



Comparison of a stand-alone surface renewal method to weighing lysimetry and eddy covariance for determining vineyard evapotranspiration and vine water stress

Christopher K. Parry¹ · Thomas M. Shapland² · Larry E. Williams^{2,3} · Arturo Calderon-Orellana^{2,4} · Richard L. Snyder⁵ · Kyaw Tha Paw U⁵ · Andrew J. McElrone^{1,2} 

Received: 22 May 2018 / Accepted: 6 March 2019 / Published online: 16 October 2019
© Springer-Verlag GmbH Germany, part of Springer Nature 2019

Abstract

Surface renewal (SR) is a biometeorological technique that uses high-frequency air temperature measurements above a plant canopy to estimate sensible heat flux. The sensible heat flux is then used to estimate latent heat flux as the residual of a surface energy balance equation. SR previously relied on calibration against other methods (e.g., eddy covariance) to obtain accurate measurements of sensible heat flux, and this need for calibration limited the use of SR to research applications. Our group recently showed that compensating for the frequency response characteristics of SR thermocouples causes the calibration factor to converge near the theoretically predicted value of 0.5 (Shapland et al., *Agric For Meteorol* 189:36–47, 2014). This led to the development of an inexpensive, stand-alone SR system to measure sensible heat flux without the need for calibration, and here we evaluated the SR system in a mature vineyard containing a weighing lysimeter. Vineyard evapotranspiration (ET) measured with SR was strongly and positively correlated with that from the lysimeter, eddy covariance, and a soil water budget approach. ET measured with the various techniques responded similarly to changes in the microclimatic conditions (i.e., day to day variability) and when water was withheld from the entire vineyard for an extended period. A stress index, calculated using reference and actual ET from SR and lysimetry, was correlated to leaf water potential, stomatal conductance, and volumetric soil water content measurements, but some of these relationships were more variable than others. Our results suggest that the new SR method could potentially be used as a low-cost tool to provide growers with field-specific estimates of crop water use and stress for irrigation management in vineyards.

Communicated by L. Testi.

Christopher K. Parry and Thomas M. Shapland contributed equally to this work.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s00271-019-00626-6>) contains supplementary material, which is available to authorized users.

✉ Andrew J. McElrone
ajmcelrone@ucdavis.edu

¹ USDA-ARS Crops Pathology and Genetics Research Unit, Davis, CA 95616, USA

² Department of Viticulture and Enology, University of California, Davis, CA 95616, USA

³ Kearney Agricultural Research and Extension Center, 9240 S. Riverbend Ave, Parlier, CA 93648, USA

⁴ Department of Engineering and Soils, Faculty of Agricultural Sciences, University of Chile, Santiago, Chile

⁵ Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA

Introduction

Much of the Western United States has suffered recently from extended, severe drought, and competing needs of municipal, industrial, environmental and agricultural entities for the limited water supply have exacerbated a pre-existing water scarcity issue across this region. Similar water scarcity conditions threaten agriculture in many growing regions worldwide. The constant threat of water scarcity in California will require growers to use water judiciously, and new technologies and irrigation strategies are needed for informed management of water resources.

Deficit irrigation is a common management practice used to improve fruit quality in commercial vineyards (Williams and Matthews 1990). The implementation of deficit irrigation practices requires reliable estimates of crop water requirements. Irrigation requirements based on actual crop evapotranspiration (ET_a) have been commonly estimated using the following equation:

