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ORIGINAL PAPER

Biophysical response of young pomegranate trees to surface and sub-surface drip irrigation and deficit irrigation

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Abstract Due to recurring agricultural water shortages, many farmers are looking for crops such as pomegranate that have both some degree of drought resistance and a higher economic value. To manage limited water effectively, it is necessary to know how pomegranate trees respond to varying levels of applied water and the type of irrigation system used. This study was conducted in experimental orchards located at the University of California Kearney Agricultural Research and Extension (UC KARE) Center and the USDA-ARS San Joaquin Valley Agricultural Sciences Center in Parlier, California. The impact of surface drip (DI) and subsurface drip irrigation (SDI) at the UC KARE orchard and irrigation levels (35, 50, 75, 100% of crop water use) at the USDA-ARS orchard on tree canopy size [fractional canopy ground cover (f_c), normalized difference vegetation index (NDVI), normalized difference infrared index (NDII)], canopy-to-air temperature difference, and fruit yield was determined during the 2012–2014 growing seasons. There was no difference in tree canopy size between the DI and SDI systems at the UC KARE site; but trees under SDI produced larger fruit in 2013 and higher yield whilst saving about 10% of water application. The difference in water application highlights an advantage of SDI over DI systems to conserve water without creating negative impacts on tree size or yield. At the USDA-ARS site, the 35 and 50% irrigation treatments significantly reduced tree canopy size in 2013 and 2014, compared to the 75 and 100% irrigation treatments. In 2014, trees irrigated with 75% of crop water use produced more yield than trees irrigated at 35% of crop water use. Furthermore, NDVI and NDII were correlated to f_c. The relationships between NDVI to f_c and f_c to pomegranate crop coefficient were established. The derived crop coefficient from ground-based remotely sensed data may potentially be used as a tool by farmers and water managers to estimate pomegranate tree water use on a field or regional scale using aerial or satellite imagery.

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Introduction

Pomegranate (*Punica granatum* L., *Punicaceae*) is native to Central Asia and is grown throughout the world including in California because of its adaptability to a wide range of climates and soil conditions (Holland et al. 2009; Wang et al. 2015). It is currently in demand because research has shown potential health benefits for the treatment and prevention of cancer and other human diseases (Michel et al. 2005; Lansky and Newman 2007). Because of recent recurring water shortages, many farmers are looking for crops that have some degree of drought resistance and high economic value, like pomegranate. There are currently approximately 11,000 ha of pomegranate under cultivation in California. Most pomegranate orchards are managed by flood or furrow irrigation, and few farmers use either high-frequency surface drip (DI) or subsurface drip irrigation (SDI).

Irrigation is required in most growing areas where commercial growth of pomegranates is practiced (Holland et al.

2009). Past studies (Prasad et al. 2003; Shailendra and Narendra 2005; Sulochanamma et al. 2005) have found that drip irrigation had positive effects on vegetative growth, yield and fruit weight of pomegranate. Drip irrigation has also shown positive effects on pomegranate growth parameters such as tree height, stem diameter, and plant spread (Sulochanamma et al. 2005) and saved up to 60% of water compared to surface irrigation (Behnia 1999; Chopade et al. 2001). Research has shown that well-managed surface drip irrigation and subsurface drip irrigation systems can eliminate runoff, deep drainage, minimize surface soil and plant evaporation, reduce transpiration of drought tolerant crops, and significantly reduce fertilizer losses, thus protecting groundwater quality (Phene et al. 1989; Ayars et al. 1999).

Knowledge of pomegranate's water requirement, especially during the early plant development, is critical for reducing production cost particularly during periods of drought. Deficit irrigation has been applied in fruit trees because fruit yield and quality at harvest may not be sensitive to water shortage (Goldhamer et al. 2006; Fereres and Soriano 2007; Zhang and Wang 2013). Some researchers have investigated pomegranate tree performance under deficit irrigation. Khattab et al. (2011) reported a study on growth and productivity of pomegranate trees under five different irrigation levels in Egypt and the results indicated that the highest irrigation level simulated vegetative growth by increasing shoot length, number of leaves per shoot and leaf area, whereas the lowest irrigation level decreased these parameters and increased fruit cracking. Mellisho et al. (2012) found that water stress at fruit growth stage, mainly during July and August in pomegranate trees, has critical impact on fruit size and total yield. Intrigliolo et al. (2013) reported tree responses related to vegetative growth under different deficit irrigation management with drip irrigation. Their results showed that DI irrigation with 50% of the crop water use during the entire season resulted in similar yields comparable to trees with 100% of crop water use. Water relations of leaves of pomegranate trees under different irrigation conditions have also been investigated to monitor plant water status for better irrigation management. Hepaksoy et al. (2009) found that leaf water potential values, in both deficit and full irrigation were significantly different before and after irrigation, especially in July and August when the air temperature was high. Intrigliolo et al. (2011) reported that leaf photosynthesis rates and stomatal conductance have a greater potential for irrigation scheduling than midday stem water potential.

