treatment, due to the marginal decrease in P_n value associated with the greater decrease in T_r value under this treatment 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. However, the values for LWUE in 2011 were significantly higher than that in 2010 in corresponding irrigation regimes, due to higher P_n with lower T_r with the treatments in 2011 compared with that in 2010.

3.6. Canopy reflectance

The hyperspectral reflectance of plant canopies during EFGP during 2010 and 2011 are shown in Fig. 2. The effect of irrigation on canopy reflectance was statistically insignificant in near infrared region (NIR, 700–1350 nm), whereas in short wave infrared region (SWIR, 1350-2500 nm) RDI$_0$ resulted in higher reflectance (10–13%) than that with RDI$_{50}$ (7–11%) and FI (6–9%), indicating that the plant water content played a major role in affecting canopy reflectance in the SWIR. The earlier observations in citrus also showed the similar trend of canopy reflectance values in response to irrigation in the NIR and SWIR (Dzikiti et al., 2011; Stuckens et al., 2011). Eitel et al. (2006), Jacquemoud et al. (2009) and Dzikiti et al. (2011) attributed such findings from different DI treatments to insignificant variation in leaf structure including cell size, and cell wall composition and structure which are the dominating factors in influencing canopy reflectance in the NIR, while leaf water content is the major factor in influencing reflectance in the SWIR in citrus. Moreover, in SWIR, the lower reflectance with higher irrigation treatment (FI) indicates the higher absorption of energy by increased water content in leaves in this treatment (Gutierrez et al., 2010). The previous studies by Dzikiti et al. (2011) observed the similar trend of reflectance in SWIR (10–12%) with irrigated 'Valencia' orange in South Africa. The reflectance in the SWIR during 2010 (6–10%) was observed

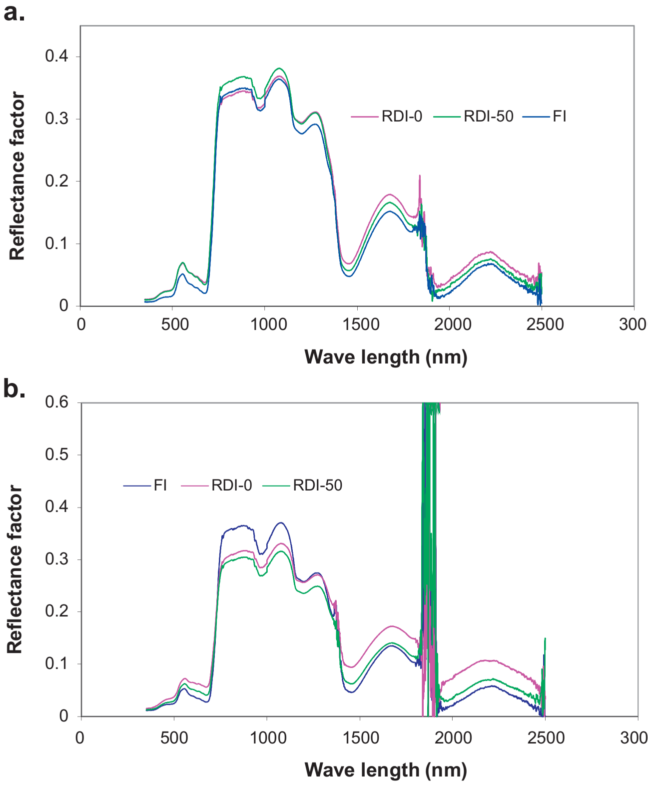

Fig. 2. Reflectance of 'Kinnow' mandarin plants under RDI$_0$ (no irrigation), RDI$_{50}$ (irrigation at 50% crop evapotranspiration) and FI (full irrigation: 100% crop evapotranspiration) at early fruit growth period (a) in 2010 and (b) in 2011.

Table 6
Variation of water band index (WBI), normalised difference water index (NDWI) and moisture stress index (MSI) of 'Kinnow' mandarin under Regulated deficit irrigation (RDI) and full irrigation (FI) during EFGP in 2010 and 2011.