$$ET_a = K_s \times K_c \times ET_o = K_s \times ET_c \quad (1)$$

where K_s is the water stress coefficient, K_c is the crop coefficient, and ET_o is reference evapotranspiration of a well-watered reference crop surface (usually grass or alfalfa) under similar climatic conditions (Allen et al. 2005). The coefficient K_c is calculated from the ratio of ET_c/ET_o , where ET_c is well-watered crop evapotranspiration measured with lysimeters (Bryla et al. 2010), soil water budgeting (Williams 2014), eddy covariance, or other biometeorological methods, and ET_o is estimated using a standardized equation (Allen et al. 2005, 2006). K_s is assumed to be 1 for the well-watered crop. In field situations, where lysimeters and these other methods are not available, the K_c can be estimated from various semi-empirical models that can use the fraction of shaded area (also referred to as fraction of canopy cover) beneath the crop (Williams and Ayars 2005; López-Urrea et al. 2012; Picón-Toro et al. 2012), leaf area index (Allen et al. 1998; Williams et al. 2003a, b), or cumulative degree days (Williams 2014). Although the K_c and ET_o are relatively simple to apply in commercial agricultural production, this approach may lack accuracy compared to direct measurements (Jones 2004). According to English et al. (2008), common errors in ET_c estimates can arise from: (1) microclimatic variability between sites where ET_o and ET_c are measured; (2) uncertainty of ET_o estimations due to poorly established or maintained ET_o stations; and (3) uncertainty of published K_c values due to differences in aerodynamic resistance and agronomic conditions between crops used to measure ET_o and ET_c . Additionally, ET_c uncertainties can arise from biometeorological measurement techniques. The method described by Eq. 1 is used widely for estimating ET_a , but inaccuracies in ET_c estimates and errors in estimating water and salinity stress impacts on ET_a can result in over- or under-estimation of irrigation needs. Due to the difficulty to accurately measure salinity and water stress effects on ET_a , a direct measurement of ET_a with relatively low-cost methods, e.g., surface renewal, is desirable.

Surface renewal (SR) is a biometeorological technique that has been used to accurately measure site-specific sensible heat flux (H) in various plant canopies (Paw U and Brunet 1991; Suvocarev et al. 2014), including vineyards (Shapland et al. 2012a; Castellví and Snyder 2010b), alfalfa (Hanson et al. 2007), wheat, sorghum (Spano et al. 1997), lettuce (Gallardo et al. 1996), citrus (Castellví et al. 2012), and rice (Linquist et al. 2015). The SR technique estimates energy fluxes of air parcels that transiently reside within a crop canopy during the turbulent exchange process (Paw U et al. 1995). When SR is used to measure H , one can estimate LE using the residual of the energy balance equation:

$$LE = R_n - G - H \quad (2)$$

where R_n and G are the measured net radiation and ground heat flux density, respectively, for the same time interval as

used for the SR estimates of H . The SR technique involves measuring high-frequency temperature data with fine-wire thermocouples and analyzing the temperature traces using structure functions to identify mean ramp characteristics (amplitude and ramp duration) of a sampling period. Then, the mean ramp characteristics are used to estimate sensible H using a conservation of energy equation. While the technique gave estimates of uncalibrated SR H (H') that were highly correlated with sonic anemometer H values, calibration was required to yield accurate measurements. Calibration was accomplished with least squares regression of H versus H' , and the slope of the regression line through the origin (α) was used to estimate H as: $H = \alpha H'$. The “eddy covariance” estimate of LE (LE_{EC}) in this paper was calculated using the residual of the energy balance equation (Eq. 2) and H measured with a sonic anemometer.

Recent advances in the SR technique (Shapland et al. 2012b, c, 2014) have simplified the SR estimation of H , and potentially eliminates the need for complex and expensive equipment (i.e., sonic anemometer) for calibration using the eddy covariance method. Shapland et al. (2014) demonstrated that the α converges close to the theoretical value of 0.5 when fine-wire thermocouples are compensated for their frequency response characteristics. These recent advances enable the application of the residual of the energy balance calculations with compensated SR estimates of H for determining LE and hence ET of various crops in commercial settings.

For irrigation management, growers require information about crop ET, but also when to apply it based on plant stress thresholds. In theory, plant stress can be detected with SR or other similar techniques by solving for the stress component in Eq. 1. Mild water stress can inhibit growth that reduces canopy development and ET_a drops below ET_c in the long term, i.e., weeks or months, due to smaller canopy development relative to a crop exposed to no stress. Under moderate to severe water stress, ET_a drops below ET_c when the crop cannot keep up with atmospheric demand, leaf stomata partially close, and transpiration is reduced. Because varying levels of water stress reduce ET_a through different mechanisms, it is difficult to determine the K_c and K_s factors for crops like wine grapes that are exposed to a full range of stress within a growing season. Because of the inability to differentiate the long- and short-term stress effects on the ET_a calculation in Eq. (1), the use of SR to measure ET_a in situ is clearly advantageous for determining crop water use. Supporting this idea, strong correlations between mid-day values of leaf water potential (Ψ_{LEAF}) and stomatal conductance (g_s) with the ET_a/ET_o ratio were reported by Williams et al. (2012) for full-canopy grapevines growing in a weighing lysimeter. Similarly, a previous work with both SR and EC also has shown that a crop stress index decreases when a field has insufficient water to keep up

with atmospheric demand (e.g., Snyder et al. 2006, Shapland et al. 2012a). More work is needed to validate different stress indicators obtained from SR measurements.

