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Sensing Tree for Yield Forecasting under Differential Irrigation

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Abstract: *Tree itself is assumed to be a better indicator of water stress. Sensing of plant behavior in relation to leaf physiology, plant water status and canopy reflectance are the major factors indicating the water need of the trees. In this study, different response factors (leaf physiological parameters, leaf nutrients, leaf water content and canopy reflectance) of citrus tree have been observed under differential water stress condition by supplying deficit irrigation and fruit yield has been forecasted based on these factors. For the first year a yield response model has been formulated employing principal component regression (PCR) methodology and the model has been validated for second year data. Among different factors, leaf-N, leaf-K, stem water potential stress index, stomatal conductance and water band index have been found as the best predictors for yield and resulted higher accuracy ( ) in yield prediction of citrus tree. Overall, the study reveals that sensing tree is one of the better options to quantify water stress for efficient irrigation scheduling and to get target yield from orchards.*

Keywords: *tree sensing; water stress; yield forecasting; principal component analysis*

1. INTRODUCTION

Water supply is a major constraint to crop production in world. Water demand for rapid industrialization and high population growth reduces water share for agriculture. The further scarcity of irrigation water for crop production should be addressed for sustaining the food supply through efficient water conservation and management practices even in high rainfall areas [5]. Moreover, the harvest per every drop of irrigation water should be enhanced while considering the best water use efficiency (WUE) associated with any crop.

Horticulture plays an important role in economy development and nutritional security of a country. The population increase and the improved living standards of the people would force the producers to produce more fruits and vegetables in the next decades. The enhancement of production of the crops from limited water availability can be possible by using microirrigation (drip irrigation) under deficit water supply [8]. Drip irrigation has proved its worth resulting in higher yield with better quality produces in different vegetables and fruits, besides saving substantial amount of irrigation water over surface irrigation [6].

In recent years, climate change becomes a major huddle to crop production in both rainfed and irrigated agriculture. The shifting of rainfall in space and time, temperature fluctuation and changes in other environmental factors affect crop yield drastically. It is therefore a need to quantify water stress in crops to optimize irrigation water supply for better yield and quality of the produce in water scarce regions. Moreover, it is utmost necessary to develop the simple methodologies to predict economic yield of a crop by sensing crop parameters under differential water stress conditions. Keeping this in view, a yield forecasting model has been formulated using principal component regression (PCR) and validated for the test crop citrus.

2. MATERIALS AND METHODS

The study was conducted for 2 years (2010 and 2011) with 10-year-old citrus plant at Indian Agricultural Research Institute, New Delhi. The soil of the experimental site varied from sandy loam with bulk density of 1.47 g cm^{-3}. The experimental site is having semi-arid, sub-tropical climate with hot and dry summers. The hottest months of the year are May and June with mean daily temperature of 39 ^{0}C, whereas January is the coldest month with mean temperature of 14 ^{0}C. The mean annual rainfall of the site is 770 mm, out of which around 85% is concentrated mainly during June-September.

Two irrigation regimes *viz.,* 50% and 75% of the crop evapotranspiration (ETc) were imposed through deficit irrigation strategy (DI), and compared with full irrigation (FI: 100% ETc).

Irrigation water was applied in each alternate day using drip system. The water quantity applied under FI was calculated based on 100% class-A pan evaporation rate using the following formula [6]:

$$ETc = Kp \times Kc \times Ep \qquad (1)$$

where ETc, the Crop-evapotranspiration (mm/day); Kp, the pan coefficient (0.8), Kc, the crop-coefficient (0.85) and Ep the 2-days cumulative pan evaporation (mm). The volume of water applied under FI was computed following the formula [2]:

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

where V_{id} is the irrigation volume (litre plant^{-1}) applied in each irrigation, D the mean plant canopy diameter measured in N-S and E-W directions (m), ETc the crop-evapotranspiration (mm), R_e the effective rainfall depth (mm), and E_i the irrigation efficiency of drip system (90%).

Towards the end of each irrigation season, 3- to 5- months old leaf samples (3rd and 4th leaf from tip of non-fruiting branches) at a height of 1.5 m from ground surface were collected from the trees and analysed for macronutrients (N, P, K), and micronutrients (Fe, Mn, Cu, and Zn) following standard method [11].