Treatments	Canopy reflectance indices					
	2010			2011		
	WBI	NDWI	MSI	WBI	NDWI	MSI
RDI_0	1.20^{aA}	0.06^{aA}	0.86^{aA}	1.11^{aB}	0.05^{aB}	0.78^{aB}
RDI_{50}	1.04^{bA}	0.04^{bA}	0.55^{bA}	0.97^{bB}	0.03^{bB}	0.49^{bB}
FI	0.91^{cA}	0.03^{cA}	0.47^{cA}	0.81^{cB}	0.02^{cB}	0.38^{cB}

Data in one column followed by different small letters are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test and data in different years for each variable with same irrigation treatment followed by different capital letters are significantly different at $P < 0.05$.
RDI_0: no irrigation at early fruit growth period (EFGP); RDI_{50}: irrigation at 50% crop evapotranspiration at EFGP and FI: full irrigation (100% crop evapotranspiration) at EFGP.

Table 7
Annual incremental plant growth parameters of 'Kinnow' mandarin under various irrigation treatments in 2010 and 2011.

Treatments	2010				2011			
	PH[a] (m)	STGD[b] (mm)	SGD[c] (mm)	CV[d] (m^3)	PH (m)	STGD (mm)	SGD (mm)	CV (m^3)
RDI_0	28.31^{cA}	17.14^{aA}	24.64^{cA}	0.66^{cA}	22.16^{cB}	15.21^{aB}	21.75^{cB}	0.57^{cB}
RDI_{50}	37.90^{bA}	20.81^{aA}	29.91^{bA}	0.79^{bA}	30.72^{bB}	19.90^{aB}	25.22^{bB}	0.69^{bB}
FI	40.72^{aA}	26.22^{aA}	48.74^{aA}	0.86^{aA}	36.05^{aB}	25.64^{aB}	32.35^{aB}	0.78^{aB}

[a] PH: Plant height
[b] STGD: Stock girth diameter
[c] SGD: scion girth diameter
[d] CV: canopy volume

Data in one column followed by different small letters are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test and data in different years for each variable with same irrigation treatment followed by different capital letters are significantly different at $P < 0.05$.
RDI_0: no irrigation at early fruit growth period (EFGP); RDI_{50}: irrigation at 50% crop evapotranspiration at EFGP and FI: full irrigation (100% crop evapotranspiration) at EFGP.

to be lower than that during 2011 (9–13%), due to higher leaf water content in 2011 compared with that in 2010. The reflectance under all treatments was markedly different between wave lengths of 1500–2500 nm, suggesting the development of spectral indices integrating the reflectance in these wavelengths with that in NIR for better prediction of the plant water status in citrus.

The values for WBI, NDWI, MSI at the EFGP for assessing the water stress of the crop canopy is presented in Table 6. All the indices showed an increasing trend from FI to RDI_0, indicating the higher canopy water content and better health of fully irrigated plants in comparison with that with RDI_{50} and RDI_0. However, the value of the indices in 2010 was significantly higher than that in 2011, due to higher plant water deficit in 2010, caused by higher atmospheric evaporative demand and low rainfall during EFGP in this year compared with that in 2011.

3.7. *Plant vegetative growth*

The irrigation treatments significantly influenced the different growth parameters (PH, STGD, SGD and CV) of plants (Table 7). The minimum incremental PH, STGD, SGD and CV was observed with rain-fed plants, whereas the maximum values were with fully-irrigated plants. The greater vegetative growth under higher irrigation regime was probably due to better leaf photosynthesis rate and higher metabolic activities of fully-irrigated plants under favourable soil water condition in the root-zone in this treatment. However, the increase in growth was more in 2011 than 2010, probably due to larger rainfall amounts and other weather parameters which favoured better plant growth in former year than the latter year. Earlier study by García-Tejero et al. (2010a) showed the similar findings of decrease in vegetative growth of deficit-irrigated 'Salustiano' orange plants in Spain.