However, monitoring plant water status, such as leaf or stem water potential, leaf gas exchange, and trunk diameter shrinkage measurements, are very labor intensive and lack spatial representation. As an alternative for less laborious method, remote sensing has been applied to monitor

crop water status and determine crop water demand. For example, thermographic measurement of canopy temperature has been used to predict water deficit effect on fruit weight in citrus trees (Ballester et al. 2013) and to estimate maize crop stress for irrigation management (Han et al. 2016). Infrared thermometry has been used to monitor canopy temperature and further to use canopy temperature as a method for controlling deficit irrigation for fruit trees (Glenn et al. 1989; Zhang et al. 2017) and for annual crop (Wanjura et al. 1995). What's more, many studies have used remote sensing-derived fractional canopy ground cover (f_c) to estimate crop water use (Bausch 1995; Grattan et al. 1998; Trout and Gartung 2006; Johnson and Trout 2012). Trout et al. (2008) and Zhang et al. (2015) have demonstrated a remote sensing methodology using normalized difference vegetation index (NDVI) to estimate f_c as a basis for developing crop coefficients. Their results indicated that remotely sensed NDVI may be a good way to monitor growth stage, and potentially irrigation water demand of horticultural and field crops. Past studies have related leaf or canopy water content with reflectance at near-infrared (NIR) and shortwave infrared (SWIR) portion of the spectrum due to energy absorption by leaf water. Tucker (1980) first suggested that 1.55–1.75-μm spectral region was the best-suited spectral band for monitoring crop water status. Hardisky et al. (1983) developed the Normalized Difference Infrared Index (NDII) for the Landsat Thematic Mapper to estimate canopy water content. NDVI has no sensitivity to high leaf area index (LAI) values compared to NDII, due to its weaker liquid water absorption feature.

Therefore, with the limited knowledge on remote sensing applications on pomegranate trees, this objective of this study was to investigate pomegranate trees over three consecutive growing seasons, either under different irrigation systems, or under different levels of irrigation. This manuscript reports the impact of irrigation system type and depth of applied water on tree canopy growth characterized by fractional canopy cover, NDVI, NDII, canopy temperature, and fruit yield of pomegranate.

Materials and methods

Field studies were conducted at the University of California Kearney Agricultural Research and Extension (UC KARE) Center (36.599°N, 119.512°W) and the USDA-ARS San Joaquin Valley Agricultural Sciences Center (36.594°N, 119.512°W) in Parlier, California in the 2012–2014 growing seasons. Both fields have automated weighing lysimeters (Phene et al. 1989, 1991; Ayars et al. 1996; Schneider et al. 1996) installed on-site to determine crop water use. The meteorological data were downloaded from CIMIS (California Irrigation Management Information

Table 1 The monthly air temperature, relative humidity, and precipitation during three crop-growing seasons

Year	Month	Air temperature (°C)		Relative humidity (%)		Precipitation (mm)
		Max	Min	Max	Min	
2012	June	31.9	14.6	79	26	0
	July	34.9	16.9	83	28	0.1
	August	36.9	17.9	84	25	0
	September	34.2	15.4	85	27	0
	October	26.1	9.9	91	43	0
2013	June	33.6	16.7	78	32	1
	July	36.9	18.8	77	24	0
	August	35.2	16.2	78	24	0.3
	September	31.3	14.3	80	31	0
	October	25.6	7.6	83	31	0.7
2014	June	34	14.7	73	16	0
	July	36.3	19.3	75	24	0
	August	35.4	17.2	79	23	0
	September	33.5	17.6	81	27	2.2
	October	28.4	13.5	86	30	7.3

System, http://www.cimis.water.ca.gov/) weather station 39 located at a distance of approximately 700 m from the fields. The monthly maximum and minimum air temperature, maximum and minimum relative humidity, and precipitation during the three crop-growing seasons are summarized in Table 1. It was hot and dry during the summer time and the experimental sites received very little rainfall. The soil types of both experimental sites are a Hanford fine sandy loam (coarse-loamy, mixed, thermic Typic Xerorthents).

