Final Report

A. Project Information:

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Title: Improving Pomegranate Fertigation and Nitrogen Use Efficiency with Drip Irrigation Systems

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B. OBJECTIVES

The overall objective of this project was to determine nitrogen and water requirements of drip irrigated maturing pomegranate to minimize nitrogen losses.
Specific objectives were:

1. Determine the real time seasonal nitrogen requirements (N) of surface drip irrigated (DI) - and subsurface drip irrigated (SDI) maturing pomegranate that improve nitrogen fertilizer use efficiency (NUE) without yield reduction.
2. Determine the effectiveness of three nitrogen injection rates with DI and SDI on maintaining adequate N levels in maturing pomegranates.
3. Determine the effect on N leaching losses of real time seasonal nitrogen injections (N) with DI- and SDI irrigated maturing pomegranate.
4. Develop fertigation management tools that will allow the growers to achieve objective 1 and present these results to interested parties at yearly held field days and seminars.

C. ABSTRACT

This project is a continuation of a previously CDFA funded project on the fertigation of a developing pomegranate orchard conducted at the University of California, Kearney Agricultural Research and Extension Center (KARE). We used a statistically replicated layout on a 3.5-ac field. Pomegranate trees (*Punica granatum L var. Wonderful*) were planted in 2010 with a row spacing of 16 ft. and a within row spacing of 12 ft. The two main treatments were surface drip irrigation (DI) and subsurface drip irrigation (SDI)

with three N sub-treatments (N application rates of 50, 100, and 150 % of required N, based on bi-weekly tissue analyses) with 5 replications. To ensure accurate irrigation management, hourly crop evapotranspiration (ET_c) measured with the KARE weighing lysimeter located in the experimental field was used to automatically irrigate the orchard (0.04 in/irrigation [1.0 mm/irrigation]). Potassium (K_2T) and phosphorus (PO_4-P) were applied by continuous injection of P=15 ppm and K=50 ppm to maintain adequate plant tissue levels. The pH of the irrigation water was automatically maintained at 6.5+/-0.5 by injection of N=pHURIC (10% N). The trees received uniform application of fertilizers and water during the first two years to insure uniform stand establishment prior to beginning this experiment. Differential N treatments were started in 2012 and continued throughout the current project. The trees were harvested for yield and quality in for the first time in 2012. We report the results of the study from 2013 to 2015. In 2013 applied N ranged from 62 to 249 lbs/ac. Total yield ranged from 29,521 to 51,455 lbs/ac but did not respond to the difference in applied N. In 2014 the applied N ranged from 55 to 305 lbs/ac and the total yield ranged from 40,065 to 44,154 lbs/ac with no response to additional nitrogen. In 2015 the applied N ranged from 100.7 to 295.9 lbs/ac and the average yield ranged from 45,091 to 46,180 lbs/ac with no response to the N treatments. The yearly applied irrigation water increased as the trees increased in size. In 2013 the applied water was 25.4 in and 23.0 inches in the DI and SDI, respectively. In 2014 the DI was 33.4 in and SDI was 30.7 in. In 2015 the DI being 36.7 and SDI was 33.2 in. The use of SDI resulted in lower weed pressure than in the DI irrigated plots in all three years. High frequency irrigation demonstrated that nitrate can be managed within the soil profile by minimizing deep percolation which minimizes or eliminates losses to the groundwater. There was minimal pruning and the trees were maintained in a bush shape throughout the study. The shaded area was correlated to the crop coefficient and provides an easy method for irrigation scheduling. In general the SDI irrigated trees were larger than the DI irrigated trees throughout the study and had higher yields.

D. INTRODUCTION

Pomegranate acreage in California increased to approximately 30,000 ac as a result of the demand for juices with healthy bioactive compounds, mineral nutrients, and high antioxidant contents. However, there has been some reduction in acreage in the past few years due to economic drivers. Despite this being an "ancient" crop, there are few studies quantifying the water and nitrogen requirements of a pomegranate orchard and none using either high frequency surface drip or subsurface drip irrigation. Research has shown that well managed surface drip (DI) and subsurface drip irrigation (SDI) 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 (Ayars, et al. 1999). Avoiding N deficiency or excess is critical to maintaining nitrogen use efficiency (NUE) and knowledge of the operation of DI and SDI, especially for deep installation of SDI, is critical for effective management of N-fertigation. This project was initiated to determine the nitrogen fertilizer and water requirements of a maturing pomegranate orchard.

E. MATERIALS AND METHODS

This project was located on the University of California Kearney Agricultural Research and Extension Center (KARE) and used a 3.5 ac pomegranate orchard (*Punica granatum, L* var. Wonderful) that included a large weighing lysimeter (Fig. 1). Trees were planted with 16 ft. row spacing and a within row spacing of 12 ft. The orchard was laid out in a randomized complete block design with 2 main treatments and 3 sub-treatments with 5 replicates. The main treatments were surface drip irrigation (DI) and subsurface drip irrigation (SDI) with the laterals installed at a depth of 20-22 inches. There were 2 laterals per tree row with a lateral located at 3.5 ft. on each side of the tree row. The fertility sub treatments were 3 N treatments (50% of adequate N (N1), adequate N (N2), and 150% of adequate N (N3) based on biweekly tissue analysis. The nitrogen was applied by variable injection of N-pHURIC (10% N as urea, 18% S), AN-20 (10% NH_4-N and 10% NO_3-N) depending on the treatment. The pH of the irrigation water was automatically maintained at 6.5+/-0.5 using continuously applied N-pHURIC. AN-20 was added at variable rates to provide the nitrogen required for treatments N2 and N3. Potassium thiosulfate (K_2T, 25% K from K_2O and 17% S) and phosphorus (from H_3PO_4, PO_4-P) were supplied by variable injection of P=15-20 ppm and K=50 ppm to maintain adequate uptake levels.

There was one tree on the lysimeter and it was irrigated using a SDI system with the same number of emitters per tree as the rest of the orchard. The lysimeter determined the water use for a fully irrigated (100%) subsurface drip irrigation (SDI) with adequate nitrogen (N2) treatment and automatically managed the hourly irrigation scheduling for the field. When the differential nitrogen treatments were begun in 2012 the water applied to the DI treatments was increased by 10% to account for evaporation from the soil surface and water used by weeds.
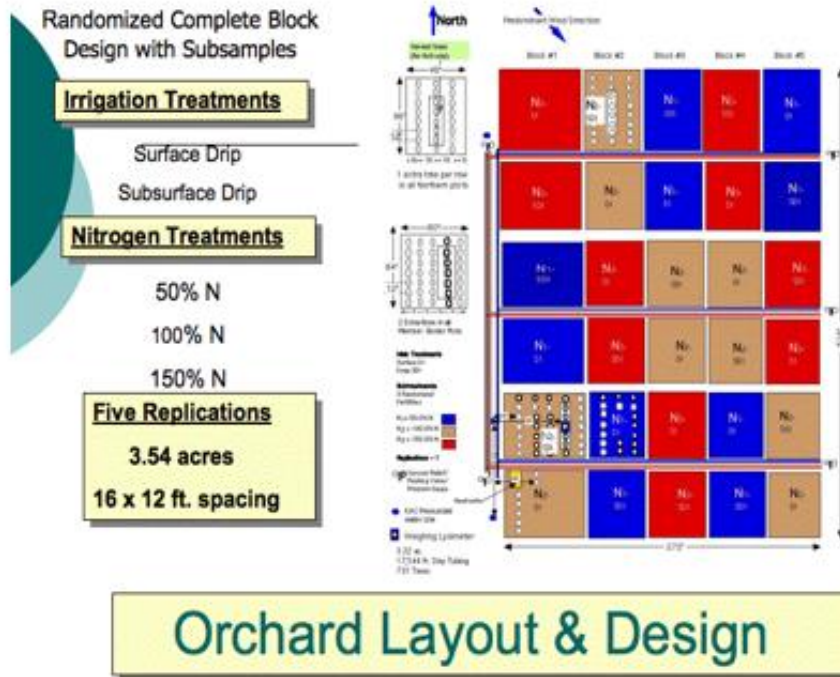
Figure 1. Orchard treatment, design and layout for surface drip irrigated (DI) and subsurface drip irrigated (SDI) pomegranate located on the Kearney Agriculture Research and Extension Center.

Tree and fruit responses were determined by canopy measurements using a multispectral camera to determine shaded area, bimonthly plant tissue analyses for total nitrogen and carbon analysis, and fruit yield and quality. The fruit were harvested in a single harvest each year and separated into prime and subprime fruit. Prime fruit were characterized as being suitable for the fresh market with good red color and minimal surface cracking. Subprime fruit were used for the juice market and had deep surface cracking. Green fruit were counted and discarded. The number and weight of the fruit were determined from 5 trees in each replication and used for analysis. A split plot mixed model was fit using the SAS PROC MIXED program (SAS, 2013). Irrigation, N and the interaction are the fixed effects and the replications (reps) and irrigation by reps are random effects. Means were taken over the trees subsamples prior to analysis. Soil sampling was done in the Spring before irrigation began and then in the Fall after fertigation was completed. The soil profile was sampled to a depth of 48 inches in 6 inch increments in each replication of each treatment and analyzed for nitrates. The samples were averaged by depth across each treatment.

F. Data/Results

1. Crop Water Use/Potential Evapotranspiration/Crop Coefficient

The potential evapotranspiration determined from the CIMIS station (#39) adjacent to the site and the crop evapotranspiration measured by the weighing lysimeters were used to calculate a crop coefficient for 2013, 2014, and 2015 in Figs. 2, 3, and 4, respectively.

The data in figures 2 to 4 show that the crop water use was increasing each year as the plants grew larger. The maximum daily use was about 0.3 inches per day (8 mm). The maximum crop coefficient (K_c) also increased from a 0.85 in 2013 to 1 to 1.05 in 2015. A crop coefficient was developed using the data from 2015 which should be typical of a mature crop. The crop coefficient was determined with a 5th order regression with the x value being the day of the year. The resulting equation is

$K_c = 3e^{-09}x^4 + 0.0004x^3 - 25.92x^2 + 703849\ x - 7e^{+09}$ with an $R^2 = 0.98$.

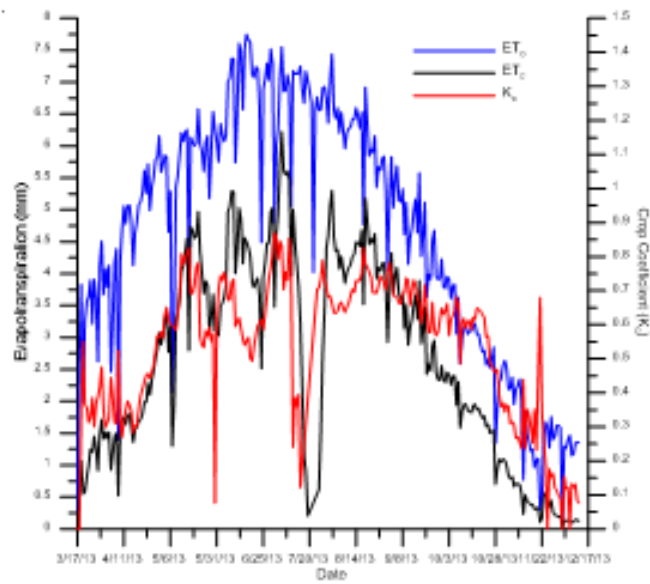This equation would be suitable for use in irrigation scheduling.

Figure 2. Daily potential evapotranspiration (ET$_o$), crop evapotranspiration (ET$_c$) and 7-day averaged crop coefficient (K$_c$) in 2013.
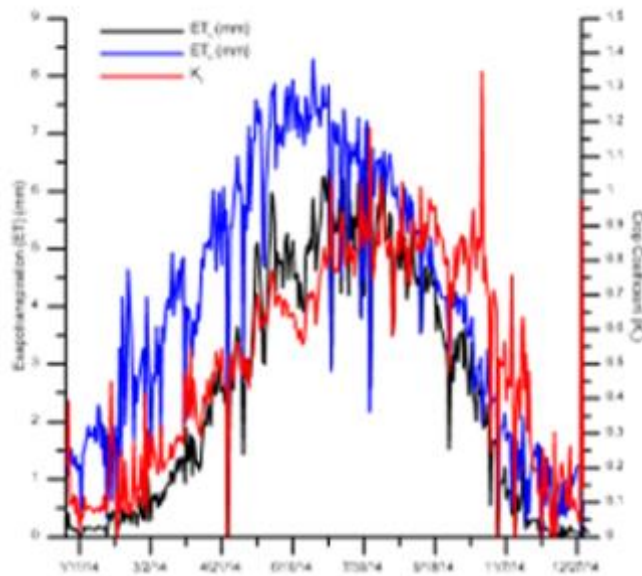

Figure 3. Daily potential evapotranspiration (ET$_o$), crop evapotranspiration (ET$_c$) and 7-day averaged crop coefficient (K$_c$) in 2014.
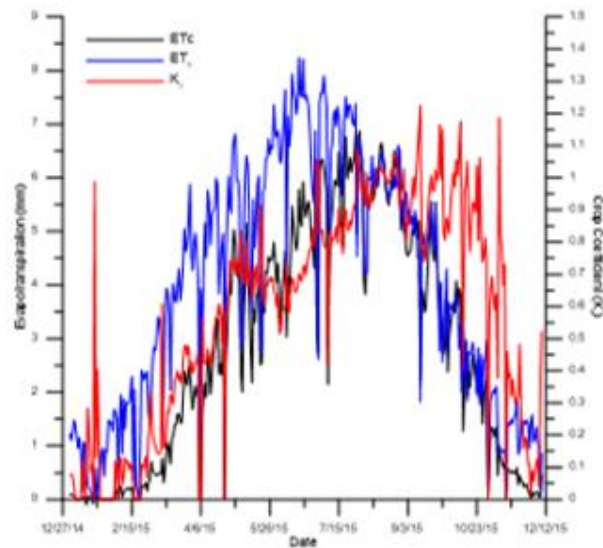
Figure 4. Daily potential evapotranspiration (ET$_o$), crop evapotranspiration (ET$_c$), and 7-day averaged crop coefficient (Kc) in 2015.

2. Pomegranate Water Balance

Table 1 gives the components of the water balance from 2010 until December 15, 2015. The first 2 years of data were included to characterize the crop development. The trees were removed from the field surrounding the lysimeter starting December 10, 2015. There was also cold weather prior to the tree removal that resulted in leaf drop and the cessation of transpiration. Reference evapotranspiration (ET$_o$) was taken from the CIMIS weather station located on KARE. The crop water use (ET$_c$) came from the weighing lysimeter and was adjusted for field tree spacing. Precipitation came from the lysimeter weather station, drainage was measured in the lysimeter using a tipping bucket rain gauge, and there was no runoff. The applied water to the SDI and DI systems was measured with water meters.

The total annual reference evapotranspiration (ET$_o$) increased during the 6 years of the combined studies. From 2013 to 2015 there was approximately a 6% variation in the total ET$_o$. The rainfall values are below the regional averages of 10 inches due to the drought of the last 4 years. Most of the rainfall occurred during the winter which is typical for California.