3.8. *Fruit growth*

The fruit growth pattern (FGP) showed a differential response to irrigation (Fig. 3a and b). In EFGP, fruit growth was decreased significantly by deficit irrigation (2.3–3.0 cm) compared with full irrigation (3.2–3.5 cm). After water application/rainfall in post-EFGP (mid fruit growth period, MFGP), fruit growth increased significantly only in fruits from deficit-irrigated tress (RDI_{50}), reaching some higher diameter (2–3 mm) than the fruits from other treatments. Overall, due to increased growth in MFGP, the fruits with RDI_{50} achieved greater diameter (85–87 mm) in comparison to that with FI (82–83 mm). The enhancement of fruit growth after the relief of water stress reflected the compensated growth rate

Table 8
Number of fruits harvested, average fruit weight, fruit yield and irrigation water use efficiency (IWUE) of 'Kinnow' mandarin under Regulated deficit irrigation (RDI) and full irrigation (FI) annually during 2010 and 2011.

Treatments	2010				2011			
	No. fruits tree^{-1}	Fruit weight (g fruit^{-1})	Fruit yield (t ha^{-1})	IWUE (t ha^{-1} mm^{-1})	No. fruits tree^{-1}	Fruit weight (g fruit^{-1})	Fruit yield (t ha^{-1})	IWUE (t ha^{-1} mm^{-1})
RDI_0	487.3^{cB}	125.7^{bB}	30.6^{bB}	0.070^{cB}	502.1^{cA}	129.4^{bA}	32.5^{bA}	0.101^{cA}
RDI_{50}	703.4^{bB}	169.5^{aB}	59.6^{aB}	0.092^{aB}	726.5^{bA}	171.7^{aA}	62.4^{aA}	0.135^{aA}
FI	763.7^{aB}	162.3^{aB}	62.0^{aB}	0.073^{bB}	776.1^{aA}	162.8^{aA}	63.2^{aA}	0.105^{bA}

Data in one column followed by different small letters are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test and data in different years for each variable with same irrigation treatment followed by different capital letters are significantly different at $P < 0.05$.
RDI_0: no irrigation at early fruit growth period (EFGP); RDI_{50}: irrigation at 50% crop evapotranspiration at EFGP.

