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EDITORIAL

Forward to the GRAPEX special issue

William P. Kustas[1] · Nurit Agam[2] · Samuel Ortega-Farias[3]

Agricultural production in California faces weather and hydrologic extremes of both floods and drought, both of which are detrimental to crop yield. Californian producers of high-valued perennial crops, thus, increasingly rely on groundwater extraction to sustain and even expand production (Matios and Burney 2015). The extreme consecutive droughts that have recently occurred significantly impacted California's ground water resources. At current levels of groundwater pumping, the long-term sustainability of groundwater resources is in jeopardy (Richey et al. 2015). As a result, the state and its agricultural community have recognized the need to develop long-term water management strategies. Operatively, California enacted the Sustainable Groundwater Management Act in 2014, which mandates development of management plans for critical basins within California. Achieving such long-term water use sustainability in an economically viable way will almost certainly require more efficient irrigation management to successfully address future water shortages.

Currently, the irrigation management decisions for many California crops are based on a combination of in situ observations of plant available water via root zone soil moisture measurements, using crop coefficients with reference evapotranspiration (ETo) from a nearby weather station, or estimates of actual evapotranspiration (ETa) via micrometeorological techniques that are assumed to represent crop water status of whole fields. For obtaining spatially distributed information on crop water use and condition, some have adopted a simple remote sensing-based estimate of normalized difference vegetation index (NDVI) for quantifying fractional canopy cover in conjunction with the Food and Agriculture Organization of the United Nations (FAO) crop model with crop coefficients that have been tuned for specific crops (Allen et al. 1998). None of these methods can provide spatially distributed information of actual crop ET and plant water status, and are not sufficiently robust for strongly clumped and highly structured canopies such as vineyards and orchards. Moreover, none are capable of separating row crop water use from the interrow soil and/or cover crop water use, and the crop coefficients are not well defined for stressed conditions, particularly for perennial crops (e.g., Ting et al. 2016).

Producers of wine grapes—a California crop valued at nearly $6 billion annually—have actively sought tools to better monitor crop water status and manage water use. Along those lines, E. & J. Gallo Winery contacted scientists with the US. Department of Agriculture-Agricultural Research Service (USDA-ARS) Hydrology and Remote Sensing Laboratory (HRSL) seeking advice on robust yet practical methods for applying earth observations to guide irrigation decisions. It is well established that in wine grape production, there are vine and berry development stages where the timing and amount of irrigation are critical for optimal quality and yield. Generally, these include (1) when to initiate irrigation in the spring; (2) the timing and amount of water to apply early in the growing season that balances vine growth and berry development; and (3) in later stages during berry ripening when there are carefully timed periods of mild stress imposed (deficit irrigation) to improve berry quality for wine production. Spatial information on variations in vine water status across vineyard blocks is necessary to ensure best quality yield through judicious application of water only where it is needed.

E. & J. Gallo Winery researchers realized that accurate maps of ETa at daily to weekly increments and at subfield spatial resolutions could significantly reduce water use and

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✉ William P. Kustas
Bill.Kustas@ARS.USDA.GOV

1 USDA-ARS Hydrology and Remote Sensing Laboratory, 10300 Baltimore Ave., Bldg. 007, BARC-West, Beltsville, MD, USA

2 Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede-Boqer Campus, Midreshet Ben-Gurion, Israel

3 Research and Extension Center for Irrigation and Agroclimatology (CITRA), University of Talca, Talca, Chile

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enhance crop quality. HRSL scientists were developing physically based ETa models using satellite remote sensing for routine ETa mapping from field to regional scales. This led to a research and applications collaboration between E. & J. Gallo Winery and USDA-ARS, which has evolved into the ongoing Grape Remote Sensing Atmospheric Profile and Evapotranspiration eXperiment (GRAPEX) project. The GRAPEX project, initiated in 2013, has expanded to include personnel from other USDA-ARS laboratories, the National Aeronautics and Space Administration (NASA), several universities, and industry. The goal of GRAPEX is to provide wine grape producers and, in the longer term, fruit and nut orchard growers, with the tools to generate robust high-resolution maps of ETa that can be used to guide water management decisions. These tools will have the advantage over current approaches for assessing water needs by being applicable year-round and by providing water use information with higher spatial and temporal detail.

The tools being developed under GRAPEX will differentiate between water uptake by the grapevines and the water used by the grass cover crop typically planted in the interrow between the vine rows. An early detection of vine stress will thereby be achieved. In addition, the project is investigating the utility of using very-high-resolution imagery collected via unmanned aerial vehicles (UAVs) at critical times during the growing season to assess intra-vineyard spatial variability condition and facilitate precision management.