Table 1. Yearly water balance data 2010 to December 15, 2015 for surface (DI) and subsurface (SDI) drip irrigated pomegranate measured with a weighing lysimeter irrigated with SDI.

Year	ETₒ (in)	Precipitation (in)	DI (in)	SDI (in)	ETc (in)	Drainage (in)
2010	49.7	17.3	1.0	1.0	2.1	n/a
2011	50.9	10.4	8.5	8.5	9.8*	0
2012	54.6	9.0	18.6	16.8	19.0	0
2013	55.0	3.2	25.4	23.0	26.9	0
2014	57.8	8.6	33.4	30.7	35.9	0
2015**	54.3	6.6	36.7	33.2	37.5	0

* ETc measured from 5/1 – 12/8/11 only
** As of: Dec. 15, 2015

There was a uniform depth of applied irrigation water in 2010 and 2011 to insure good stand development and reasonably uniform plant size. The irrigation data for the DI and SDI systems shows a progressive increase in applied water to meet crop water use which was expected as the trees matured and increased in size over the six-year period of the study. The difference in SDI and DI applied water beginning in 2102 was the deliberate addition of approximately10% more water to the DI treatment to compensate for water loss due to surface evaporation and water use by weeds. The last two years show that the crop water use is in the range of 37 inches which reflects the mature crop water requirement.

The lack of drainage from the lysimeter was the result of high frequency irrigation with SDI. The ability to meet crop water demand with small applications of water minimizes the potential for deep percolation with SDI. With high frequency irrigation it is possible to control the soil matric potential and hydraulic gradients with the net result being no net deep percolation. This is discussed in the next section of the report. The data support the determination of zero drainage over the experimental period that is given in the water balance calculation. Also, no drainage was measured with the tipping bucket rain gauge that measured drainage from the lysimeter.

3. Soil Matric Potential (SMP) measurements and Hydraulic Gradient (HG) Calculations in the SDI irrigated lysimeter: With the concern for transport of nitrate to the groundwater it is essential to quantify the movement of NO_3 through and below the crop root zone. We used heat dissipation soil water matric potential (SMP) sensors (Campbell Scientific Inc. CSI-229)[1] calibrated at 25 ^{0}C at pressures ranging from 1.0 to 15.0 bar. These SMP sensors were installed in the lysimeter in two columns of SMP sensors installed at depths of 24, 36, 48 and 60 in. from the soil surface. These SMP

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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. USDA is an equal opportunity provider and employer.

sensors provide the SMP status in the lysimeter and were used to calculate the hydraulic gradient to determine the direction of water flow in the root zone and to infer the leaching potential under high frequency SDI (Phene et al., 1989). Figure 5 gives the soil matric potential (SMP) at depths of 24 in. (0.6 m), 36 in. (0.9 m), 48 in (1.2 m) and 60 in. (1.5 m) in 2013.
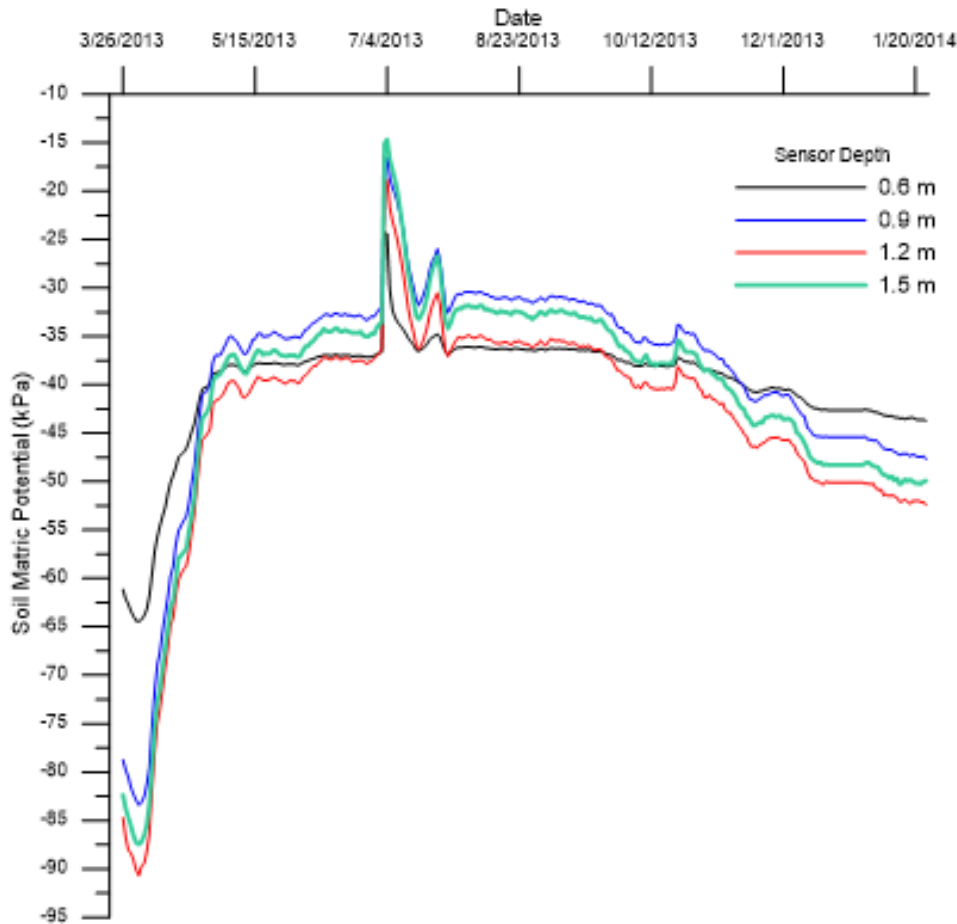

Figure 5. Daily average soil matric potential (SMP) sensor measurements from 3/24/2013 until 1/25/2014 in KARE weighing lysimeter.

The data show that the SMP was maintained in a range of -30 to -45 kPa (-3.0 to -4.5 bar) which is a well-watered ranged for this Hanford silty loam soil. The spike in the data in June of 2013 occurred when the irrigation was not controlled, and excess water was applied. This also demonstrates the sensitivity of the sensors to changes in water content. The hydraulic gradient was calculated using Darcy's law (1865) with the data from the SMP's

$$\Delta H / \Delta Z = (H2 - H1)/(Z2 - Z1) \qquad (1)$$

with $H = \Psi - Z$ where Ψ is the soil matric potential, H is the head, and Z is the depth.

This results in
$$\Delta H / \Delta Z = (\Psi_2 - \Psi_1)/(Z_2 - Z_1) - 1 \qquad (2)$$

with $(\Psi_2 - \Psi_1)$ is the difference between 2 depths and the $(Z_2 - Z_1)$ is the soil depth difference measured downward from the soil surface and (-1) represents the gravitational component of the gradient. However, the downward flow due to gravity was insignificant due to the high frequency of irrigation with the SDI systems. The unsaturated hydraulic conductivity is low due to the matric potential being maintained in the root zone. As a result, the equation 2 reduces to

$$\Delta H / \Delta Z = (\Psi_2 - \Psi_1)/(Z_2 - Z_1). \qquad (3)$$

Calculated daily averaged hydraulic gradients (HG) from 3/26/13 to 1/25/14 are shown in Figure 6 (HG > 0 indicates upward flux and HG < 0 indicate downward flux). HG-1 is the gradient from 24 to 36 inches. HG-2 is the gradient from 36 to 48 inches and HG-3 is the gradient for 48 to 60 inches. Results in Figure 6 indicate that HG-1 and HG-3 are positive with upward flow while the zone from 36 to 48 inches has water moving downwards. However, the gradient from 48 to 60 inches is upward thus preventing drainage and nitrate leaching (none measured from the lysimeter). Root uptake in the 36 to 48-in. depths is probably causing this HG behavior. The rise in hydraulic gradient starting on 7/4/13 (day 180) resulted from a relay failure causing the irrigation pump to stay on for several hours (Murphy's Law) longer than required and resulted in excess irrigation. Despite the excess irrigation there was no drainage. These HG patterns would be expected to occur as well in the DI and SDI systems in the orchard.
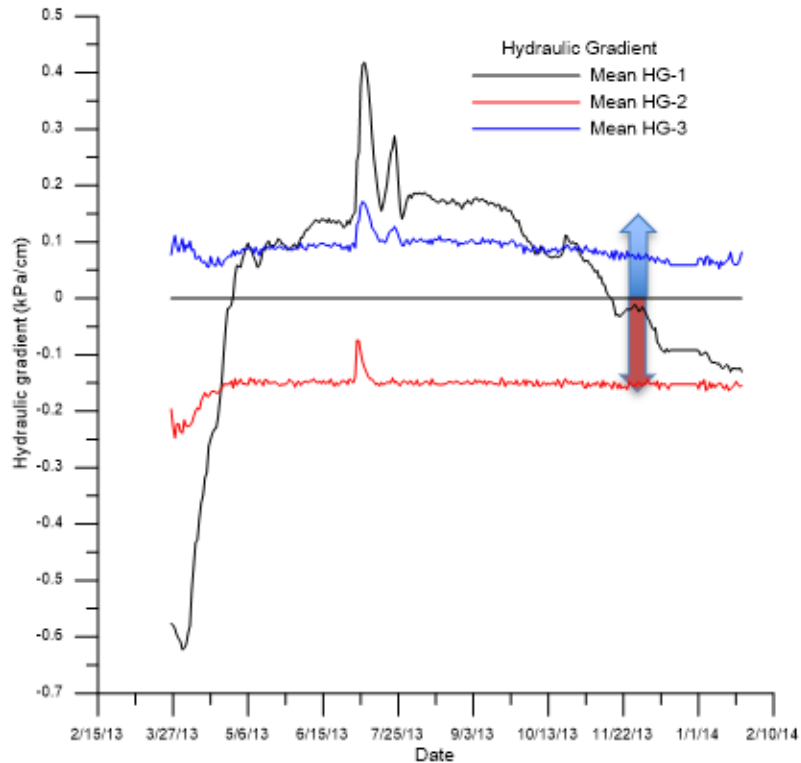
Figure 6. Soil hydraulic gradients (HG) calculated daily soil matric potential from 3/24/2013 until 1/25/2014 in KARE weighing lysimeter. The arrows indicate direction of flow.

The values for the average SMP for 2014 are given in Fig. 7 and the resulting hydraulic gradients are given Fig. 8. The changes in potential around day 80 in Fig. 7 were in response to a 1.3-inch rainfall. The subsequent decline in the potential was a result of the trees leafing out. This is followed by the beginning of irrigation and the trees reaching full bloom about day 110. The goal was to control the soil matric potential in the range of -30 to -45 kPa (-3 to -4.5 bar). This was done very successfully throughout the season. The periods outside of this range reflected instances when there were some problems with the water supply or the end of the season at:
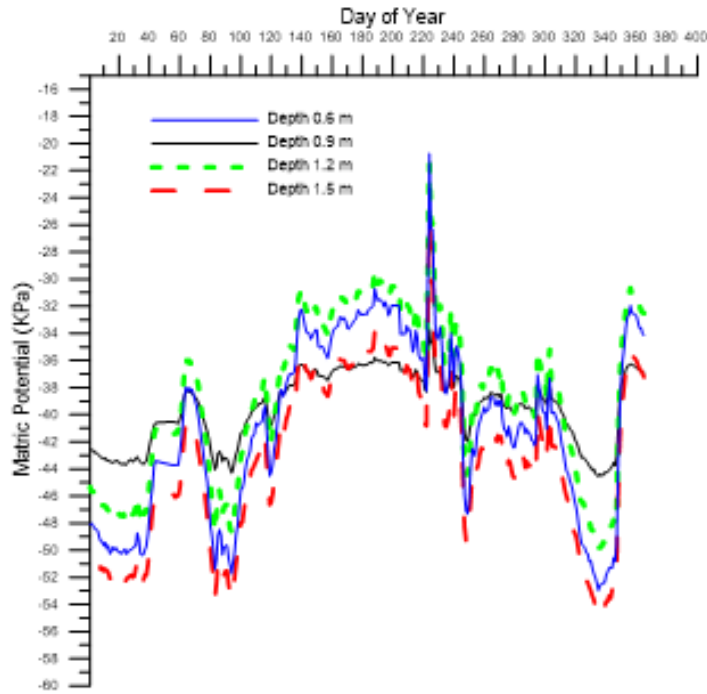
Figure 7. Daily average soil matric potential sensor measurements in 2014 measured in KARE weighing lysimeter.
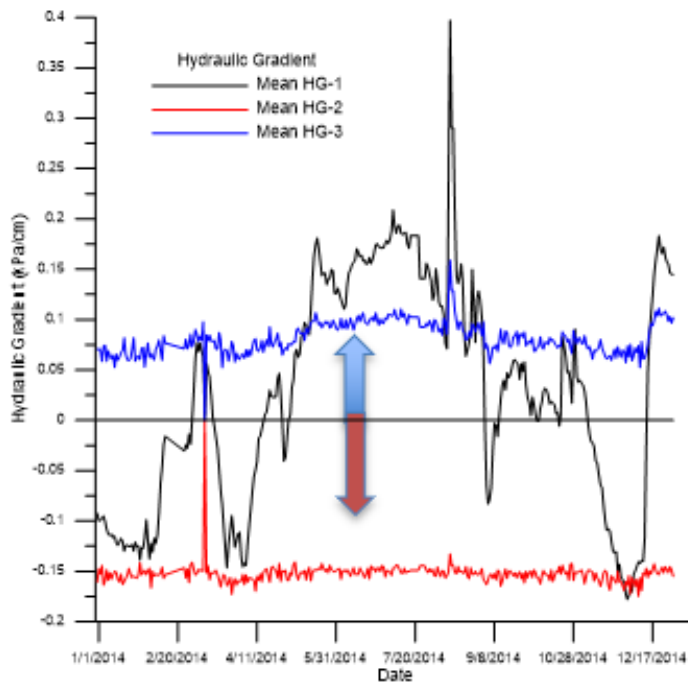
Figure 8. Soil hydraulic gradients (HG) calculated from soil matric potential in KARE weighing lysimeter in 2014. The arrows indicate direction of flow.

harvest and finally when the system was shut down for the season. Note that in 2013 when there were problems with the irrigation system the sensors responded quickly to the additional water which was the case with the rainfall.