While several studies have tested SR against eddy covariance and lysimetry for a variety of crop surfaces, evaluation of the new uncalibrated SR method against these standard methods has yet to be reported despite the fact that commercial sensors are now available to farmers. Also, as described above, Williams et al. (2012) suggested that stressed-induced changes in ET could be used to track water status of grapevines, but would require cost-effective, real-time measurements of ET_a in commercial vineyards. No studies have tested how well this would work using various manipulations of plant water stress and stomatal control of transpiration. To address these needs, we used a 25-year-old *Vitis vinifera* L. (cv. Thompson Seedless) table grape vines in a weighing lysimeter surrounded by an experimental vineyard, and made comparisons of daily water use measured with SR (ET_{SR}), eddy covariance (ET_{EC}), weighing lysimetry (ET_{LYS}), and estimated ET_c (Eq. 1). In addition, we derived a stress index from SR (ET_{SR}/ET_c) and compared it to Ψ_{LEAF} and g_s measurements. If effective, the improved SR technique could provide a cost-effective and site-specific estimate of ET and crop stress for a variety of crops for irrigation management decisions.

Methods

This study was conducted in a 1.4 ha vineyard containing a weighing lysimeter at the University of California, Kearney Agricultural Research and Extension (KARE) Center near Parlier, California (36°48'N, latitude 119°30'W, longitude). The vineyard was planted with *Vitis vinifera* L. cv. Thompson Seedless (clone 2A) grapevines in 1987 with in-row vine spacing of 2.15 m and between row spacing of 3.51 m, and rows oriented approximately east to west. A detailed description of the lysimeter is available in Williams et al. (2003a) and Williams and Ayars (2005). Briefly, two Thompson Seedless grapevines were planted in the 2 × 4 × 2 m deep lysimeter when the surrounding vineyard was planted. The trellis of the vines used in the study consisted of a 2.13 m wooden stake driven 0.45 m into the soil at each vine. A 0.6 m cross-arm was placed atop the stake and wires attached at either end of the cross-arms to support the vine's fruiting canes. Vines in the lysimeter and the surrounding vineyard were head trained and cane pruned. The top of the canopy was at about 2.0 m during the mid-season period. Vines within the lysimeter were irrigated at 100% of ET_c with irrigations taking place whenever 16 L was lost from the lysimeter (8 L vine⁻¹), except during a few mid- to late-season dry-down periods, it was assumed the vineyard was irrigated to avoid

inducing water stress during most of the season in both years. Therefore, $K_s = 1.00$ and $ET_a = ET_c$ in Eq. (1).

Irrigation requirements for the vineyard surrounding the lysimeter were estimated using Eq. 1. Reference ET (ET_o) was obtained from the California Irrigation Management Information System (CIMIS) weather station (#39) at the KARE Center. Previously published seasonal K_c values as a function of degree days using the sine method with a lower threshold of 10 °C after March 15th were used in these calculations (per Williams et al. 2003a, b); the original temperature data used in calculating degree days were captured at the same #39 CIMIS station and obtained from the University of California Statewide Integrated Pest Management Project's website. The previous week cumulative ET_c was determined on Mondays, and that information was used to determine the application amount for three or four irrigation events during the coming 5-day work week. The mean ET_o from the previous 7 days was used for the ET_c calculation. The crop coefficients used to irrigate the vineyard surrounding the lysimeter started at 0.92 on 29 June (day of year-[DOY]-181) in 2012, increased to 0.95 on 15 July (DOY 197) and reached a maximum of 0.96 on 22 July (DOY 204) and remained at that level throughout the remainder of the season. The crop coefficients used to irrigate the vineyard were 0.90 on 10 June (DOY 161) and increased to 0.96 on 8 July (DOY 189) in 2013 where it maxed out and remained such thereafter. Irrigations to the vineyard surrounding the lysimeter were terminated during the same time frames that water was withheld from the lysimeter as mentioned above. In 2013, the last irrigation of the vines in vineyard surrounding the lysimeter for the first dry-down period occurred on 18 August (DOY 230), while that to the vines in the lysimeter occurred on 15 August (DOY 227). Irrigation resumed on 26 August (DOY 238) for both the lysimeter and vines surrounding the lysimeter. Irrigation was terminated on 6 September (DOY 249) to the vineyard to facilitate harvest. Irrigation resumed on 19 September (DOY 262) after mid-day Ψ_{LEAF} was measured. Applied water was measured with water meters positioned between the riser and the drip line of each row (20 rows 2012 and 7 rows 2013) ensuring that the water meters were located down rows in which soil water content was measured.