The mid-day leaf water potential (MLP) was measured on two fully expanded leaves per plant (4 plant per treatment) using a Pressure chamber (PMS instrument, Oregon, USA) at mid-day (12:00-13:00 hr). The water stress integral (S_ψ) for each treatment was calculated using the the equation [4]:

$$S\psi = Absolute\ value\ of\ \sum_{i=0}^{i=1}\{(\psi i, i+1) - c\}\ n \qquad (3)$$

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

The relative water content (RLWC) and water concentration (LWC) were determined by taking two leaves per plant (4 plants per treatment), in a similar position of leaves taken for water potential measurement. The detached leaves were then brought to laboratory for taking fresh weight (FW), and then were cut into small pieces and placed for overnight in distilled water inside the petri dishes. Next day, leaf pieces were taken out of the water and water was removed from the leaf surface using tissue paper. Weight of the leaves (turgid weight, TW) was recorded and again placed in the distilled water of petri dishes. At 2 hours interval, the leaf pieces were taken out and repeated the same procedure for taking TW, till it attends a constant weight. Finally, TW of the leaves was taken and leaves were placed in the oven at 80 ^{0}C until they attain constant dry weight (around 48 hours). Then the dry weight (DW) was recorded. RLWC was calculated using the formula [1]:

$$RLWC\ (\%) = \{(FW - DW) / (TW - DW)\} \times 100. \qquad (4)$$

Leaf water concentration (LWC) was determined using the formula

$$LWC = \{(FW - DW) / (FW)\} \times 100 \qquad (5)$$

The net photosynthesis rate (P_n), stomatal conductance (g_s), and transpiration rate (T_r) of leavs were recorded fortnightly, in one hour interval from 9 am to 3pm on a clear-sky day by portable infrared gas analyzer (LI-COR-6400, Lincoln, Nebraska, USA) during irrigation seasons. Leaf water use efficiency (LWUE) was calculated as P_n divided by T_r of leafs [9].

Canopy reflectance spectra in the range of 350-2500 nm with 1nm bandwidth were measured at the top the trees around midday (12:00 to 13:00 hr) on cloudless days with the help of hand held ASD FieldSpec Spectroradiometer (Analytical Spectral Devices Inc., Boulder, CO, USA). The spectral reflectance indices were calculated as: water band index (WBI) = (R_{900}) / (R_{970}); normalized difference water index (NDWI) = ($R_{857} - R_{1241}$) / ($R_{857} + R_{1241}$); moisture stress index (MSI) = (R_{1599}) /

(R_{819}); normalized difference infrared index (NDII) = (R_{819}-R_{1649}) / (R_{819}+R_{1649}), where R and the subscript numbers indicate the light reflectance at the specific wavelength (in nm).

Plant vegetative growth parameters such as plant height, stem height, canopy diameter and stem girth diameter were recorded annually and their incremental magnitudes were calculated under different treatments.

The data generated were subjected to analysis of variance (ANOVA) using statistical software SAS 9.2 [10]. Correlation matrix (Pearson's coefficient) was developed for 19 plant-based measured parameters and/or their derived indices.

Principal component analysis (PCA) was done to derive the variables having maximum variability (principal components, PCs), which further used for multi-regression analysis to predict yield. This statistical technique is used when the number of predictor variables is large, or when strong correlations exist among the predictor variables. Principal components with eigenvalues ≥ 1 were considered to have a significant contribution towards the explanation of total variation and thus retained, as suggested [3]. After determining the PCs, a multi-regression model using SAS-9.2 was developed for first year and validated for second year.

3. RESULTS AND DISCUSSION

3.1. 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 by irrigation treatments (Table 1 a & b). The highest concentration of the nutrients was registered with FI, followed by DI_{75}. Among micronutrients, the magnitudes of all nutrients (Fe, Mn and Zn) were at par under DI_{50} and DI_{75}. The higher micronutrient concentration was observed with fully-irrigated plants. However, the N, P and K concentrations in leaves in all the treatments were higher than the optimum quantity in leaves required for sustainable production of citrus in northern India.