Experimental site description

UC KARE site

This experiment used a 1.43 ha field where pomegranate trees (*Punica granatum* L., cv 'Wonderful') were planted in 2010 with a between-row spacing of 4.9 m and a within-row spacing of 3.6 m. The experiment was established as a randomized complete block design with surface drip (DI) and sub-surface drip irrigation (SDI) treatments. All treatments were replicated 15 times. A large weighing lysimeter (2 m by 4 m by 2 m deep) (Phene et al. 1991) was used to determine crop evapotranspiration (ET_c) for the 100% SDI treatment and automatically initiate irrigation for the SDI and DI treatments after 1 mm ET_c (Fig. 1a). The field irrigation systems were controlled by the lysimeter datalogger and runtime was equal to the time needed to apply 1 mm of irrigation water. Based on previous experience with surface drip irrigation (Phene et al. 1992), in 2012 an additional 10% water was applied to the DI treatments to compensate

Fig. 1 Schematic of irrigation treatment and lysimeter locations in UC KARE site. **a** Treatments are DI—surface drip irrigation, SDI—subsurface drip irrigation, and USDA-ARS site **b** treatments are *1* 35, *2* 50%, *3* 75%, and *4* 100% of crop evapotranspiration (ET_c) measured with lysimeter 1. *Ly1* lysimeter 1, *Ly2* lysimeter 2

for evaporative water loss and weed growth. The single lysimeter tree was irrigated using a SDI system with the same number of emitters (8) per tree as the rest of the orchard. Fifteen plots were irrigated with DI with laterals placed on the soil surface on both sides of the trees at 0.9 m from the tree row. The other 15 plots were irrigated by SDI with the lateral lines buried at 0.5 m depth at 0.9 m from the tree row. The emitter spacing was 1 m and the discharge rate was 2.0 L/h (Toro Ag Irrigation, EL Cajon, CA). Each treatment plot contained three rows with seven trees per row. The trees were minimally pruned and retained a bush-like shape and the height was limited to approximately 3 m. To reduce edge effect, two border rows were planted on west and north side of the field using the same between-row and within-row spacing, and the same irrigation system as within the adjacent plot.

USDA-ARS site

Pomegranate (*Punica granatum* L., cv 'Wonderful') was planted in 2010 but with a 5 m spacing between rows and a 2.75 m within-row tree spacing in a 1.3 ha field that contained two large weighing lysimeters (Ayars et al. 1996; Schneider et al. 1996). The lysimeters are 2 m × 4 m by 3 m deep and have a resolution of approximately 0.1 mm of water loss and are located in the center of the experimental site (Fig. 1b). The experimental design was a randomized complete block design, with four replications, to test four levels of irrigation rates on pomegranate growth and fruit yield (Fig. 1b). The applied irrigation volumes were 35, 50, 75, and 100% of ET_c, as measured by lysimeter 1 (Fig. 1b) and represent severe, medium, mild water stress, and full water treatment. The irrigation system was controlled by the lysimeter and irrigation occurred after 4 mm of crop water use was measured by the lysimeter 1. The lysimeter trees were irrigated at the 100% treatment level. A total of 4 mm water was applied each irrigation to the field plots, as a result the irrigation interval varied across treatments. Surface drip with a single lateral on each row was used to irrigate the trees with 4 L/h emitters positioned 0.5 m on each side of the tree with an additional 8 L/h emitter placed half way between the trees. As a result of the in-row tree spacing on this location, two trees were planted in the lysimeters for measuring crop water use. Each experimental plot contained 3 rows with 15 trees per row with the center row used as the experimental row. The trees were pruned to develop a vase shape with four principal branches unlike the trees on the UC-KARE site that were allowed to be free form with multiple branches. Plant height was maintained at approximately 3 m similar to what was done on the UC-KARE site.

Measurements and data collection

During each growing season, f_c and spectral reflectance measurements were taken from the middle tree in the center row of each plot and the trees in the lysimeters at both locations. At the end of each season, the middle five trees in the center row of each plot were used to determine yield parameters: total fruit yield (kg), number of fruits per tree, and fruit size (g per fruit).

Tree fractional canopy ground cover was measured with a TetraCam ADC multispectral camera (TetraCam Inc., Chatsworth, CA).[1] The camera contained a single precision 3.2 megapixel image sensor optimized for capturing green, red, and near-infrared wavebands of reflected light. During the measurement, the camera was suspended from a telescoping pole tripod system (GeoData Systems Management Inc., Berea, OH) approximately 7 m above the ground surface directly above the trees and aimed vertically downward at nadir view. Images were taken over the predetermined pomegranate tree of the center row in each treatment plot from both experimental fields. Images were preprocessed in LView Pro Image Processor software (CoolMoon Corp., FL) to separate the pixels of pomegranate from soil, grass, shadow, and other background. The preprocessed image was then analyzed using PixelWrench software (TetraCam Inc., Chatsworth, CA) to calculate the percentage of the pixels representing the tree canopy area. The fraction of canopy cover occupied by the pomegranate tree over a representative area (i.e., row spacing x tree spacing) was determined by multiplying the percentage of canopy cover from the image by the ratio of the camera field of view (FOV) to the representative ground area per tree.

