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**Project Title: Effects of irrigation and management practices on soil health and crop properties of processing tomatoes**

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**Introduction:** Severe drought is expected to be the new norm in the Mediterranean regions of the world (Mann and Gleick 2015). These regions, which are some of the most agriculturally productive in the world and often require supplemental irrigation, will need to develop new farming methods that make farms more resilient in an increasingly arid and unpredictable climate (Lauer et al. 2012).

Efficient irrigation systems are a key component of sustainable and climate-smart agroecosystems.

Adoption of subsurface drip irrigation (SSDI) on California’s processing tomato acreage has exploded in recent years, from being used on less than 2% of acres in 2001 to 78% by 2012 (Geisseler and Horwath 2016). SSDI has many benefits: it can increase crop yields and quality, reduce the amount of applied water, and lower the costs associated with weed control, fertilization, and tillage. In conventionally-managed systems, highly soluble mineral fertilizers are also easily distributed via fertigation through drip lines and can be delivered directly to the crop root zone (Ayars et al. 2015). However, a large portion of the tomato soil bed, including the surface layer, remains dry, which could have implications for residue decomposition, soil organic matter formation, aggregation, and other parameters associated with soil health.

Figure 1. Statewide processing tomato yields from 1991-2016. (Data from USDA-NASS.)

Increasing adoption of drip irrigation during the 2000s was accompanied by a dramatic increase in processing tomato yields statewide (Figure 1). However, this yield bump has leveled off in recent years, and anecdotes from some growers indicate that yields have declined on some farms over time. This yield plateau/decline may be related to indirect effects of long-term SSDI use, such as reduced soil health in areas not receiving water or increased disease/weed pressure from continuous tomatoes. Despite its widespread use, there is still more to learn about unanticipated impacts of SSDI in processing tomatoes and also how to best optimize management on both conventional and organic farms. We hope to address this gap by collecting data on SSDI and management practices in conventional and organic processing tomatoes from farms throughout the state, which will be used to evaluate soil health (Objective 1). Information on soil biological communities and their activities is rare and difficult for farmers to access because of the costs of lab analyses and their lack of availability in typical soil analysis laboratories. This study will combine common soil tests used on-farm with new soil biological indicators, and this information will be used to help tomato growers understand: 1) soil biological activity on their farms, 2) how their management practices interact with soil microbial community functions, and 3) how soil microbial communities may be impacting tomato crop management and growth. By aggregating data across farms we will be able to better understand the trends of tomato yields and what practices may help mitigate potential declines and support farm resilience.

Results from the farm survey will inform an economic analysis that will allow us to evaluate tradeoffs at the farm-scale (Objective 2). Many farmers lack a means to explore through an economic lens how irrigation choices, such as SSDI systems, interact with other aspects of farm management—including the best type of fertility management and whether SSDI impacts critical components of soil health (soil stability, water-holding capacity, water use efficiency, infiltration, nitrogen-use efficiency)—to guide managerial decision-making on the farm. Through our economic Land Use System model we will assess the economic and ecological pros and cons of using different fertility management and irrigation methods. The model will help answer questions such as: *Are reduced costs associated with water savings from SSDI worth the yield loss seen in some organic systems?*, and *Is incorporation of cover crops into conventional tomato systems an economic solution to improve soil health?*

**The main *Goal* and the *Objectives* under that goal:** We conducted a survey on 34 fields (11 farms) throughout the Sacramento and San Joaquin Valleys. The goal of this survey was to identify and characterize soil chemical, physical, and biological parameters on northern and central CA tomato farms, and assess how these parameters impact tomato crop management, health, and yields. We also evaluated different irrigation and fertility management strategies in processing tomato systems using a Land Use System (LUS) economic model to quantify and evaluate tradeoffs associated with those strategies. Our objectives were to:

* Identify relationships between soil health properties, irrigation history, agricultural management practices and inputs, and tomato yields/quality.
* Identify relationships between particular management practices (e.g., SSDI management, compost inputs, cover cropping, crop rotation, etc.) and how these impact soil health indicators and soil fertility, ultimately impacting productivity.
* Evaluate impacts of irrigation management and potential strategies to improve soil health (e.g. cover crops, compost) on farm economics by quantifying tradeoffs related to water use, labor inputs, and crop performance.