Recall that HG-1 is the zone from 24 to 36 inches depth. HG-2 is the zone from 36 to 48 inches in depth and HG-3 is the zone from 48 to 60 inches of depth. The data show that there was a gradient of flow downward in the middle zone but continuously upward in the lowest zone. During most of the irrigation season the gradient and thus the flow was upward. The net result is that we controlled the flow within the root zone and no water and thus no nitrogen was lost to the groundwater.
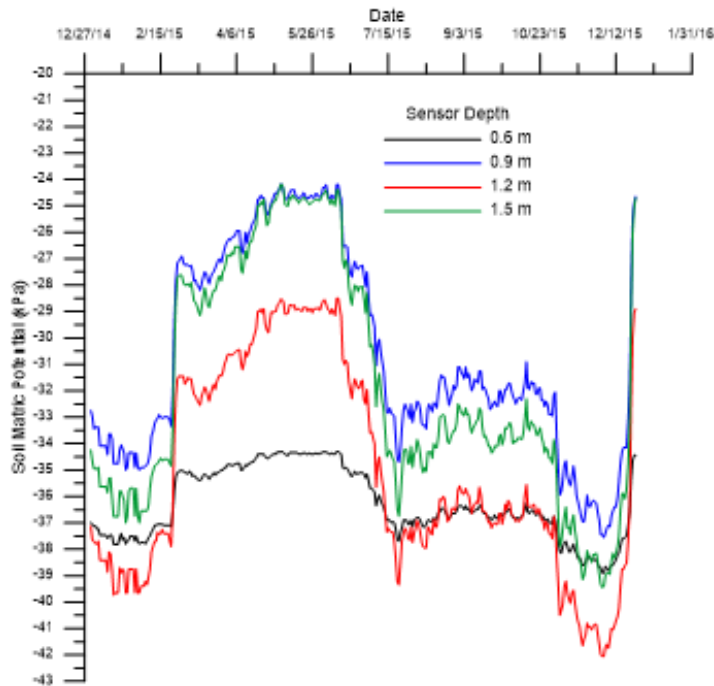

Figure 9. Soil matric potentials measured in the KARE weighing lysimeter in 2015.
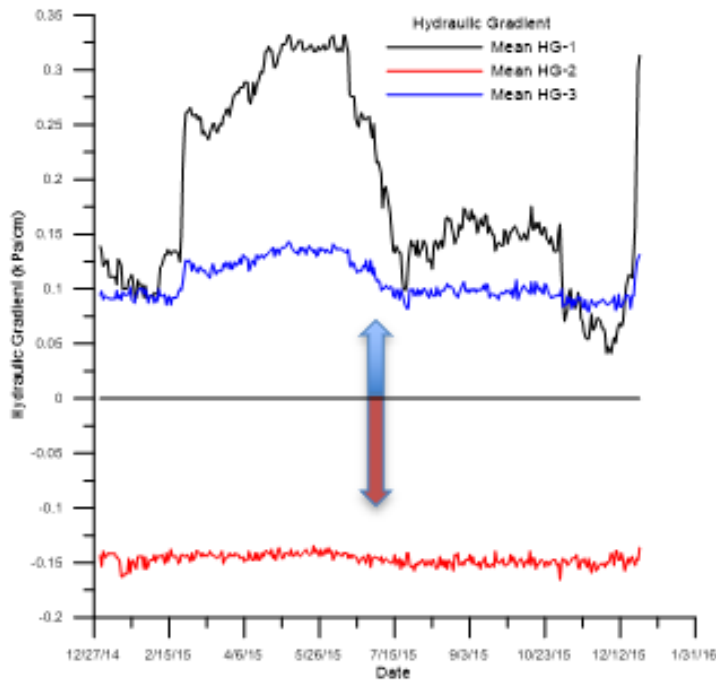
Figure 10. Soil hydraulic gradients calculated using soil matric potential in the KARE weighing lysimeter in 2015. Arrows indicated direction of water flow.

The average SMP for 2015 in the KARE weighing lysimeter are summarized in Fig.9 and the gradients of flow are given in Fig.10. The same flow pattern is shown as was demonstrated in 2013 and 2014. The gradient in the zone from 36 to 48 inches (HG-2) is down while it is up in the zones above and below it. The net result is that there is no deep percolation loss from the rootzone. Recall that the SDI drip tube is installed at a depth of approximately 22 to 24 inches and drainage below this zone into the region from 36 to 48 inches would be expected. In all years the high frequency irrigation maintained the SMP between 30 and 45 kPa (-3 to -4.5 bar) during the irrigation season.

4. Automated fertigation management:
a. Nitrogen--The three-nitrogen fertility sub-treatments (N1-50%, N2-100% and N3-150% of adequate N) were determined from biweekly tissue analyses. All N is automatically applied by continuous injection of N-pHURIC (50 lb N/ac) for all treatments starting during the last week in May and additionally as AN-20 (20% N) for N-2 and N-3 treatments, starting in the second week in June. The nitrogen injections are given in Fig. 11 for 2013 (A), 2014 (B), and 2015 (C), respectively. In all years the majority of the N was applied by mid-June each year to meet the demand for budbreak and leaf and fruit development. After the initial injection of N early in the season the bulk of the remaining application is a result of the continuous injection of the N-pHURIC,
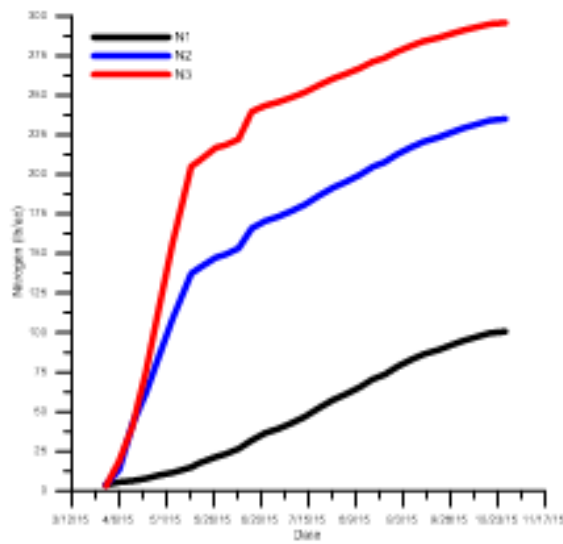
which was used for pH control and provide N for the N1 treatment. This is reflected in the curves having roughly the same shape and increase following the initial high rate injections.

A
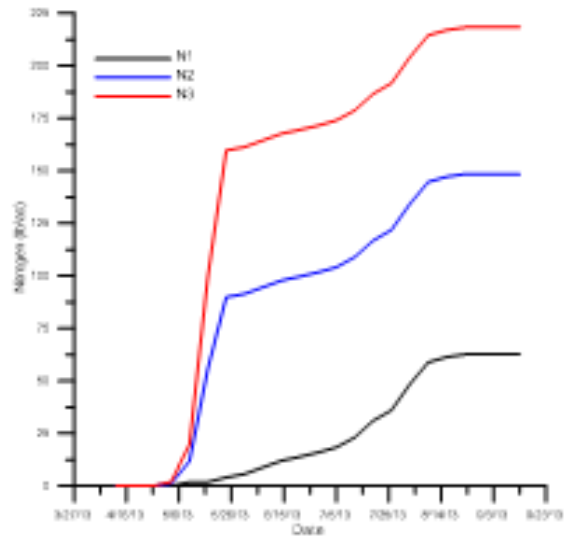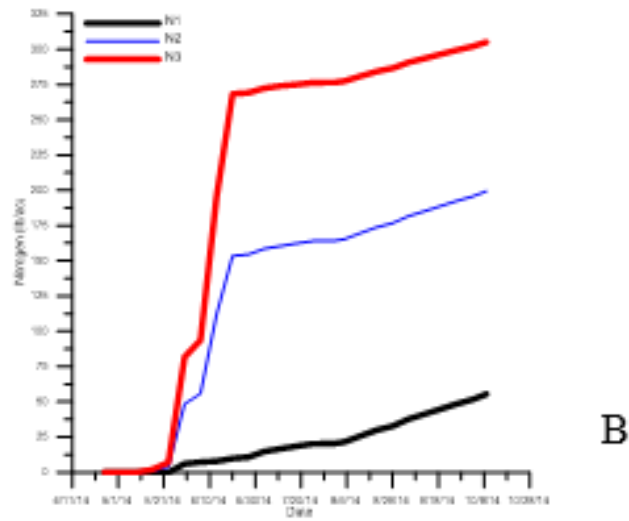
Figure 11. Cumulative injected N from N-pHURIC for all treatments and additionally from AN-20 for the N-2 and N-3 treatments in 2013 (A), 2014 (B), and 2015(C)

Phosphorus—Phosphoric acid (H_3PO_4) is continuously injected at a rate of P=15 ppm to maintain adequate P level in the SDI treatment. Previous research has shown that phosphorus becomes deficient at soil depths greater than 8 in. The pH of the irrigation water was automatically maintained at 6.5+/-0.5 with the N- pHURIC to avoid precipitation of phosphates that typically starts occurring with pH greater than 7.2. The total seasonal phosphorous application will depend on the total applied water since the injection is at a constant level of 15 ppm and applied throughout the irrigation season. The applied phosphorous is given in Fig.12 for 2013 to 2015. The total applied increased over the years in part due to the increased applied water.
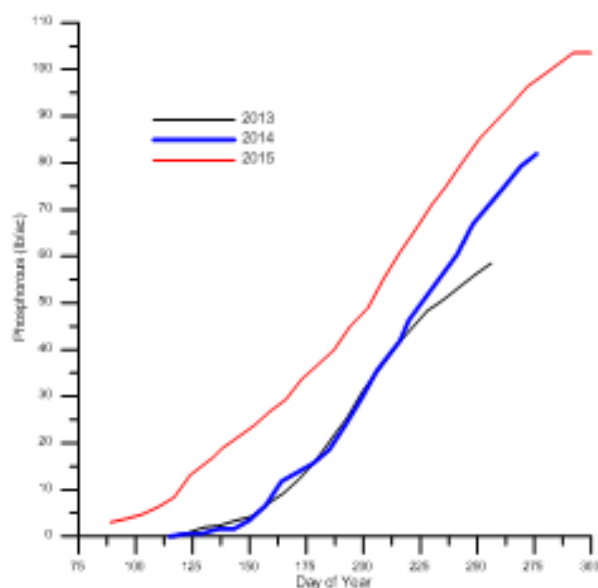
Figure 12. Cumulative injected phosphorus as PO4-P from phosphoric acid (H3PO4) injected uniformly at 15 ppm to all treatments of pomegranate in 2013, 2014, and 2015.

c. Potassium—Potassium (K2T) was injected once weekly at a rate of K=50 ppm to maintain adequate K level in both SDI and DI treatments. Previous research has shown that potassium may become extremely deficient in sandy loam soil, especially as soil depth increases. The total applied potassium is given in Fig. 13 for 2013 to 2015.

The total applied N, P and K for the 3 years of the study are summarized in Table 2.

Table 2. Summary of applied nitrogen treatments (N1, N2, N3) and phosphorous (P) and potassium (K).

Year	N1 (lbs/ac)	N2 (lbs/ac)	N3 (lbs/ac)	P (lbs/ac)	K (lbs/ac)
2013	62.3	148.5	218.3	58.5	65.0
2014	55.4	199.4	305.1	82.0	76.1
2015	100.7	235.1	295.9	103.6	161.6

The resulting applied fertilizers provided a wide range of application to evaluate the response of yield to applied fertilizer. The yield responses are discussed in the next section. The higher value of K in 2015 was the result of control problems with the fertilizer injection pump.

5. Yields, Water Use Efficiency (WUE) and Nitrogen Use Efficiency (NUE):

Pomegranate prime fruits were harvested by a local packer and sub-samples were harvested from the 5 center trees of each of the yield rows and measured for total number, weight, and quality. The quality designations for prime, subprime, green, and marketable varied from year to year depending on the market conditions. We combined the various categories in prime and subprime. The prime fruit will include fruit with good color, and minimal cracking with no open cracks. These were marketable as fresh fruit. The subprime included fruit suitable for juicing and contained some green and open cracked fruit. The sum of all the categories gave the total production. The totals have been broken down in SDI and DI across all N treatments and N treatments for DI and SDI averaged. These data are given in Table 3. The yield data were statistically analyzed by
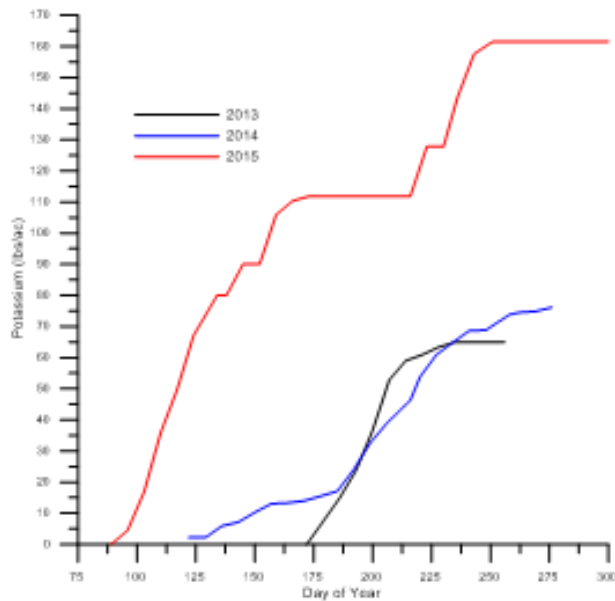

Figure 13. Cumulative potassium as K_2T (lb/ac) injected to all treatments of pomegranate in 2013, 2014, 2015.

aggregating all N treatments by irrigation system and by aggregating by irrigation system within the N treatments.

Table 3. Summary of prime and subprime and total yields for 2013, 2014 and 2015 by irrigation system (DI and SDI) and nitrogen levels N1, N2, and N3.

Year	Irrigation System	Prime (lbs/ac)	Sub Prime (lbs/ac)	Total (lbs/ac)	Nitrogen treatment	Prime (lbs/ac)	Sub Prime (lbs/ac)	Total (lbs/ac)
2013	SDI	21934	9551	31485	N1	19320	10191	29511
	DI	20402	9250	29652	N2	21483	9381	30864
					N3	22815	8640	31455
2014	SDI	33366	9129	42495	N1	28181	12072	40253
	DI	29975	10511	40486	N2	30463	9603	40065
					N3	36367	7787	44154
2015	SDI	36533	8429a	44962	N1	34510	11670	46180
	DI	30132	16291b	46423	N2	33280	11810	45091
					N3	32206	13600	45806

We evaluated the interactions between irrigations, between irrigation systems and nitrogen treatments, and between nitrogen treatments in all three years. There was no interaction between irrigation system and nitrogen treatments in any year of the study for any of the variables.

In 2013 there were statistical differences between the fruit weight of the prime and subprime fruit in the SDI and the DI categories. There was no difference in the total weight between the SDI and DI and the 3 nitrogen levels.

In 2014 the prime yields were different by N treatments with yield increasing with applied N. The opposite was true with the subprime yield and yield decreased as N increased. The net effect was that the total yield was not different across the nitrogen treatments. In 2015 the only effects that were identified were between irrigation system types. The subprime yield differed between DI and SDI but between N treatments. There were no statistical differences in total yield in any of the years.

There were no consistent statistical trends across the 3 years of the study that demonstrate a yield response to increasing applied nitrogen or between irrigation systems. The average yield was consistently higher in the SDI system compared to the DI system but not statistically different. With the exception of 2014 there was no increase of yield with increased levels of applied nitrogen between 100 lbs/ac and 300 lbs/ac. This means that 100 lbs/ac is the nitrogen requirement for this crop.

The water use efficiency (WUE) was calculated as the total yield per acre divided by the applied water in ac-inches for the SDI and DI systems. This was done for the prime, subprime, and total production. These data are given in Table 4.