In an additional attempt to alter vineyard ET, a synthetic abscisic acid (ABA) (Protone SG, s-abscisic acid, 20% wt./wt., Valent USA Corporation, Walnut Creek, CA) was sprayed on the vines in the lysimeter and the surrounding vineyard on 4 October in 2012 (DOY 278) to induce stomatal closure and reduce vine transpiration. The amount of Protone SG applied was 1070 g ha⁻¹ in a spray volume of 1867 L ha⁻¹ resulting in an application rate of 0.81 g active ingredient per vine. Latron B-1956 (J.R. Simplot Company, Lathrop, CA) was used as an adjuvant.

SR was used to determine evapotranspiration (ET_{SR}) from approximately mid-June to mid-September for 2012 and 2013. A micrometeorological flux tower was established in the study vineyard using standard methods (see additional details in McElrone et al. 2013; Shapland et al. 2012a), and data collection procedures and analysis to measure and compare the residual of the energy balance calculations of ET_{SR} and ET_{EC} followed those described in Shapland et al. (2013). The station's instrumentation included a net radiometer, sonic anemometer, a fine-wire thermocouple, soil temperature probes, and soil heat flux plates, and a CR1000 datalogger (Campbell Scientific Inc. Logan, UT, USA), which were assembled to measure components of surface energy fluxes as described in detail below. A datalogger program similar to that described in Shapland et al. (2013) was used for ET measurements that streamlines the data collection and post-processing procedures.

Sensible heat flux (H) was measured with both eddy covariance using a sonic anemometer and SR using fine-wire thermocouples. The H with SR was estimated using high-frequency temperature data ($f=10$ Hz) that were compensated for the thermocouple size (according to Shapland et al. 2014) to test how well the temperature-compensated SR H compared with eddy covariance H . Estimates of H by SR were calculated from temperature data measured with a 76 μ m diameter Type E thermocouple (FW3, Campbell Scientific) placed above the vine canopy (i.e., above the vine row) ($z=2.09$ m) according to the following equation:

$$H = \alpha \cdot z \cdot \rho C_p \left(\frac{a}{d+s} \right) \quad (3)$$

where α is the calibration factor, z is the thermocouple height above the soil (m), ρ is the air density (g m^{-3}), C_p is the specific heat of air at constant pressure ($\text{J g}^{-1} \text{K}^{-1}$), a is the average ramp amplitude (K), d is the duration of the air parcel heating (s), s is the quiescent period that follows the sweep phase of the air parcel (s), and $(d+s)$ are collectively called the mean ramp period (s). Within the SR processing scheme, the second-, third-, and fifth-order structure function were calculated for each thermocouple over the 30 min sampling interval. The structure function time lag was set to that associated with the microfront duration (as described in Chen et al. 1997a) accounting for the increased size of the microfront duration with the more robust thermocouple (Shapland et al. 2014). The Van Atta (1977) procedure was used to resolve the scale one (smaller scale, see details in Shapland et al. 2012a regarding larger and smaller scales) ramp amplitude and period. The scale two (larger scale) ramp amplitude and period were resolved by setting the structure function time lag to either the scale one gradual rise period or half the ramp period, depending on the smaller-scale ramp intermittency (Shapland et al. 2012a). Shapland et al. (2014) reported that the relationships for

the microfront duration among varying thermocouple sizes were the same for both unstable and stable conditions at both sites. The α calibration factor was determined according to an empirical compensation method, in which the theoretical alpha coefficient of 0.5 is multiplied by the thermocouple compensation factor specific to the 76 μ m diameter thermocouple used here (Shapland et al. 2014). Rather than applying the thermocouple frequency response compensation to the raw thermocouple temperature data, the thermocouple frequency response compensation was applied instead to the SR H values. The 2.16 compensation factor was determined previously as the slope of a regression analysis of H from raw 13 μ m data versus H from raw 76 μ m temperature data (Shapland et al. 2014).

