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Water use efficiency for fruit quality, ecosystem benefits and resilience in fresh market tomato production
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Huge thanks go to our grower collaborators in the farm trials in 2015:
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Jeff Larkey, Route One Farms, Santa Cruz, California
Joe Scoto, Scoto Bros Farming, Merced, California
Bob Giampaoli, Live Oak Farms, Le Grand, California
Merced College, Merced, California

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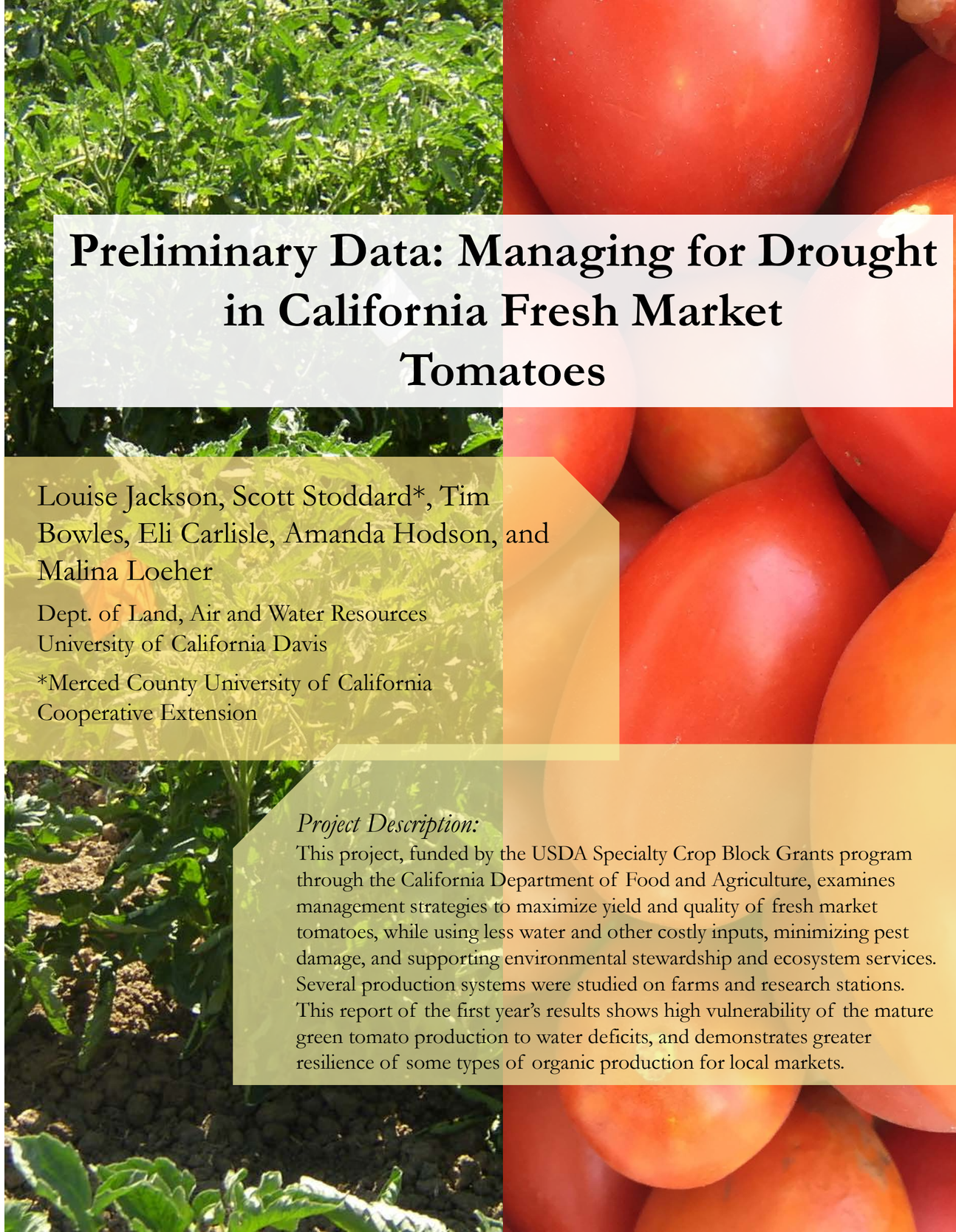

Preliminary Data: Managing for Drought in California Fresh Market Tomatoes

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Project Description:
This project, funded by the USDA Specialty Crop Block Grants program through the California Department of Food and Agriculture, examines management strategies to maximize yield and quality of fresh market tomatoes, while using less water and other costly inputs, minimizing pest damage, and supporting environmental stewardship and ecosystem services. Several production systems were studied on farms and research stations. This report of the first year's results shows high vulnerability of the mature green tomato production to water deficits, and demonstrates greater resilience of some types of organic production for local markets.

Conventional Mature Green Round Tomatoes

2015 Merced Station Trial

This field trial was conducted at Merced Community College in Merced, CA. Transplanting of the 'Bobcat' cultivar was on 6/4/15 and harvest was on 9/10/15. There were four different drip irrigation regimes: a control that followed recommended practices by replacing crop evapotranspiration (ET_c) (19.3 acre-in) (control was 107% not 100% of (ET_c)), and three reductions of the control, 69% (13.4 acre-in), 59% (11.4 acre-in), and 52% (10.2 acre-in) that began 6 weeks after planting. Reference Et_o was 25.7 inches. Conventional fertilizer and pest management methods were used. At harvest, shoot and fruit biomass was taken from a 10-ft transect and fruit was sorted according to size and quality. Pest surveys were conducted two times.

Management Context

Effects of severe terminal water deficit on yield and quality of drip-irrigated mature green tomatoes

Agroecological Focus

Shoot and fruit development in response to terminal water deficit

Research Questions

- Were severe water cutbacks more detrimental to yield or to quality, and why?
- Did water use efficiency (WUE; lbs of fruit per inch of water) increase with deficit irrigation?
- Did deficit irrigation greatly curtail shoot growth?
- How did the deficit affect the number of fruit per plant, and the biomass of individual fruits?

