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EDITORIAL

From vine to vineyard: the GRAPEX multi-scale remote sensing experiment for improving vineyard irrigation management

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Abstract
This second special issue of the Grape Remote sensing Atmospheric Profile and Evapotranspiration eXperiment (GRAPEX) further advances and expands upon the initial research findings of the first GRAPEX special issue on the measurement and remote sensing of vine water use and stress. This is a highly collaborative and interdisciplinary experiment, which involves USDA-ARS scientists, industry, and university researchers. The large scope of this research has allowed the development of new measurement and remote sensing tools and techniques to quantify vine evapotranspiration, moisture status, and stress, with the ultimate goal of improving irrigation management in California vineyards.

Keywords Evapotranspiration · Remote sensing · Irrigation management · Eddy covariance flux towers · Unmanned aerial vehicles, vine water use · Vine water stress · Vine water status

Introduction

The major goal of GRAPEX is to test, refine, and apply a multi-scale remote sensing evapotranspiration (ET) toolkit for mapping crop water use and stress for precision irrigation management in California vineyards. To achieve this goal, the GRAPEX project involves measurements over a large spatial range. The most proximal involve leaf and canopy level gas exchange and water status measurements as well as network of point scale surface and root zone soil moisture measurements. Sub-field scale ranged from micrometeorological measurement techniques including eddy covariance and surface renewal to remote proximal sensing, using airborne platforms (both manned and unmanned), and ultimately satellite data, capturing spatial resolutions from centimeters to kilometers (see Fig. 1). Used collectively, these earth observations provided both greater fundamental understanding of soil–plant–atmosphere exchange processes of vineyard systems and a means to refine remote sensing-based retrieval of vine biomass, water use and stress.

The first GRAPEX special issue focused on understanding water and energy exchange from the vine and interrow systems through micrometeorological measurements above and below the vine canopy and surface energy balance modeling using remote sensing for a vineyard site in Sacramento County, CA. Through the support of a NASA Applied Sciences grant as well as continued support from USDA and E&J Gallo, GRAPEX validation sites were expanded both north to the coastal growing region in Sonoma County and south to Madera/Fresno Counties. This expansion resulted in a significant north–south climate gradient, different vine varieties, soil properties, topography, trellis systems, canopy size, water requirements, and management practices. Many of the manuscripts in the current special issue focus on analyses across these expanded sites.

Wine grape vineyards are a dominant agricultural feature in California's semi-arid landscape. They occupy 300,000 hectares, and their annual production is valued at ~ $6.5B, which further supports $120B in economic activity across the US. Wine grape production in the state is highly dependent on water resources that are rapidly decreasing due to

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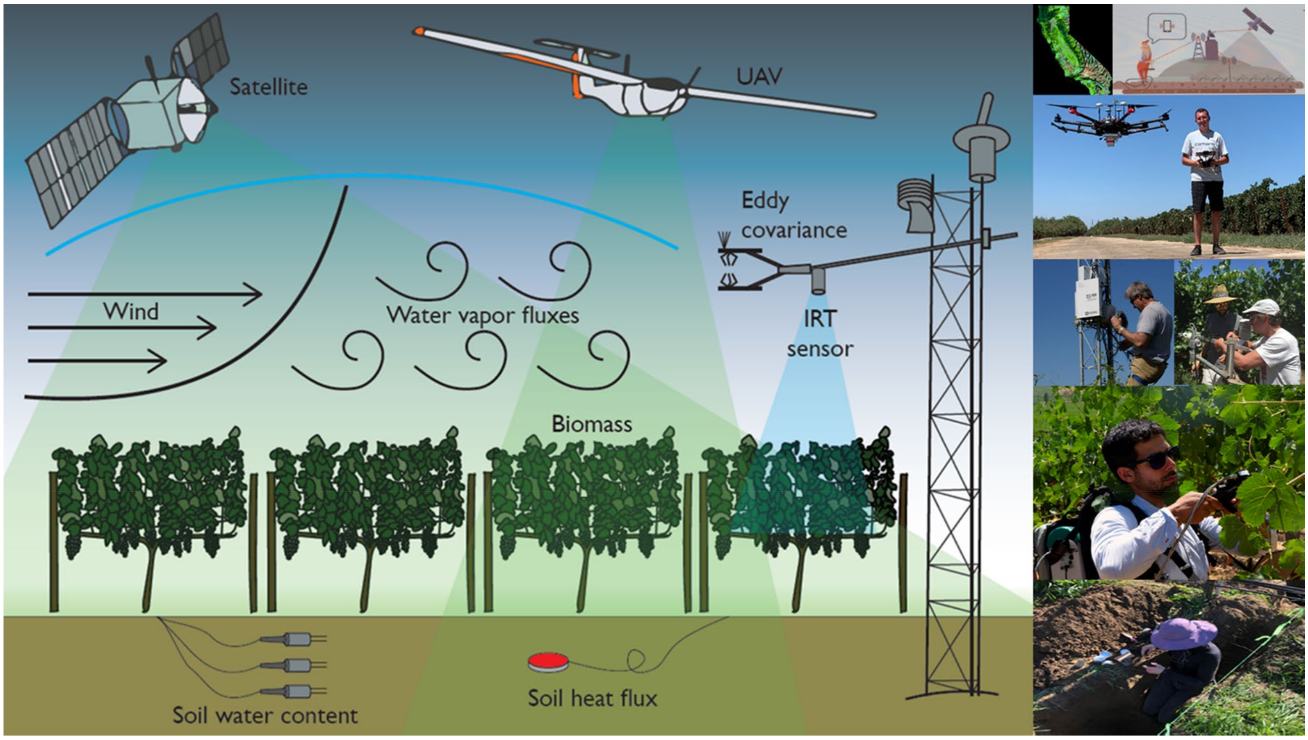