**Methodology:**

We interviewed 11 tomato farmers/farm operators, and collected soil samples on 34 tomato fields. Three of the farms (8 fields) were located in the San Joaquin Valley, and eight farms (28 fields) were in the Sacramento Valley. Interviews were recorded and are in process of being transcribed to examine links between qualitative data like grower experiences with soil tilth and management, disease management, and soil health management practices, as they relate to tomato production. Soils were collected from the center (4 inches from the drip line) and the edge (12 inches) of tomato beds. Comprehensive analysis of soils was undertaken; soils were analyzed for texture (percent sand, silt, clay), nutrient content (nitrate, P, K, Na, Ca, Mg, cation exchange capacity), chemical attributes (pH, water-soluble carbon and nitrogen), biological indicators (soil organic matter content, microbial biomass nitrogen and carbon, total microbial biomass content, biomass of mycorrhizal fungi, gram negative and gram positive bacteria, eukaryotes, and actinomycetes), and physical parameters (percent of large and small macroaggregates, microaggregates). Aggregation is a measurement of how soil particles group/bind together. The more stable aggregates are, the better they can resist breaking apart from erosion and management practices. In addition, stable aggregates help build soil structure, an important factor in water and nutrient movement. Some soil properties and management practices that can promote aggregation include crop rotation, high clay content, high organic matter, high calcium levels, and presence of soil fungi. Soil properties that can limit aggregation include high sodium levels and high sand content.

About forty percent of the preliminary reports have been sent to grower participants in the survey thus far, and the rest will be sent this month. Actual 2018 yields were collected from two growers; the rest of the yields shown are grower estimates of what each surveyed field would yield in 2018. All data have been anonymized to preserve farmer and field identities when sharing pooled data among all farms. Relationships differed among the Sacramento and San Joaquin Valleys, and data are presented separately for each region.

**Results:**

Soil organic matter ranged from 2.7 to 2.8% in the Sacramento Valley and 2.1 to 2.2% in the San Joaquin Valley. In general, soil organic matter was about 20% higher in Sacramento than San Joaquin Valley soils. In the San Joaquin Valley, a significant positive relationship was observed between soil organic matter content and tomato fruit yields; for every one percent increase in soil organic matter, tomato yields increased by 18 ton/acre (Figure 2). In contrast, in Sacramento Valley soils, there was a weak negative relationship between soil organic matter and tomato yield estimates where, as soil organic matter increased, tomato yields tended to decrease by about 7 tons/acre per unit increase in soil organic matter (Figure 2).

Mean total soil microbial biomass (bacteria + fungi PLFAs) ranged from 35 to 36 nmoles/g dry soil in the center of the bed in soils from both Valleys. Total microbial biomass was lower on the edge of beds than in the center of beds in Sacramento Valley soils, but not in San Joaquin Valley soils (Figure 3. Within each Valley, microbial biomass showed a slight positive relationship with SOM (Figure 4). Microbial community composition was characterized by fatty acid profiles (PLFA analysis) in each of the soil samples. These data are still being analyzed and, once completed, will be compared to other measured soil parameters to develop relationships between management practices and microbial community composition and soil health indices.

We determined soil aggregate stability using the wet-sieve method. Water-stable aggregates were separated into four size fractions: >2000 µm (large macroaggregates), 250 to 2000 µm (small macroaggregates), 53 to 250 µm (microaggregates), and < 53 µm (silt and clay). For each soil, a weighted percentage was calculated for each fraction, i.e. the percent of the total soil that makes up each fraction. Large macroaggregates made up 2.9 to 89.4 % of the soils sampled (Figure 5). Small macroaggregates made up 1.9 to 50.6% of the soils sampled (Figure 6). Microaggregates made up 7.1 to 34.1% of the soils sampled, and the silt and clay fraction made up 2.8 to 46.5% of the soils sampled. There were positive relationships between soil organic matter content and both the large and small macroaggregate fractions in the Sacramento but not San Joaquin Valley soils. There was a negative relationship between soil clay content and the large macroaggregate fraction in the Sacramento but not San Joaquin Valley soils.

Figure 3. Soil organic matter (left) and total microbial biomass (right) in the center and edge of tomato beds on surveyed fields in the Sacramento and San Joaquin Valleys.

Figure 2. Estimated 2018 tomato yields on surveyed fields in the Sacramento (blue circles; blue line) and San Joaquin (orange triangle; orange line) Valleys versus soil organic matter content.

Figure 4. Soil organic matter in the center of tomato beds in the Sacramento (blue circles; blue line) and San Joaquin (orange triangle; orange line) Valleys versus total microbial biomass content.