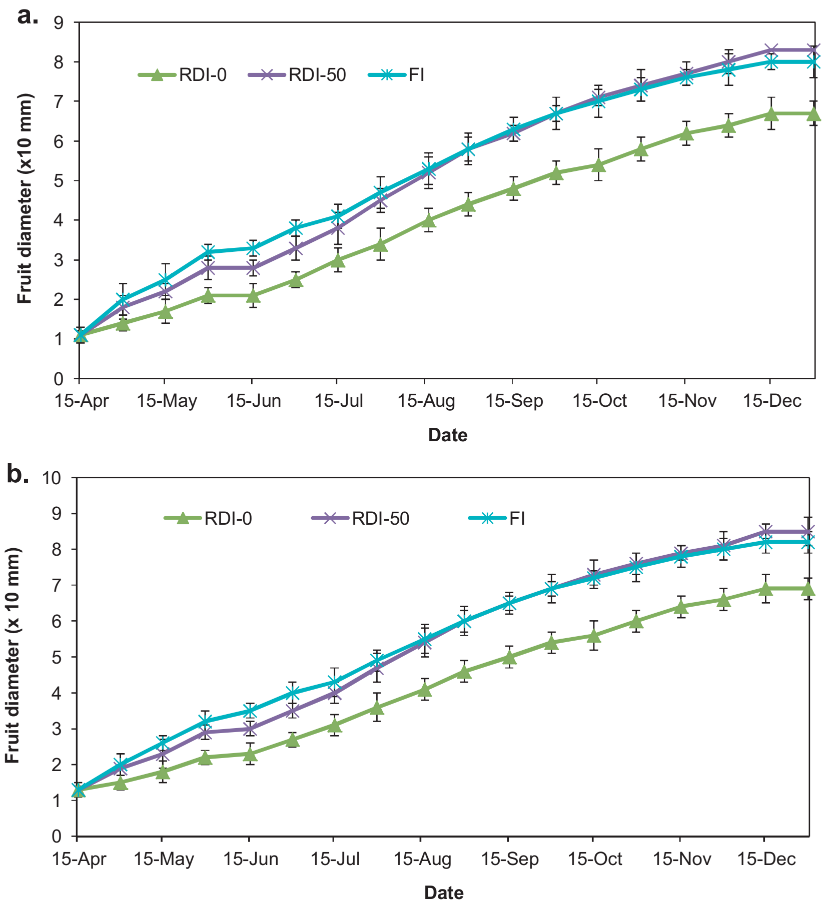

Fig. 3. Fruit growth pattern of 'Kinnow' mandarin under RDI$_0$ (no irrigation), RDI$_{50}$ (irrigation at 50% crop evapotranspiration) and FI (full irrigation: 100% crop evapotranspiration) (a) in 2010 and (b) in 2011. The vertical bar at each data point represents the standard error of mean.

of fruits under deficit irrigation which was also earlier observed in peach (Chalmers et al., 1981) and pear (Chalmers et al., 1986). However, withholding irrigation in both EFGP significantly reduced the final fruit size. The similar results of smaller fruits produced under no irrigation were previously reported by Pérez-Pérez et al. (2008b) in 'lane late' orange and García-Tejero et al. (2010a) in 'Salustiano' orange.

3.9. Fruit yield and water use efficiency

Table 8 presents the fruit harvested (number of fruits tree^{-1}, average fruit weight and total fruit yield) and irrigation water use efficiency under different irrigation treatments. The number of fruits harvested per tree and total fruit yield increased with increase in irrigation regime from no irrigation to FI. Conversely, the highest fruit weight was recorded with RDI$_{50}$ followed by FI. The lower fruit weight in FI treatment over RDI$_{50}$ treatment might be due to the higher fruit number under the former treatment over later one. However, the fruit yield recorded with fully-irrigated plants was statistically ($P < 0.05$) at par with that under RDI$_{50}$.

The IWUE decreased with increase in irrigation regime from RDI$_{50}$ to FI and the values were comparatively greater than that with RDI$_0$. The higher IWUE under RDI$_{50}$ was attributed to greater increase in fruit yield with comparatively less water supply in this treatment over other treatments. However, the possible reasons for higher fruit yield per unit quantity of water applied under RDI$_{50}$ treatment may be that the water deficit (15–20% available soil water depletion) in root zone under this treatment suppressed the vegetative growth of the plants without bringing much effect on leaf photosynthesis rate, and the citrus plants under this treatment invested higher portion of photosynthates towards reproductive growth (fruiting) than towards vegetative growth over that under full irrigation. An improvement in IWUE in response to optimum RDI over FI was also reported earlier in citrus (Pérez-Pérez et al., 2008b; García-Tejero et al., 2010a).

3.10. Correlation of fruit yield with other plant-based parameters and yield prediction

The degree of linear association of fruit yield with other plant-based observations (SGD, CV, leaf-N, leaf-K, leaf-Fe, leaf-Mn, leaf-Zn, ψ, S_ψ, RLWC, LWC, P_n, T_r, g_s, WBI, NDWI and MSI) is presented by correlation matrix (Table 9). Yield was observed to be highly correlated with S_ψ, ψ, leaf-K, g_s, leaf-N, P_n, WBI and T_r. Earlier studies by García-Tejero et al., 2010a in sweet orange and Pérez-Pérez et al. (2008b) in Salustian mandarin observed the higher correlation of yield with S_ψ. It was also observed that a better co-relationship existed between S_ψ and ψ, LWC and RLWC, ψ and LWC, g_s and T_r, ψ and RLWC, S_ψ and LWC, S_ψ and RLWC, T_r and S_ψ, T_r and RLWC, T_r and ψ, g_s and S_ψ, MSI and WBI, T_r and P_n, g_s and P_n, g_s and RLWC, g_s and ψ, P_n and S_ψ, WBI and leaf-N, T_r and LWC, WBI and S_ψ, P_n and RLWC, T_r and leaf-N, g_s and LWC, and WBI and RLWC.