Spectral reflectance of tree canopy was measured with CropScan MRS5 multispectral radiometer (CROPSCAN, Inc., Rochester, MN) in both experimental sites. Sensors measured reflectance from five wavebands, blue (450–520 nm), green (520–600 nm), red (630–690 nm), NIR (760–900 nm), and SWIR (1550–1750 nm), that are compatible with Landsat Thematic Mapper. NDVI was calculated as (Reflectance (NIR) − Reflectance (Red))/(Reflectance (NIR) + Reflectance (Red)). Normalized difference infrared index (NDII) was calculated as (Reflectance (NIR) − Reflectance (SWIR)/(Reflectance (NIR) + Reflectance (SWIR)). In addition, the radiometer was equipped with an external infrared thermometer (IRT/c.2-K-80F/27C, Exergen, Watertown, MA) to measure tree canopy temperature. The radiometer was mounted on a support pole and held

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[1] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Table 2 Mean of pomegranate tree fractional canopy ground cover (f_c) in UC KARE field (DI—surface drip irrigation; SDI—subsurface drip irrigation; Ly—lysimeter tree)

Treatment	f_c (%)				Irrigation amount (mm)
2012	13 June	17 July	16 August	27 September	
DI	20.5	18.9[a]	20.9	20.2	472
SDI	22.6	21.7[b]	21.0	21.1	427
Ly	27.3	24.3	23.0	24.3	427
SDI vs. DI	+10%	+15%	+1%	+4%	−11%
Pr > F	0.21	0.035	0.90	0.45	
2013	18 June		28 August		
DI	37.4[a]		46.2		645
SDI	42.0[b]		51.0		584
Ly	40.6		37.4		584
SDI vs. DI	+12%		+10%		−11%
Pr > F	0.048		0.21		
2014		8 July	13 August	8 September	
DI		61.5	69.8	81.3	848
SDI		65.5	77.6	85.7	780
Ly		66.5	68	79.2	480
SDI vs. DI		+6.5%	+11.2%	+5.4%	−9%
Pr > F		0.35	0.20	0.52	

Means followed by a different letter within column are significantly different at $p < 0.05$

at a level above the tree canopy with a view perpendicular to the ground. Downward-facing sensors measured the reflected irradiation of light by the tree and upward-facing sensors measuring the incident irradiation from the sun. The field of view of the thermometer was 28° and the diameter of the field of view was approximately one half of the height of the radiometer above the canopy. For each measurement day, the radiometer was held at the same distance above the ground. Measurements were taken within 2 h of the solar noon. Canopy to air temperature difference was calculated as $T_c - T_a$, where T_c was canopy temperature measured by the IRT sensor and the corresponding air temperature T_a was taken from CIMIS weather station measurements. Remotely sensed data and fractional canopy ground cover were measured monthly from June to September during 2012–2014. The measurement period was characterized by high air temperature, low relative humidity, and no rainfall (Table 1).

Daily crop coefficient for each orchard was calculated as $K_c = ET_c/ET_o$ (Allen et al. 1998), where ET_c was determined by the weighing lysimeter measurements and the reference evapotranspiration (ET_o) obtained from the CIMIS weather station #39 in Parlier, CA.

Stomatal conductance was measured twice using Licor 6400XT portable photosynthesis system (Li-Cor, Lincoln, NE, USA) in August and September 2014 in the USDA-ARS field. Two or three sunlit leaves from the middle tree in the center row of the 35, 50, and 100% irrigation treatment plots were measured from 1100 to 1500 h Pacific Daylight Savings Time.

All statistical analyses, analysis of variance, mean comparison, and regression were carried out using JMP 11.0 (SAS Institute Inc., Cary, NC).

Results and discussion

The effect of irrigation system on tree canopy ground cover at UC KARE site

Both NDVI and NDII showed no response to the two different irrigation systems. There was also no significant treatment effect on f_c between DI and SDI in the period from 2012 to 2014 due to high tree variability within treatments (Table 2), except for the measurements in July 2012 and June 2013. In July of 2012, the SDI f_c was 15% greater than the DI and then the difference reduced to approximately 4% at the end of season 2012. In June of 2013, the SDI f_c was 12% greater than the DI. This difference was reduced to 10% by August 2013. The trend for reduction in the difference in canopy size continued until there was a 5.4% difference by the end of 2014 season. The SDI lateral irrigation line was buried at 50 cm below the soil surface which eliminated soil evaporation and reduced water use by weeds. Surface drip wets the soil surface and causes evaporation losses on the soil surface particularly when the crop is small and there is little shade. As the trees grew bigger, the canopy cover increased and the potential for evaporation from the soil surface was reduced. Bryla et al. (2003) studied the growth and production of young peach