Table 1. Total yield, total marketable yield (TMY), agronomic water use efficiency (AWUE) and culls of fresh market tomatoes grown under four different water regimes: grower's standard (107% of ET_c), and three subsequent reductions. Marketable tomatoes are mature green tomatoes graded XL, L, M. All irrigation reductions decreased yield, TMY, and the AWUE based on TMY. Percentage of culls due to red fruit increased with <60% of Et_c, but no difference in percentage of sunburn or worms occurred. Conversions: 1 inch = 2.54 centimeter. 1 acre = 0.404 hectare. 1 pound = 0.45 kilogram.

Merced Station Mature Green Yield and Water Use Efficiency							Merced Station Culls					
	Water	TMY	Total yield	TMY	Total yield AWUE	TMY AWUE	Percentage of Total Yield					
Water Applied (% ETc)	acre-inch	boxes per acre	lbs per acre	lbs per acre	lbs per in water	lbs per in water	Small	Red	Sun-burn	Worms	Other	Total Culls
107%	20.6	1140	78413	28490	3806	1383	10.9	7.3	11.6	13	22.4	65.2
69%	13.4	668	53840	16700	4018	1246	13.9	13.8	14.3	8.6	25.8	76.4
59%	11.4	295	48149	7387	4223	648	17.9	9.6	13.1	11.7	32.8	85.1
52%	10.2	87	28285	2182	2773	214	16.3	16.8	15.3	12.5	33.3	94.2

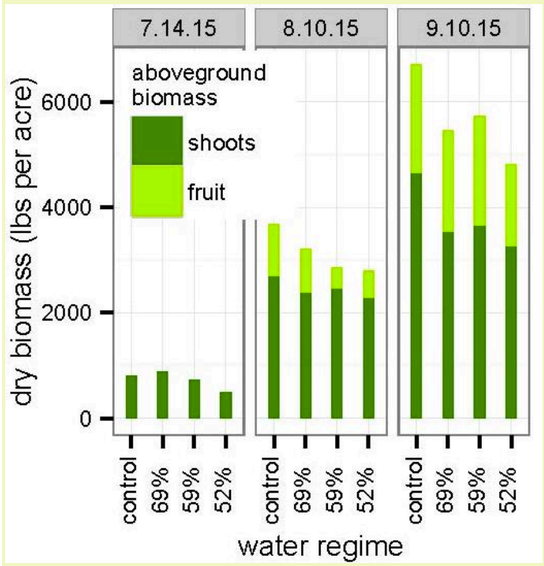


Fig. 1: Shoot and fruit dry biomass at three sampling times over the growing season under four water regimes: control (107% of ET_c), and 69%, 59%, and 52% of ET_c. The lower water deficits had a significant effect on the fruit dry biomass on 8/10/15 (p=0.018).

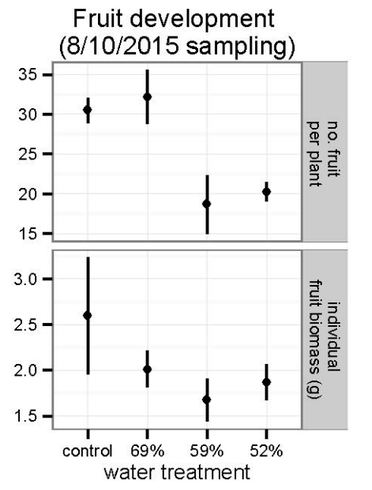


Fig. 2: Tomato fruit development at mid-season (8/10/15) under four water regimes. The lower water deficits had a significant effect on the number of fruit per plant (p=0.01). Shown are means ± se.

Table 2. Canopy temperature depression (CTD)* and leaflet $\delta^{13}C$ from tomatoes under four water regimes: a grower standard (107% of ET_c), and three subsequent reductions (69, 59, and 52% of the standard). CTD is the mean of two sampling dates (8/3 and 8/11/15). Leaflets were collected on 9/10/15. The water deficits had a significant effect on leaflet $\delta^{13}C$ (p=0.012).

Canopy Temperature Depression (CTD) and Leaflet $\delta^{13}C$		
Water Applied	CTD mean	Leaflet $\delta^{13}C$
Control	10.2	-28.2
69%	10.0	-27.8
59%	10.9	-28.1
52%	10.2	-27.3

*Canopy temperature depression (CTD) describes the difference in air temperature due to the tomato canopy presence. CTD decreases with water stress. Leaflet $\delta^{13}C$ is the difference in carbon isotopic ratios; a more positive value is an indicator of stomatal closure under water stress.

Fig. 3: Tomato fruitworm on a mature green tomato. Typical symptoms include chewing and cavities, often filled with castings. Damage was high in all treatments regardless of irrigation treatment. Photo credit Payton Strawser, Ohio State University.

Results

Deficit irrigation with 50% to 70% of crop evapotranspiration (ET_c) for conventional fresh market mature green tomatoes greatly affected yield quality. Much of the crop yield was culled in the lowest water treatments due to early ripening, sunburn, and aesthetic defects. This severely reduced water use efficiency of total marketable yield in the two lowest deficit irrigation treatments. Despite the sharp reductions in total and marketable yield, the tomato plants produced comparable shoot biomass in all treatments. The allocation of biomass to fruit was much more affected by water deficit than shoot growth. By mid-season, the number of fruit per plant had already decreased in the 59% and 52% water treatments, whereas the biomass of individual fruits was not significantly different. This implies that delaying the onset of deficit irrigation is worthwhile.

Conventional Mature Green Round Tomatoes

2015 Le Grand On-Farm Trial

The field trial was conducted on Live Oak Farms in Le Grand, CA. Transplanting of the 'Valley Cat' cultivar was 5/20/15 and harvest was 8/10/15. Treatments consisted of three drip irrigation regimes starting 6 weeks after planting: grower standard (28 acre-in), and 60% and 50% deficits (16.8 and 14.0 acre-in). Et_o was 20.4 inches. The 50% deficit initially was severe then tapered off. Soluble fertilizer and pesticides for thrips and worms were applied frequently. At harvest, shoot and fruit biomass was taken from a 10-ft transect and fruit was sorted according to quality. Pest surveys were conducted three times.