Fig. 1 A schematic illustration of GRAPEX measurements, highlighting the large range of spatial scales. At the point/leaf/canopy scale, they included soil moisture and soil heat flux and net radiation measurements, leaf water potential and gas exchange, interrow and canopy temperature measurements; and at the patch and subfield scale, they included eddy covariance-based momentum, water vapor, heat and carbon fluxes and leaf area index measurements. With remote sensing, UAV imagery spanned from canopy to field scale while satellite observations have a spatial resolution at the subfield to field, landscape and regional scales

increased demand from expanding agricultural production, a growing population, and more frequent and severe droughts. GRAPEX started in 2014, which was during a period of exceptional drought in California spanning 2011–2017 (https://www.drought.gov/california-no-stranger-dry-conditions-drought-2011-2017-was-exceptional). In fact, a recent study based on tree ring analysis indicates that California and most of the West are in a "megadrought" that began in 2000 and continues through 2022 (Williams et al. 2022); this 22+ year period ranks as the driest in at least 1200 years. In addition, increasing temperatures and related heat waves associated with anthropogenic climate change are exacerbating the impacts of droughts.

The impacts on reservoirs and groundwater resources have been severe in California and elsewhere in the West, and will require the use of technologies that can dramatically reduce water consumption by agriculture, the largest user of fresh water resources (~ 70%), while ensuring it remains sustainable and profitable. This is especially critical for perennial crops in California, which have significant front-end costs, supply 2/3 of the country's fruits and nuts and > 80% of the wine, and occupy over 3 M acres.

Management strategies vary considerably across California's wine growing regions due to varied grape yield, quality targets, and economic thresholds. Southern counties (i.e., Madera and Fresno) account for the largest share of the State's wine grape crush, while counties in the North Coast region (i.e., Sonoma and Napa) receive the highest average price per ton. Cabernet Sauvignon, for example, is the most widely planted red wine grape in the State, accounting for 15% of the total tonnage crushed. In District 13, which includes Madera county, growers received on average $436 per ton, while those in Sonoma and Napa received $2728 and $8082 per ton of Cabernet Sauvignon, respectively, for the 2021 harvest (NASS 2021). Through the GRAPEX project, we aim to provide water management tools for precision irrigation management that can address varying needs for grape growers in different regions.

One key to improving agricultural water management is the ability to determine actual crop ET. This information in turn can be used to determine how efficiently precipitation or water applied via irrigation are used by the crop to meet atmospheric demand and when conditions indicate the crop is under water stress. Mapping ET at subfield to landscape and regional scales requires the use of remote sensing. Development of reliable models for mapping vineyard ET is challenging due to non-uniform distribution of canopy biomass, a strong degree of vine clumping, and significant interrow spacing, which often includes a cover crop for reducing soil erosion and enhancing soil health. Modeling efforts face other difficulties including the effect of advection of hot dry air from surrounding fallow lands and pastures. During the summer months, these surfaces are essentially non-transpiring so that all the available energy goes into sensible heat, which is transported over vineyards causing additional atmospheric demand and increased ET. In this case, energy balance models can perform poorly when latent heat flux exceeds the available energy (i.e., net radiation less soil heat flux). This is challenging both to measure and model since the turbulent heat and water vapor fluxes are assumed to be transported vertically.