Fig. 2 Canopy-to-air temperature ($T_c − T_a$) difference measured during 2012–2014
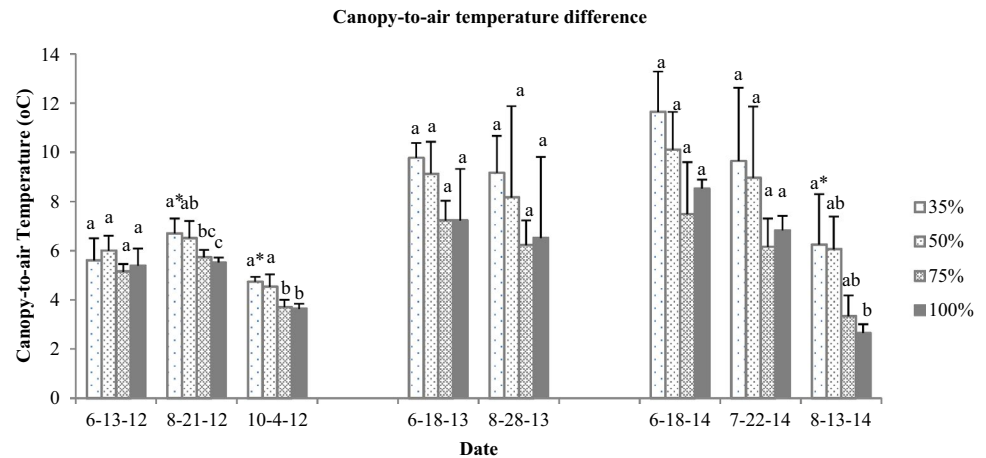
trees irrigated by different irrigation systems. They found that both surface and subsurface drip treatments produced larger trees than those irrigated by microjet systems, but the difference between DI and SDI was not significant. Bryla et al. (2003) found that there was approximately a 10% loss of water to evaporation when the crop was small and the ground surface was not completely shaded. As we mentioned previously, additional 10% more water was applied for the DI trees compared to the SDI trees to offset the losses to evaporation and weed use. Table 2 shows that an average of 10% less water was applied to SDI than DI in 3 years. Even though the f_c between DI and SDI was not significant statistically, the SDI trees had larger f_c values than the DI trees. Therefore, it indicates that the DI trees may require additional irrigation rather than the 10% to achieve the same canopy size as trees irrigated by SDI. The surface and subsurface drip systems were operating on a high frequency (multiple times daily) as a result the surface remained wetted for longer periods than would be expected if the drip system was operated with a longer frequency, every 2–3 days. The higher frequency resulted in larger evaporation losses which suggest that an additional 10% was not adequate to replace evaporation and use by weeds. The difference in water application highlights an advantage of SDI over DI systems to conserve water without creating negative impacts on tree size.

The effect of irrigation depth on canopy-to-air temperature, stomatal conductance, and tree canopy ground cover at the USDA-ARS site

At the USDA-ARS site, deficit irrigation started in early May 2012. Prior to this, all the trees were fully irrigated to establish the crop. $T_c − T_a$ did not show any effects by irrigation in June 2012 when the measurement was taken (Fig. 2). In August 2012, there was a significant difference in $T_c − T_a$ between the 35 and 100% irrigation treatments.