The data show that the WUE was consistently higher in the SDI treatments than in the DI treatments. This was a result of the higher yields in the SDI treatments and lower values of applied water each year. The WUE values were consistent across the treatments in the 3 years of the study.

The yield data were sorted by nitrogen level and the SDI and DI yields were averaged at a given N level and the WUE was calculated using the average applied water. These data are given in Table 5. In 2013 and 2014 the prime yields increased with increased applied nitrogen, but the opposite demonstrated in 2015. There was no significant difference in total yield as a function of N level in any given year. The total yield increased from 2013 to 2015. This would be expected as the trees size increased.

Table 4. Water use efficiency for prime, subprime, and total production for SDI and DI.

Year	Irrigation System	Prime (lbs/ac)	WUE (lbs/ac-in)	SubPrime (lbs/ac)	WUE (lbs/ac-in)	Total (lbs/ac)	WUE (lbs/ac-in)
2013	SDI	21934	953.7	9551	415.3	31485	1368.9
	DI	20402	803.2	9250	364.2	29652	1167.4
2014	SDI	33366	1086.8	9129	297.4	42495	1384.2
	DI	29975	897.5	10511	314.7	40486	1212.2
2015	SDI	36533	1100.4	8429	253.9	44962	1354.3
	DI	30132	821.0	16291	443.9	46423	1264.9

The nitrogen use efficiency was calculated by dividing the yield by the applied water and the total applied N. these data are summarized in Table 6. The data show that SDI had a higher NUE than the DI treatments in 2013 and 2014 but not in 2015. This can be explained in part due to the placement of the nitrogen with the root zone with the SDI system which would improve the uptake by the plant. In each year the NUE decreased with increasing levels of applied nitrogen since there was no yield increase associated with the increased levels of applied nitrogen. The N1 treatment had the highest value of NUE in each year which demonstrates that 100 lbs of nitrogen per acre is the correct value to maintain yield. In all years the N1 treatment had yield values equal to the other higher nitrogen treatments.

All fruit were lumped together to determine the average yield per tree for each of the nitrogen treatments and irrigation systems. The average yield and weight of the fruit are given for each treatment in Tables 7, 8, and 9 for 2013, 2014, and 2015, respectively. The yield and size data were also averaged within nitrogen treatments for the irrigation system. These data are given in Tables 7, 8, and 9.

The yield per tree increased each year for the N treatments averaged by irrigation system. There was no difference in yield by N treatment within a given year. This is true for the yields by nitrogen and irrigation treatment over the year. The average fruit

size was the same within treatments in a given year. The average fruit size appears to be smaller in the 2015 than in the previous year which may be a result of higher numbers of fruit per tree in 2015 than the other 2 years.

Table 5. Water use efficiency for nitrogen treatments averaged across irrigation systems.

Year	Nitrogen treatment	Prime (lbs/ac)	WUE (lbs/ac-in)	SubPrime (lbs/ac)	WUE (lbs/ac-in)	Total (lbs/ac)	WUE (lbs/ac-in)
2013	N1	19320	798.3	10191	421.1	29511	1219.5
	N2	21483	887.7	9381	387.6	30864	1275.4
	N3	22815	942.8	8640	357.0	31455	1299.8
2014	N1	28181	879.3	10191	421.1	40253	1663.3
	N2	30463	950.5	9381	387.6	40065	1655.6
	N3	36367	1134.7	8640	357.0	44154	1824.5
2015	N1	34510	987.4	11670	482.2	46180	1908.3
	N2	33280	952.2	11810	488.0	45091	1863.3
	N3	32206	921.5	13600	562.0	45806	1892.8

The nitrogen use efficiency was calculated using the yield in pounds per acre divided by the applied nitrogen in pounds per acre. The data are given in table 6.

Table 6. Nitrogen use efficiency (NUE) calculated as the yield in pounds per acre divided by the total nitrogen applied in pounds per acre.

Year	Irrigation System	Prime NUE	SubPrime NUE	Total NUE	Nitrogen treatment	Prime NUE	SubPrime NUE	Total NUE
2013	SDI	153.38	66.79	220.17	N1	311.61	164.37	475.98
	DI	142.67	64.69	207.36	N2	144.18	62.96	207.14
					N3	104.66	39.63	144.29
2014	SDI	178.81	48.92	227.73	N1	508.68	217.91	726.59
	DI	160.64	56.33	216.97	N2	152.77	48.16	200.93
					N3	119.20	25.52	144.72
2015	SDI	173.47	40.02	213.49	N1	342.70	115.89	458.59
	DI	143.08	77.36	220.43	N2	141.56	50.23	191.79
					N3	108.85	45.97	154.82

Table 7. Average yield per tree and fruit weight for all the nitrogen by irrigation system treatments and the nitrogen treatments averaged by irrigation system for 2013, 2014, and 2015.

Year	Irrigation System	Yield (lb/tree)	Average Fruit wt (lb)	Nitrogen treatment	Yield (lb/tree)	Average Fruit weight (lb)
2013	SDI	138.4	0.93	N1	138.8	0.91
	DI	133.1	0.87	N2	135.2	0.90
				N3	138.1	0.91
2014	SDI	186.4	0.98	N1	174.4	0.95
	DI	171.4	0.97	N2	172.9	1.02
				N3	189.5	0.94
2015	SDI	198.1	0.89	N1	203.4	0.85
	DI	204.5	0.81	N2	198.6	0.87
				N3	201.8	0.84

6. Weed population under DI and SDI: One of the advantages of SDI is the potential for lower weed populations than with surface drip. We evaluated this proposition in 2013 by sampling and drying the total weed mass in a square meter in each replicate. The residual weed biomass in the pomegranate orchard (Fig. 14) was measured on August 28, 2013 after
herbicide burn-down and results are shown in Table 10. Results indicate that the weed biomass in the SDI treatment was significantly lower than that in the DI treatment. The relationship between weeds and the soil temperature at solar noon were measured on Sept. 3, 2013 and there was a significant relationship. R = -0.636, P=0.0002. The infrared soil surface temperature was significantly higher in the SDI than in the DI treatments due to lack of weeds.

Table 10. Residual weed biomass and the relationship between weeds and solar noon temperatures measured on August 28, 2013 after herbicide burn-down.

	Weed Biomass	IR Surface Temperature
	g/m^2 (d.w. basis)	ºC
Irrigation method (I)		
Surface Drip	569 a	49.9 b
Subsurface Drip	81 b	57.0 a
Prob. > "F: value:	0.0001	0.0001
Nitrogen rate; (N)		
46 lb/ac	250 b	53.7 ab
148 lb/ac	416 a	55.2 a
249 lb/ac	310 ab	51.6 b
Prob. > 'F" value	0.07	0.12
I X N interaction:	NS	NS

Figure 14. Differences in weed population between DI and SDI irrigated pomegranate.

We didn't do a detailed analysis of the weed mass each year but noted visually that the weed mass was significantly higher in the DI than in the SDI treatments.

7. **Soil Nitrate Profiles.** The fate of nitrogen and nitrate movement is a significant environmental concern in irrigated agriculture. The fate will be determined by both the placement and the total application of nitrogen fertilizers. Using SDI places nitrate below the soil surface and within the tree root zone while a DI system applies the water and thus nitrogen to the soil surface. The effect of irrigation system on nitrate placement was measured using soil samples. Soil nitrate (NO_3) was measured every 6-in. from the soil surface down to 48-in depth in April and December 2013. Figure 15 shows nitrate values in April for the 3 N treatments for both irrigation systems (A) with the means for the DI and SDI measurements averaged for all the N treatments (B). In nearly every case, the NO_3 in the SDI treatment was lower than those measured in the DI treatments.
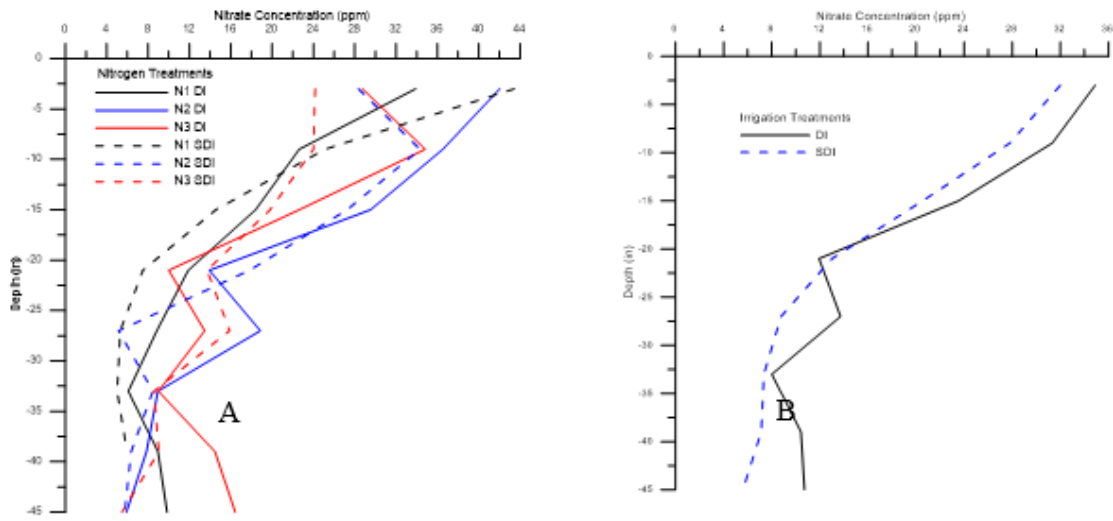
Figure 15. Soil nitrate (NO₃) distribution averaged by nitrogen treatment (A) and by surface (DI) and subsurface drip irrigation [SDI](B) April 2013.

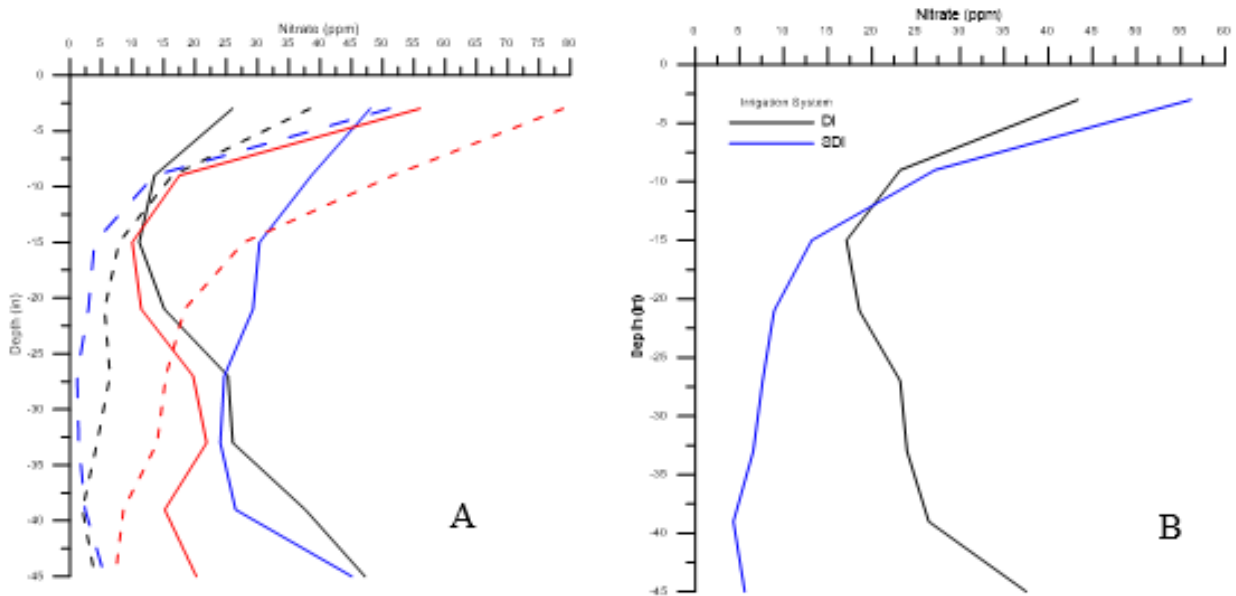
Figure 16. Soil nitrate (NO₃) distribution averaged by nitrogen treatment (A) and by surface (DI) and subsurface drip irrigation [SDI] (B) December 2013.
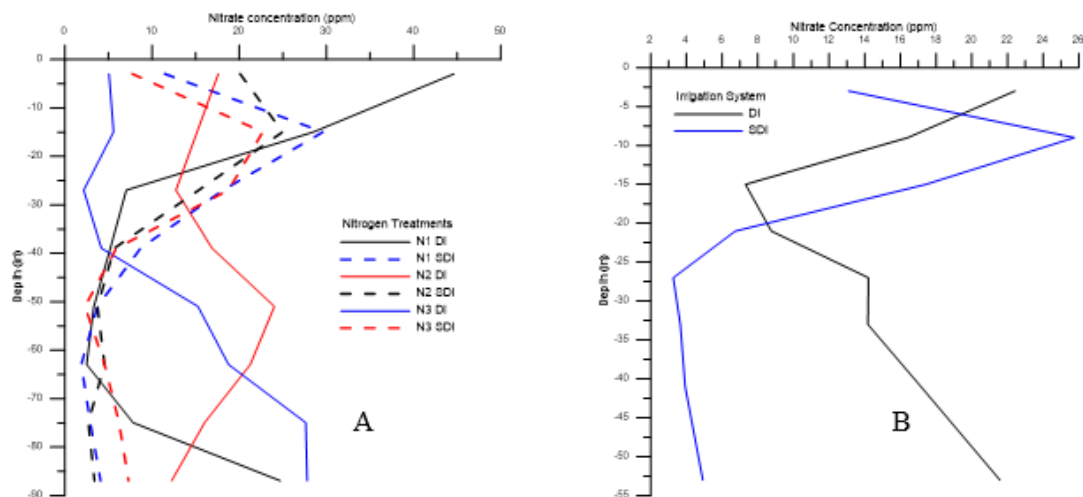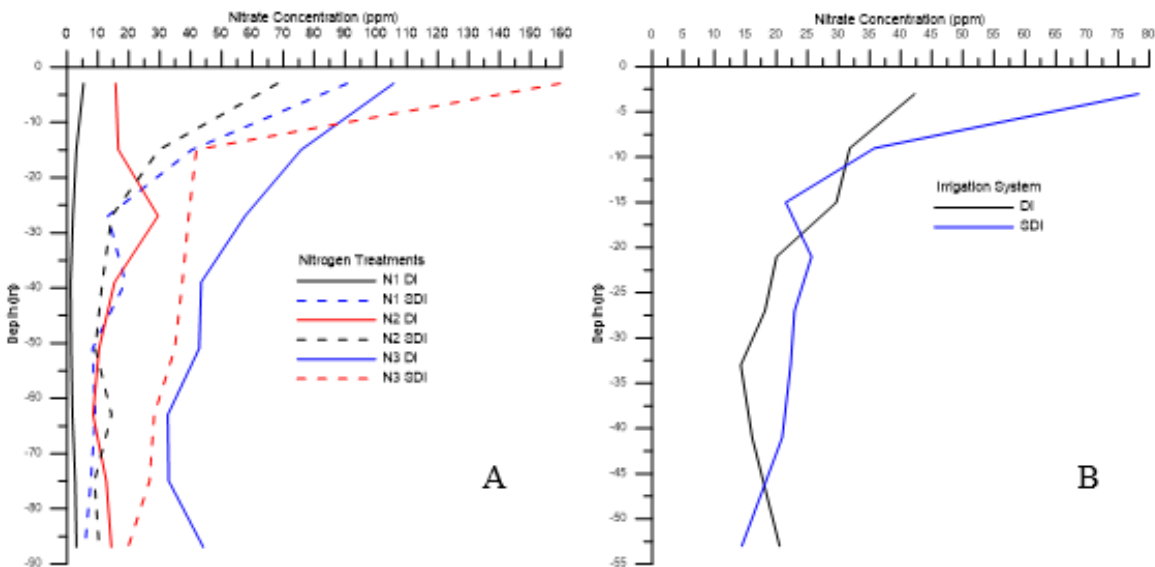
Figure 17. Soil nitrate (NO$_3$) distribution averaged by nitrogen treatment (A) and by surface (DI) and subsurface drip irrigation (SDI) (B) in March 2014.
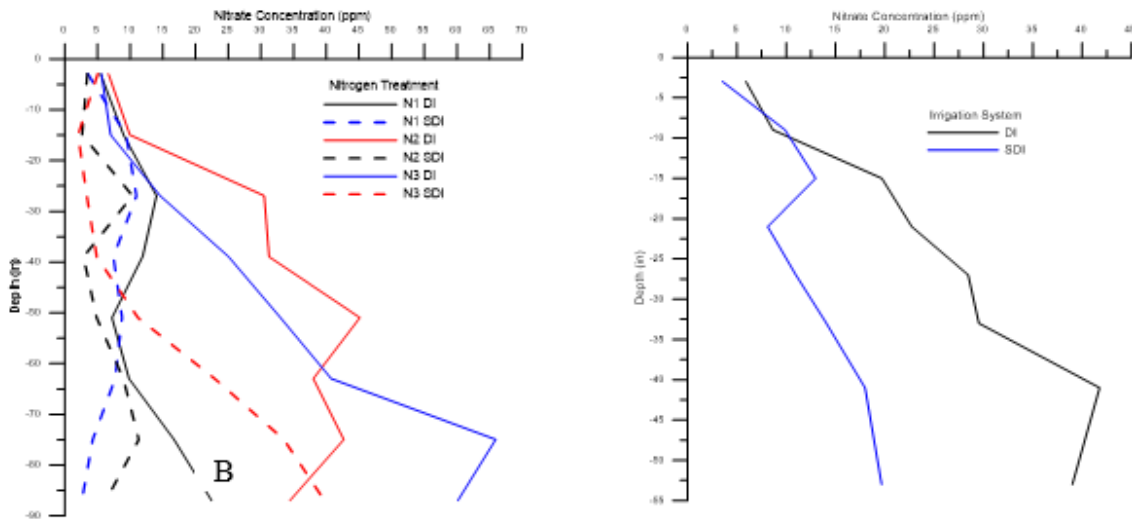