Soil exchangeable sodium increased with length of time using SSDI in San Joaquin Valley soils, by about 70 ppm per year in SSDI (Figure 8). Soil sodium did not change with length of time in SSDI in Sacramento soils (Figure 8). The ratio of microbial biomass nitrogen (the amount of nitrogen in microbial bodies) to soil nitrate (plant-available nitrogen) was calculated for each soil by dividing microbial biomass nitrogen by soil nitrate content. This ratio (MBN/nitrate) was plotted against soil nitrate levels (Figure 9). There was a negative logarithmic relationship between MBN/nitrate and soil nitrate content.

With regard to salinity, soil sodium concentrations were less than 100 ppm in the Sacramento Valley soils but were significantly higher, ranging from <100 to 800 ppm, in the San Joaquin soils. Soil exchangeable sodium increased with length of time using SSDI in San Joaquin Valley soils, by about 70 ppm per year in SSDI (Figure 8). There was no relationship, however, between soil sodium and length of time in SSDI in Sacramento soils (Figure 8).

The ratio of microbial biomass nitrogen (the amount of nitrogen in microbial bodies) to soil nitrate (plant-available nitrogen) was calculated for each soil by dividing microbial biomass nitrogen by soil nitrate content. This ratio (MBN/nitrate) was plotted against soil nitrate levels (Figure 9). There was a negative logarithmic relationship between MBN/nitrate and soil nitrate content. The ratio of microbial biomass nitrogen/soil nitrate was greater than 1 (more nitrogen in the microbial biomass than in the soil nitrate pool) up to soil nitrate levels of ~15 ppm, and was less than 1 (e.g., relatively more nitrogen in the nitrate pool than in the microbial biomass) at soil nitrate levels >15-20 ppm.

Figure 6. Small macroaggegate fraction, expressed as a percent of all aggregate fractions in terms of mass, vs. soil organic matter in the Sacramento (blue circles; blue line) and San Joaquin (orange triangles) Valleys. The blue line depicts the positive relationship observed in Sacramento Valley soils, but no relationship was observed in the San Joaquin Valley soils.

Figure 5. Large macroaggegate fraction, expressed as a percent of all aggregate fractions in terms of mass, vs. soil organic matter in the Sacramento (blue circles; blue line) and San Joaquin (orange triangles) Valleys. The blue line depicts the positive relationship observed in Sacramento Valley soils, but no relationship was observed in the San Joaquin Valley soils.

Figure 7. Large macroaggegate fraction, expressed as a percent of all aggregate fractions in terms of mass, vs. soil clay content in the Sacramento (blue circles; blue line) and San Joaquin (orange triangles) Valleys.

Figure 8. Soil test sodium on surveyed fields in the Sacramento (blue circles; blue line) and San Joaquin (orange triangle; orange line) Valleys versus years under SSDI.

Figure 9. Ratio of microbial biomass nitrogen (MBN) and soil nitrate (MBN/NO3), versus soil nitrate levels, across all soils measured. There was a logarithmic relationship observed between these parameters; equation shown on figure. The red arrow indicates the soil nitrate level at which competition for nitrate between soil microbes and crop plants likely decreases.

***Objective 3:*** Using agricultural inputs and yield data collected at Russell Ranch Sustainable Agriculture Facility, we have conducted an economic analysis to compare costs, revenue, and net present value (NPV) of organic furrow-irrigated, organic drip-irrigated, and conventional drip-irrigated systems. We used a Land Use System (LUS) model (Vosti et al. 1997), which accounts for the quantity and monetary value of all inputs and outputs on a piece of land, and it aggregates over time to value future costs and benefits.

*Work in progress*: We are in the process of transcribing, coding and analyzing the results of the grower interviews that were also conducted at the same time the soil samples were collected. This activity will be completed by early 2019. In addition, we are doing more in-depth analyses of the soil microbial community data and will conduct statistical analyses of their relationships with different soil health indicators. After we complete compilation and analysis of the grower interview data, we will then be able to determine relationships between management practices, farm history, soil properties, and the soil health indicators that we measured in farmer fields. The different relationships between tomato fruit yields and soil organic matter content among Valleys is surprising finding, and identifies a crucial question for further research to explore how soil organic matter affects productivity factors in tomato systems.



Figure 10. Breakdown of major costs per year in organic furrow-irrigated, organic drip-irrigated, and conventional drip-irrigated systems at Russell Ranch. Dotted lines represent the total revenue of each system based on the yield and the price for organic and conventional processing tomatoes. A gap between the dotted line and costs represents a profit.