Initial research results presented in this special issue from the GRAPEX project cover a broad range of topics as well as a full range in spatial and temporal scales. It starts with a set of papers dealing, at micrometeorological scales, with analysis of turbulent intermittency above and below the vine/interrow system, surface energy balance (SEB) above and below the vine canopy, evaluation of surface renewal technique for ETa estimation, modeling and measurement of radiation divergence through the vine canopy, the micro-scale distribution of soil heat flux, and investigation of the temporal behavior of canopy/leaf level crop water stress index. A paper on evaluation of several indirect measurement methods of vine leaf area index used in validating remote sensing retrievals is also presented, which is critical for upscaling remotely sensed leaf area beyond the canopy to the field, landscape and regional scale using satellite data. Following these studies are aspects of land surface temperature (LST)-based two-source energy balance (TSEB) model and its utility in ETa partitioning between vine and interrow: validation at the micrometeorological scale; the impact of modifications to TSEB wind extinction algorithms through the vine canopy layer to account for unique vine row and canopy architecture/structure; and sensitivity of TSEB model SEB output to uncertainty in aerodynamic roughness parameters. At the canopy to field scale, the utility of very-high-resolution imagery is then examined: use of very-high-resolution UAV imagery for mapping vineyard ETa and partitioning of ET between vine and interrow and detection and impact of shadows in UAV imagery on SEB modeling. Finally, validating the satellite-based data fusion ETa modeling system that generates daily 30-m ETa year-round at field to regional scales completes the special issue. The listing of the scale, main focus, approach and key findings of each of the manuscripts in this special issue are summarized in Table 1. The papers are ordered and grouped primarily in terms of scale and focus.

Since the publication of this special issue, GRAPEX continues to evolve (Kustas et al. 2018), with an expansion of experimental vineyard sites further to the south (Ripperdan Ranch, near Madera CA, 36.84°N, 120.21°W) and north (Barrelli Creek, near Cloverdale CA, 38.75°N, 122.98°W). This establishes both a climate gradient for testing the transferability of the research results and models developed at the original GRAPEX vineyard sites to these different climate zones and to different vine varieties and trellis designs. Results are yet to be published.

The preliminary findings in this collection of publications suggest that the unique canopy structure and large row separation with an interrow cover crop affect the microclimate and energy partitioning of the vine and interrow systems. These agroecosystems pose challenges to traditional methods of both the measurement and modeling of the water and energy exchange applied to more uniform crop canopies. However, the preliminary results suggest that the remote sensing-based modeling approaches applied over these vineyard sites managed to reproduce measured fluxes and that other indirect measurement methods such as surface renewal may provide reasonable estimates of local water use.

There are still a number of scientific and practical challenges to address in monitoring vine and interrow water use and stress. These include improvement in the separation of vine water use and stress from interrow bare soil and cover crop, which can account for a significant percentage of the surface area during much of the growing season. A better understanding on how advection and turbulent intermittency affects both flux measurements and the below canopy parameterizations of flux-gradient exchanges assumed in land surface model formulations. Furthermore, the role of vine canopy architecture, which includes trellis design, pruning, and row orientation on radiation and energy exchange needs further study. Additionally, the role of vine carbon assimilation and its relationship to ETa and water stress has yet to be investigated.

Finally, a key issue to address is how do we take these research findings on the measurement and modeling of vineyard water and energy exchange and transfer or synthesize the key results into the development of tools and techniques useful to vine growers, mangers, wine makers, and policy makers. If the research can lead to better management

Table 1 A listing of the main focus, approach, and key findings of the GRAPEX Special Issue papers, ordered according to their spatial scale from interrow variability to regional

Paper	Scale	Main focus	Approach	Key finding
Kustas et al. (2019a)	Canopy and interrow	Interrow energy balance	Micro Bowen ratio and below canopy radiation observations	Surface energy fluxes below the vine canopy were dominated by the amount of transmitted radiation, while soil moisture appeared to have a second-order effect
Parry et al. (2019a)	Canopy and interrow	Radiation extinction	Inter-comparison of five radiation transfer models of different complexity	Best agreement with measurements was for the most complex and a geometric elliptical hedgerow model which considers row orientation and vertical biomass distribution and can be readily incorporated into a mechanistic ETa model
Agam et al. (2019)	Canopy and interrow	Micro-scale spatial variability in soil heat flux (SHF)	Unique 11-sensor array of soil heat flux measurements within the interrow	Variability of incoming solar radiation reaching the ground was the primary source for spatial and temporal variation of SHF once the vine canopy was fully developed A transect of 5 equally distributed sensors across the interrow accurately represented the area-average SHF
White et al. (2019)	Canopy and interrow	Indirect estimation of leaf area index (LAI)	Seven methods for indirect LAI estimation using light bar sensor versus destructive (direct) LAI measurements	The method facing the canopy, with four readings across the interrow estimated reliable LAI. Using more readings did not significantly improve the indirect LAI estimates
Los et al. (2019)	Canopy air space and lower atmosphere	Intermittent turbulent transport	High-frequency water vapor and 3D wind measurements above and below vine canopy	Intermittent events were found to exist under periods of light winds and highly unstable/convective conditions requiring longer flux-averaging periods than more steady conditions. This intermittence may cause additional errors in model output
Prueger et al. (2019)	Canopy	Diurnal behavior of the crop water stress index (CWSI)	Network of in situ infrared radiometers measuring land surface temperatures (LST) over different locations of the vine canopy	There was significant variation in computed CWSI for each of the hourly averaged canopy temperature sensors; however, the diurnal trends were similar among the infrared radiometers with highest CWSI values in morning and lowest in the late afternoon which had the highest evaporative demand