Figure 18. Soil nitrate distribution averaged by nitrogen treatment (A) and by surface (DI) and subsurface drip irrigation system (SDI) (B) in July 2014.

Results obtained in December 2013 after the crop was harvested further substantiate the effect of SDI on nitrate placement compared to DI. Figure 16 (A) shows nitrate values for the 6 N treatments by irrigation method in December. In every case, especially at the deepest depths the NO$_3$ in the SDI treatment were lower than those measured in the comparable N - DI treatments.

Nitrate means are shown in Fig. 16 (B) for the DI and SDI treatments averaged for all the N treatments. In nearly every case, the NO_3 in the SDI treatment was lower than those measured in the DI treatments below a depth of 15 inches except near the soil surface where DI roots are proliferating.

In addition to the zero drainage measurements obtained in the lysimeter, these results indicate that the high frequency SDI system has the potential to eliminate or significantly reduce leaching losses of nitrates to the groundwater.

Figure 19. Soil nitrate (NO_3) distribution averaged by nitrogen treatment (A) and by surface (DI) and subsurface drip irrigation system (SDI) (B) in January 2015.

Comparing the data in Fig. 15 and 16 we see an increase in the levels of nitrate in the profile as a result of the injection nearly 300 lbs of N/acre in 2013. The data for the other two levels are similar and resulted in an increase of approximately 5 mg/L in the soil water extract to a depth of 1.35 m. The increase at the highest level (N3) was twice that the other two levels (N1, N2). The majority of the nitrate is contained in the first 30 cm which would correspond to the root zone. The data for 2014 are given in Fig. 17 and 18 for March and July samplings, respectively. Similar nitrate responses with depth and applied N can be observed the 2014. In January 2015 the nitrate concentration at a depth of 60 in was less than 10 ppm in the two lowest N treatments for SDI but not in the DI treatments (Fig. 19 A).

8. Effect of DI and SDI methods and seasonal N-levels on tree Canopy Size.

Tree canopy cover in each treatment was measured with a multispectral camera in 2012, 2013, and 2014. Table 11 shows the results from the three years of measurement. Fractional canopy ground cover was more responsive to the irrigation system than N rates treatments. By comparing DI vs SDI, we can see fractional canopy

ground cover in SDI plots is always greater than those in DI plots. There were no significant differences in tree size between the irrigation systems. The percentage differences decreased with the age of the trees. There was 15% difference in July of 2012 that was reduced to 5% in 2014.

The correlation between fc and K_c was analyzed. Figure 20 shows the relationship between daily K_c and measured fc for pomegranate trees under SDI treatment in the UC KARE field and 100% of irrigation treatment in another orchard located on a USDA-ARS field adjacent to the KARE site. 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 data set was identified as an outlier in the linear regression. The linear relationship has an intercept of 0.20 and slope of 0.85 and very high correlation coefficient ($R^2 = 0.87$) after the outlier was excluded. The positive intercept and

Table 11. Effect of irrigation system on pomegranate tree fractional canopy ground cover, fc (%)† in UC KARE field (DI-Surface drip irrigation; SDI-Subsurface drip irrigation; Ly-Lysimeter plot)

Treatment	fc (%)				Irrigation Amount (in)
	6-13-12	7-17-12	8-16-12	9-27-12	
DI	20.5±4.8	18.9±3.3a*	20.9±3.9	20.2±3.2	18.6
SDI	22.6±4.4	21.7±3.3b	21.0±3.6	21.1±3.3	16.8
Ly	27.3	24.3	23.0	24.3	
SDI vs. DI	10%	15%	1%	4%	11%
Prob. > F-Value	0.21	0.035	0.9	0.45	
	6-18-13		8-28-13		
DI	37.4±6.2a*		46.2±9.3		25.4
SDI	42.0±6.2b		51.0±11.5		23.0
Ly	40.6		37.4		
SDI vs. DI	12%		10%		11%
Prob. > F-Value	0.048		0.21		
		7-8-14	8-13-14	9-8-14	
DI		61.5±11.7	69.8±14	81.3±14.3	33.4
SDI		65.5±11.3	77.6±17	85.7±16.3	30.7
Ly		66.5	68	79.2	
SDI vs. DI		6.5%	11.2%	5.4%	9%
Prob. > F-Value		0.35	0.2	0.52	

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

higher K_c to fc ratio were due to the sparse canopy at early growth stage of the tree. Trout et al. (2007) has found similar parameters in 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. The USDA-ARS field was pruned to a vase type configuration and the KARE field was left as a bush. The relationship

$$y = 0.852 \, x + 0.1999 \qquad\qquad\qquad\qquad (4)$$

where x is the percent canopy ground cover provides an easy method for obtaining a K_c value that can be used with potential evapotranspiration from a CIMIS weather station to schedule irrigation.
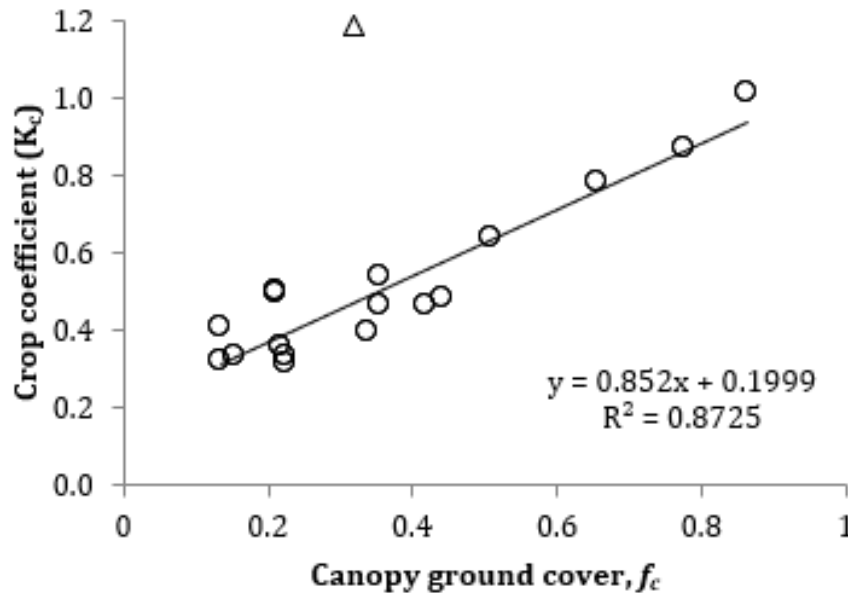

Figure 20. Crop coefficient as a function of % ground cover in well-watered pomegranate.

11. Plant N and C status: Most of the N-uptake by plants is in the NO_3-N form because of its solubility and mobility with water from the soil to the plant. Total N analysis was used to characterize the long-term N response to the 3 N treatments. Tissue N was sampled bi-weekly from April 15 to October 1 and results were used as a feedback for N injection. The total nitrogen and carbon data for 2013 to 2015 are summarized in Fig. 21 to 26. The data are presented as averages by irrigation system (DI, SDI) across all N treatments and averages by nitrogen level for the irrigation systems. The individual nitrogen by irrigation system data is also given. In each year the total N in the leaves across all treatments was initially between 2 and 2.5% and this fell during the growing season to below 1.8%. There was quite of variability in the response across each of the years. The C total increased each as the plant grew which would be expected.
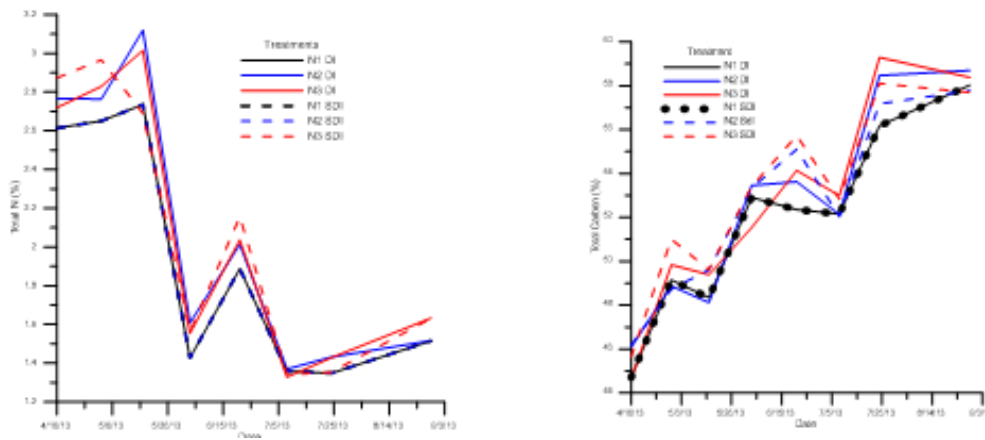
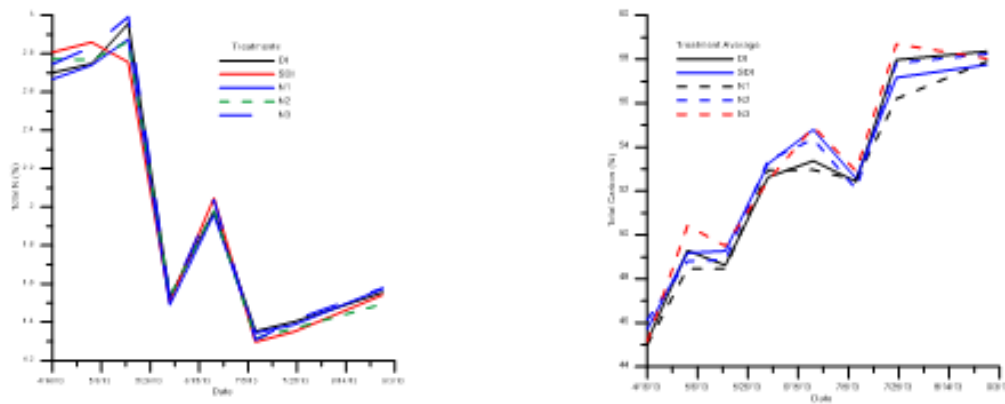Figure 21. Total N and C for all nitrogen treatments in 2013.

Figure 22. Total N and C for nitrogen averaged irrigation treatments (DI, SDI) and by irrigation level N1, N2, and N3in 2013.
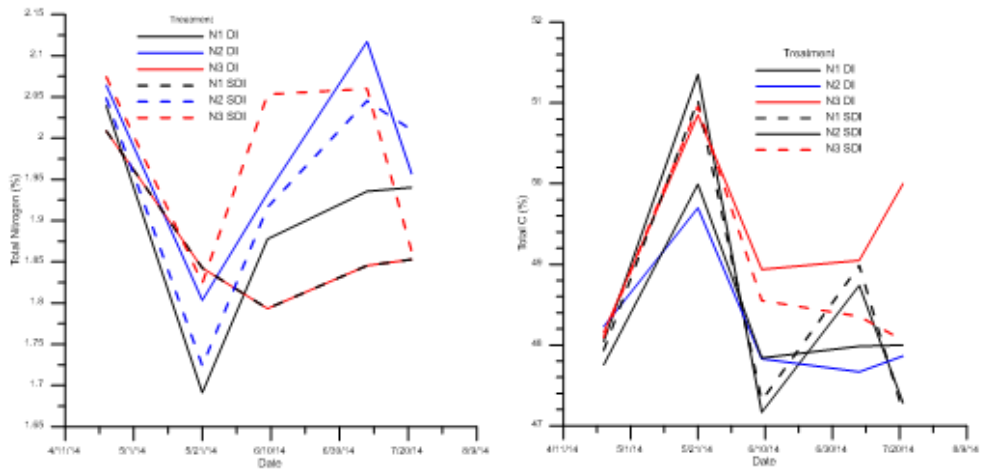
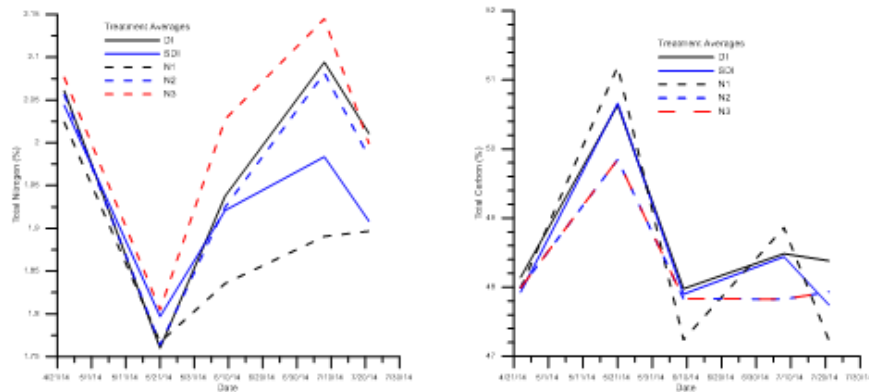Figure 23. Total N and C for all nitrogen treatments in 2014.

