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Spatially variable evapotranspiration over salt affected pistachio orchards analyzed with satellite remote sensing estimates

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ABSTRACT

Recent prolonged droughts in California have emphasized the urgent need to implement more efficient water management practices for high value tree crops. Accurate estimation of evapotranspiration (ET), a main component of consumptive water use, is critical for improving management of micro-irrigated pistachio orchards grown in the San Joaquin Valley of California. We estimated ET of three mature commercial pistachio orchards on non-saline and increasingly saline soils in 2015 and 2016, using the Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) method and Landsat 8 satellite observations. Based on a comparison with field observations at 8 sites, we modified the parameterizations of the momentum roughness length and net radiation for pistachio tree crops and reduced the uncertainty of daily ET estimates. When compared with field data, the recalibrated METRIC ET estimates had an R^2 of 0.59, a mean absolute error of 1.1 mm/day, and a RMSE of 1.4 mm/day during Landsat overpass dates (n = 72). The METRIC ET map captured the temporal dynamics and spatial heterogeneity both within and among the orchards. The mean annual crop season estimated ET (mid-March to mid-October in 2016) with remote sensing decreased by 32% from 1064 ± 99 mm in the non-salt affected control orchard to 725 ± 82 mm in the orchard with the highest level of soil-water salinity. The ET reduction was consistent with canopy volume differences among the study orchards, as shown by summer Normalized Difference Vegetation Index (NDVI) from Landsat observations, e.g., 0.72 ± 0.06 in the control vs. 0.52 ± 0.06 in the most saline orchard. The available energy was controlled mostly by canopy features and explained 64% of daily ET variation among all Landsat pixels and satellite overpass days. The normalized differenced water index (NDWI) could be considered as an important parameter to capture the partitioning of available energy for ET (R^2 = 0.38), suggesting that the lower soil osmotic potential in saline orchards further reduced crop ET.

1. Introduction

California's Central Valley, an area of about 155,000 km^2, is among one of the world's most productive agricultural regions. A total of 101,327 bearing hectares (1180 km^2) of pistachios generated an overall production of 448,000 metric tons and a $1.5 billion in revenue in 2016 (California Department of Food and Agriculture (CDFA), 2016). Approximately 95% of the US commercial pistachios are produced in the San Joaquin Valley. In the last decades, pistachio acreage expanded largely to areas with saline soils previously used for cotton (Goldhamer, 2005). Soil salinity is a known constraint on agricultural production in the Central Valley, particularly in the western San Joaquin Valley, where soils are naturally high in salts due to the marine origin of their Coastal Range alluvium parent material (Letey, 2000). Although the need of subsurface drainage was long understood for these agricultural production areas, it failed to materialize due to lack of collective actions

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(Oster and Wichelns, 2014). In addition to the geological nature, meteorological and management factors affect the salinity levels of irrigated soils in the western San Joaquin Valley, including irrigation water quality, fertilization, irrigation management, drainage conditions, rainfall and evapotranspiration totals and cultural practices (Scudiero et al., 2017). A recent study projected the direct economic costs would exceed $1.5 billion/year for all crops by 2030 if salt management practices do not change (Howitt et al., 2009). The severe 2012–2016 California drought (Griffin and Anchukaitis, 2014) and resulting aquifer overdraft (Xiao et al., 2017) further exacerbated the soil and water salinization, threatening the economic sustainability of fruit and nut production including pistachio.

Increasing salt concentration in the soil water reduces the osmotic potential of the soil-water solution, which in turn increases the energy expended by plants to extract water and reduces water uptake, transpiration and photosynthetic rate, eventually decreasing tree growth and nut production (Sanden et al., 2004, 2005). More efficient water management is urgently needed in the face of the San Joaquin Valley's increasingly limited, degraded and costly water supplies. California's growers have traditionally relied on reference evapotranspiration and land use-based crop coefficients for irrigation scheduling (*Snyder et al.*, 2012). Reference ET for well-watered standardized grass (ETo) is easily accessible from the California Irrigation Management Information System (CIMIS) network of 155 fully-automated active weather stations on well-watered grass fields (http://www.cimis.water.ca.gov/) (Hart et al., 2009). However, little information is available on the actual ET of pistachio orchards grown with micro-irrigation on saline soils, where canopy development, orchard water use and production may be adversely affected by the low soil osmotic potential. This lack of accurate ET information prevents the adoption of resource-efficient water management practices.