In order to group the correlated plant-based variables to the smallest possible subsets representing the majority of variation, principal component analysis (PCA) was performed using the 19 variables (Table 10). As the first 3 PCs explained 88.90% variability of data set, these were considered for further analysis. The variables from PC-1 (ψ, S_ψ, Leaf-N, Leaf-K, RLWC), PC-2 (g_s, P_n) and PC-3

Table 9
Correlation matrix (Pearson's) for plant-based observations during 2010 for 'Kinnow' mandarin in EFGP.

Parameters	Fruit yield	SGD	CV	Leaf-N	Leaf-K	Leaf- Fe	Leaf- Mn	Leaf- Zn	RLWC	LWC	Ψ	SΨ	P_n	T_r	g_s	WBI	NDWI
SGD	0.27^{*}																
CV	0.33^{*}	0.45^{*}															
Leaf-N	0.54^{+}	NS	0.27^{*}														
Leaf-K	0.57^{+}	NS	0.35^{*}	0.38^{*}													
Leaf- Fe	0.31	NS	NS	NS	NS												
Leaf-Mn	0.23	NS	0.20	NS	NS	0.58^{+}											
Leaf-Zn	0.31^{*}	NS	NS	NS	NS	0.35^{*}	0.28^{*}										
RLWC	0.41	0.11^{*}	0.18^{*}	0.21	0.30^{*}	NS	NS	NS									
LWC	0.38	NS	NS	0.20	0.28^{*}	NS	NS	NS	0.92^{+}								
Ψ	**0.63^{+}**	**0.23^{*}**	**0.22^{*}**	**0.31^{*}**	**0.43^{*}**	NS	NS	NS	0.88^{+}	0.89^{+}							
SΨ	**0.72^{+}**	**0.37^{*}**	**0.30^{*}**	**0.39^{*}**	**0.57^{*}**	NS	NS	NS	0.86^{+}	0.86^{+}	**0.95^{+}**						
P_n	0.51^{+}	0.41^{*}	0.38^{*}	0.51^{+}	0.43^{*}	0.51^{+}	0.33^{*}	0.27^{*}	0.65^{+}	0.53^{+}	**0.59^{+}**	**0.72^{+}**					
T_r	0.50^{+}	NS	NS	0.48^{*}	0.65^{+}	0.47^{*}	0.38^{*}	0.22^{*}	0.79^{+}	0.68^{+}	**0.78^{+}**	**0.81^{+}**	0.76^{+}				
g_s	0.57^{+}	NS	NS	0.36^{*}	0.58^{+}	0.42^{*}	0.40^{*}	0.30^{*}	0.73^{+}	0.64^{+}	**0.72^{+}**	**0.78^{+}**	0.74^{+}	0.89^{+}			
WBI	0.51	0.27^{*}	0.24^{*}	0.69^{+}	0.46^{*}	NS	NS	NS	0.61^{+}	0.50^{+}	**0.56^{+}**	**0.66^{+}**	0.40^{*}	0.59^{*}	0.51^{*}		
NDWI	0.44	NS	NS	0.52^{*}	NS	NS	NS	NS	0.57^{*}	0.42^{*}	**0.47^{*}**	**0.47^{*}**	0.27^{*}	0.36^{*}	0.32^{*}	0.58^{+}	
MSI	0.43	0.29^{*}	0.20^{*}	0.48^{+}	0.38^{*}	NS	NS	NS	0.49^{+}	0.42^{+}	**0.49^{+}**	**0.39^{+}**	0.37^{+}	0.47^{+}	0.39^{*}	0.77^{*}	0.51^{*}

EFGP: early fruit growth period; SGD: scion girth diameter; CV: canopy volume; RLWC: relative leaf water content; LWC: leaf water concentration; WBI: water band index; NDWI: normalised difference water index and MSI: moisture stress index.
Bold digits in the table indicate the "–" correlation; data followed by "*" indicates their significant correlation at $P < 5\%$ probability level and data followed by " + " indicate their significant correlation at $P < 1\%$; NS: not significant.