Figure 24. Total N and C for nitrogen averaged irrigation treatments (DI, SDI) and by irrigation level N1, N2, and N3in 2014.
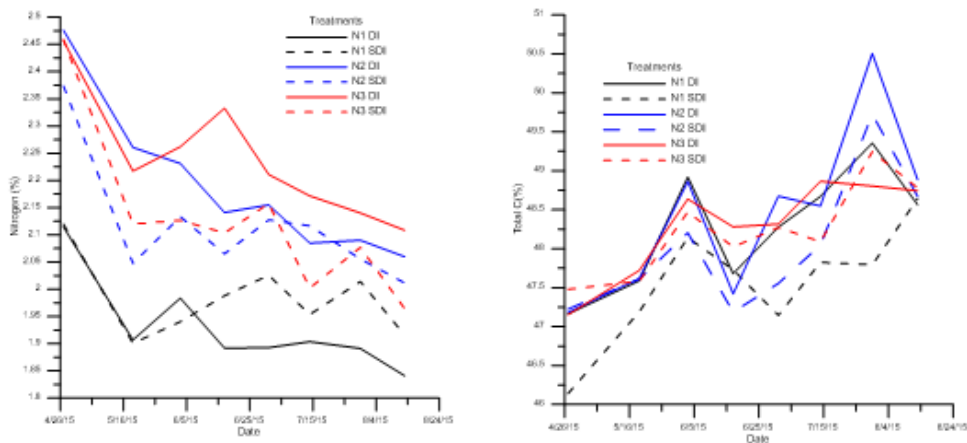

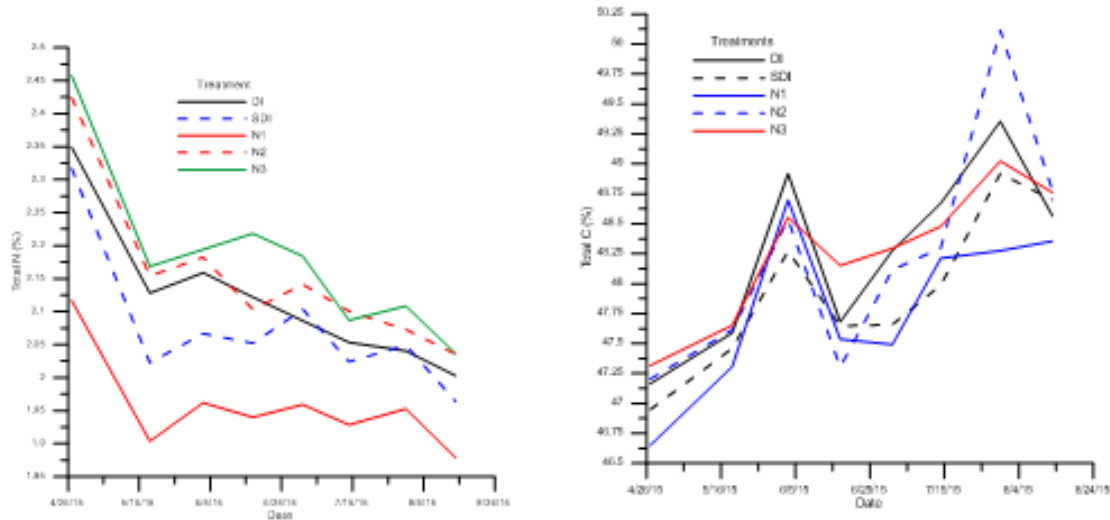Figure 25. Total N and C for all nitrogen treatments in 2015.

Figure 26. Total N and C for nitrogen averaged irrigation treatments (DI, SDI) and by irrigation level N1, N2, and N3 in 2015.

G. DISCUSSION AND CONCLUSION

1. Water Use: The peak water use was approximately 0.3 inches (7 to 8 mm) per day for the mature plant. The resulting crop coefficient was 1 to 1.05 for well-watered subsurface drip irrigated pomegranate.

2. Pomegranate Water Balance: The crop water use increased as the plants grew which would be expected the crop water use in the last year of the project was 37 inches for the DI and 33 inches for the SDI. This difference was by design to provide additional water to the DI to account for weed use and evaporation. The data demonstrate that the water requirement for a mature pomegranate with bush type architecture is 37 in when irrigated with surface drip. This value can be reduced with subsurface drip.

3. Soil Matric Potential (SMP) measurements and Hydraulic Gradient Calculations in the SDI irrigated lysimeter: With the concern for transport of nitrate to the groundwater, it is essential to quantify the movement of NO_3 through and below the crop root zone. Results indicate that the hydraulic gradient (HG) is positive with upward flow in the zones from 24 to 36 inch and the zone from 48 to 60 inches while the zone from 36 to 48 inches has water moving downwards. However, the gradient from 48 to 60 inches is upward thus preventing drainage and nitrate leaching (none measured in the lysimeter during the course of the experiment). High frequency irrigation and root uptake in the 36 to 48-in. depths are causing this HG behavior. These HG patterns would be expected to occur as well in the DI and SDI systems in the orchard where soil nitrate measurements indicated insignificant nitrate level at the 45 in depth for the 3 N levels in the SDI systems.

4. Automated fertigation management:

a. Nitrogen: All N was automatically applied by continuous injection of N-pHURIC for all treatments starting during the last week in May and additionally as AN-20 (20% N) for N-2 (86 lb/ac) and N-3 (187 lb/ac) treatments, starting in the second week in June. This resulted in applied nitrogen levels between 62 to 295 lbs per ac.

b. Phosphorus: Phosphoric acid (H_3PO_4) was continuously injected at a rate of P=15 ppm to maintain adequate P level in the SDI treatment (total P = 58 lb/ac). Previous research has shown that phosphorus becomes deficient at soil depths greater than 8 in. The pH of the irrigation water was automatically maintained at 6.5+/-0.5 with the pHURIC to avoid precipitation of phosphates that typically start occurring at excess of 7.2 pH.

c. Potassium:, Potassium (K_2T) was injected once weekly at a rate of K=25-35 ppm to maintain adequate K level in both SDI and DI treatments (total K = 64 lb/ac). Previous research has shown that potassium may become extremely deficient in sandy loam soil, especially as soil depth increases.

5. Yields, Water Use Efficiency (WUE) and Nitrogen Use Efficiency (NUE): The
total yield was not statistically affected by the increased levels of nitrogen above 100 lbs per acre. There was an increase in the total yield from 2013 to 2015 which probably reflected the increased plant size. The 2013 yield ranged from 29,511 to 31,455 lbs/ac, in 2014 the yield range was 40,065 to 44,154 lbs/ac and in 2015 the range was 46,180 to 45,091bs/ac. In each year when the yield was averaged by irrigation system the SDI was greater than the DI. The WUE and NUE are calculated using the yield and applied water (WUE) or yield and applied nitrogen (NUE). As a result the efficiencies will be higher when similar yields are obtained with lower values of applied water and nitrogen. This is the pattern in these data. The SDI treatments have better WUE than DI since there was less applied. The NUE will have the highest values with the N1 treatment since this is the lowest applied N with no significant differences between in yield across the nitrogen treatments.

The yield was also characterized as lb/tree and there was not a significant difference across treatments and across years. The fruit sizes were similar across treatments. The fruit weight was smaller in 2015 compared to 2013 and 2014.

6. Weed population under DI and SDI: The residual weed biomass in the
pomegranate orchard was measured on August 28, 2013 after herbicide burn-down. Results indicate that the weed biomass in the SDI treatment was significantly lower than that in the DI treatment. The infrared soil surface temperature was significantly higher in the SDI than in the DI treatments due to lack of weeds. Reduced weeds will result in reduced water requirements and improved WUE. It will also reduce labor and fertilizer costs.

7. Soil Nitrate Profiles: The soil nitrate profiles demonstrated that increasing the
applied N resulted in increased levels of nitrate with depth to 48 inches. Generally, the

N concentrations with depth were greater with DI than SDI systems. The crop used significant quantities as demonstrated by the nitrate distribution in the winter.

8. Effect of DI and SDI methods and seasonal N-levels on tree Canopy Size: Tree canopy cover was measured with a multispectral camera in 2012, 2013, and 2014. The percentage of canopy ground cover was more affected by irrigation method than nitrogen treatments. The SDI treatments were generally larger than the DI. This suggests that the SDI treatments will reach a mature size more quickly than the DI treatments. The fractional ground cover was linearly related to the crop coefficient and thus provides a simple method to estimate crop water use for irrigation scheduling purposes.

9. Plant N and C status: Total N analysis was used to characterize the long term N response to the 3 N treatments. There was not a significant difference in the N concentrations in leaf tissue in response to the nitrogen treatments. The total N was in excess of 2.5% at the beginning of the irrigation season and was approximately 1.8% later in the season. This was true across all the years.

H. Project Impacts: The project demonstrated that the nitrogen requirement for mature pomegranate is 100 lbs per acre. Application in excess of this amount is wasted and has the potential for transport of nitrogen to groundwater. The majority of the fertilizer should be applied in the first month after leaf out and during fruit development. The water requirement of a mature pomegranate tree with surface drip irrigation is approximately 37 inches of water. Use of subsurface drip irrigation can easily reduce this amount by 10%. High frequency subsurface drip irrigation (SDI) controlled deep percolation losses below the root zone and there was no deep percolation during the 3 years of the experiment. Matching the crop water use on a daily basis should have similar results as the high frequency irrigation. Yield was higher with the subsurface drip irrigation (SDI) than in the surface drip irrigation (DI). The subsurface drip irrigated trees were generally larger than the surface drip irrigated trees. There was less weed growth with SDI than DI. Analysis of the crop coefficient as a percentage of ground cover determined a good correlation between shaded area and the crop coefficient. This relationship was not affected by the canopy architecture which means that the simple relationship for the crop coefficient based on shaded area is applicable to most plantings.

I. Outreach activities summary: The research staff presented preliminary findings at the UCCE Pomegranate Field Day on 10/7/2013 to approximately 60 growers, UCCE advisors and irrigation industry representatives. A tour of the orchard research was conducted (Figure 27) and specific control facilities were shown and specific questions were answered. In addition, the staff presented several local, national, and international papers and some of them are in the publication process. Field days were held on 10/2/2014 and 10/20/2105 with a total of approximately 30 participants each year. We provided presentations that covered the previous year's research. This was followed by a field tour.

J. Factsheet/Database

1. Project Title: Improving Pomegranate Feritgation and Nitrogen Use Efficiency with Drip Irrigation Systems

2. Grant Agreement Number (CDFA): 12-0387-5A

3. Project Leaders: Dr. James E. Ayars, USDA-ARS, SJVASC, Dr. Claude J. Phene, SDI+

4. Start Year/End Year: 2013 – 2015

5. Location: University of California, Kearney Agricultural Research and Extension Center, Parlier, California

6. County: Fresno

7. Highlights:
　　a. Pomegranate was grown using high frequency surface and subsurface drip irrigation with 3 levels of applied nitrogen to determine water and nitrogen requirements.
　　b. Water requirements were determined to be 37 inches a year with a weighing lysimeter and a crop coefficient was determined using the lysimeter data and CIMIS data. The crop coefficient is available as function of the percentage of ground cover or day of the year.
　　c. Yield was not affected by total applied nitrogen above the base level of 100 lbs/ac.

8. Introduction:
Pomegranate acreage in California increased to approximately 30,000 ac as a result of the demand for juices with healthy bioactive compounds, mineral nutrients, and high antioxidant contents. However, there has been some reduction in acreage in the past few years due to economic drivers. Despite this being an "ancient" crop, there are few studies quantifying the water and nitrogen requirements of a pomegranate orchard and none using either high frequency surface drip or subsurface drip irrigation. Research has shown that well managed surface drip (DI) and subsurface drip irrigation (SDI) 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 (Ayars, et al. 1999). Avoiding N deficiency or excess is critical to maintaining nitrogen use efficiency (NUE) and knowledge of the operation of DI and SDI, especially for deep SDI, is critical for effective management of N-fertigation. This project was initiated to determine the nitrogen fertilizer and water requirements and nitrogen use efficiency of a pomegranate orchard.

9. Methods and management:

This project was located on the University of California Kearney Agricultural Research and Extension Center (KARE) and used a 3.54 ac pomegranate orchard (*Punica granatum, L* var. Wonderful) that included a large weighing lysimeter. Trees were planted with 16 ft row spacing and a within row spacing of 12 ft. The orchard was laid out in a randomized complete block design with 2 main treatments and 3 sub-treatments with 5 replicates. The main treatments were DI and SDI (installed at 20-22-in depth) systems with drip irrigation laterals, located at 3.5 ft on each side of the tree row. The fertility sub treatments were 3 N treatments (50% of adequate N (N1), adequate N (N2), based on biweekly tissue analysis and 150% of adequate N (N3), all applied by variable injection of N-pHURIC (10% N as urea, 18% S), AN-20 (10% NH_4-N and 10% NO_3-N). Potassium thiosulfate (K_2T, 25% K from K_2O and 17% S) and phosphorus (from H_3PO_4, PO_4-P) were supplied by variable injection of P=15-20 ppm and K=50 ppm to maintain adequate uptake levels. The pH of the irrigation water was automatically maintained at 6.5+/-0.5. The lysimeter determined the water use for the fully irrigated (100%) subsurface drip irrigation (SDI) with adequate nitrogen (N2) treatment and automatically managed the hourly irrigation scheduling on the site. Water applied to the DI treatments was increased by 10% to account for evaporation from the soil surface and water used by weeds. There was one tree on the lysimeter and it was irrigated using a SDI system with the same number of emitters per tree as the rest of the orchard. Tree and fruit responses were determined by canopy measurements, bimonthly plant tissue analyses and fruit yield and quality. The fruit were harvest in a single harvest each year and separated into prime and subprime fruit. The number and weight of the fruit were determined for 5 trees in each replication and used for analysis. A split plot mixed model was fit using the SAS PROC MIXED program (SAS, 2013). Irrigation, N and the interaction are the fixed effects and the replications (reps) and irrigation by reps are random effects. Means were taken over the tree's subsamples prior to analysis. Soil sampling was done to a depth of 48 inches in 6-inch increments in each replication and analyzed for nitrates. The samples were averaged by depth.