Field measurements of ET, using the eddy covariance technique (Wilson et al., 2002) and more recently less costly surface renewal technique (Shapland et al., 2013, 2014), can provide more accurate information on actual crop consumptive water use at individual sites. However, it is difficult to apply these site-level small-area measurements to estimate ET at orchard and watershed scales effectively. Various remote sensing approaches have been developed (Bastiaanssen et al., 2005; Allen et al., 2007a; Fisher et al., 2008; Jin et al., 2011; Anderson et al., 2011) to use satellite observations to estimate crop ET across space and time in agriculture and natural ecosystems (Anderson et al., 2012; Semmens et al., 2016). Satellite Irrigation Management Support system (SIMS), for example, estimates crop fractional cover and basal crop coefficient values in real-time by tracking crop canopy development with satellite observations in the visible and near infrared spectral region (Melton et al., 2012). This crop-coefficient approach can be easily implemented to estimate ET from well-watered crops when combined with spatial reference ET maps. The empirical relationship between fractional cover and basal crop coefficient, however, needs to be developed and validated with field measurements over various crop types and growing conditions.

Several algorithms also used thermal infrared data from satellite to estimate ET based on surface energy budget. One-source energy balance approaches, such as Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 2005) and Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) (Allen et al., 2007a, b), assume that the near-surface vertical air temperature gradient (dT) for estimating the sensible heat flux is an indexed function of radiometric surface temperature (Allen et al., 2011). The latent heat flux (LE) is then calculated as the residual to the surface energy budget. More complicated dual-source methods, on the other hand, integrate the biophysical processes and remote sensing data in both visible and thermal spectrum to estimate the plant transpiration and evaporation from non-vegetated surfaces separately (Kustas and Norman, 1999; Timmermans et al., 2007). The Disaggregated Atmosphere-Land Exchange Inverse (DisALEXI) (Anderson et al., 2011), for example, has been implemented for routine ET mapping and drought monitoring at continental scales (Anderson et al., 2007).

The METRIC approach has been widely used to estimate and map water use, mostly in field row crops in western US, with Landsat satellite observations (Allen et al., 2011; French et al., 2015). Tree crops have more complex canopy structure and physiology, which make the soil-vegetation-atmosphere interaction processes more complicated. Only a few studies have evaluated the METRIC method for estimating ET over areas with complex canopy structures, e.g., in apple, olive and almond orchards (Santos et al., 2012; Pôças et al., 2014; de la Fuente-Sáiz et al., 2017; He et al., 2017). These limited case studies indicated that the adjustment of some intermediate parameters in the standard METRIC, such as momentum roughness length (Z_{om}) and ground heat flux, reduced the uncertainties of ET estimate for the heterogeneous woody canopies (de la Fuente-Sáiz et al., 2017). We are unaware of any study about METRIC ET estimation in pistachio orchards, and it is not clear about its capability to map the relative effects of salinity on pistachio ET and potential uncertainty or challenges as well.

In this study our objective was to assess the accuracy and reliability of the standard and adjusted METRIC approach in estimating daily ET of pistachio orchards, and examine the variations of water use by pistachio orchards with various levels of soil-water salinity in the San Joaquin Valley. We also investigated the relative importance of various factors affecting spatial and temporal ET variation among and within the study orchards.

2. Materials and methods

2.1. Study areas

This study focused on three commercial mature pistachio orchards located in the areas of Hanford and Lemoore in Kings County, California (Fig. 1). The size of each orchard is about 60 ha (600,000 m^2). The control orchard was planted on sandy clay loam soil with a 5.8 m by 5.2 m tree spacing in 1990, with a mean tree height of 4.29 ± 0.09 m and a trunk diameter 0.28 ± 0.02 m. In 2015 our project team collected soil samples at 0.30 m increments up to 90 cm deep, and lab analyses were then performed by the UC Davis Analytical Laboratory, which revealed an average electrical conductivity of the saturated soil paste extract (ECe) of 2.30 dS/m, with min and max ECe of 0.95 and 4.0 dS/m respectively. The other two orchards, adjacent to each other, were planted in late 1980s on clay soil with a 5.8 m by 6.0 m and 5.2 m by 5.2 m spacing, respectively. One orchard had a low to moderate salinity with average ECe value of 4.0 dS/m, with min and max ECe of 1.3 and 6.9 dS/m, respectively (hereafter called med-S orchard), whereas the other orchard has highly heterogeneous salinity with average ECe of 5.2 dS/m, with min and max ECe of 1.8 and 11.0 dS/m, respectively (high-S). On average, trees are much smaller in the salt-affected orchards, with a height of 2.5 ± 0.01 m and a trunk diameter of 0.2 ± 0.02 m at the high-S sites. The light interception measured below trees at each orchard at full canopy (late June) varied from 74%, 65% to 41% in the control to med-S, to high-S orchards, indicating substantial canopy cover and leaf area differences among the orchards as a result of long-term impact of soil salinity on tree development.

All the orchards are equipped with micro-irrigation system that consist of 10 drippers per tree (Netafim Uniram) with nominal flow rate of 3.8 liters per hour at the control orchard, and 8 drippers per tree (Netafim Triton X) with nominal flow rate of 1.9 liters per hour at the two salt-affected orchards, respectively. In all study orchards, the drippers are pressure compensating and regularly spaced along dual driplines.

2.2. Field measurements of ET

The three study orchards were instrumented with a total of eight stations, one in each of the control and med-S orchard and six in the