Figure 11. Cumulative Present Value (blue) and Annual Discounted Net Benefits (orange) for each system over 12 years.

**Discussion:**

*Soil Health Analysis (Objectives 1 and 2)*

It is well known that properties of soils and climates differ markedly between the Sacramento and San Joaquin Valley. Not surprisingly these differences were also related to regional differences in soil health indicators. In general, organic matter contents in the Sacramento Valley soils were greater than those in San Joaquin Valley soils. In the Sacramento Valley, a slight negative relationship was observed between soil organic matter content and tomato yields, but in the San Joaquin Valley, tomato yields increased with increasing organic matter. Surprisingly, soil microbial biomass was similar in the two regions despite differences in soil organic matter. Soil organic matter provides microbes with a source of carbon, which microbes feed upon for energy. Therefore, it was expected that a larger soil organic matter pool would support a larger soil microbial community. Organic matter was also positively correlated with soil P and K, implying that P and K availability to tomato plants increases with increasing soil organic matter, in general. Some of the differences in soil properties between regions included:

1) lower Ca:Mg ratio (1.2:1) in Sacramento Valley, compared to a 3.2:1 ratio in San Joaquin Valley,

2) higher soil P concentrations in Sacramento Valley,

3) higher soil K concentrations in San Joaquin Valley, and

4) higher soil cation exchange capacities (CEC) in San Joaquin Valley.

The relatively lower Ca and K availability to tomatoes in the Sacramento Valley soils may have contributed to the relationship between fruit yield and soil organic matter. The lower Ca:Mg ratios may have disrupted the beneficial effects of soil organic matter and microbes to tomato productivity in the Sacramento Valley. Low Ca availability in soils could be limiting microbial growth, potentially decreasing beneficial effects of soil organic matter and soil microbes to tomato plants.

Despite the slight negative correlation between soil organic matter and yields in the Sacramento Valley, increasing soil organic matter content improved macroaggregate formation of both the large and small aggregate fractions (Figures 5 and 6). Large macroaggregate formation is important for good soil structure, with macroaggregates linked to improved water infiltration, decreased soil crusting, and resistance to compaction. Large macroaggregate formation was negatively correlated with clay content, implying that increasing soil organic matter in clay soils could mitigate poor soil structure with low macroaggregate fractions in high-clay soils. Increasing soil organic matter content in the Sacramento Valley is still important for improving soil structure and soil carbon storage, though these findings suggest that more research is needed to understand if fertility management in these soils may need to change across soil organic matter gradients.

In the San Joaquin Valley, where there was a positive relationship between soil organic matter and crop yields, the higher SOM could be associated with a higher CEC and soil microbial activity. Soil microbial biomass was also correlated with higher mycorrhizal fungal biomarkers (data not shown) and soil total P. It is possible that microbes in the presence of higher SOM were mobilizing P in the soil, making it more available to tomato plants. Higher soil organic matter may have also increased soil water holding capacity and water storage, both essential water-conserving functions in the arid San Joaquin Valley. However, more research is needed to understand how soil organic matter affects soil water dynamics.

While few of the soil health indicators showed relationships with length of time the farm was under SSDI, one such positive relationship was observed in San Joaquin Valley soils with soil sodium (Na) concentrations increasing with time in SSDI (Figure 8). This relationship was not observed in Sacramento Valley soils. Sodium could be an indicator of salt buildup over time with SSDI in the San Joaquin Valley, though there was no relationship between soil sodium levels and tomato yields based on data available so far. Soil organic matter’s ability to increase the CEC could help mitigate sodium buildup over time in SSDI systems, representing a potential benefit of increasing soil organic matter in San Joaquin Valley soils.

Finally, an interesting relationship between microbial uptake of nitrogen and plant-available nitrogen (nitrate) was observed. Nitrogen exists in different forms in the soil, loosely defined as two “pools”: 1) organic, which is not readily available for uptake by plants or microbes, and 2) inorganic (nitrate and ammonium) which are biologically available forms. The microbial biomass nitrogen (MBN), a portion of the organic pool, represents how much N microbes have taken up. Therefore the ratio of MBN to nitrate (MBN/nitrate) indicates the portion microbes have removed from the previously available inorganic nitrogen pool, relative to the total inorganic pool.