Table 10
Principal components (PCs) for plant-based variables with eigen values during 2010 in EFGP.

PC	Variables	Eigen values	% Variance	Cumulative % of variance
1	Ψ, Leaf-N, Leaf-K, RLWC, SΨ	7.374	51.70	51.70
2	g_s, P_n	2.810	24.03	75.73
3	WBI, MSI	2.633	13.17	88.90

EFGP: early fruit growth period, RLWC: relative leaf water content; WBI: water band index and MSI: moisture stress index.

(WBI, MSI) having eigenvalues > 1 were retained for interpretation. The first and the most important factors which explained 51.7% of the variations were under PC-1. The second important variables under PC-2 collectively explained 24.03% of the sample variance, whereas variables under PC-3 explained 13.17% of variance. Due to the strong correlation between ψ and S_{ψ} ($r = -0.95$), and between ψ and RLWC ($r = 0.88$), ψ and RLWC were not considered from PC-1 to develop principal component regression (PCR). Moreover, S_{ψ} was considered due to the reason that it had better correlation with fruit yield compared with other variables (ψ, RLWC). From PC-2, g_s was involved in PCR, as it has good correlation with P_n ($r = 0.74$) and better correlation with fruit yield than P_n. In between WBI and MSI, WBI was selected for PCR, due to it's better correlation with yield than that of MSI, and a good correlation in between WBI and MSI ($r = 0.77$).

The multi-regression model developed between fruit yield and other selected plant variables (S_{ψ}, Leaf-N, Leaf-K, g_s and WBI) from PCA and correlation matrix for 2010 was:

$$\begin{aligned} Fruit\,yield &= 370.373\,(Leaf-N) - 406.404(Leaf-K) + 1.490(Sy) \\ &\quad -4.936(gs) - 33.379(WBI) - 78.711(at\,P < 0.05;\,R^2 \\ &= 0.908\,and\,RMSE = 1.879\%) \end{aligned}$$

The above model is well validated in 2011 to predict the fruit yield from the proposed plant-based variables with coefficient of determination (R^2) of 0.87 and root mean square error (RMSE) value of 6.25% (Fig. 4).

3.11. Fruit quality

The effect of irrigation on fruit quality parameters (juice content, TSS, TA, ascorbic acid) is presented in Table 11. Juice per cent increased from RDI_0 to FI. However, juice percent under RDI_{50} was at par ($P < 0.05$) with that under FI, indicating the excess dehydration of juice sacs of fruits with no irrigation (RDI_0), which could not be fulfilled by osmotic adjustment to maintain sufficient turgidity of fruits in this treatment. The TSS in juice increased from RDI_0 to RDI_{50} and then decreased at FI. The higher juice content is one of the reasons for dilution of soluble solids concentrations in fruits with FI. Moreover, the TA percentage in juice was recorded maximum with RDI_0. The higher TA and lower TSS with the fruits in RDI_0 treatment compared to that in RDI_{50} was probably caused by enhanced transformation of acids to sugars in dehydrated juice sacs which is required to maintain the osmotic pressure of fruit cells under mild water deficit condition prevailed under RDI_{50} (Huang et al., 2000). Earlier studies also demonstrated the greater TSS in citrus fruits under soil water deficit condition in root zone of plants (Navarro et al., 2010). However, the TSS and TA did not show any significant difference at RDI_{50} and FI. The ascorbic acid concentration in juice, which is a vital vitamin of citrus fruits, increased from RDI_0