Table 1a. *Total N, P and K in leaves (%) of 'Kinnow' Mandarin as Affected by Various Irrigation Treatments**

Treatments	2010				2011		
	N	P	K		N	P	K
DI_{50}	2.51^{a}	0.25^{a}	1.51^{a}		2.54^{a}	0.27^{a}	1.55^{a}
DI_{75}	2.66^{b}	0.29^{a}	1.64^{b}		2.57^{a}	0.20^{a}	1.67^{b}
FI	2.89^{c}	0.32^{a}	1.74^{c}		2.83^{c}	0.31^{a}	1.77^{c}

Data in one column followed by different letter are significantly different

Table 1b. *Total Fe, Mn, Cu and Zn in Leaves (ppm) of 'Kinnow' Mandarin as Affected by Various Irrigation Treatments*

Treatments	2010					2011			
	Fe	Mn	Cu	Zn		Fe	Mn	Cu	Zn
DI_{50}	55.0^{a}	49.6^{a}	7.4^{a}	24.8^{a}		56.6^{a}	50.4^{a}	7.9^{a}	25.0^{a}
DI_{75}	59.4^{a}	58.8^{a}	7.5^{a}	25.7^{a}		58.8^{a}	58.3^{a}	8.1^{a}	24.2^{a}
FI	63.6^{b}	62.5^{b}	8.3^{a}	27.0^{b}		62.9^{b}	61.7^{b}	9.0^{a}	27.8^{b}

3.2. Leaf and Stem Water Potential, Relative Leaf Water Content and Leaf Water Concentration

The mid day-leaf (Ψ_l) and -stem water potential (Ψ_s), leaf water stress integral ($S\Psi_l$), and stem water stress integral ($S\Psi_s$) of the mandarin plants affected significantly by irrigation treatments (Table 2a). The mean Ψ_l and Ψ_s were higher under FI, followed by DI_{75}. However, maximum $S\Psi_l$ and $S\Psi_s$ were observed under DI_{50}, whereas the minimum value was with FI. Earlier observed the similar response of leaf and stem water potential to deficit irrigation in citrus [12].

The mean relative leaf water content (RLWC) and leaf water concentration (LWC) under different irrigation treatments were affected significantly under various irrigation treatments (Table 2b). The highest value of RLWC and LWC were observed with fully-irrigated plants, whereas the lowest values were observed with the plants under DI_{50}.

Table 2a. *Mean Seasonal Mid-day Leaf Water Potential (Ψ_l), Stem Water Potential (Ψ_s), Leaf Water Stress Integral ($S\Psi_l$), Stem Water Potential Integral ($S\Psi_s$), Integrated Leaf Water Potential (Ψ_{intl}) and Integrated Stem Water Potential (Ψ_{ints}) of Kinnow Mandarin in 2010 and 2011.*

Treatments		2010					2011			
		Ψ_l (MPa)	Ψ_s (MPa)	$S\Psi_l$ (MPa day)	$S\Psi_s$ (MPa day)		Ψ_l (MPa)	Ψ_s (MPa)	$S\Psi_l$ (MPa day)	$S\Psi_s$ (MPa day)
DI_{50}		-1.9^{a}	-1.3^{a}	52.7^{a}	38.4^{a}		-1.5^{a}	-1.2^{a}	44.9^{a}	31.5^{a}
DI_{75}		-1.7^{c}	-1.1^{c}	39.3^{c}	29.3^{c}		-1.4^{c}	-1.0^{c}	38.1^{c}	22.8^{c}
FI_{100}		-1.3^{e}	-0.8^{e}	24.6^{e}	19.0^{e}		-1.1^{e}	-0.7^{e}	22.6^{e}	22.3^{e}

Data in one column followed by different letter are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test.

Table 2b. *Relative Leaf Water Content (RLWC) and Leaf Water Concentration (LWC) of Kinnow Mandarin as Affected by Deficit Irrigation in 2010 and 2011*

Treatments		2010			2011	
		RLWC (%)	LWC (%)		RLWC (%)	LWC (%)
DI_{50}		79.4^{a}	68.9^{a}		80.3^{a}	69.4^{a}
DI_{75}		89.4^{c}	72.8^{c}		89.7^{c}	73.6^{c}
FI_{100}		92.8^{e}	78.4^{e}		93.2^{e}	79.6^{e}

3.3. Leaf Physiological Parameters

The mean net photosynthesis rate (P_n), stomatal conductance (g_s), transpiration rate (T_r) , leaf water use efficiency (LWUE: P_n / T_r) under different irrigation treatments were significantly affected (Table 3). The maximum Pn value was registered with fully-irrigated trees, followed by the trees under DI_{75}. The g_s and T_r followed the same trend of P_n under different treatments. Earlier observed similar results of Pn, Tr and g_s under DI in citrus [9].