10. Findings:

The water requirement was determined to be in the range of 33 to 37 inches depending on which irrigation system was used. The larger value was from the surface drip irrigation system. The irrigation system was controlled by the weighing lysimeter and irrigated when 0.04 inches of water was lost. The peak crop water use was 0.3 inches per day. We applied 50%, 100% and 150% of what was considered adequate nitrogen fertilizer and monitored the crop uptake by leaf sampling throughout the season. The total N in the leaf tissue was not statistically different across the nitrogen treatments. The total yield was the sum of prime (fresh market quality) and subprime (juice quality) fruit. There were no statistical differences in the yield as a function of the applied nitrogen. The average yield across the 3 nitrogen levels in 2015 was 45,700 lbs per ac. The average yield increased over the 3 years of the project in part due to the increase size of the tree. This means that the lowest value of applied nitrogen in the range of 100 lb/ac was adequate to meet the crop plant needs and yield. The highest water use efficiency was found with the lowest nitrogen levels. This was true of the nitrogen use

efficiency as well. We determined that the crop coefficient was functionally related to the percentage of ground cover which provides and simple method to estimate crop water use for irrigation scheduling. This relationship was not impacted by the canopy structure and thus is suitable for most pomegranate orchards. Nitrate transport to groundwater is an environmental quality issue and is the result of over irrigation that results in deep percolation losses. Higher frequency irrigation that meets the crop on a daily basis has been shown to minimize or eliminate deep percolation losses. Our research demonstrated the high frequency subsurface drip irrigation controlled the soil matric potential and eliminated deep percolation losses. This suggests that producers should increase the irrigation frequency to daily or near daily to minimize losses. Soil nitrate values demonstrated that subsurface drip irrigation was more effective at controlling nitrate at 60 inches that surface drip.

Figure 27. Photo montage from the UCCE Pomegranate Field Day on 10/7/2013.

K. Copy of the Product/Result

The following publications were prepared and/or published: Sent as attachment with final report.

D. Wang, C. J. Phene, R. C. Phene, J. E. Ayars, R. Tirado-Corbala, and D. Makus. 2013**.** Water and Nitrogen Management of Young and Maturing Pomegranate Trees. International Society of Horticultural Sciences (ISHS) Symposium, Shandong, China.

Ayars, J. E., C. J. Phene and R.C. Phene. 2015. Water and Nitrogen Requirements of Subsurface Drip Irrigated Pomegranate. USCID Meeting, Reno, NV.

Phene, C. J., J. E. Ayars, R. C. Phene and R. S. Schoneman. 2015 Approved for publication in: ASABE/IA, Emerging Technologies for Sustainable Irrigation Symposium, Nov.10-12 2015, Long Beach, Ca.

Ayars, J, E. and C.J. Phene/ 2016. Protecting groundwater with subsurface drip irrigation. Proceedings of USCID Conference, Water Shortages and Drought: From Challenges to Solutions. San Diego, Ca. May 17th to 19th.

L. LITERATURE CITED

Ayars, J.E., C.J. Phene, R.B. Hutmacher, K.R, Davis, R.A. Schoneman, S.S. Vail, and R.M. Mead, 1999. Subsurface drip irrigation of row crops: a review of 15 years of research at the Water Management Research Laboratory. Agricultural Water Management. 42:1-27.

Darcy, H. (1856). Les Fontaines Publiques de la Ville de Dijon. Dumont, Paris.

Phene, C.J., R.L. McCormick, K.R. Davis, J. Pierro, and D.W. Meek. 1989. A Lysimeter feedback irrigation controller system for evapotranspiration measurements and real time irrigation scheduling. Trans of the ASAE 32(2):477-484, March-April 1989.

SAS Institute Inc. 2013. SAS OnlineDoc® 9.4. Cary, NC: SAS Institute Inc.

Trout, T. J., Johnson, L. F. 2007. Estimating crop water use from remotely sensed NDVI, crop models, and reference ET. Proceedings of 2007 USCID Fourth International Conference on Irrigation and Drainage.

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WATER AND NITROGEN REQUIREMENTS OF SUBSURFACE DRIP IRRIGATED POMEGRANATE

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ABSTRACT

Surface drip irrigation is a well-developed practice for both annual and perennial crops. The use of subsurface drip is a well-established practice in many annual row crops, e.g. tomatoes, strawberries, lettuce. However, the use of subsurface drip on perennial crops has been slow to develop. With the on-going drought, interest has increased for use on both annual and perennial crops because of the ability to improve water productivity and reduce applied water. Pomegranate acreage is California is approximately 25,000 acres. However, there is very little information about the water and nutrient requirements of the crop. We developed a replicated trial to determine the water and nutrient requirements of a maturing pomegranate crop being grown with surface and subsurface drip irrigation. The system is controlled by a weighing lysimeter that irrigates both systems when 1 mm of crop water use has been measured. Nitrogen fertilizer is injected with the irrigation water at 50%, 100%, and 150% of what is considered adequate for the N needs of the crop. The marketable yields were 15.7 and 14.8 t/ac for the SDI and DI respectively in 2013 and 21.2 and18.1 t/ac in for the SDI and DI in 2014. The water use efficiency was higher in the SDI plots compared the DI plots in both years. The applied water in 2014 was 31 inches in the SDI treatments and 33 inches in the DI treatments. Applied nitrogen ranged from 55 to 305 lbs/ac over 2013 and 2014.

INTRODUCTION

The California Department of Water Resources (DWR) Bulletin 160-05 states: "In the future, water management challenges will be more complex as population increases, demand patterns shift, and environmental needs are better understood…". The competition for water will increase as the population of California increases to nearly 50 million people by 2050 and the environmental flows will increase to meet the demands in the Sacramento San Joaquin Delta. California agriculture is facing severe, recurring water availability shortages, groundwater quality deterioration, and accumulation of salts in the shallow, perched water table. To compensate for the lack of sufficient surface water, growers on the west side of the San Joaquin Valley are pumping from deep saline aquifers, bringing salts to the surface that are causing drainage issues and irrigated acreage to be drastically reduced. Senate Bill (SBX 7-7) was enacted in

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January 2012 and will require irrigation districts to measure delivery of water to growers by July 2012. A recent University of California Davis report on groundwater quality released on March 13, 2012 and entitled: "Nitrate in Drinking Water Raises Health Concerns for Rural Californian" indicated that "one in ten people living in California's most productive agricultural area is at risk of exposure to harmful levels of nitrates contamination in their drinking water". Laws on groundwater quality will soon be enacted controlling leaching of agricultural NO_3-N to the groundwater.

Research and demonstration have demonstrated that well managed surface drip (DI) and subsurface drip irrigation (SDI) systems can eliminate runoff, deep drainage, minimize surface soil and plant evaporation and reduce transpiration of drought tolerant crops. Reduction of runoff and deep drainage can also significantly reduce soluble fertilizer losses and improve groundwater quality. The success of DI and SDI methods depends on the knowledge and management of fertigation, especially for deep SDI. Reductions in wetted root volume, particularly if combined with deficit irrigation practices, restrict available nutrients and impose nutrient-based limits on growth or yield. This is particularly important with an immobile nutrient such as phosphorus (P). Avoiding nutrient deficiency or excess is critical to maintaining high water and fertilizer use efficiencies (WUE & FUE). This interaction has been demonstrated for field and vegetable crops (Ayars, et al. 1999) but no similar research has been conducted for permanent crops.

Pomegranate acreage in California is now about 28,900 ac and Kevin Day, UC Farm Advisor, noted that "from 2006 to 2009 the area planted with pomegranate trees has increased from approximately 11,800 ac to 14,800 ac in 2006 to 28,900 ac in 2009" (Personal communication K. Day, 2009). The rising demand for juices, e.g. pomegranate, blueberry, with healthy bioactive compounds, mineral nutrients and high antioxidant contents are partially contributing to this growth in acreage. Pomegranate is thought to be both a drought and salt tolerant crop that can be grown on saline soils and is thus ideally suited for the Westside of the San Joaquin Valley as a replacement for lower value crops.

There have been no studies that evaluated the water and fertilization requirements of developing pomegranate orchard using either surface drip or subsurface drip irrigation. We will describe the results of the last 2 years of a project that is characterizing the water and nitrogen requirement of a recently planted (2010) pomegranate orchard.

MATERIALS AND METHODS

This project is located on the University of California Kearney Agricultural Research and Extension Center (KARE) and uses a 3.54-ac pomegranate orchard (*Punica granatum, L* var. Wonderful) that includes a large weighing lysimeter (Fig. 1) (Phene et al. 1989) Trees were planted with rows spaced 16 ft. apart and trees in the rows spaced 12 ft. along the row. The orchard is laid out in a complete randomized block with sub-treatments and 5 replicates.

A plot consists of three rows of trees with a minimum of 7 trees in length. The center row is used as the experimental row with the center 5 trees being used for sampling. The lysimeter is used to determine the water use for the fully irrigated (100%) subsurface drip irrigation with adequate nitrogen treatment and to automatically manage the hourly irrigation scheduling on the site. Water applied to the surface drip treatments is increased by 10% over the SDI treatment to account for evaporation from the soil surface and water used by weeds. The lysimeter tree is irrigated using a SDI system with the same number of emitters per tree as the rest of the orchard. All flow is measured by flow meters for each of the treatments.

The main irrigation treatments are surface drip (DI) and subsurface drip (SDI) (installed at 20-22-in depth) systems with dual drip irrigation laterals, each 3.5 ft. from the tree row. The drip system uses 2 L/hr in line emitters spaced at 3.3 ft. The fertility treatments are 3 N treatments 50% of adequate (N1), 100% of adequate (N2) and 150% of adequate (N3), based on biweekly leaf tissue analysis. The fertilizers are all applied by variable injection of N-pHURIC (10% N as urea, 18% S), AN-20 (10% NH_4-N and 10% NO_3-N). Potassium thiosulfate (K_2T, 25% K from K_2O and 17% S) and phosphorus (from H_3PO_4, PO_4-P) are supplied by variable injection of P=15-20 ppm and K=50 ppm to maintain adequate uptake levels. The pH of the irrigation water is automatically maintained at 6.5+/-0.5. Flow and concentration of fertilizers are measured.

With the concern for transport of nitrate to the groundwater it is essential to characterize the movement of NO_3 through and below the crop root zone. We did this by calculating the soil matric potential gradient through the root zone. We used heat dissipation soil water matric potential (SMP) sensors (Campbell Scientific Inc. CSI-229[5]) calibrated at 25° C at pressure ranging from 10 to 150 kPa to measure the soil matric potential. These SMP sensors were installed in two columns of 4 SMP sensors each at depths of 24 in. (0.6 m), 36 in. (0.9 m), 48 (1.2 m) and 60 in.(1.5 m) from the soil surface. These SMP's provide the SMP status in the lysimeter and are used to calculate the hydraulic gradient to infer the leaching potential under high frequency SDI (Phene et al., 1989).

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[5] 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. USDA is an equal opportunity provider and employer.

Fruit yield was determined from the trees in the experimental row. Statistical analysis was done by Dr. Bruce Mackey, ARS Biometrician.

RESULTS

The yearly cumulative grass reference ET (CIMIS ET_o) and the orchard evapotranspiration (ET_c) measured hourly by the weighing lysimeter were used to develop the irrigation requirement and crop coefficient for maturing pomegranate. The crop coefficient (K_c) and the 5th order polynomial regression of the daily K_c were developed for grower's use.
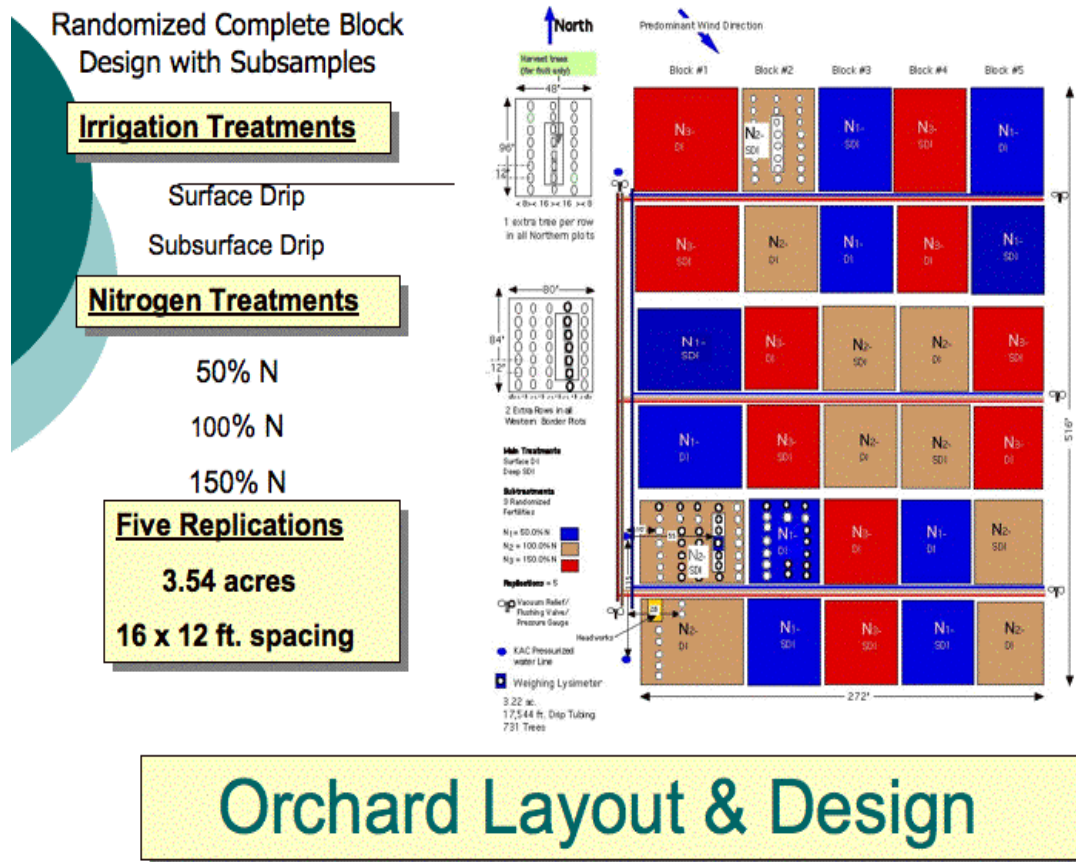

Figure 1. Orchard treatment, design and layout for surface drip irrigated (DI) and subsurface drip irrigated (SDI) pomegranate located on the Kearney Agriculture Research and Extension Center.

The 5th order polynomial regression of the crop coefficient (K_c) is $K_c = 3e^{-10} x^4 - 5e^{-05} x^3 + 2.8x^2 - 75424 x + 8e^{08}$ with an R^2 of 0.92 was determined using the data from 2013.