Sonic temperature and high-frequency wind velocity data were obtained with a three-dimensional sonic anemometer (81000RE, RM Young, USA) mounted on the SR station ($z=2.89$ m). These data provided independent H estimates according to the eddy covariance method in which a two-dimensional coordinate rotation correction was applied to the anemometer data (Shapland et al. 2013). Due to equipment failure, no SR data were collected from 7 to 9 July (DOY 187–189) and 13 August to 10 September (DOY 224–252) in 2012.

Daily estimates of latent heat flux (LE) residuals from SR and EC were based on Eq. 2. R_n was measured with a net radiometer placed at $z=3.3$ m ($Q^*7.1$, REBS, Inc. Washington, USA) and modeled using the longwave net radiation sub-model in the ASCE standardized reference evapotranspiration equation (Blonquist et al. 2010) with measured incoming solar radiation, relative humidity, and air temperature from the Parlier CIMIS station. Ground heat flux (G) was measured using soil heat flux plates (HFP-1, REBS, Inc.) buried at 0.05 m in depth and soil thermocouples (Tcav, Campbell Scientific) positioned to span the volume of soil above the ground heat flux plates at a depth of roughly 0.04 m to 0.01 m. The soil surface G was estimated using the temperature and heat flux plate data following the procedure of de Vries (1963) using a soil bulk density (ρ_b) value 1.3 Mg m^{-3} and a volumetric soil water content (θ) of 0.25 (%v/v) to estimate the volumetric heat capacity (C_v) (Jensen et al. 1990). The surface G calculations were averaged to determine the half-hourly G for the vineyard. LE was then estimated every half hour and converted to ET by dividing the LE in MJ m^{-2} per half hour by $L=2.45 \text{ MJ kg}^{-1}$, which is approximately the energy needed to vaporize a volume of water 1 mm deep over 1 m^2 of area. Hourly and daily ET of the vineyard were calculated from the half-hourly data collected.

Canopy size of vines in the lysimeter was compared to those of vines in the surrounding vineyard by measuring the shaded area to obtain the fraction of ground cover (see summary in Table 1). The shaded area was measured

on nine individual vine replicates in 2012 and seven individual vine replicates in 2013 with measurements taking place between 1230 and 1330 h on several dates each year. The shaded area was determined by taking an image of the area beneath the vines with a digital camera (Sony α 300; CCD resolution—ranged from 4 to 6 megapixels, image dimensions— 1024×768 , aperture setting— $f9$, shutter speed— $1/100$ s, file format—JPEG). The camera was held at a height of approximately 1.5 m or lower. Two images per vine were taken in the vineyard surrounding the lysimeter, one on the north side and the other on the south side. Four images were taken on the vines in the lysimeter. A known rectangular area encompassing all the shades of each vine in the lysimeter and the other vines within the vineyard, for use as a reference area, was outlined with flagging tape attached to small wooden stakes driven into the soil. The reference area and shade within the reference area was digitized with Sigma Scan Pro Version 5 (Aspire Software International, Leesburg, VA). For comparison with the K_c used for irrigation as described above (i.e., using degree day method from Williams et al. 2003b), the percent shaded area was used to calculate a crop coefficient using the relationship reported in Williams and Ayars (2005):

$$K_{csh} = -0.008 + 0.017 \times SH \quad (5)$$

where K_{csh} is the crop coefficient calculated using the shaded area model and SH is the percent of shaded area beneath the vine.

Volumetric soil water content (SWC) was monitored using the neutron backscattering technique with a neutron moisture probe (Model 503 DR Hydroprobe Moisture

Gauge, Campbell Pacific Nuclear, Martinez, CA, USA) utilizing some of the same access tubes used in a previous study (Williams et al. 2010). Nine access tube sites were monitored in 2012 and seven sites in 2013. Three access tubes were monitored to a depth of 2.9 m at each site, one tube within the vine row, one midway between rows, and one midway between the former two access tubes. The access tube sites were located in three of four quadrants originally assigned to the vineyard in a previous study. Vineyard ET was estimated using the soil water budgeting technique (Rana and Katerji 2000). Techniques used and assumptions and calculations were as given in Williams (2014) and Williams et al. (2010).