Table 3. *Net Photosynthesis Rate (Pn, μmol $m^{-2}s^{-1}$), Stomatal Conductance (gs, mmol m^{-2} s^{-1}), Transpiration Rate (Tr, mmol m^{-2} s^{-1}) and Leaf Water Use Efficiency (LWUE) of 'Kinnow' Mandarin under Different Irrigation Treatments in 2010 and 2011.*

Treatments	2010					2011			
	Pn	gs	Tr	LWUE		Pn	gs	Tr	LWUE
DI_{50}	2.89^{a}	21.07^{a}	1.66^{b}	1.74^{a}		3.14^{a}	20.50^{a}	1.40^{b}	2.24^{a}
DI_{75}	3.17c	24.80^{d}	1.84^{d}	1.72^{a}		3.86^{c}	23.48^{d}	1.60^{d}	2.41^{b}
FI_{100}	3.88^{d}	37.78^{e}	2.08^{e}	1.86^{c}		4.37^{d}	31.07^{e}	1.74^{e}	2.51^{c}

3.4. Reflectance

The values for hyperspectral indices (WBI, water band index; NDWI, normalised difference water index; MSI, moisture stress index, NDII, normalised difference infrared index and SR, simple ratio) of the crop under different irrigation treatments are presented in Table 4 . The minimum value of the indices was observed with FI, whereas the maximum values were with DI_{50}. The values for the indices in 2011 was marginally lower than that in 2010, reflecting the lower water stress condition of the trees in 2011 than 2010.

Table 4. *Mean Water Band Index (WBI), Normalised Difference Water index (NDWI), Moisture Stress Index (MSI) and Normalised Difference Infrared Index (NDII) of Kinnow Mandarin*

Treatments	Hyperspectral Indices										
	2010						2011				
	WBI	NDWI	MSI	NDII	SR		WBI	NDWI	MSI	NDII	SR
DI$_{50}$	1.056	0.042	0.561	0.266	3.002		0.992	0.031	0.462	0.219	2.937
DI$_{75}$	0.966	0.035	0.472	0.243	2.802		0.981	0.032	0.417	0.206	2.811
FI	0.917	0.033	0.469	0.239	2.711		0.815	0.031	0.384	0.203	2.629

3.5. Plant Vegetative Growth

The plant vegetative growth parameters (plant height, PH; stem girth diameter, SD; canopy diameter, CD and canopy volume, CV) were significantly affected by irrigation treatments during 2010 and 2011 (Table 5). The highest growth of the plants was observed with FI, followed by DI$_{75}$. The higher vegetative growth under higher irrigation regime was probably due to higher photosynthesis rate and its proportionate portioning towards vegetative growth under this treatment. Previously, similar finding of decrease in vegetative growth was observed with deficit-irrigated citrus [8].

Table 5. *Plant Growth of Kinnow Mandarin under Various Irrigation Treatments in 2010 and 2011*

Treatments	2010					2011			
	TPH (cm)	SD (mm)	CD (cm)	CV (m^3)		TPH (cm)	SD (mm)	CD (cm)	CV (m^3)
DI$_{50}$	34.4^a	21.4^b	26.8^a	0.90^a		22.7^a	20.2^b	21.1^b	0.741^a
DI$_{75}$	37.2^b	23.5^d	32.3^d	0.93^b		27.7^b	21.9^c	28.5^d	0.878^b
FI$_{100}$	41.7^c	27.2^e	49.0^e	0.96^c		37.0^c	26.6^d	33.3^e	0.883^c

TPH: total plant height; SD: stem diameter; CD: canopy diameter; CV: canopy volume

Data in one column followed by different letter are significantly different at $P < 0.05$, as per separation by Duncan's multiple range test.

3.6. Fruit Yield

The number of fruit harvested per plant, average fruit weight and total fruit yield in various treatments are presented in Table 6. The highest fruit yield was recorded in FI, followed by DI$_{75}$. The similar result of lower fruit yield with DI was earlier reported in citrus [7, 12].