The peak potential evapotranspiration was in the range of 0.3 inches per day and the crop water use was approximately 0.23 inches per day (Fig. 2)

Orchard irrigations of DI and SDI were measured and recorded automatically with electronic flow meters and were based on lysimeter measurements and were used to calculate the water balance. Table 1 gives the components of the water balance from 2010 until December 31, 2014. Reference evapotranspiration (ET_0) was taken from the California Irrigation Management Information System (CIMIS) weather station located on KARE. The crop water use (ET_c) came from the weighing lysimeter and was adjusted for tree spacing. Precipitation came from the lysimeter rain gauge, drainage was measured in the lysimeter using a tipping bucket rain gauge located at the drain of the soil mass, and there was no runoff. We determined the crop water requirement with the high frequency irrigation up to 6 times per day. The crop water use increased from 2 inches at planting in 2010 to 36 inches in 2014. The increased water use of 9 inches in 2014 compared to 2013 is probably a result of the increased temperature and the increased tree size. The plants are reaching maturity and a size that will be maintained for yield and manageability. The crop water use in 2014 is probably representative of the long term requirement for trees that have been trained as a bush with the height limited to approximately 9 ft.
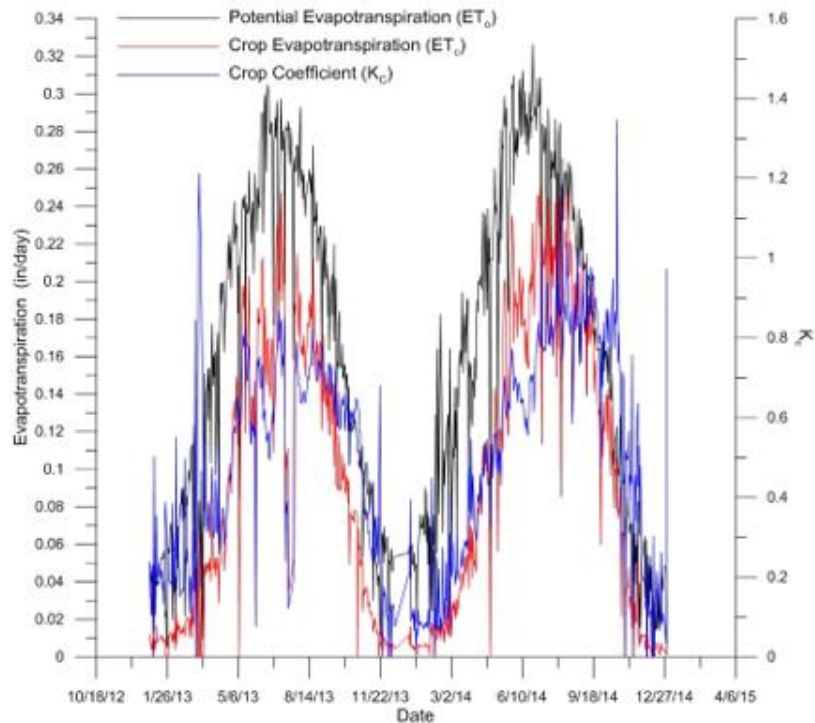

Figure 2. Daily pomegranate potential evapotranspiration (ET_0), crop evapotranspiration (ET_c) and crop coefficient (K_c) for 2013 and 2014.

Table 1. Components of the pomegranate water balance for 2010-2014.

Year	ETo In.	Precipitation In.	DI Irrigation In.	SDI Irrigation In.	ETc In.	Drainage In.
2010	49.7	17.3	1.0	1.0	2.1	n/a
2011	50.9	10.4	8.5	8,5	9.8	0
2012	54.6	8.97	18.6	16.8	19.7	0
2013	55.0	3.21	25.4	23.0	26.9	0
2014	57.8	8.62	33.4	30.7	35.9	0

Figure 3 shows the daily averaged soil matric potential measurements for these eight SMP sensors for 2013 and 2014. The management goal was to maintain the SMP in a range between -30 and -40 kPa. It is apparent that we were able to achieve this objective during the growing season each year. The spikes with the SMP were decreased (less negative) were a result of excess water being applied due to a malfunction of the irrigation system.
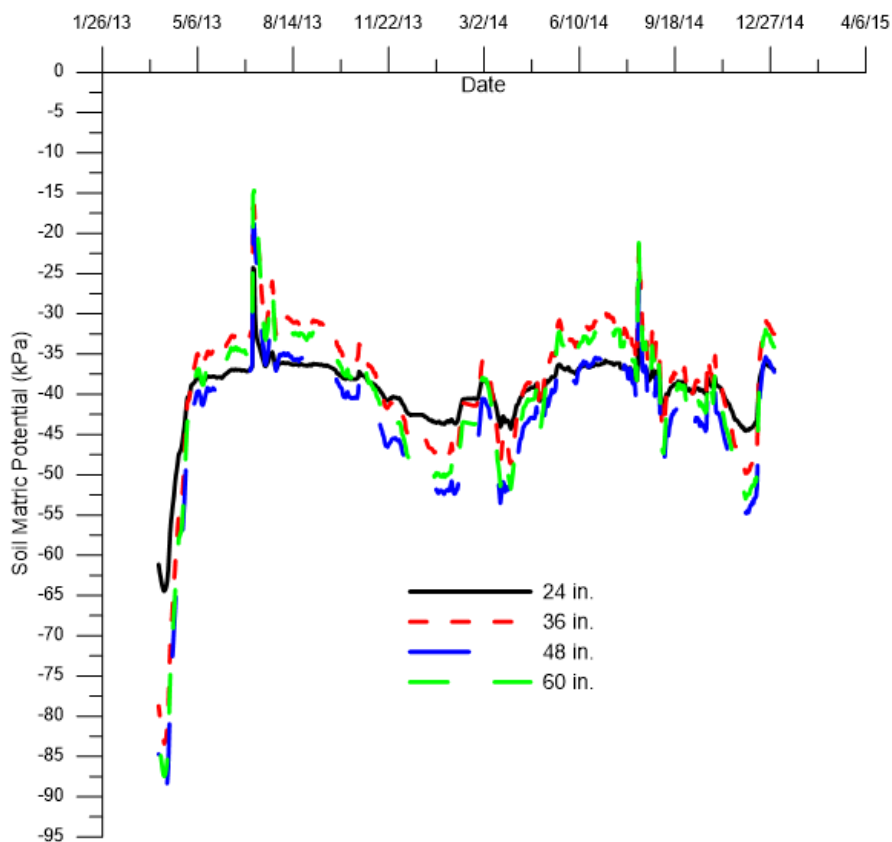

Figure 3. Daily average soil matric potential sensor measurements for 2013 and 2014.

Calculated daily averaged soil matric potential gradients (SMPG) from are shown in Fig. 4. The gradient is calculated using the Darcy's equation assuming a unit gradient. The arrows indicate the direction of flow within the root zone, with up being toward the soil surface and down towards the groundwater. HG-1 is the zone from 24 to 36 inches depth. HG-2 is the zone from 36 to 48 inches in depth and HG-3 is the zone from 48 to 60 inches of depth. The data show that there was a gradient of flow downward in the middle zone but continuously upward in the lowest zone HG-3. During most of the irrigation season the gradient and thus the flow was upward. The net result is that we control the flow within the root zone and no water and thus nitrogen was lost to the groundwater.

The three nitrogen fertility sub-treatments (50, 100, and 150% of adequate N) were based on biweekly leaf tissue analyses and applied by continuous injection of N-pHURIC (50 lb N/ac) for all treatments starting during the last week in May and additionally as AN-20 (20% N) for N-2 and N-3 treatments, starting in the second week in June in each year.
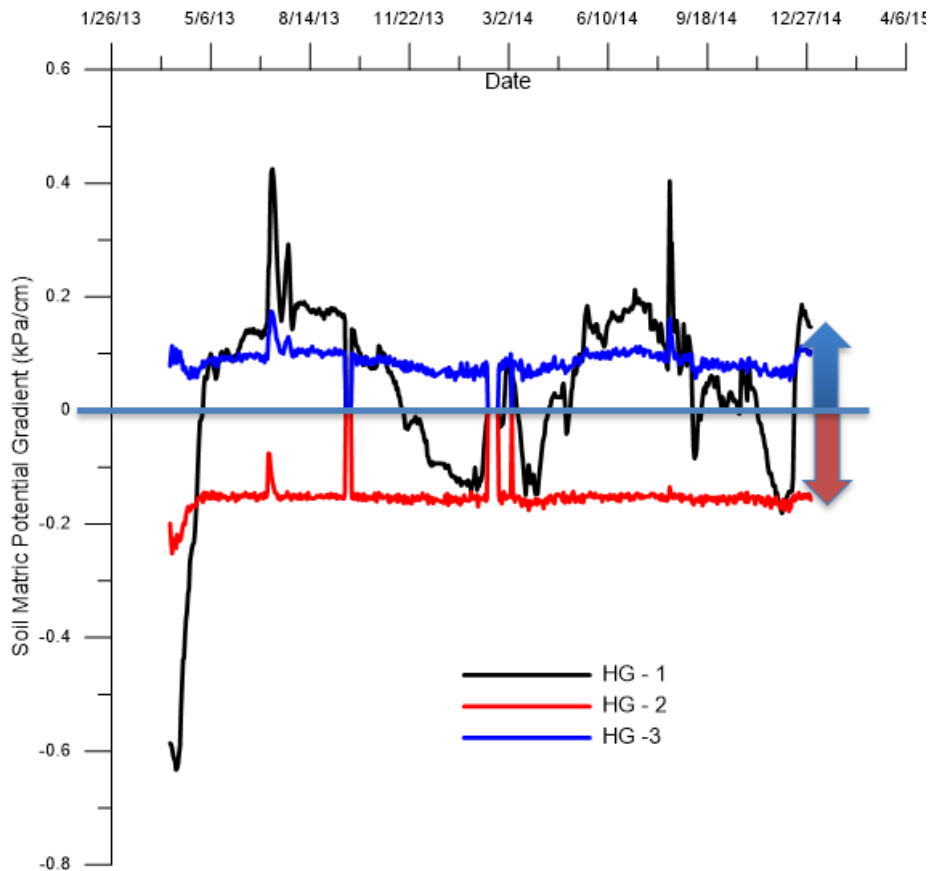

Figure 4. Soil matric potential gradients (SMPG) calculated daily for 2013 to 2014.

Phosphoric acid (H_3PO_4) is continuously injected at a rate of P=15 ppm to maintain adequate P level in the SDI treatment. Previous research has shown that phosphorus becomes deficient at soil depths greater than 8 inches. The pH of the irrigation water was automatically maintained at 6.5+/-0.5 with the N-pHURIC to avoid precipitation of phosphates that typically starts occurring when the pH is greater than 7.2.

Potassium (K_2T) was injected once weekly at a rate of K=25-35 ppm to maintain adequate K level in both SDI and DI treatments. Previous research has shown that potassium may become extremely deficient in sandy loam soil, especially as soil depth increases.

The total applied fertilizers in pounds per acre are given in table 2 for 2013 and 2014.

Year	N1 (lb/ac)	N2 (lb/ac)	N3 (lb/ac)	P (lb/ac)	K (lb/ac)
2013	62	149	249	58	65
2014	55	199	305	82	76

Yields, Water Use Efficiency (WUE) and Nitrogen Use Efficiency (NUE)

The per acre yield was estimated based on the average per tree yield as follows, ((kg/tree)x(2.205 lb/kg) X (227 tree/ac) which is equal to lb./ac. Five trees were harvested in each plot and used to calculate an average for each treatment that was used in the yield determination. The values from the individual nitrogen treatments for SDI and DI were averaged to obtain a single yield value for the drip treatments.

Table 3. Pomegranate yields in pounds per acre (lb/ac) for 2013 and 2014 by nitrogen treatments N1, N2, N3. N1 is 50% of adequate, N2 is 100% of adequate and N3 is 150% of adequate nitrogen.

	Prime (lb/ac)		Sub-Prime (lb/ac)		Green (lb/ac)		Total (lb/ac)	
	2013	2014	2013	2014	2013	2014	2013	2014
N1	6006	28245	22924	11760	581	338	29511	40343
N2	7268	30531	23085	4271	511	568	30864	35190
N3	8199	34749	22735	7967	521	634	31455	43350

Table 4. Average pomegranate yields in pounds per acre for subsurface drip irrigation (SDI) and surface drip irrigation (DI) in 2013 and 2014.

	2013		2014	
	SDI (lb./ac)	DI (lb./ac)	SDI (lb./ac)	DI (lb./ac)
Prime	7118	7188	33442	28909
Subprime	23716	22043	8761	7573
Green	651	421	389	637
Total	31485	29652	42592	37120

Table 5. Pomegranate water use efficiency (WUE) tons of fruit (T) divided by applied water in ac-in. (T/ac-in).

	2013		2014	
WUE	SDI	DI	SDI	DI
Prime	0.16	0.14	0.54	0.43
Subprime	0.52	0.43	0.14	0.11
Green	0.01	0.01	0.01	0.01
Total	0.68	0.58	0.69	0.56

Table 6. Nitrogen use efficiency (NUE) calculated as total marketable fruit (P) in pounds divided by average applied N in pounds per ac. (lb P/lb n/ac-in) by irrigation treatment in 2013 and 2014.

Year	SDI	DI
2013	201	191
2014	226	196

DISCUSSION AND CONCLUSION

Table 1 shows the components of the water balance from 2010 until December 31, 2014. There was a continued increase the water requirement as the plant developed. The water requirement in 2014 ranged from 31 to 33 inches for SDI and DI systems. This is probably representative of the mature plant requirement. With only 8.6 inches of rain in 2014, we did not record any drainage in the lysimeter even though the majority of the rain fell in December. The water use increased in 2014 compared to 2013 as a result of higher temperatures throughout the year, as well as an increase in the tree size. The trees have reached a mature stage that will be maintained as reasonable for production purposes. Except for 2010, when the drainage system was inoperative, no

drainage was recorded by the lysimeter in any of the years of this experiment. This means that the rain and irrigation applied were used by the crop or were stored in the soil profile.

With the concern for transport of nitrate to the groundwater, it is essential to quantify the movement of NO_3 through and below the crop root zone. The SMP data indicate that there was good control on the irrigation system and that the soil matric potential was well controlled throughout the irrigation season. This implies that there would not have been any deep percolation losses. This is confirmed by the lack of measured drainage from the lysimeter. The hydraulic gradient calculations in figure 4 demonstrate that water was moving downward in the region of 36 to 48 inches, however in the gradient was up in the zone from 48 to 60 inches. For most of the season the SMP was maintained in the zone from 30 to 40 kPa which was the goal for the operation of the system.

The was an increase in yield over the years as the plants matured as would be expected the statistical analysis indicated that there was a response to the applied N averaged between the irrigation systems in 2014. The statistics did not indicate a response to the irrigation system type in either year, even though there were higher yields in the SDI compared to the DI system. These differences in yield were reflected in the higher WUE and NUE efficiency for the SDI system compared to the DI system, a result of higher yields and less applied water. The differences in prime weights between the years were a result of surface cracks that developed in 2013 due to a delay in harvest.

LITERATURE CITED

Ayars, J.E., C.J. Phene, R.B. Hutmacher, K.R, Davis, R.A. Schoneman, S.S. Vail, and R.M. Mead, 1999. Subsurface drip irrigation of row crops: a review of 15 years of research at the Water Management Research Laboratory. Agricultural Water Management. 42:1-27.

Phene, C.J., R.L. McCormick, K.R. Davis, J. Pierro, and D.W. Meek. 1989. A Lysimeter feedback irrigation controller system for evapotranspiration measurements and real time irrigation scheduling. Trans of the ASAE 32(2):477-484, March-April 1989.

K. ACKNOWLEDGEMENTS