The collection of papers in this special issue applies remote sensing tools and models and micrometeorological measurements to better understand how the vine and interrow systems respond to atmospheric demand, utilize plant available water, and how they can be used to detect vine water status. The challenges posed by vine canopy architecture and wide interrow on modeling and measurement of water and energy exchange and the impact of advection as well as satellite retrieval of vine leaf area/fractional cover are investigated. Remote sensing from proximal, aerial, and satellite platforms with different spectral bands were utilized to detect vine stress conditions as well as sensitivity of spectral and thermal-based ET models to key input variables either from remote sensing retrievals (e.g., leaf area index) or atmospheric forcing (i.e., local versus regional meteorological inputs) for these vineyard landscapes. There are also papers estimating vineyard water balance for a more complete description of plant available water for irrigation scheduling. Finally, there are papers describing the potential of remote sensing information on vine leaf area index, ET, and vegetation indices used operationally for determining management zones and irrigation scheduling.

In the next section, we provide a brief overview of the papers and their major findings. While the research conducted under the GRAPEX project has advanced the application of remote sensing for monitoring vineyard ET and vine stress, challenges remain in the measurement of ET, particularly under strong advection conditions, the impact on turbulent transport from the vine canopy structure, and large interrow spacing. These vine characteristics also affect remote sensing retrieval of leaf area, add complexity in modeling fluxes caused by a cover crop understory, and make it significantly challenging to determine root zone soil moisture in drip irrigated vineyards, where extreme moisture gradients exist between the dry non-irrigated interrow and the frequently irrigated vine row.

A brief summary and highlights

This second GRAPEX special issue is divided into two volumes. The first volume is comprised of papers describing the measurement and modeling of vineyard ET and associated uncertainties and sensitivities of key model inputs and factors affecting micrometeorological measurements. In addition, there are new remote sensing ET model applications and refinements proposed. In the second volume, papers investigate the potential of remote sensing methods and models for deriving vine water status and stress, determine vineyard water balance and root zone soil moisture for irrigation scheduling. Finally, one paper attempts to utilize remote sensing to delineate vineyard management zones, while the other focuses on a near-real-time application of the remotely sensed ET modeling framework for irrigation scheduling in an operational vineyard. The key finding from these papers are described in Table 1.

In the first volume, the papers on micrometeorological observations discuss measurement uncertainties in the surface energy balance using eddy covariance and variation in the derived daily ET using different closure methods (Bambach et al. 2022a in Table 1). The results suggest that there can be significant differences in daily ET of up to 30% between closed and unclosed ET, and that factors such as the degree of advection can impact the ET uncertainty. Another paper by Bambach et al. (2022b) analyzes surface fluxes from a network of GRAPEX towers, representing a north–south climate gradient affected by climate, phenology and management. Based on the analysis, irrigation and other management practices likely tied to grape yield and quality targets played a key role in the differences observed in seasonal water use. Also evaluating fluxes in the vineyards, Alfieri et al. (2022) used a profile of sonic anemometers above the vine canopy to describe characteristics of the vertical structure of turbulence. They found that this differed significantly from other cropping systems because of the wide row spacing and non-uniform distribution of vine biomass concentrated in the upper part of the canopy. This in turn was shown to affect algorithms estimating near-surface wind profile for aerodynamic resistance used in remote sensing ET models, which may require modification when applied to vineyards for more accurate heat flux estimation.

There are several papers focused on evaluating the sensitivity of thermal and spectral-based ET models of key inputs. The paper by Bhattarai et al. (2022) evaluates the sensitivity of modeling domain and meteorological forcing data on daily ET estimates from the Shuttleworth–Wallace model using Sentinel-2 surface reflectance data over the three vineyard regions. They found that the modeling domain had a marginal effect on ET estimates, but that meteorological forcing provided by regional weather models significantly degraded model ET performance.