Management Context

Effects of late-season irrigation on yield and quality of drip-irrigated mature green tomatoes

Agroecological Focus

Thrips and leaf damage in response to late-season irrigation deficits

Research Questions

- How much did irrigation deficits in the last 5 weeks affect total and/or marketable yields?
- Did water use efficiency (WUE; lbs fruit per inch of water) increase with less irrigation?
- Did irrigation regime affect the relationship between thrip counts and leaf damage?

Table 3. Total yield, total marketable yield (TMY), agronomic water use efficiency (AWUE) and culls of fresh market tomatoes under three water regimes: grower standard (100%), and 60% and 50% deficits. Marketable tomatoes are mature green tomatoes graded XL, L, M. Deficits significantly decreased total and marketable yield, but not % culled fruit. Conversions: 1 inch = 2.54 centimeter. 1 acre = 0.404 hectare. 1 pound = 0.45 kilograms.

Le Grand Mature Green Yield and Water Use Efficiency							Le Grand Culls				
	Water	TMY	Total yield	TMY	Total yield AWUE	TMY AWUE	Percentage of Total Yield				
Water Applied	acre-in	boxes per acre	lbs per acre	lbs per acre	lbs per in water	lbs per in water	XL	Reds	Sun-burn	Other	Total
100%	28	1800	71855	45007	2566	1607	18.1	4.0	1.0	12.1	35.2
60%	16.8	1302	53024	32560	3156	1938	16.1	9.6	1.6	15.0	42.3
50%	14.0	1218	50126	30459	3580	2175	14.3	9.4	1.2	12.7	37.6

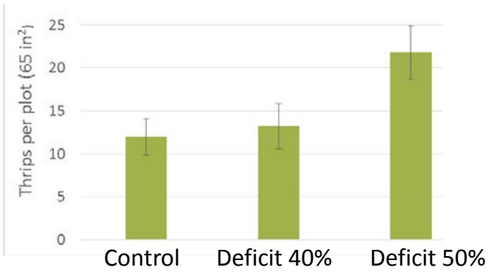


Fig. 4. Average number of thrips caught per 65 in^2 of ground surface above two plants on 7/14/15. There were almost twice as many thrips in the 50% deficit treatment as the control (p=0.02).

Results

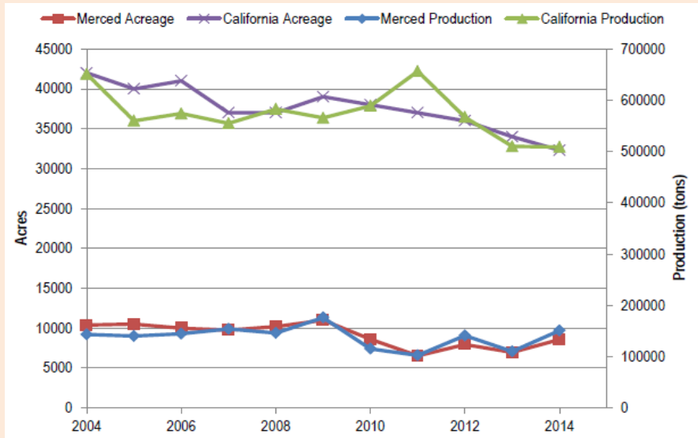
Grower standard irrigation (28 acre-in), produced 25 to 30% higher total and marketable yield than late-season deficit irrigation in the last 5 weeks. Deficit treatments had somewhat better water use efficiency, with no difference in leaflet $\delta^{13}C$. No differences in shoot biomass occurred at harvest suggesting that the deficits directly damaged fruit growth more than canopy growth. Leaf damage and thrip counts increased in the 50% deficit irrigation treatment. Thrips were not identified at the species level, but were likely to have been pest species since leaf damage scores were also higher in the 50% deficit treatment.

2015 Merced On-Farm Trial

This furrow-irrigated field trial was with Scoto Bros Farming in Merced, CA. Transplanting of the 'Sunbrite' cultivar was on 3/11/15 and harvest was on 6/9/15. Et_o was 17.4 inches. Treatments consisted of grower standard, skip-row, and skip-row at 80% of the run length, starting with the third irrigation event. An unexpected flood occurred mid-season. Even so, the deficit treatments decreased yield by 30% and 35%, respectively, and sunburn was higher in the 80% skip-row treatment.

Statistics for California Fresh Market Tomatoes, 2004-14

Fig. 5. California fresh market tomato production 2004-2014. Comparison of Merced County's total marketable yield in tons and total acres harvested to that of California. NASS (USDA National Agricultural Statistics Service).



- Mature green tomatoes account for most of NASS-reported California fresh market tomato production; local and protected culture production is not included.
- A decline in California and Merced County production and acreage has been occurring since 2008, when the recession began.
- According to UC Specialist Roberta Cook:
  - The food service industry, the main market of mature green tomatoes, is now recovering from the recession, which may stimulate demand.
  - But an abundant supply of tomatoes is now available from several locations in North America. Hothouses are competing with open-field mature green production.
  - Given the competitive situation, it is unclear if production will increase in coming years.

Conventional Tomatoes: Main Findings

- This set of experiments emphasized responses of mature green tomatoes to severe water deficit (35 to 60% of typical practices).
- Water deficits decreased total marketable yield mainly due to loss of quality (e.g. sunburn and reds), and to some extent, less fruit.
- Lack of fruit sizing and low quality also explained why water use efficiency (lbs per in of applied water) showed little or no increase under irrigation deficits.
- More thrips occurred at 50% water deficits at one site, with no other differences in disease symptoms, pest nematodes, or weeds.
- The vulnerability of fruit quality to drought adds to other problems facing the California industry, and may further reduce acreage in mature green tomato production in the Central Valley.