Table 6. *Fruit Yield of Kinnow Mandarin under Different Irrigation Treatments During 2010 and 2011.*

Treatments	2010				2011		
	No. fruits harvested/tree	Average fruit weight (g)	Fruit yield (t ha^{-1})		No. fruits harvested/ tree	Average fruit weight (g)	Fruit yield (t ha^{-1})
DI$_{50}$	682^a	163.7^a	52.23^a		693^a	165.7^a	53.75^a
DI$_{75}$	729^c	172.6^b	59.01^b		740^c	174.1^b	61.26^b
FI$_{100}$	774^d	173.3^b	62.91^b		787^e	173.8^b	64.20^b

3.7. Principal Component Analysis of Fruit Yield and Other Plant-based Parameters for Yield Prediction

The correlation matrix between fruit yield and other variables presents that yield is highly correlated with SΨ_s, gs, Leaf-K, SΨ_l, Leaf-N, Pn, and WBI under DI (Table 7). The higher correlation between yield and SΨ_s indicates the use of stem water potential as a tool for irrigation scheduling.

PCA for 19 variables indicate that the first 3 PCs explained 89% and 84.3% variability of data set under DI and PRD, respectively (Table 8). A multi-regression model developed between fruit yield and other selected plant variables (SΨ_s, Leaf-N, Leaf-K, gs and WBI) in DI for 2010 was:

Fruit yield = -0.846 (Leaf-N) + 31.331 (Leaf-K) – 0.165 ($S\Psi_s$) + 0.127 (gs) + 15.212 (WBI) – 16. 510 ($P < 0.05$; $R^2 = 0.98$; RMSE = 0.30%)

Table 7. *Correlation Matrix for Plant-based Observations under DI Treatments During 2010 and 2011*

Parameters	yield	SD	CV	Leaf-N	Leaf-K	Leaf-Fe	Leaf-Zn	$S\Psi_l$	$S\Psi_s$	RLWC	LWC	Pn	Tr	gs	LWUE	WBI	NDWI	MSI
SD	0.25^{*}																	
CV	0.33^{*}	0.69^{*}																
Leaf-N	0.87^{+}	NS	0.29^{*}															
Leaf-K	0.89^{+}	NS	0.41^{*}	0.43^{*}														
Leaf-Fe	NS	NS	NS	NS	NS													
Leaf-Zn	0.68^{*}	NS	NS	NS	NS	0.41^{*}												
$S\Psi_l$	**0.89^{+}**	**0.21^{*}**	**0.29^{*}**	**0.43^{*}**	**0.47^{*}**	NS	NS											
$S\Psi_s$	**0.92^{+}**	**0.26^{*}**	**0.32^{*}**	**0.52^{*}**	**0.49^{*}**	NS	NS	**0.96^{+}**										
RLWC	0.85^{+}	0.20^{*}	0.17^{*}	0.32	0.32^{*}	NS	NS	**0.74^{+}**	**0.89^{+}**									
LWC	0.73^{+}	NS	NS	0.30	0.25^{*}	NS	NS	**0.69^{+}**	**0.69^{+}**	0.94^{+}								
Pn	0.85^{+}	NS	0.23^{*}	0.85^{+}	0.44^{*}	0.78^{+}	0.36^{*}	**0.62^{+}**	**0.53^{+}**	0.66^{+}	0.55^{+}							
Tr	0.81^{+}	NS	NS	0.69^{*}	0.51^{+}	0.43^{*}	0.29^{*}	**0.88^{+}**	**0.83^{+}**	0.81^{+}	0.69^{+}	0.61^{+}						
gs	0.91^{+}	NS	NS	0.58^{*}	0.55^{+}	0.45^{*}	0.38^{*}	**0.89^{+}**	**0.86^{+}**	0.75^{+}	0.66^{+}	0.79^{+}	0.81^{+}					
LWUE	0.68^{+}	NS	NS	0.47^{*}	0.36^{*}	0.42^{*}	0.21^{*}	**0.73^{+}**	**0.69^{+}**	0.59^{+}	0.48^{+}	0.39^{+}	0.69^{+}	0.57^{*}				
WBI	0.87^{+}	0.29^{*}	0.29^{*}	0.59^{+}	0.47^{*}	0.44^{*}	NS	**0.65^{+}**	**0.67^{+}**	0.69^{+}	0.52^{+}	0.47^{*}	0.55^{*}	0.51^{*}	0.30^{+}			
NDWI	0.53^{*}	NS	NS	0.53^{*}	NS	NS	NS	**0.38^{*}**	**0.48^{*}**	0.57^{*}	0.40^{*}	0.33^{*}	0.49^{*}	0.40^{*}	0.21^{*}	0.59^{+}		
MSI	0.79^{+}	0.22^{*}	0.23^{*}	0.51^{+}	0.40^{*}	NS	NS	**0.44^{*}**	**0.41^{+}**	0.52^{+}	0.47^{+}	0.42^{+}	0.43^{+}	0.45^{*}	0.17^{+}	0.79^{*}	0.54^{*}	
NDII	0.49^{*}	NS	NS	0.43^{*}	0.36^{*}	0.27^{*}	NS	**0.26^{*}**	**0.32^{*}**	0.47^{*}	0.49^{*}	0.39^{*}	0.37^{+}	0.39^{*}	0.26^{*}	0.55^{*}	0.68^{*}	0.51^{*}