Table 1 List of the 20 papers published in GRAPEX second special issue, highlighting their key topics and findings

First volume—application, uncertainties and sensitivities in the measurement and remote sensing of vineyard ET

	Paper	Title	Key topic	Key finding
1	Bambach et al. (2022a)	Evapotranspiration uncertainty at micrometeorological scales: the impact of the eddy covariance energy imbalance and correlation methods	Uncertainty in eddy covariance/energy balance estimate of ET due to closure method and environmental conditions	Different approaches designed to address energy imbalance can lead to uncertainty in daily observed ET estimates of up to 50%, underscoring the importance of recognizing the limitations on micrometeorological observational techniques for field monitoring and model validation
2	Bambach et al. (2022b)	Inter-annual variability of land surface fluxes across vineyards: the role of climate, phenology, and irrigation management	Variation in vineyard water use due to climate, vine variety and management using flux tower network	Daily, seasonal, and inter-seasonal surface flux patterns and relationships across vineyards in three distinct California wine production regions show significant differences in ET related to a combination of canopy size, atmospheric demand, irrigation inputs, as well as management practices
3	Alfieri et al. (2022)	The vertical turbulent structure within the surface boundary layer above a vineyard in California's Central Valley during GRAPEX	Impact of vine structure on turbulent exchange and flux–gradient relationships used in remote sensing-based energy balance models	Turbulent structure over a vineyard is strongly influenced by the underlying canopy, and as such, surface energy balance modeling via remote sensing may require modifications to reliably estimate vine ET
4	Bhattarai et al. (2022)	Influence of modeling domain and meteorological forcing data on daily evapotranspiration estimates from a Shuttleworth–Wallace model using Sentinel-2 surface reflectance data	Sensitivity of key inputs to the satellite-based ET model using spectral data from Sentinel-2 and Shuttleworth–Wallace model	The source and quality of meteorological forcing data, in particular vapor pressure deficit and wind speed, have a strong influence on model output, suggesting that simple regression for local bias correction will improve model performance
5	Doherty et al. (2022)	Effects of meteorological and land surface modeling uncertainty on errors in wine grape ET calculated with SIMS	Impact of uncertainty in weather data used in operational SIMS ET model	Relative error contribution from meteorological inputs versus SIMS varies across sites, while biases also correlate with time of year and vary in space, underscoring the importance of characterizing spatial uncertainty in meteorological forcing of ET
6	Kang et al. (2022)	Evaluation of satellite Leaf Area Index in California vineyards for improving water use estimation	Impact of LAI retrieval on TSEB ET estimates and E and T partitioning	TSEB ET is more sensitive to positive LAI biases than negative ones and even when of minimal changes of ET are reported, soil evaporation and plant transpiration respond to LAI change divergently
7	Aboutalebi et al. (2022)	Downscaling UAV Land Surface Temperature using a Coupled Wavelet-Machine Learning-Optimization Algorithm and its impact on evapotranspiration and energy balance components estimated by the TSEB model	Improving the accuracy of thermal sharpening using UAV imagery and impact on TSEB ET	The proposed sampling algorithm significantly accelerated the computation time for the UAV temperature sharpening efforts while also offering improved parameter estimation for input into the TSEB model

Table 1 (continued)