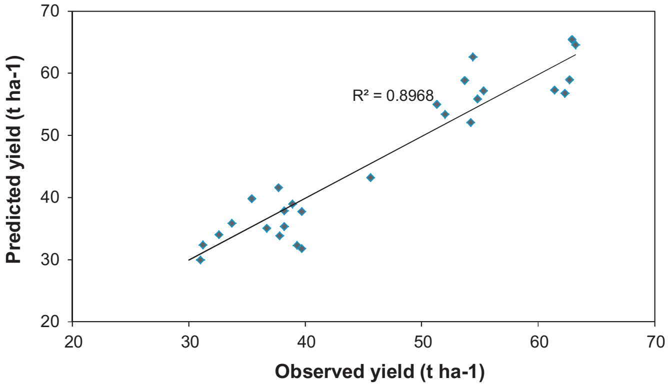

Fig. 4. Observed yield vs. predicted yield of 'Kinnow' mandarin plants in 2011.

Table 11
Fruit quality parameters (juice content; Total soluble solids, TSS; Titrable acidity, TA and ascorbic acid) of 'Kinnow' mandarin under different irrigation treatments during 2010 and 2011.

Treatments	2010				2011			
	Juice content (%)	TSS (^{0}Brix)	TA (%)	Ascorbic acid (mg/l)	Juice content (%)	TSS (^{0}Brix)	TA (%)	Ascorbic acid (mg/l)
RDI_0	42.5^{bB}	9.7^{cB}	1.04^{aA}	101.3^{cB}	43.8^{bA}	10.2^{cA}	1.02^{aB}	103.6^{cA}
RDI_{50}	47.3^{aB}	10.8^{aB}	0.76^{cA}	116.8^{aB}	48.6^{aA}	10.9^{aA}	0.74^{cB}	119.1^{aA}
FI	49.6^{aB}	10.2^{bB}	0.81^{bA}	105.3^{bB}	50.8^{aA}	10.4^{bA}	0.79^{bB}	106.9^{bA}

Data in one column followed by different small letters are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test and data in different years for each variable with same irrigation treatment followed by different capital letters are significantly different at $P < 0.05$.

RDI_0: no irrigation at early fruit growth period (EFGP); RDI_{50}: irrigation at 50% crop evapotranspiration at EFGP and FI: full irrigation (100% crop evapotranspiration) at EFGP.

to FI. However, the RDI_{50} and FI were statistically at par ($P < 0.05$) in relation to ascorbic acid content.

4. Conclusions

The fully-irrigated 'Kinnow' mandarin plants produced the highest vegetative growth and fruit yield. However, deficit irrigation scheduled at 50% crop evapotranspiration at early fruit growth period improved irrigation water use efficiency substantially, due to greater water saving with a decrease in yield compared with that of the full irrigation treatment. Moreover, better quality citrus fruits were harvested from the deficit-irrigated plants. The higher leaf nutrient concentration of fully-irrigated plants was associated with greater availability of such nutrients in soil under this treatment. However, the consistent reduction of micronutrients in soil supports the need for the application of appropriate quantity of the nutrients to the plants. The greater variation of soil water content at 0–0.20 m depth under deficit irrigation suggests that irrigation scheduling based on soil water deficit (20% available soil water content) at 0–0.20 m soil through drip may be used for 'Kinnow' mandarin. The principal component regression technique using plant-based measurements has been found as a potential tool to predict yield of citrus plants well in advance of fruit harvest under water stress condition. Based on these results, it can be inferred that application of irrigation water at 50% crop evapotranspiration at early fruit growth period could be a better option for 'Kinnow' mandarin cultivation in water scarce northern India and elsewhere having similar agro-climatic condition. This will help in bringing more area under irrigation, resulting in higher production of quality citrus fruits. Further studies related to optimizing the quantities of NPK-based fertilizers and micronutrients for deficit-irrigated 'Kinnow' mandarin plants under drip system are suggested.

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