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Monitoring daily evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion approach

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ABSTRACT

California's Central Valley grows a significant fraction of grapes used for wine production in the United States. With increasing vineyard acreage, reduced water availability in much of California, and competing water use interests, it is critical to be able to monitor regional water use and evapotranspiration (ET) over large areas, but also in detail at individual field scales to improve water management within these viticulture production systems. This can be achieved by integrating remote sensing data from multiple satellite systems with different spatiotemporal characteristics. In this research, we evaluate the utility of a multi-scale system for monitoring ET as applied over two vineyard sites near Lodi, California during the 2013 growing season, leading into the drought in early 2014. The system employs a multi-sensor satellite data fusion methodology (STARFM: Spatial and Temporal Adaptive Reflective Fusion Model) combined with a multi-scale ET retrieval algorithm based on the Two-Source Energy Balance (TSEB) land-surface representation to compute daily ET at 30 m resolution. In this system, TSEB is run using thermal band imagery from the Geostationary Environmental Operational Satellites (GOES; 4-km spatial resolution, hourly temporal sampling), the Moderate Resolution Imaging Spectroradiometer (MODIS) data (1 km resolution, daily acquisition) and the new Landsat 8 satellite (sharpened to 30 m resolution, ~16 day acquisition). Estimates of daily ET generated in two neighboring fields of Pinot noir vines of different age agree with ground-based flux measurements acquired in-field during most of the 2013 season with relative mean absolute errors on the order of 19–23% (root mean square errors of approximately 1 mm d^{-1}), reducing to 14–20% at the weekly timestep relevant for irrigation management (~5 mm wk^{-1}). A model overestimation of ET in the early season was detected in the younger vineyard, perhaps relating to an inter-row grass cover crop. Spatial patterns of cumulative ET generally correspond to measured yield maps and indicate areas of variable crop moisture, soil condition, and yield within the vineyards that could require adaptive management. The results suggest that multi-sensor remote sensing observations provide a unique means for monitoring crop water use and soil moisture status at field-scales over extended growing regions, and may have value in supporting operational water management decisions in vineyards and other high value crops.

1. Introduction

California, as the state producing over 90% of wine in the United States, has seen steady growth in the amount of acreage dedicated to wine-grape production with approximately 615,000 acres planted in 2014, up from 610,000 in 2013 (California Department of Food and Agriculture & USDA National Agricultural Statistics Service, 2014). Given the high value of this crop commodity, the continued growth in production, and limited water availability in the state, there is significant interest in developing efficient water management strategies for California vineyards. Of particular importance for high quality wine grapes is controlled water stress at key points during the growing season. To effectively manage water stress, adequate moisture is maintained from bud break until fruit set, followed by moderate water stress through veraison (change of color of grapes) and ripening in

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order to focus plant resources on fruit maturation rather than foliage expansion (Robinson, 2006). Ideally, this balancing of water stress would require daily monitoring of vineyard soil moisture status, but ground-based measurements may not always be representative of whole-field conditions and are costly to install and maintain, especially for large scale and distributed production systems. One method to efficiently assess and monitor water use and stress in vineyards is through satellite based estimation of evapotranspiration (ET), quantifying the net loss of water vapor from the crop field to the atmosphere.

ET is a major surface water balance component in semi-arid environments typical of many viticulture areas (Moussa, Chahinian, & Bocquillon, 2007). For vineyards, ET is usually modeled as a function of potential ET under unstressed conditions and vegetation cover fraction (Riou, Pieri, & Le Clech, 1994; Riou, Valancogne, & Pieri, 1989). However, more complex Soil–Vegetation–Atmosphere Transfer (SVAT) models have been developed to estimate seasonal ET and account for common soil management practices in viticulture such as the use of grass cover between rows (Montes, Lhomme, Demarty, Prevot, & Jacob, 2014). ET has been estimated for vineyards using weighing lysimeters, eddy covariance, or energy balance using the Bowen ratio but such "point measurements" are difficult to extrapolate to whole fields and basins and in-field spatial variability is missed (Teixeira, Bastiaanssen, & Bassoi, 2007). Thus, complete field-scale maps of ET can be of significant value in managing vineyards and efficiently planning irrigation schemes, particularly when implemented over extensive acreages.

Irrigation amounts at 80% of full potential ET have been found to maximize berry size for raisin and table grapes (Williams, 2001). Over-irrigation can reduce yield and compromise quality in certain grape varieties (Chaves et al., 2007; Williams, Grimes, & Phene, 2010), but there is still debate over amounts and timing of irrigation for a given environment and grape variety (Chaves et al., 2007). Regardless of the debate on application amount, it is clear that ET and water use estimates are necessary to effectively manage high productivity and quality in viticultural systems.