	Paper	Title	Key topic	Key finding
First volume—application, uncertainties and sensitivities in the measurement and remote sensing of vineyard ET				
8	Kustas et al. (2022)	Impact of advection of Two-Source Energy Balance (TSEB) canopy transpiration parameterization for vineyards in the California Central Valley	Evaluating transpiration algorithms in TSEB to account for advection causing enhanced ET	Performance of the original transpiration algorithm in TSEB is satisfactory in all but the most extreme advective conditions, while a transpiration algorithm based on Shuttleworth–Wallace performs well in all cases
9	Burchard-Levine et al. (2022)	Application of a remote sensing three-source energy balance model to improve evapotranspiration partitioning in vineyards	Revising TSEB model to explicitly partition vineyard ET between interrow cover crop and vine ET	The three-source energy balance model improved estimates of ET over the vineyard of study, while also improving the partitioning of individual E and T fluxes when compared against the original two-source energy balance model
10	Xue et al. (2022)	Improving the spatiotemporal resolution of remotely sensed ET information for water management through Landsat, Sentinel-2, ECOSTRESS and VIIRS data fusion	Improving the frequency of satellite-based daily ET observations for capturing ET dynamics	Augmenting additional thermal-based sensors demonstrates value added to operational capabilities in monitoring daily ET variability and reducing latency for real-time applications
11	Safre et al. (2022)	Performance of Sentinel-2 SAFER ET model for daily and seasonal estimation of grapevine water consumption	Evaluating a satellite-based ET model using Sentinel-2 data for vineyards	The proposed SAFER ET algorithm once calibrated, using Sentinel-2 imagery, produced satisfactory ET estimates when validated, however the model had difficulty capturing stress conditions
Second volume—remote sensing methods for monitoring vine water status and stress, root zone soil moisture and management applications				
12	Davitt et al. (2022)	The complementary uses of Sentinel-1A SAR and ECOSTRESS datasets to identify vineyard growth and conditions: a case study in Sonoma County, California	Combining satellite Sentinel radar with ECOSTRESS thermal to assess vine conditions	Sentinel-1A SAR dual-polarization backscatter measurements can provide indications of vine leaf volume and moisture state that can be related to LST and ET measurements
13	Wong et al. (2022)	Detecting short-term stress and recovery events in a vineyard using tower-based remote sensing of photochemical reflectance index (PRI)	Evaluating the potential of photochemical reflectance index (PRI) for detecting vine stress	Photochemical reflectance index is effective at tracking the short-term stress-induced declines and recovery of GPP associated with soil water depletion and increased air temperature, as well as reductions in GPP from decreased PAR caused by smoky conditions
14	Nieto et al. (2022)	Evaluating different metrics from the thermal-based two-source energy balance model for monitoring grapevine water stress	Potential for deriving reliable vine stress metrics from thermal-based two-source energy balance (TSEB) model	The most robust variable to track water stress is the TSEB-derived leaf stomatal conductance, while metrics acquired early afternoon are better at tracking stress
15	Tang et al. (2022)	Vine water status mapping with multispectral UAV imagery and machine learning	Detecting vine leaf water potential using UAV imagery with machine learning	Proposed UAV-based aerial multispectral imaging reliably estimated leaf water potential across space and time, offering a scalable tool to facilitate data-driven precision irrigation

Table 1 (continued)

Second volume—remote sensing methods for monitoring vine water status and stress, root zone soil moisture and management applications

	Paper	Title	Key topic	Key finding
16	Gao et al. (2022)	LAI estimation across California vineyards using sUAS multi-seasonal multispectral, thermal, and elevation information and machine learning	Improving remote sensing-based LAI retrieval with machine learning and impact on TSEB-derived ET	A proposed hybrid machine learning technique (Random Forest and Relevance Vector Machine) adequately models LAI with few input variables and the utilization of these LAI estimates within the TSEB model results in improved performance of the model
17	Kisekka et al. (2022)	Spatial–temporal modeling of root zone soil moisture dynamics in a vineyard using machine learning and remote sensing	Modeling root zone soil moisture using machine learning with soil moisture measurements and remote sensing of ET	Strong correlations exist between in situ measured soil moisture and random forest generated soil moisture, demonstrating its ability to predict spatially distributed RZSM when using ground measurements and remote sensing as input
18	Chen et al. (2022)	Application of the vineyard data assimilation (VIDA) system to vineyard root zone soil moisture monitoring in the California Central Valley	Soil moisture/water balance modeling using thermal-based ET, radar soil moisture and data assimilation	VIDA generally captures daily temporal variations in root zone soil moisture (RZSM) and the assimilation of remote sensing products produces modest improvement in the temporal accuracy of VIDA RZSM estimates
19	Ohana-Levi et al. (2021)	Time-series clustering of remote sensing retrievals for defining management zones in a vineyard	Using time-series clustering techniques with remote sensing retrievals of LAI and ET for identifying management zones	Management zones using time-series clustering with LAI as input achieve the best cluster separation, while yield values within each management zone were significantly different, suggesting management practices based on these zones may be beneficial from a precision agriculture perspective
20	unpublished	Evaluation of a remote sensing-based toolkit to monitor vine water use and stress for irrigation scheduling: a case study in Sonoma Valley, California	Evaluating the utility of near-real-time satellite-based actual ET for making irrigation scheduling decisions	Remote sensing techniques were effective in capturing vine water use and water status and remote sensing-based irrigation recommendations were similar to those made by highly skilled vineyard managers

Papers are listed according to their order in the two volumes of the special issue