These differences persisted through October in 2012. In 2013 and 2014 growing seasons, because of the high variability within treatments, there were no significant treatment effects on most of the measurement days. $T_c − T_a$ was significantly higher in the 35% irrigation treatment than the 100% treatment plots in August 2014. The values of $T_c − T_a$ were relatively higher compared to other studies that monitored tree canopy temperature using IRT sensors (Ballester et al. 2013; Zhang and Wang 2013). One reason could be the relatively high values of midday solar radiation. Another reason might be smaller size of young pomegranate tree canopy and much larger bare soil space between trees compared to matured peach and olive trees, thus additional convective heating from the surroundings.
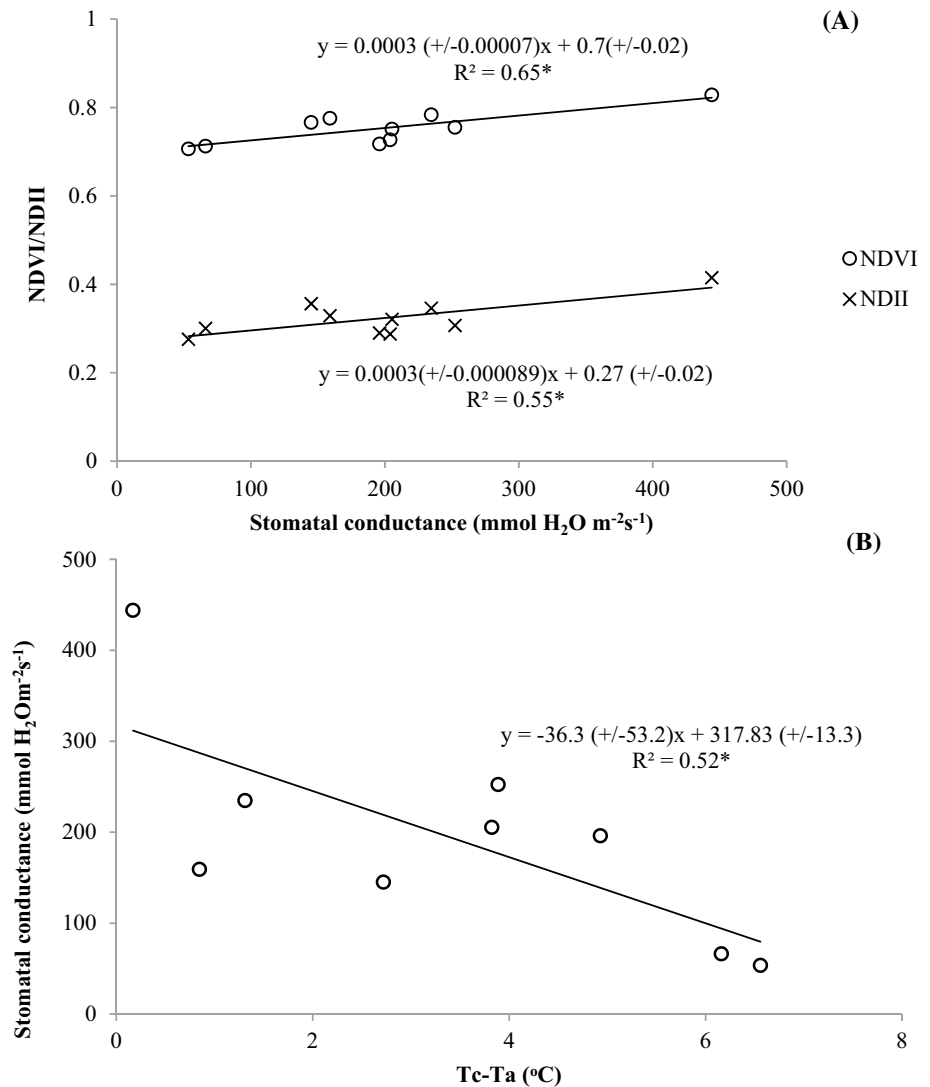
The averaged stomatal conductance values for each treatment ranged from 60 to 270 mmol H_2O m^{-2} s^{-1} (Table 3). Stomatal conductance in the 35% irrigation treatment plots was significantly lower compared to those in the 50 and 100% irrigation treatment plots (Table 3); however, there was no significant difference in stomatal conductance between the 50 and 100% irrigation treatments. The 50% irrigation plots were over-irrigated on 11 July 2014 due a malfunction in the control valve resulting in irrigation staying on for a couple of hours on that day.

Table 3 Mean of pomegranate tree stomatal conductance (mol H_2O m^{-2} s^{-1}) in the 35, 50, and 100% irrigation treatments in USDA-ARS field

Treatment	13 August 2014	9 September 2014
35%	0.082[a]	0.060[a]
50%	0.209[b]	0.219[b]
100%	0.272[b]	0.262[b]
Pr > F	<0.0001	<0.0001

Means followed by a different letter within column are significantly different at $p < 0.05$

Fig. 3 The relationships between NDVI/NDII and stomatal conductance (**a**); canopy-to-air temperature difference ($T_c - T_a$) and stomatal conductance (**b**) on August 13, 2014 in USDA-ARS field

(A)

$y = 0.0003\ (+/-0.00007)x + 0.7(+/-0.02)$
$R^2 = 0.65*$

$y = 0.0003(+/-0.000089)x + 0.27\ (+/-0.02)$
$R^2 = 0.55*$

○ NDVI
× NDII

(B)

$y = -36.3\ (+/-53.2)x + 317.83\ (+/-13.3)$
$R^2 = 0.52*$

Therefore, the 50% irrigation plots were shown as over-irrigated than it was targeted and the irrigation amount was even close to 100% treatment for the rest of the season. As a result, the 50% irrigation plots were no longer under medium water stress as was originally planned. A significant correlation was found between stomatal conductance measurements and NDVI/NDII that were taken concurrently on 13 Aug 2014 (Fig. 3a). The result was consistent with findings from a recent study (Marino et al. 2014) that also showed good relationships between stomatal conductance and NIR-based indices. Serrano et al. (2010) showed that NDVI is a good indicator of vineyard water status, reporting a good correlation between NDVI and predawn leaf water potential, and between $T_c - T_a$ and stomatal conductance. Figure 3b shows the relationship between $T_c - T_a$ and stomatal conductance. There was a noticeable increase in $T_c - T_a$ while stomatal conductance decreased. Although the correlation was