Organic Ripe Roma Tomatoes

2014 UC Davis Station Roma Trial

This drip-irrigated field trial was conducted in Davis, CA, at the University of California Davis Student Farm, under certified organic management. After pre-plant application of 40 kg N ha^{-1} as feather meal, seedlings were transplanted 4/21/14 and harvest was on 8/7/14. The treatments were: control replacing crop evapotranspiration (ET_c) (12.8 acre-in) and 43% deficit (7.4 acre-in), starting a month after planting. Et_o was 28.7 inches. Sub-plots consisted of two genotypes of Roma-type tomatoes ('Rio Grande' cultivar), MYC+ (mycorrhizal) and *rmc* (greatly reduced mycorrhizal colonization). Physiology and biomass were measured through the growing season. Tomatoes were harvested once according to criteria similar to those for commercial tomato crops.

Management Context

Effects of season-long water deficit on yield and quality of drip-irrigated fresh-market roma tomatoes

Agroecological Focus

Role of root symbiotic arbuscular mycorrhizal fungi (AM fungi) in plant responses to water deficit

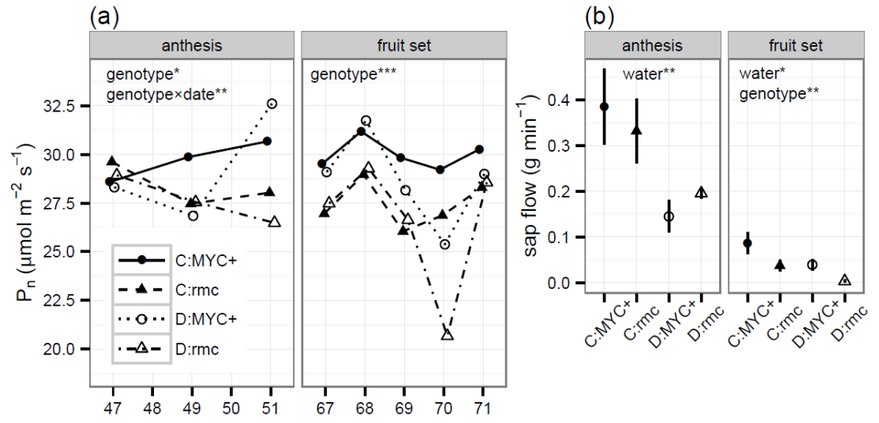
Research Questions

- Does the AM fungal symbiosis affect fruit yield or quality, either under control or deficit irrigation?
- Did water use efficiency (WUE; lbs fruit per inch of water) increase with AM fungi or deficit irrigation?
- At what point in the season did the water deficit markedly decrease photosynthesis and xylem sap flow?
- Did the symbiosis increase crop nitrogen and phosphorus status in this low input organic system?

Table 4. Total yield, total marketable yield (TMY), agronomic water use efficiency (AWUE) and culls of two varieties of fresh market Roma tomatoes, mycorrhizal (MYC+) ~~non colonized~~ (*rmc*), grown under two different water regimes, a control and a deficit. Total marketable yield was significantly higher for the mycorrhizal genotype, and marginally so for full irrigation. WUE was significantly higher for mycorrhizal plants and with deficit irrigation, based on either total yield or TMY. Conversions: 1 inch = 2.54 centimeters. 1 acre = 0.404 hectares. 1 pound = 0.45 kilograms.

UCD Farm Roma Yield and Water Use Efficiency							UCD Farm Culls			
		Water	Total yield	TMY	Total yield AWUE	TMY AWUE	Percentage of Total Yield			
Treatment	Variety	acre-in	lbs per acre	lbs per acre	lbs per in water	lbs per in water	Green	End rot	Rotten	Total Cull
Control	MYC+	12.8	75284	69829	5882	5455	26.9	2.5	0.6	29.9
Control	rmc	12.8	56721	52611	4431	4110	36.9	3.0	1.1	41.1
Deficit	MYC+	7.4	69239	60996	9357	8243	21.7	3.2	0.6	25.6
Deficit	rmc	7.4	54635	48131	7383	6504	28.3	2.6	0.7	31.6

Fig. 6: Leaf photosynthetic rates (P_n) and xylem sap exudation rate (sap flow) of detopped tomato plants at anthesis (flowering onset) and fruit set. Mycorrhizal (MYC+) and reduced mycorrhizal (*rmc*) tomato genotypes were grown with two water regimes (Control (C): ET_c replenished, and Deficit (D): 50% ETc after 29 DAP). Significant differences due to water inputs or genotype are shown by *. (a) Leaf photosynthetic rates; (b) sap exudation rates. Shown are means ± se.



Results

Marketable yield in organic romas showed a 15% reduction under deficit irrigation (40% of calculated ET_c), and was >25% higher in mycorrhizal plants. Water use efficiency was higher with deficit irrigation and with fungal symbiosis. Fewer greens and total culls occurred as well. Photosynthetic rates were higher with the symbiosis at anthesis (flowering) in the well-watered control treatment, and by fruit set at both irrigation levels. During fruit set, the mycorrhizal genotypes had higher sap flow. Fruit concentrations of nitrogen and phosphorus were higher in mycorrhizal plants. Thus managing for the root-fungus symbiosis contributes to yield and quality.

2015 Santa Cruz On-Farm Roma Trial

This dry-farmed trial was conducted in Santa Cruz, CA, on Route One Farms, under certified organic management. After incorporation of a winter cover crop and manure-based compost, transplanting was followed by one sprinkler irrigation, then received only rainfall (total of 2.75 acre-in). Et_o was 26.6 inches. Roma-type tomatoes with reduced mycorrhizal colonization (*rmc*) were transplanted 4/9/15 and harvested 9/15/15. Harvests occurred weekly to fit with demands of local businesses and farmers' markets. Pest surveys were conducted three times.