However, nominal calibration (simple regression) of the CIMIS weather station data (used in California for estimating potential or reference ET) closest to the vineyard site for local meteorological conditions yielded very similar results to using the local flux tower meteorological observations. In a similar study, Doherty et al. (2022) examines how uncertainty in atmospheric meteorological forcing data and land surface conductance contribute to uncertainty in ET estimation from the Satellite Irrigation Management Support (SIMS) model that uses reflectance data. The uncertainty in meteorological forcing is found to be a major contributing factor to errors in SIMS ET estimation while improvement in the land surface conductance algorithm can also be a significant source of error. The other two papers evaluate the impact of remote sensing retrieval of leaf area index on surface energy balance and ET estimation using the thermal-based two-source energy balance (TSEB) model. Kang et al. (2022) used a satellite version of TSEB and found that a positive bias in LAI could cause a comparable change in ET, while negative biases lead to much lower deviations in ET. However, even when changes were minimal in ET, the partitioning of ET into transpiration and soil evaporation by TSEB was adversely affected. This points to a real need in obtaining accurate LAI for vineyards, especially if trying to separate vine transpiration from interrow evaporation. From unmanned aerial vehicle (UAV) imagery, Aboutalebi et al. (2022) generated a reliable LAI product using machine learning and used TSEB to derive canopy and soil temperatures that yielded significant improvements in ET.

There are two papers on modifications to TSEB for this vineyard environment using local measurements. The paper by Kustas et al. (2022) investigates the application of the TSEB model, using local observations in a vineyard having significant advection. Four versions of the transpiration algorithm in TSEB are applied and evaluated with tower eddy covariance. The results suggest the performance of the original transpiration algorithm based on Priestley–Taylor used in TSEB is satisfactory in all but the most extreme advective conditions, while a transpiration algorithm based on Shuttleworth–Wallace with a canopy resistance formula performs well in all cases. The other manuscript by Burchard-Levine et al. (2022) applies a three-source energy balance (3SEB) model, which adds a vegetation source to TSEB to explicitly consider the understory cover crop. Results indicate that 3SEB improved upon TSEB ET estimates with the largest differences being concentrated in the spring, when there is greater mixing between grapevine foliage and the cover crop. Moreover, the 3SEB-modeled ET partitioning (i.e., T/ET) compared well against an eddy-covariance-based T/ET retrieval method, suggesting the potential to improve T/ET estimations and to quantify the contribution of the cover crop to ET.

Satellite-based ET methods applied to the vineyard sites were also evaluated. The paper by Xue et al. (2022) investigated the utility of a data fusion method combining thermal-IR from multiple medium-resolution sensors for generating high spatiotemporal resolution ET products for better capturing ET dynamics. The thermal-IR data from Landsat and NASA's ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and NOAA's Visible Infrared Imaging Radiometer Suite (VIIRS) are sharpened to a common 30-m grid and used to create daily, 30-m ET image time-series. Results demonstrate the operational value of incorporating a suite of TIR sensors compared to Landsat alone for capturing daily ET variability. The other study by Safre et al. (2022) evaluates the utility of the Simple Algorithm for Evapotranspiration Retrieving (SAFER) to estimate daily and seasonal ET using Sentinel-2 images with 10 m spatial resolution and 5-day revisit time. Once calibrated, the model provides satisfactory vineyard daily ET; however, SAFER has difficulty capturing vine stress conditions, which needs to be improved if it will be used for irrigation management.

Findings in this first volume highlight challenges in measuring and modeling ET in vineyard systems, which often have a vegetated understory, a complex canopy architecture and are managed quite differently depending on grape yield and quality targets. The uncertainties in the measurement and modeling of vineyard ET are presented along with some potential solutions in dealing with the unique canopy structure affecting remote sensing retrievals of key inputs (i.e., leaf area index) and addressing advection effects on ET and partitioning of E and T from interrow and vine canopy systems. Clearly, more work is needed to improve the meteorological inputs to some of the remote sensing models. There are also opportunities presented to incorporate both thermal and spectral-based approaches to improve the frequency of ET estimates to better capture the dynamics of irrigation and stress that can occur rapidly during hot summer months in combination with strong heat advection from surrounding fallow areas.

In the second volume, several studies focused at the plant level to derive vine water status and more accurate leaf area estimates, a key input in many ET modeling applications. Most of these investigations use different remote sensing wavebands than traditional visible/near-infrared and thermal-IR bands on Landsat. There are two papers on estimating vine root zone soil moisture, which is needed to determine initiation of springtime irrigation and during the peak period of vine growth, to control biomass accumulation prior to grape development. Finally, there are two studies investigating the potential of using remote sensing products for defining vine management zones and using actual ET to schedule irrigation.