We found a logarithmic relationship between the MBN:nitrate ratio and soil nitrate levels, with an inflection point around 15 to 20 ppm nitrate. This point could be interpreted as representing where the MBN:nitrate ratio stops being as responsive to increasing soil nitrate concentrations. This range (15 to 20 ppm soil nitrate) can be hypothesized to be the concentration range at which microbial uptake of nitrogen slows down considerably, likely because microbial growth becomes limited by another nutrient or condition not related to nitrogen. Therefore, at levels above 15 to 20 ppm nitrate, microbial competition for soil nitrate with crop plants is likely to be low. Below 20 ppm nitrate, microbial competition for soil nitrate may be high, suggesting that inputs of nitrate fertilizers may be feeding the microbial community rather than the crop plants. This finding could be important for fertigation management of nitrate because it implies that low uptake efficiency in tomato may occur in situations when fertilization injections are too low, e.g. resulting in soil nitrate levels lower than 20 ppm. This interesting relationship, showing a dependency of fertilizer inputs on the soil microbial biomass concentration, is novel and will be explored further in future research.

The large differences between the San Joaquin and Sacramento Valley soils with respect to soil health indicators, and some of the relationships between indicators and management, underscoring the importance of better understanding the variety of soils and regions in which processing tomatoes are grown. Therefore, we are proposing to focus a proposed continuation of this research next year on farms in the southern part of the state. This will help in developing *regionally sensitive indicators* and management practices for soil health.

*Economic Analysis (Objective 3)*

In our impact analysis of quantifying tradeoffs related to water use, labor inputs, and crop performance on farm economics, we first looked at the value of inputs and outputs in a single year. We hypothesized that water would account for the major difference in costs between furrow-irrigated and drip-irrigated systems as furrow used more than twice as much water as drip-irrigation, and with water as a major cost for growers. However, farm labor costs were the major difference between irrigation systems. Without chemical options for organic systems, hand weeding was the only option for weed control. Organic furrow-irrigated plots required 150 person-hours/acre of labor for hand weeding whereas in drip-irrigated fields, weed pressure was dramatically reduced due to lack of moisture in the surface soils. Moving forward, we hope to use site-specific data from farmers in order to assess how these cost distributions may change at different locations in the valley where water and labor costs may vary.

Though costs were highest in the organic, furrow-irrigated system, this treatment also had the greatest revenue (shown by the dotted lines in Figure 10) due to the 25% organic premium and higher yields than in the organic, drip system (45 t acre-1 vs. 39 t acre-1; 2017 yield data). The conventional, drip-irrigated system had the highest yields (46.3 t acre-1), but lowest revenue due to lower prices. Nonetheless, the conventional, drip-irrigated system has the greatest potential for profit as there is the greatest difference between costs and revenue. Both drip systems were substantially more profitable than the furrow-irrigated system, which had costs slightly higher than revenue due to high labor inputs.

To calculate NPV of each system, we used the LUS model to project out 12 years. We modelled each system with a rotation of 3 years of tomato followed by corn every 4th year. Drip systems were reinstalled every 6 years. We used an annual inflation rate of 2% and a discount rate of 4.25%. Figure 11 shows the cumulative present value (adding up to the 12-year NPV) and the annual discounted net benefits of each of the systems. We see that over 12 years, both of the drip-irrigated systems have a positive NPV, though the organic has lower NPV and annual discounted net benefits each year than the conventional due to slightly greater labor inputs from weeding and more field operations. The organic, furrow-irrigated system has a negative NPV, and we see that the annual discounted net benefits are negative each year due to consistently greater costs (primarily due to labor) than revenue.

A factor not considered in the LUS model yet an important topic for future research is the potential economic value of soil health for the farming system over the long term. It is possible that degradation of soil may feedback into declines in yield or need for interventions to restore degraded soil.  There is also potential for farmers to be rewarded for soil health practices and outcomes, e.g. through CO2 offset. A healthy soil ideally provides a variety of private benefits to the farmer (e.g. increased water and nutrient retention, reduced disease pressure), as well as broader social benefits to human societies and to ecosystems, such as filtering of pollutants, flood mitigation, reduced sediment erosion and dust generation, increased soil biodiversity, reduction of non-CO2 greenhouse gas emissions, and recycling of wastes. In many cases, however, farmers do not see economic benefits, particularly in the short-term, and there is little incentive for growers to implement these practices, as they generally increase input costs without increasing revenue. A potential policy response is to compensate farmers annually for the increased societal benefits they provide in implementing soil health-promoting practices. In this way, the private benefits to the farmer are increased to equal the public benefits.

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