Results

The organic dry-farmed romas had high yields and very high water use efficiency. This is possibly due to the mild, foggy coastal climate and high soil organic matter (3%; Table 12), which boosts soil water-holding capacity. There were few culls, but local markets require a lower quality threshold than do large-scale fresh market green tomatoes growers.

Santa Cruz Roma Yield and Water Use Efficiency					
Water	Total yield	TMY	Total yield AWUE	TMY AWUE	Culls
acre-in	lbs per acre	lbs per acre	lbs per in water	lbs per in water	% of Total Yield
2.75	68325	63023	24845	22917	7.8

Table 5. Total yield, total marketable yield (TMY), agronomic water use efficiency (AWUE) and culls of organic fresh market dry-farmed Roma tomatoes. Conversions: 1 inch = 2.54 centimeters. 1 acre = 0.404 hectares. 1 pound = 0.45 kilograms.

Organic Ripe Round Tomatoes

2015 Esparto Heirloom Trial

Management Context

Effects of drip tape position and water deficit on heirloom tomatoes in pole production

Agroecological Focus

Cultivars of organic heirlooms

Research Questions

- Were yields and quality affected by a 10% irrigation deficit with two rows of drip tape?
- Was organic pole production water use efficient (WUE; lbs fruit per inch of water)?
- Did stress differ between cultivars?
- Were deficit-irrigated plants more susceptible to high thrip populations?

The drip-irrigated trial was conducted in Esparto, CA, at Durst Organic Growers, under certified organic management. After incorporation of composted poultry manure and a cover crop, two irrigation regimes were set up: a grower-standard control with a dripline at 12 in deep under the plant row, and a Hi/Lo deficit treatment, with driplines at 12 in and 4 in depths, beside the plant. The control delivered 58.8 acre-in of water vs. 52.4 acre-in (11% deficit) for the Hi/Lo deficit. Et_o was 30.7 inches. Transplanting on 4/28/15 was with two varieties of heirloom tomatoes, 'Cherokee Purple' and 'Gold Medal', which were later staked. Weekly harvests were completed on 9/1/15. Pest surveys were conducted three times.

Table 6. . Total yield, total marketable yield (TMY), agronomic water use efficiency (AWUE) and culls of two varieties of heirloom tomatoes, 'Cherokee Purple' (CP) and 'Gold Medal' (GM), under two water regimes. No significant differences occurred between genotypes or irrigation treatments. Conversions: 1 inch = 2.54 centimeters. 1 acre = 0.404 hectares. 1 pound = 0.45 kilograms.

Esparto Heirloom Yield, Water Use Efficiency, and Culls

Treatment	Variety	Water acre-in	Total yield lbs per acre	TMY lbs per acre	Total yield AWUE lbs per in water	TMY AWUE lbs per in water	Culls % Total Yield
Control	CP	58.8	68202	54275	1160	923	20.4
Control	GM	58.8	72024	56192	1225	955	22.0
Hi/Lo Deficit	CP	52.4	52100	42933	994	819	17.6
Hi/Lo Deficit	GM	52.4	47222	35355	901	675	25.1

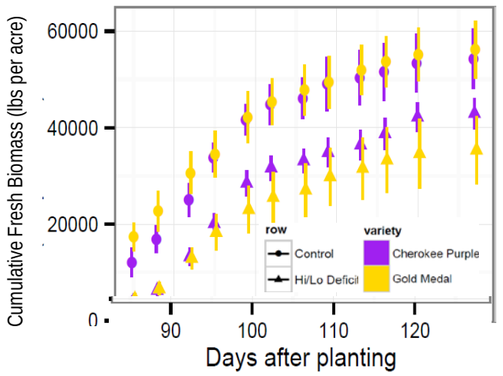


Fig. 7. Marketable fruit (including fruit with blossom end rot) harvested of two varieties of heirloom tomatoes, 'Cherokee Purple' (CP) and 'Gold Medal' (GM), grown with two different water regimes, a control and a Hi/Lo deficit. No significant yield differences occurred. Shown are means ± se.

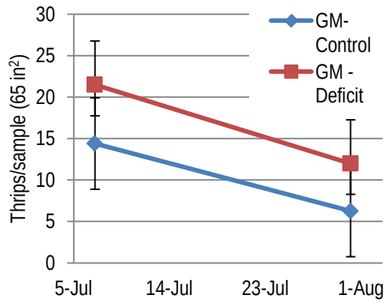


Fig. 8. Average number of thrips caught per 65 in^2 of ground surface above two 'Gold Medal' plants on two dates. 'Cherokee Purple' shared the same trend. Shown are means ± se.

Results

Hi/Lo irrigation with a 10% deficit had no significant effect on yield, water use efficiency, or culls, compared to the grower standard. Yet the trend was for a decrease in yield and water use efficiency, which was low for these pole-produced cultivars with high fruit water content. No differences in leaflet relative water content or $\delta^{13}C$ occurred at harvest. While not statistically significant, 'Cherokee Purple' generally fared better under deficit irrigation. Thrip counts tended to be higher in deficit irrigation treatments for both varieties.

2015 Santa Cruz "Early Girl" Trial

This dry-farmed trial was conducted on Route One Farms in Santa Cruz, CA in a similar way to the Roma-type trial above. Seedlings of the 'Early Girl' cultivar were transplanted 3/26/15 and weekly harvests were completed on 9/15/15. Et_o was 28.8 inches. Treatments consisted of two plant spacings, either 1 ft or 2 ft between individual plants. Pest surveys were conducted three times.

Management Context

Effects of spacing on dry-farmed tomatoes

Agroecological Focus

Water stress and timing of fruit production

Research Questions

- Did closer spacing reduce yield and quality?
- How water use efficient was the 'Early Girl' variety when dry-farmed?
- Did closer spacing affect physiological responses or timing of fruit production?

Fig. 9: Marketable fruit, non-marketable red, and total fruit biomass of dry-farmed 'Early Girl' tomatoes. No significant differences occurred due to spacing. Shown are means ± se.