In the first group of papers, Davitt et al. (2022) use ECOSTRESS and the European Space Agency's Sentinel-1A/B synthetic aperture radar (SAR) satellites to investigate their utility in monitoring vine condition. The results suggest that Sentinel-1A SAR backscatter can provide indications of vine leaf volume and moisture state that is correlated to ECOSTRESS land surface temperature and potentially ET from remote sensing. This approach provides useful information for vineyard management. Wong et al. (2022) explores the capability of the photochemical reflectance index (PRI) from a tower-based sensor to track variations of eddy covariance estimated gross primary productivity (GPP) during four stress events. Compared to the Normalized Difference Vegetation Index (NDVI), which was invariant during stress events, PRI was effective at tracking the short-term stress-induced declines and recovery of GPP associated with soil water depletion, increased air temperature, and decreased PAR caused by smoky conditions from regional wildfires. The study by Nieto et al. (2022) evaluated different TSEB output metrics related to its estimates of actual ET, transpiration and stomatal conductance, to track vine water stress. These TSEB output metrics were compared to root zone soil moisture, stomatal conductance and leaf/stem water potential measurements collected within the experimental vineyard. They found the TSEB derived leaf stomatal conductance of greatest utility for tracking water stress, as it had the best correlation with both the measured root zone soil moisture and gas exchange measurements of stomatal conductance. Tang et al. (2022) using UAV multispectral imagery and machine learning found that air temperature, vapor pressure deficit, and red edge indices such as the normalized difference red edge index (NDRE) are the most important variables in estimating spatial and temporal variability in leaf water potential. Maps of the estimated leaf water potential yielded patterns that were consistent with irrigation management and variations observed from the ground measurements. Gao et al. (2022) used a machine learning approach to improve LAI estimation in vineyards. They showed estimated ET and E and T partitioning using TSEB is improved when applying these new approaches.

For root zone soil moisture (RZSM) estimation, the study by Kisekka et al. (2022) compared two models: (1) a remote sensing-based approach, pySEBAL and EFSOIL; and (2) a data-driven model based on machine learning. The pySEBAL and EFSOIL approach was unable to reliably predict RZSM at all monitored locations, while the machine learning model trained with in situ soil moisture data combined with meteorological, soil properties, EF (evaporative fraction), and a vegetation index has the potential to estimate spatially distributed RZSM combined with remote sensing information. Chen et al. (2022) applied the Vineyard Data Assimilation (VIDA) system for soil water balance modeling which is complicated by inaccurate or unavailable irrigation inputs and complex sub-surface water-flow processes within vineyards. VIDA is based on the assimilation of high-resolution (30-m) soil moisture information obtained from synthetic aperture radar and thermal-infrared remote sensing into a one-dimensional soil water balance model. It is shown that VIDA can generally capture daily temporal variations in RZSM beneath the vine row; however, results also reveal shortcomings in the ability of VIDA to correct biases in assumed irrigation applications—particularly during well-watered portions of the growing season when thermal-based ET from TSEB are not moisture limited and, therefore, decoupled from RZSM.

The last two papers describe the application of remote sensing products for operational applications in vine management. Ohana-Levi et al. (2021) applied an approach for generating management zones using time-series clustering to enable time-specific management. It is found that time-series clustering using remotely sensed LAI achieved the best cluster separation related to the yield maps, while ET showed weaker similarities to NDVI and LAI. Thus, time-series clustering with remote sensing information has potential to define within-field spatial variability and temporal dynamics for precision irrigation applications. Unfortunately, the paper applying satellite remote sensing retrievals of NDVI for vine biomass and Normalized Difference Infrared Indices for vine water content along with satellite-based actual ET from TSEB to prescribe irrigation scheduling recommendations could not be included in this special issue due to extenuating circumstances and will published at a later date. However, it is a seminal paper that warrants being highlighted in this introduction to the special issue. They found that remote sensing products effectively captured vine water use and water status throughout the season, and the remote sensing-based irrigation recommendations resulted in similar values to those of a highly skilled vineyard manager with no significant changes in vine growth, yield or quality when comparing both approaches. These results suggest that remote sensing can be used to provide reliable irrigation recommendations, and with satellites, this information has the potential to be applied routinely over large areas consisting of multiple vineyards and with little ground observations requiring highly skilled vineyard personnel.

This review of the special issue papers reveals that more of the theoretical work is done at the point/field scale, but there are also theoretical papers at the satellite resolution. This is illustrated as a two-dimensional schematic in Fig. 2 indicating for each paper, the level of theoretical to practical application versus the spatial scale from point to satellite being addressed. Interestingly, across most of the spatial scales, there are papers that cover theoretical work to more practical application. This speaks to the richness and diversity of the data being collected and the potential for more analyses that can be conducted with the GRAPEX data set.