Table 4 Mean of pomegranate tree fractional canopy ground cover (f_c) in USDA-ARS field under four rates of irrigation (as % of ET_c)
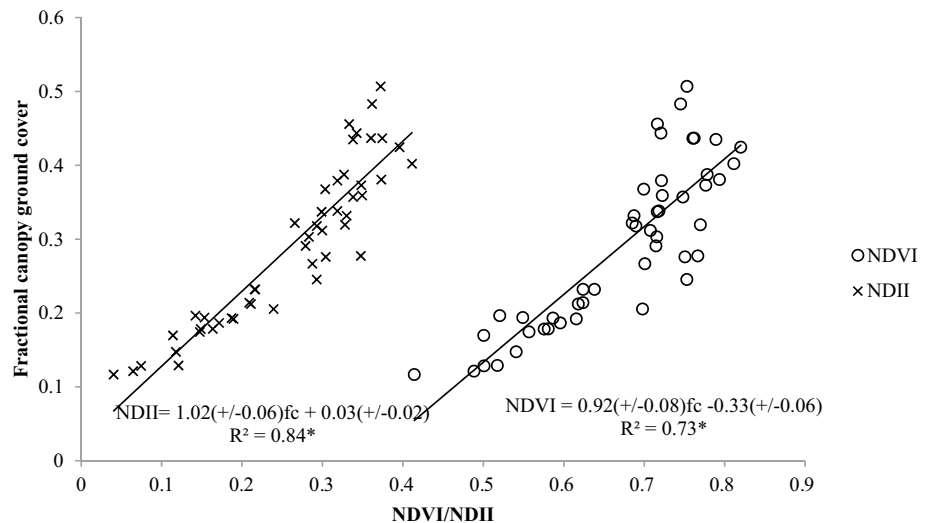
Treatment	f_c (%)		
	2012	2013	2014
More stress (35 and 50%)	14.9	33.3[a]	30.4[a]
Less or no stress (75 and 100%)	17.2	41.2[b]	37.7[b]
Pr > F	0.944	0.0364	0.0278

Means followed by a different letter within column are significantly different at $p < 0.05$

significant, they are relatively less robust than those have been reported for other tree crops (Ballester et al. 2013).

In general, f_c was larger in higher irrigation treatments (75 and 100%) than that in lower irrigation treatments (35 and 50%) (Table 4). Only one tree was measured from each treatment plot. There was a particularly a small tree in one

replicate of the 100% irrigation treatment. The f_c value of the small tree in 100% treatment was 14% in 2012 and 25% in 2014; however, the trees in the other three replicates had averaged f_c values of 20% in 2012 and 41% in 2014. As a result, variability of f_c was higher in the 100% treatment plots than those in the other treatment plots. Therefore, no significant difference in f_c was found in this orchard in response to different depths of irrigation within each year. We averaged f_c values for the trees in both the 35 and 50% of irrigation treatment plots and the 75 and 100% of irrigation treatment plots. The result shows that the trees under severe/medium stress treatments were significantly smaller than those under mild stress or fully irrigated in 2013 and 2014 growing seasons (Table 4). Therefore, water deficit with high air temperature and dry weather has shown an effect on tree growth process in terms of tree canopy size. Moreover, using remotely sensed multispectral images is a fast and non-destructive method to estimate tree canopy cover, which is one of the important biophysical parameters used to characterize tree growth status.

The f_c values in USDA-ARS field were much smaller than those from the UC-KARE field due to the different canopy structure as a result of the pruning protocols. In the USDA-ARS field site there was no increase in f_c from 2013 to 2014 because of winter pruning to maintain the vase shape. The tree branches in USDA-ARS field were held upright by ropes after planting to support trees growing upright instead of spreading out.

Figure 4 shows the linear correlation between NDVI, NDII, and f_c for the data taken from the 16 plots during 2012–2014, which indicates that both NDVI and NDII are robust indicators of pomegranate tree canopy ground cover. Kimes et al. (1981) used NDII to examine biophysical variables of crops and found that NDII performed about the same as the NDVI. However, higher correlation

coefficient was found in NDII vs. f_c ($R^2 = 0.84$) than NDVI vs. f_c ($R^2 = 0.73$). Water in the canopy is absorbing the most energy in the short wave infrared region (Gao 1996). The greater the amount of water in a leaf, the more absorption there will be. For crops under water stress, NDII may be an alternative to estimate fractional canopy ground cover in lieu of NDVI.