Land-surface temperature (LST), derived from thermal infrared (TIR) imagery acquired from satellites such as Landsat, has successfully been used to estimate ET over a range of spatial scales. This is because LST is sensitive to local moisture variations, providing valuable information on surface energy budget partitioning (Anderson, Allen, Morse, & Kustas, 2012). Several workable approaches to TIR-based ET mapping have been developed (e.g., Bastiaanssen, Menenti, Feddes, & Holtslag, 1998; Su, 2002; Allen, Tasumi, & Trezza, 2007; Anderson, Kustas, et al., 2012). Due to large uncertainties in determining absolute LST, most of these approaches use relative variability in LST, measured either temporally (time-differential methods) or spatially (end-member pixel scaling), to more accurately estimate ET. The Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 1998) and the Mapping Evapotranspiration with Internalized Calibration (METRIC; Allen et al., 2007) are examples of approaches using TIR end-member pixels to represent limiting and non-limiting moisture conditions. The Atmosphere–Land Exchange Inverse (ALEXI; Anderson, Norman, Diak, Kustas, & Mecikalski, 1997; Anderson et al., 2007) model uses the time-differential approach, measuring the morning LST rise and relating the change to surface moisture and heat fluxes. Another approach for estimating ET, the crop coefficient approach, uses meteorological data and crop specific coefficients instead of LST (Allen, Pereira, Raes, & Smith, 1998). Crop coefficient techniques, however, do not capture short-term variability in soil moisture and vegetation stress conditions (Anderson, Allen, et al., 2012) which are important to vineyard management. Vegetation stress and soil moisture status do have a thermal signature, which is effectively exploited in energy balance approaches.

For viticultural decision making, water use information is most useful at field or sub-field scales, making the 30 m resolution of Landsat imagery particularly important. Unfortunately, the Landsat overpass frequency is often insufficient, typically with an ~16 day revisit interval or longer if cloud cover is persistent. While there are TIR satellites that provide daily coverage (e.g., geostationary satellites, and moderate resolution polar orbiting systems like the Moderate Resolution Imaging Spectroradiometer — MODIS), these are too coarse in resolution (km-scale or larger) to provide the required field-scale information. Therefore, an integrated multi-sensor approach that combines the benefits of the high spatial resolution of Landsat and the high temporal resolution of MODIS and geostationary satellites to provide daily field-scale ET estimates may be of significant benefit to vineyard managers.

In this paper, we extend the multi-sensor ET mapping technique described by Cammalleri, Anderson, Gao, Hain and Kustas (2013, 2014) to viticultural systems and evaluate its performance in comparison with field measurements. This energy balance approach combines multi-scale and multi-temporal sharpened TIR imagery from geostationary satellites (4 km, hourly), MODIS (1 km, daily) and Landsat (30 m, ~bi-weekly to monthly) using the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) data fusion methodology developed by Gao, Masek, Schwaller, and Hall (2006). Cammalleri et al. (2013) described initial implementation and evaluation of the ET fusion methodology over rainfed corn and soybean fields in the Walnut Creek watershed (Iowa) using flux data collected during the Soil Moisture Experiment of 2002 (SMEX02). It was subsequently tested for corn and cotton under both rainfed and irrigated management at two sites with contrasting climate conditions: a semi-arid site (part of the Bushland Evapotranspiration and Agricultural Remote sensing EXperiment 2008; BEAREX08, Evett et al., 2012) near Bushland, TX, and at a more temperate Ameriflux site near Mead, NE (Cammalleri, Anderson, Gao, et al. 2014). Both of these studies used data from Landsats 5 and 7.

This paper discusses application of the multi-scale ET data fusion system to a new kind of crop (wine grapes) grown in a Mediterranean climate, and to data collected with the new Thermal Infrared Sensor (TIRS) system on-board Landsat 8, which was launched in Feb of 2013. The vineyard architecture presents unique challenges to the Two-Source Energy Balance (TSEB) model that forms the land-surface representation in the retrieval algorithm, given the highly structured nature of the vine rows and the common practice of growing a cover crop between rows to control springtime soil moisture conditions. The data fusion algorithm was applied over a region in the California Central Valley near the city of Lodi for the 2013 growing season, and evaluated with micrometeorological data collected in two Pinot noir vineyards at different stages of maturity. The satellite-based flux retrievals are compared to eddy covariance measurements, as well as in-field soil moisture and yield data.

In Section 2 we provide a description the data fusion package, followed by a description of the study area and input and evaluation datasets in Section 3. Results and conclusions are presented in Sections 4 and 5, including planned future work.

2. Model descriptions

A schematic overview of the data fusion processing package, including inputs and image processing steps, is shown in Fig. 1. The main diagnostic input, the land surface temperature (LST), can be retrieved from various thermal imaging sensors over a range of different spatial and temporal resolutions. Remotely sensed LST inputs drive a multi-scale surface energy balance algorithm (Anderson, Kustas, et al., 2012), as described below.

2.1. ALEXI

The multi-scale energy balance modeling scheme has its foundation on coarse-scale regional flux estimates from the Atmosphere–Land Exchange Inverse (ALEXI) model, driven primarily by a diagnostic measurement of the morning rate of surface temperature rise, which can be acquired from geostationary satellites. The use of a time-differential LST measurement, rather than absolute instantaneous measurements