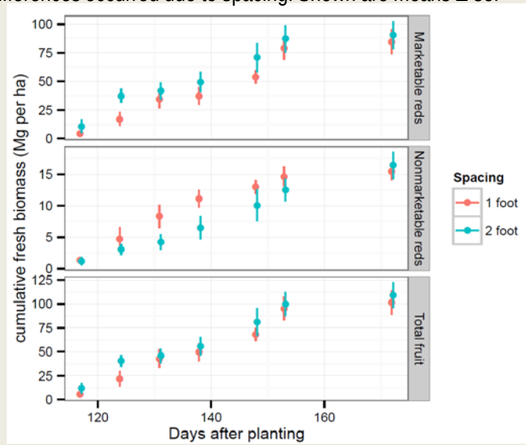
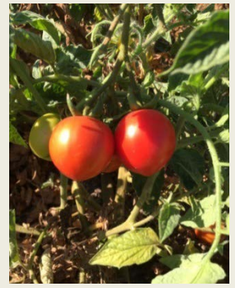


Table 7. Total yield, total marketable yield (TMY), agronomic water use efficiency (AWUE) and culls of dry-farmed 'Early Girl' tomatoes under two spacings, 1ft or 2 ft between plants. No significant differences occurred for any parameter. Conversions: 1 inch = 2.54 centimeters. 1 acre = 0.404 hectares. 1 pound = 0.45 kilograms.

Santa Cruz "Early Girl" Yield, Water Use Efficiency, and Culls

Treatment	Water acre-in	Total yield lbs per acre	TMY lbs per acre	Total yield AWUE lbs per in water	TMY AWUE lbs per in water	Culls % of Total Yield
1' Spacing	2.75	90434	75487	32885	27449	16.5
2' Spacing	2.75	97398	80695	35417	29343	17.1



Results

Dry-farmed 'Early Girl' tomatoes were remarkably high-yielding and water-efficient. Blemishes were the main reason for culling fruit. Spacing did not affect fruit production, culls, or canopy temperature (CTD). At harvest, leaflet relative water content (82.6%) and $\delta^{13}C$ (-27.3) indicated only moderate water stress.

Organic Tomatoes: Main Findings

- Each organic experiment tested a different type of response to low moisture.
- Organic bush production (romas) withstood deficits fairly well, with 15% loss in marketable yield with a 40% decrease in drip-irrigation, and high yields under dry-farming.
- For organic heirloom pole production, high and low drip tapes may improve deficit drip irrigation, with little effect of a 10% deficit compared to standard drip irrigation.
- Choosing a well-adapted cultivar for organic deficit production appears crucial. "Early Girl", for example, is typically used in dry-farmed production in Santa Cruz.
- Higher soil organic matter in may help withstand water deficits (See Table 12).

Pest Problems under Water Deficit for Fresh Market Tomatoes

This section shows general differences in pests and pest damage for the 2015 field trials, which were surveyed for pests with the same methods on three dates (only two dates for Merced). Two plants from each plot were scored for damage due to insect and disease symptoms. Insects that fell into collection containers (65 in^2 of ground surface) after beating stems were counted and identified. Diseased plants were sampled for pathogen identification. Nematodes were extracted from soil at 0 to 6 in depth and identified to the genus level. Weeds in a 300 in^2 plot were counted, identified, dried, and weighed. For each locations, data for all treatments and trials were combined to emphasize differences among sites and production systems. Effects of the deficit treatments are described for the individual trials above.

Fig. 10. Total insect community composition at four sites from canopies above 65 in^2 of ground surface in each plot. The number at the top of each bar shows totals. Only the identities of frequently observed insects are noted on sidebar.

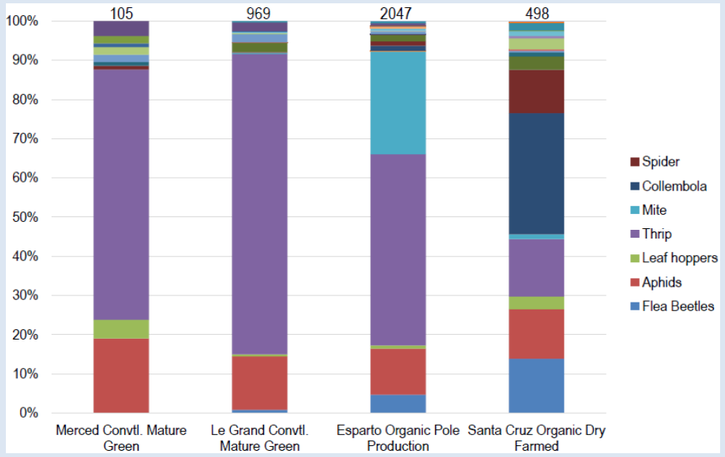


Fig. 11. Average score of each type of insect damage on leaves at four sites. Damage intensity was scored as 0=no damage, 1=some, 2=moderate, and 3 =severe.

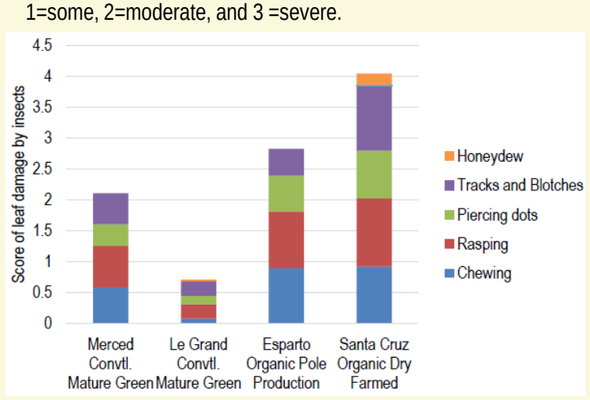


Fig. 12. Average score of each type of fruit damage at four sites. Damage intensity was scored as 0=no damage, 1=some, 2=moderate, and 3 =severe.