Trout and Johnson (2007) determined the linear relationships of NDVI to f_c, f_c to K_c and crop water use maps in the San Joaquin Valley based on Landsat 5 satellite imagery. The current study confirmed that this method is suitable for pomegranate trees. Moreover, fractional canopy ground cover can be estimated using both NDVI and NDII. Recent satellites all provide red, near-infrared, and short-wave infrared wavelength channels, for example, Landsat ETM + bands 3, 4, and 5; Landsat 8 bands 4, 5, and 6; advanced spaceborne thermal emission and reflection radiometer (ASTER) bands 2, 3, and 5.
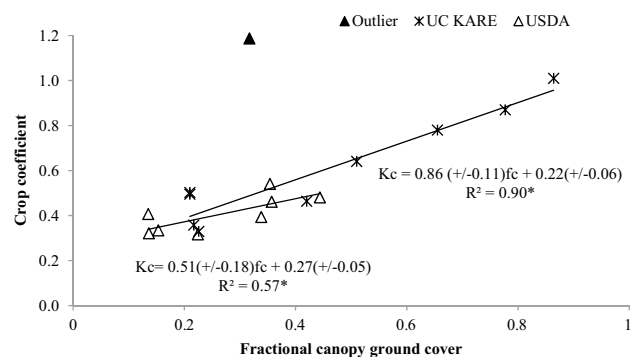
Fig. 5 Correlation between pomegranate tree fractional canopy ground cover (f_c) and crop coefficient (K_c) during 2012–2014 in UC-KARE and USDA-ARS fields for the fully irrigated crop (the *triangle symbol* is an outlier, not used in the regression analysis)

Table 5 Fruit yield in USDA-ARS and UC-KARE fields respond to irrigation level and methods of irrigation (DI—surface drip irrigation; SDI—subsurface drip irrigation)

Site	Treatment	2013			2014		
		Total fruit weight per tree (kg)	Fruit no per tree	Fruit size (g)	Total fruit weight per tree (kg)	Fruit no per tree	Fruit size (g)
USDA-ARS	35%	18.6	44	427	20.6[a]	63	330[a]
	50%	19.6	48	407	29.7[ab]	76	390[b]
	75%	24.4	57	430	32.5[b]	79	410[b]
	100%	26.6	62	429	31.4[ab]	75	421[b]
Pr > F		0.0814	0.0545	0.5727	0.044	0.295	0.0087
UC-KARE	DI	59.3	155	392[a]	77.9[a]	182	441
	SDI	62.9	152	419[b]	84.7[b]	197	443
Pr > F		0.145	0.693	0.0022	0.0086	0.0535	0.9281

Means followed by a different letter within column are significantly different at $p < 0.05$

Determination of K_c from f_c

The correlation between f_c and K_c was analyzed. Figure 5 shows the relationship between daily K_c and measured f_c for pomegranate trees from both the UC KARE field and the 100% irrigation treatment in the USDA-ARS field. An outlier analysis was run using an outlier analysis function, Mahalanobis Distances, in JMP and the K_c value of 1.2 from the USDA-ARS dataset was identified as an outlier in the linear regression. The linear relationship has an intercept of 0.27 and slope of 0.51 and high correlation coefficient ($R^2 = 0.57$) after the outlier was excluded for USDA-ARS site, and an intercept of 0.22 and slope of 0.86 and high correlation coefficient ($R^2 = 0.90$) for UC-KARE site. The positive intercept and higher K_c to f_c ratio were due to the sparse canopy at early growth stage of the tree. Trout and Johnson (2007) has found similar parameters for several horticultural crops: an intercept of 0.14 and slope of 1.13. It is interesting to note that the relationship was independent of the canopy structure developed during pruning.

Fruit yield

No significant difference in yield among treatments was found in 2013 in the USDA-ARS site (Table 5). Trees under 75% irrigation treatment produced the highest yield and fruit number per tree in 2014. Fruit yield increased by 4% while saving 25% of water compared to full irrigated trees. Trees under the 35% irrigation treatment in 2014 produced the lowest yield and the smallest fruit. In the UC KARE site, although the differences of fruit number per tree and fruit size were not significant, the total fruit weight per tree was significantly higher in SDI than in DI in 2014. It indicated that trees irrigated with SDI would produce higher yield than those under DI as well as saving 10% irrigation (Table 2). The difference in yield between the two

orchards was due to the tree size as a result of the pruning but mostly due to the differences in irrigation systems and irrigation scheduling. The data between the two fields demonstrate the differences in water requirement as related to tree canopy size.

Conclusions

This study investigated young pomegranate tree responses to different irrigation systems and rates of irrigation using remote sensing technology in two experimental fields in Parlier, CA in 2012–2014. There were no significant treatment effects on tree canopy size between sub-surface drip and surface drip irrigation systems. Trees under sub-surface drip irrigation produced significantly higher fruit yield than those under surface drip irrigation. Irrigation deficits at 35 and 50% of crop water use had significantly negative effects on tree canopy size and canopy-to-air temperature on certain measurement days. Trees irrigated with 35% of crop water use produced significantly less fruit weight per tree and the smallest fruit in 2014. Ground-based NDVI and NDII were highly correlated to f_c. The relationships between NDVI and f_c, and f_c and K_c have been established and can be a promising tool for farmers to estimate pomegranate tree water use in regional scale based on satellite imagery in the future.

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