Measurements of leaf water potential (Ψ_{LEAF}) and stomatal conductance (g_s) were taken at midday (1230–1330 h). A pressure chamber (Model 1000 PMS, Corvallis, OR, USA) was used to measure Ψ_{LEAF} according to the procedures of Williams and Araujo (2002) on individual leaf replicates ($n=6$ on vines within and outside the lysimeter in 2012). Beginning on the 19 August (DOY 231) measurement date in 2013 more leaves were used ($n=12$) to obtain a better representative Ψ_{LEAF} value of the vines in the surrounding vineyard. A steady-state porometer (LI-COR Model 1600, Lincoln, NE, USA) was used to measure g_s ($n=16$ on vines within and outside the lysimeter). Measurements in the vineyard surrounding the lysimeter were taken on vines in rows where water meters were installed and SWC was measured.

Statistical analyses for all parameters and relationships were conducted using Sigma Plot 13.0 (Systat Software, Inc. San Jose, CA, USA).

Table 1 Shaded area of vines in the lysimeter and those in the vineyard surrounding the lysimeter measured on several dates in 2012 and 2013

Year	Calendar Date	Day of Year	Vines in Lysimeter (m^2 vine $^{-1}$)	Estimated K_c	Vines Outside lysimeter (m^2 vine $^{-1}$)	Estimated K_c
2012	27 June	179	2.75	0.62	3.10 ± 0.13	0.70
	26 July	208	3.64	0.82	3.77 ± 0.09	0.85
	3 August ^a	216	3.49	0.79	— ^b	—
	13 Sept	257	3.96	0.89	3.89 ± 0.10	0.88
	18 Sept ^c	262	3.73	0.84	3.80 ± 0.05	0.86
2013	18 June	169	3.75	0.84	3.91 ± 0.19	0.88
	18 July	199	3.66	0.82	3.81 ± 0.09	0.86

Values for vines outside the lysimeter represent the mean of 9 and 7 individual vine replicates \pm SE for 2012 and 2013, respectively

^aIn 2012, vines in the lysimeter were hedged (portions of shoots were cut that were growing outside the lysimeter) prior to the measurement of shaded area on 3 August. In 2013, vines in the lysimeter were hedged on 14 June, removing $3.6 m^2$ leaf area across both vines

^bShaded area of the vines outside the lysimeter were not measured on this date

^cFruit on the vines in the lysimeter were harvested on this date. Some of the leaves in the interior of the two vines were removed in the process

Results

Daily ET measurements from SR and weighing lysimetry were positively correlated and responded similarly to changing microclimatic conditions and irrigation events in both years of the study and to the application of ABA (Fig. 1; Table 2), however, there were several periods when these measurements diverged significantly in both growing seasons. Both methods measured increased in ET following irrigation events, and exhibited a decrease during periods when irrigation was terminated for both the vines growing in the lysimeter and the surrounding vineyard (i.e., DOY 237–255 in 2012 and DOY 231–237 in 2013). ET_{LYS} , ET_{SR} , and ET_{EC} were all well aligned in the 2013 until irrigation was terminated on 19 August (DOY 231) (Fig. 1). While ET decreased for all three methods during this water deficit and recovered upon rewatering, ET_{LYS} exhibited a greater decrease during this period. This is likely associated with the restricted soil

volume that the lysimeter vines occupy (Fig. 1). Similarly, the ET values diverged as expected when the irrigation was terminated only in the surrounding vineyard in early- to mid-September (i.e., DOY 249–261 in 2013); during this period, ET_{SR} and ET_{EC} decreased significantly compared to ET_{LYS} . At the end of both seasons (i.e., ~DOY 300), ET was consistently overestimated with SR (especially where R_n was measured directly) compared to that from the lysimeter and soil water budget methods (Fig. 1; Table 2 Oct 23–Nov 11), which may be due to inaccuracies of the net radiometer as the values were becoming lower with shorter days.

Estimated ET_c values were in general agreement with ET_{SR} and ET_{LYS} in 2012, but were consistently higher than ET_{SR} and ET_{LYS} throughout the 2013 growing season. As expected, the estimated potential ET_c values did not decrease along with the other ET measurements during periods when irrigation was withheld (e.g., around DOY 250 in 2012; Fig. 1). In 2013, ET_{SR} decreased while the ET_{LYS} values remained steady when the irrigation was shutoff for the