Bold digits in the table indicate the –ve correlation; Data followed by "*" indicates their significant correlation at $P < 5\%$ probability level and data followed by "+" indicate their significant correlation at $P < 1\%$.

Table 8. *Principal Components with Eigen Values and Variances under DI Treatments*

PC	DI			
	Variables	Eigen value	% variance	Cumulative % of variance
1	$S\Psi_s$, Leaf-N, Leaf-K, $S\Psi_l$, RLWC	6.964	40.20	40.20
2	gs, Pn	3.716	33.54	73.74
3	WBI, SR	2.449	15.28	89.02

The above models are well validated in 2011 to predict the fruit yield from the proposed plant-based variables with coefficient of determination (R^2) of 0.916 and root mean square error (RMSE) value of 1.186% for DI and R^2 value of 0.916 and root mean square error (RMSE) of 1.186% for PRD (Fig. 1).

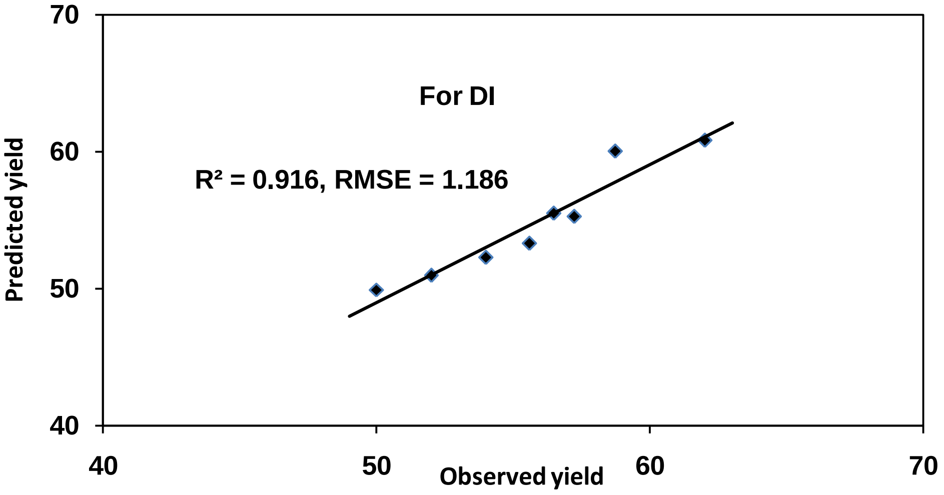

Fig 1. *Relation between predicted yield and observed yield under DI*

4. CONCLUSIONS

Deficit irrigation has been found as a potential water saving technique in citrus. Both vegetative growth and yield parameters of citrus tree showed a need for higher soil water that was evident from better growth and yield under full irrigation of the trees. Yield prediction on basis of leaf physiology, leaf water content, leaf nutrients, plant growth and canopy reflectance has been found reasonably accurate. Thus, the technique (principal component regression) may be used for plant sensing parameters to forecast yield of citrus or any other tree crops. Based on this analysis, an irrigation sensor may be also developed.

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