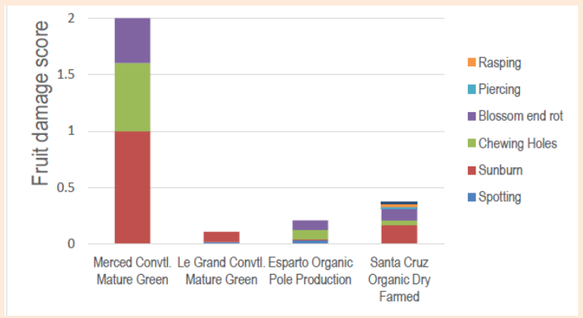


Table 8. Average insect pest abundance, total species, and a diversity indexes from above 65 in^2 of ground surface in each plot, as in Fig. 10. *Simpson's Diversity* accounts for the number of species present, and the relative abundance of each species.

Field Site	Aphids per plot	Thrips per plot	Insect Taxa per plot	Simpson's Diversity Index
Merced	0.6 + 0.2	2.4 + 0.4	1.6 + 0.2	0.28 + 0.06
Le Grand	3.2 +0.8	15.3 + 2.1	2.4 + 1.6	0.27 + 0.03
Esparto	2.8 + 0.4	11.7 + 1.3	3.6 + 1.8	0.44 + 0.02
Santa Cruz	1.3 + 0.2	1.5 + 0.3	4.4 + 0.2	0.65 + 0.02

Insects and Diseases

- Most sampled insects were pests, except at the organic dry-farmed site, where nearly half were beneficials (Fig. 10).
- No general differences organic vs. conventional were seen for aphids and thrip counts (Table 8); these were problems at all sites.
- Insect diversity was considerably higher at the organic sites (Table 8).
- Both organic sites had high leaf damage (for both insect damage and disease-induced stress symptoms) but fruit damage was not as severe (Figs. 11, 12, & 14).

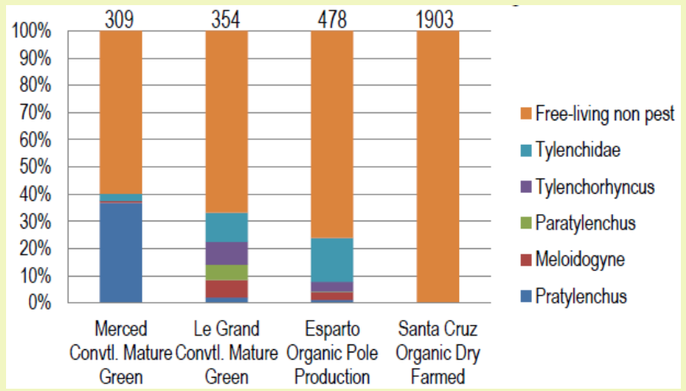
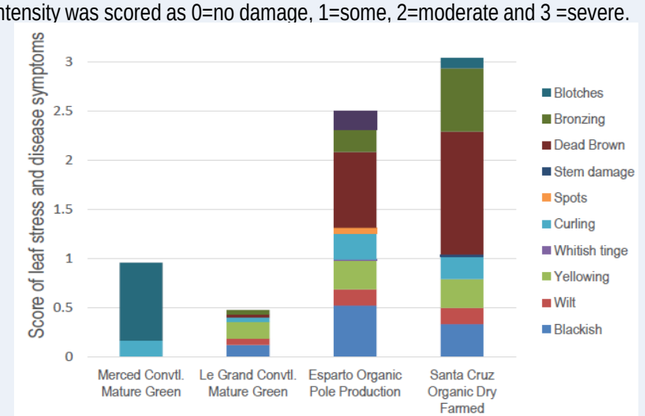


Fig. 13. Nematode community composition at four sites. Above each bar is the total for 200 cm^3 soil. Nematodes were sampled at 0 to 6 in depth at mid-season. Free living non-pest nematodes include beneficial bacterial and fungal feeding species as well as predators. While non-pest nematodes were counted, only pests were identified to genus. Nematodes in the family *Tylenchidae* are primarily root tip feeders and not considered pests in tomato production. *Tylenchorhyncus* and *Paratylenchus* and *Pratylenchus* feed on roots and can cause some damage to plants but are not major pests in tomato. *Meloidogyne* (root knot nematodes) are a major tomato root pest.

Table 9. Average nematodes extracted from 200 cm^3 soil at four sites from 0 to 6 in depth and the proportion of the community represented by pests vs. free living beneficial non-pest nematodes. Shown are means ± se.

Field Site	Pests (%)	Beneficial (%)	Total nematodes (cm^3)
Merced	8.9 + 1.2	85.0 + 1.7	1.5 + 0.1
Le Grand	44.0 + 4.0	52.5 + 4.0	1.7 + 0.2
Esparto	21.2 + 1.5	72.9 + 1.9	2.6 + 0.3
Santa Cruz	2.4 + 0.9	92.1 + 1.9	9.5 + 1.2

Fig. 14. Average for each type of leaf symptoms attributed to disease and related stress at four sites. Diseases were different at each site. Damage intensity was scored as 0=no damage, 1=some, 2=moderate and 3 =severe.



Soil Nematodes

- The only serious pest, root knot nematode, was only at two sites at low levels (Fig. 13), and was not affected by water deficit.
- No consistent organic vs. conventional differences were seen for pest vs. non-pest beneficial nematodes (Table 9).
- The dry farmed site had the highest numbers of total nematodes, most of which were beneficial non-pests (Fig. 13).

Weeds

- All production systems had only minor weed problems (Table 10) and weeds were not affected by water deficit.
- Weed biomass was higher at organic sites (Table 10).
- *Convolvulus arvensis*, field bindweed, is a perennial vine that wraps itself around plants and harvesting equipment. It reportedly increases in sub-surface drip-irrigated fields due to the lack of aggressive tillage.