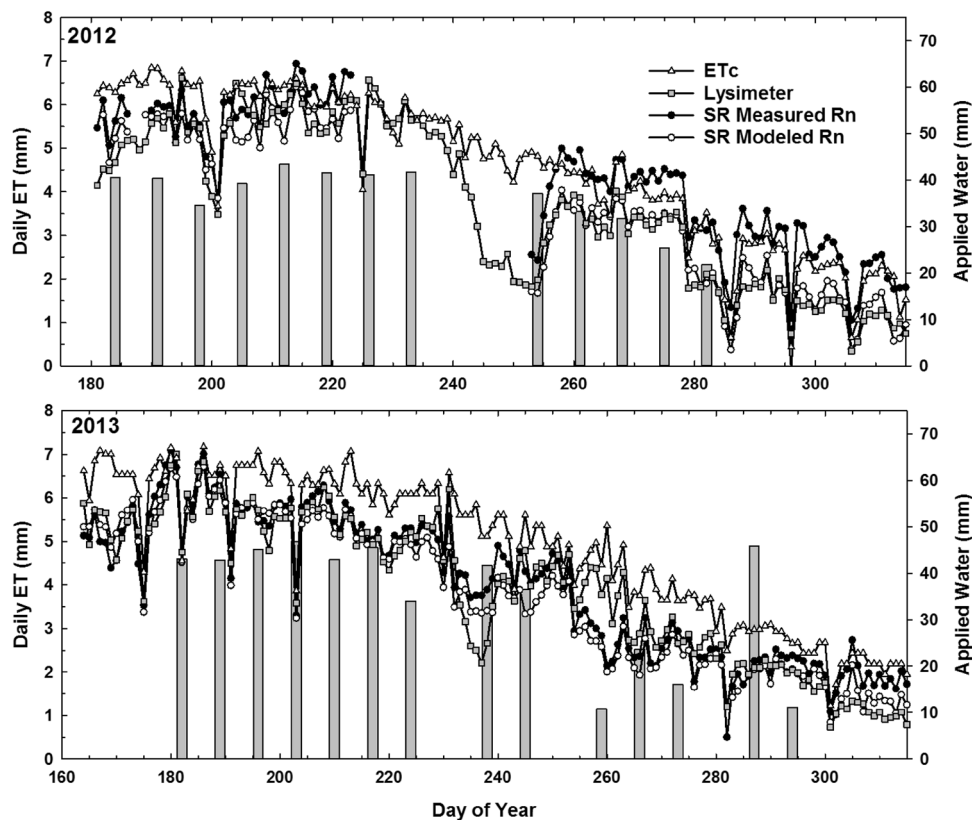


Fig. 1 Daily evapotranspiration (ET) measured with a residual of the energy balance with surface renewal and eddy covariance H and by lysimeter from 29 June (DOY 181) to 18 November (DOY 323) in 2012 (top panel) and from 13 June (DOY 164) to 11 November (DOY 315) in 2013 (bottom panel). The surface renewal ET was derived from both modeled and measured net radiation. Irrigation (each event is represented with the gray bars on each panel) was terminated for both the vines growing in the lysimeter and the surrounding vineyard

after an irrigation event on 24 August 2012 (DOY 237) and resumed on 11 September 2012 (DOY 255). Abscisic acid (ABA) was applied on 4 October 2012 (DOY 278) to all vines in the vineyard. Irrigation was terminated for both the vines growing in the lysimeter and the surrounding vineyard after an irrigation event on 19 August (DOY 231) and it resumed on 25 August 2013 (DOY 237). Vines in the surrounding vineyard were not irrigated from 6 to 18 September 2013 (DOY 249–261) to facilitate fruit harvest

Table 2 Grapevine water use values (mm) from soil water budgeting, ET_{LYS} , and ET_{SR} during the 2013 growing season

Calendar dates	Day of year	Number of days	Soil water budget	Weighing lysimeter	Surface renewal	ET_o
16–28 May	136–148	13	63.7 ± 3.0	52.3	— ^a	75.1
29 May–12 Jun	149–163	15	87.3 ± 1.2	89.0	— ^a	98.2
13–23 Jun	164–174	11	63.4 ± 5.4	59.0	61.0	79.6
24 Jun–7 Jul	175–188	14	90.7 ± 4.5	82.0	87.8	91.1
8–21 Jul	189–202	14	89.4 ± 3.7	78.0	84.4	96.0
22 Jul–4 Aug	203–216	14	85.8 ± 3.2	76.0	81.1	91.2
5–18 Aug	217–230	14	78.5 ± 2.2	70.1	75.3	87.1
19–25 Aug	231–237	7	34.0 ± 2.5	24.8	32.2	43.4
26 Aug–8 Sep	238–251	14	66.4 ± 1.6	57.5	66.0	75.4
9–18 Sep	252–261	10	30.1 ± 1.4	39.6	35.2	44.4
19 Sep–2 Oct	262–275	14	44.5 ± 2.6	42.7	42.5	57.9
3–22 Oct	276–295	20	41.8 ± 1.3	44.0	48.8	64.0
23 Oct–11 Nov	296–315	20	30.7 ± 1.4	24.4	42.3	46.2