Table 1 (continued)

Paper	Scale	Main focus	Approach	Key finding
Nieto et al. (2019a)	Canopy and interrow air space	Wind attenuation models	Two-source energy balance (TSEB) model output versus H observations for two wind attenuation models	There was no significant improvement in H estimates using the more physically based wind attenuation model; however, this model did improve H estimates when the vine canopy is in early growth stage when strongly clumped both horizontally and vertically
Parry et al. (2019b)	Sub-field	Daily actual evapotranspiration (ETa)	Surface renewal (SR) and available energy measurements	The SR method requires accurate estimates of net radiation (Rn) to obtain reliable and unbiased estimates of daily ETa in comparison to measurements with the EC technique
Alfieri et al. (2019a)	Sub-field	Surface energy fluxes – a comparative study	Micrometeorological/ eddy covariance tower measurements	No difference in meteorological conditions between the flux towers in the north and south vineyards but there were statistically significant differences in surface fluxes. These differences in the surface fluxes can be largely explained by differences in leaf area index and soil moisture content.
Alfieri et al. (2019b)	Sub-field	Aerodynamic roughness parameters	3D wind profile from five levels and TSEB model output	A well-defined sigmoidal relationship was observed between aerodynamic roughness and wind direction The TSEB model is insensitive to variation in roughness parameters in the range evaluated in this study
Kustas et al. (2019b)	Sub-field	Partitioning ETa with TSEB model using flux tower data	TSEB model with tower-based LST data	TSEB output of daytime ETa yielded ~ 15% error with flux tower measurements. TSEB model overestimated T/ETa during the winter and spring through bud break, but then underestimated during the growing season
Nieto et al. (2019b)	Canopy to field	Partitioning ETa with TSEB model using UAV data	TSEB model with composite and component LST estimates from UAV imagery	A simple contextual algorithm yielded the closest agreement with EC flux tower measurements The utility in very-high-resolution remote sensing data for estimating ETa and E and T partitioning shows promise as a methodology for testing ETa partitioning methods

Table 1 (continued)

Paper	Scale	Main focus	Approach	Key finding
Aboutalebi et al. (2019)	Canopy to field	Shadow detection methods using UAV	TSEB model and shadow detection algorithm	Shadows had the greatest impact on modeled soil heat flux (G), and less on Rn and H; however, shadows impacted the Bowen ratio (H/LE) which is often used as an indicator of plant stress level
Knipper et al. (2019)	Sub-field to regional	Evaluate satellite-derived maps of ETa and the ratio of ETa-to-ETo (fRET)	Disaggregated atmosphere land exchange inverse (ALEXI/DisALEXI) thermal-based energy balance model	Comparisons with EC flux tower measurements indicate acceptable model performance, with mean absolute errors of ~0.6 mm/day in ETa and minimal bias; values of fRET were consistent with irrigation amounts; hence, 30-m resolution both daily ET and fRET provide spatial and temporal information useful for operational irrigation management of individual fields and vineyard blocks

decisions for improving yield and/or quality while improving water use efficiency for enhancing sustainability, these will greatly benefit grape and other perennial crop industries, many of which are grown in water limited regions. To start to address the development of application tools for vineyard water management, in 2018, the first test of the ETa data fusion toolkit for irrigation scheduling was applied to variable rate drip irrigation (VRDI) system at the Ripperdan Ranch and compared to a network of four EC tower measurements and to the vegetation index-based/crop coefficient approach. The objective of this project is to evaluate the capability of the data fusion toolkit to provide reliable 30-m resolution spatially distributed ETa and the ratio of ETa-to-ETo (fRET) commensurate to the 30-m VRDI grid for irrigation scheduling to improve water use efficiency through conservation, while maintaining yield and improving grape quality (via deficit irrigation) in comparison to current vegetation index-based/crop coefficient approaches. A publication summarizing this work is in preparation.

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