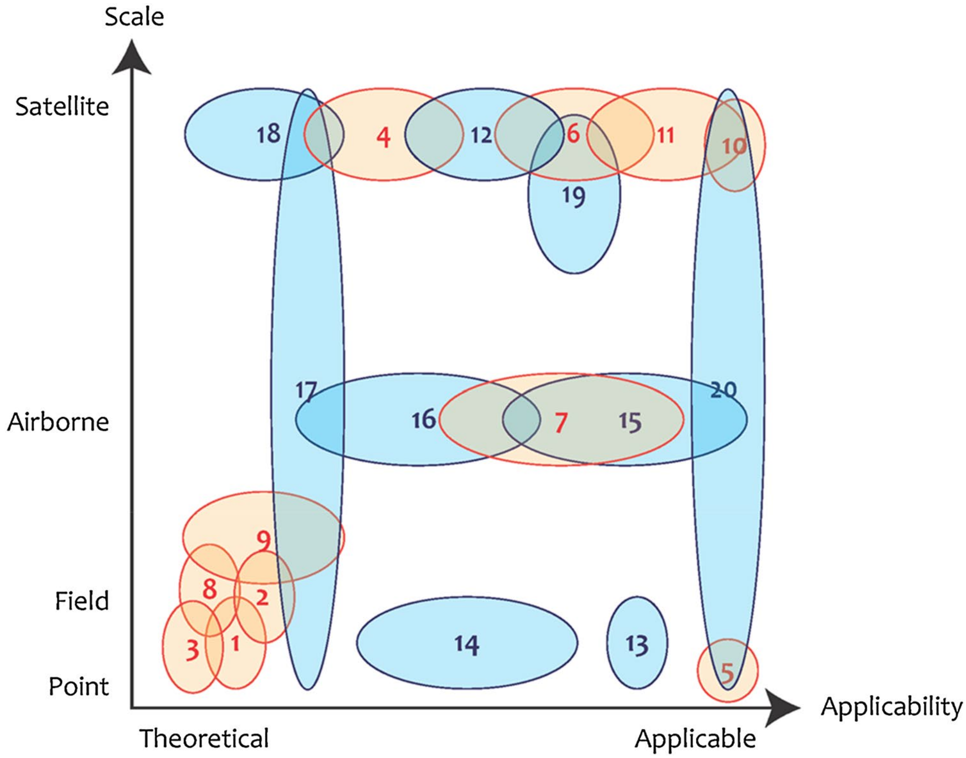

Fig. 2 Papers contributed to this special issue depicted in a two-dimensional schematic. This illustrates the level of theoretical versus practical application (x-axis) and the range in spatial scales from point to satellite addressed in each study (y-axis). The number in each oval corresponds to the manuscript number listed in Table 1, and peach and blue ovals represent papers from volume 1 and volume 2, respectively

Notable are the papers by Kisekka et al. 2022 and unpublished 20 that span the full spatial scale at the theoretical and practical end of the spectrum, respectively. This highlights the potential for combining remote sensing data with ground observations to bridge scales from plant to landscape and region.

Concluding remarks

There is great potential to integrate the different remote sensing technologies and modeling approaches evaluated in this special issue. Establishing the uncertainty in ground validation data (eddy covariance) is critical to interpreting whether modifications and adding complexity to ET models is warranted. Revisions to existing modeling approaches (TSEB), improvements in key inputs (LAI), and the synergy of using multiple remote sensing platforms and wavebands from visible, near infrared, thermal and microwave all need more research and development. There is clearly potential for operational application of remote sensing to identify management zones, identify areas of stress, and to schedule irrigation over large areas using satellites. A major hurdle is how to transfer this information and make it useful in making management decisions for the individual grower. OpenET (Melton et al. 2022) is a project that is making progress in this arena and may be a blueprint for expanding beyond ET data to also host information related to root zone soil moisture, vine water status, and yield for improving vineyard management decisions. While GRAPEX is focused primarily on vineyards, these tools will also have application to fruit and nut orchards and other crops with highly structured canopies. As such, we recently initiated efforts to apply these approaches to nut tree crops in a new project called T-REX (Tree crop Remotely sensed Evapotranspiration eXperiment). Please stay tuned for work emerging from the T-REX project.

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Declarations

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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