Table 10. Average weeds counted, , identified. dried, and weighed per plot (300 in^2) at four sites

Field Site	Merced Convtl. Mature Green	Le Grand Convtl. Mature Green	Esparto Organic Pole Production	Santa Cruz Organic Dry Farmed
No. of Weed Species	0.62 + 0.1	0.26 + 0.1	0.73 + 0.1	0.52 + 0.1
Weed biomass (g m^{-2})	10.8 + 5.9	8.05 + 3.7	25.86 + 6.9	15.1 + 5.9
Main Weed spp.	*Sorghum halepense* *Echinochloa crus-galli* *Portulaca oleracea* *Echinocloa colona*	*Portulaca oleracea* *Convolvulus arvensis* *Echinochloa colona* *Echinochloa crus-galli*	*Convolvulus arvensis* *Amaranthus albus* *Amaranthus retroflexus* *Echinochloa colona*	*Portulaca oleracea* *Amaranthus spp.* *Malva spp.*

Comparison of Tomato Systems

Yield, Quality, and Water Use Efficiency

Total yield at all sites was generally similar at ≈30-40 tons acre^{-1}. But culls were 40% of conventional vs. ≤20% of organic yields. Water use efficiency for the commercial farm sites was, in order, organic pole<conventional mature green<<<organic dry-farmed.

Management Practices and Intensification

Standard water inputs differed 20-fold among systems. High irrigation in conventional and organic pole production was accompanied by intensive inputs, but lower-input organic systems used less water.

Table 11. Comparison of management practices for field sites. C=Conventional and O=Organic. MG=Mature Green, Heirloom=H, Roma=R, and Early Girl=EG. Tillage was scored according to intensity. Irrigation refers to standard/control amount. PPI=Pre-Plant. CAN17 = Calcium Ammonium Nitrate (17-0-0), KTS = Potassium Thiosulfate (0-0-25-17S). Manure refers to any composted manure.

Management Practices of Field Trial Sites

Location	Org/ Conv	Trial	Tillage	Cover Crop?	Irrig. Acre-in	ET_o Acre-in	Fertilizer	Manure ?	Pest Management	Harvest
Merced College	C	MG	high	no	20.6	25.7	PPI, UAN30	no	Imidacloprid, 3-Herbicides, Sulfur	once
Le Grand	C	MG	high	no	28	20.4	PPI, KTS, CAN17	no	Admire, Platinum, Treflan, Dual PPI	once
Esparto	O	H	med	yes	58.8	30.7	Guano, Solubles	yes	Entrust, Lacewing Eggs, Sulfur	5x/wk
UC Davis	O	R	low	no	12.8	28.7	Feather meal	no	none	once
Santa Cruz	O	EG, R	low	yes	2.75	27, 28	Compost	yes	none	3x/wk

Site Differences in Soil Characteristics

Soil carbon, which increases water-holding capacity, was highest on the two working organic farms, as was labile carbon which boosts soil microbial activity. Nitrate was high on all soils, except at UC Davis.

Table 12. Comparison of soils at the five locations. Labile soil C is permanganate oxidizable C (POXC). All measurements were obtained from samples of the top 6 in of soil. Inorganic N is reported from mid-season. Convert total C to soil organic matter by multiplying by 1.72. ND=No data. C=Conventional and O=Organic. MG=Mature Green, Heirloom=H, Roma=R, and Early Girl=EG.

Soil Characteristics of Field Trial Sites

Location	Org/ Conv	Trial	Soil Type	Total C (%)	Total N (%)	Nitrate ug N/g	Ammonium ug N/g	Labile C (mg/kg)	Olsen P (mg/kg)	pH
Merced College	C	MG	silt loam	0.78	0.09	32.7	1.4	387.6	7.3	6.7
Le Grand	C	MG	sandy loam	0.86	ND	79.8	1.3	ND	27.9	6.9
Esparto	O	H	silt loam	1.07	0.13	36.3	1.5	478.5	3.7	6.9
UC Davis	O	R	loam	0.91	0.1	8.3	0.4	ND	12.1	ND
Santa Cruz	O	EG, R	sandy loam	1.84	0.19	20.7	1.0	729.7	70.0	7.3

Pests and Pest Management

Thrips and aphids were the most prevalent insect problems across sites, and thrip counts worsened with water deficits, based on results from two sites. Across sites, leaf damage scores were relatively similar for insects and diseases. Weeds and soil pest nematodes did not increase with water deficits. The dry-farmed site, with few inputs and few culls, had the highest insect populations and diversity, and more insect and soil nematode beneficials.

Outcomes, Trade-offs, & Next Steps

Vulnerability of Fresh Market Tomato Systems to Water Deficits

Preliminary data suggest that:

- Conventional mature green tomato systems appear highly vulnerable to water cutbacks of 30 to 50%, largely due to detrimental effects on fruit quality.
- Organic heirloom production showed a trend for declining yields at even mild deficits (10% cutbacks).
- Organic drip-irrigated romas were relatively resistant to water deficits (15% yield loss with 40% water cutbacks), especially when roots were colonized by arbuscular mycorrhizae.
- Organic dry-farmed romas and round 'Early Girl' tomatoes had high yields and very high water use efficiency, facilitated by the mild coastal climate.

Ecosystem Services in Response to Severe Future Drought

Ecosystem services are the benefits derived from an agroecosystem. Preliminary data suggest that:

- Provisioning services (*e.g.* crop production per acre) appear highest in organic systems especially for dry-farmed tomatoes, but also with drip-irrigated romas.
- Regulating and supporting services (*e.g.* environmental quality) may be higher in organic systems, since soil C storage is higher and pesticide use is lower, but nitrate leaching and nitrous oxide (a greenhouse gas) emissions may be more similar across systems (except for the dry-farmed system) due to high soil nitrate and irrigation.
- Cultural services (*e.g.* social benefits) of conventional production offer more people access to fresh market tomatoes, while organic production supports local food systems.






Next Steps

- In the 2016 field season, seven more trials will be conducted on farms and at UC Davis and Merced College field stations.
- A greater emphasis will be placed on evaluating soil and plant health under water deficits.
- Feedback from participants will help to interpret results.
- Outreach opportunities will be sought, not only for tomato growers but for audiences considering adaptation to long-term drought and climate change.