Values are expressed as mm of water across the measurement period. The ET values in the ‘Soil Water Budget’ column represent the mean ± SE of seven access tube sites to measure the change in soil water content plus applied water amounts measured with 7 water meters located down each row with access tubes. Reference ET (ET_o) across dates is also included. Vines (both in the lysimeter and surrounding vineyard) were not irrigated from 19 to 25 August. Vines in the vineyard surrounding the weighing lysimeter were not irrigated from September 6 to 18 to facilitate harvest

^aNot measured

vineyard surrounding the lysimeter (i.e., vines in the surrounding vineyard were not irrigated from DOY 249 to 261 to facilitate fruit harvest). The ET values from measured R_n (ET_{SR}) and modeled R_n (ET_{SRm}) agreed early in 2012 and throughout 2013, but the ET_{SR} was consistently higher than ET_{SRm} for the second half of 2012 (Fig. 1).

Both ET_{SR} and ET_{SRm} were significantly ($P < 0.0001$) and positively correlated with ET_{LYS} measurements (Fig. 2). The relationship between the ET_{SRm} and ET_{LYS} had a slightly better fit and a slope closer to one for modeled versus measured R_n (Fig. 2). Since the H and G data were identical for both ET_{SR} and ET_{SRm} , and it appears that the measured R_n data were considerably higher than the estimates from 11 September (DOY 255) until the end of the year during 2012 and DOY 305–365 in 2013 (Fig. 1). The difference might be related to uncertainties in R_n measurements or alternatively coincidental issues with the modeled R_n and ET_{LYS} . The data discrepancies mainly occurred during August–November 2012 and November 2013. During this period, overcast skies and light rainfall occurred in the lower San Joaquin Valley, which might affect R_n measurements. Similarly, daily ET derived from eddy covariance was significantly correlated with ET_{SR} and ET_{LYS} ($P < 0.0001$ for both; Fig. 3); these relationships were nearly 1:1, but the slope was slightly greater than unity for both. Lastly, ET_{SR} was also found to be significantly ($P < 0.001$) correlated with ET estimated using a soil water budget approach (Fig. 4).

The ET_{LYS} , ET_{SR} , and ET_{SRm} were positively correlated with estimated ET_c across dates in which vines were fully

irrigated. Data from the dry-down periods or after the application of ABA in 2012 were not included (Supplemental Fig. 1). Estimated ET_c was positively correlated with ET_{SR} and ET_{LYS} in both years of the study (Supplemental Fig. 1). Most of the ET_{LYS} values were lower than the predicted ET_c , whereas the ET_{SR} data were similar to ET_c in 2012 but less in 2013, which may be impacted by disease or other stress.

Crop coefficient values derived from various methods showed good agreement across both years of the study. The ET_{SR}/ET_c ratio from 29 June to 4 July (DOY 181–186) and 8 July to 10 August (DOY 190 to 223) averaged 0.94 in 2012, while the K_c values calculated with the degree day model that were used to irrigate the vineyard across those dates ranged from 0.92 to 0.96. The estimated K_c derived from the measurement of shaded area (i.e., K_{csh}) of the vines in the vineyard from 26 July to 18 September (DOY 208–262) in 2012 averaged 0.86 (Table 1), while the ET_{SR}/ET_c ratio averaged 0.87 during that time frame. A similar agreement was found in 2013. The actual K_c derived from the lysimeter vines in 2012 (across DOY 181–224) averaged 0.86 while that in 2013 (DOY 164–227) averaged 0.82, which was similar to that derived from the shaded area K_c calculation.

The relationship between the stress index derived from ET_{SR} and ET_{LYS} , i.e., ET/ET_c , and other indicators of plant stress (i.e., Ψ_{LEAF} and g_s) were also significantly correlated for data compiled across the growing seasons, however, there was more scatter in some of these relationships compared to others. In general, decrease in ET/ET_c coincided with increasing plant stress as indicated by decreasing (i.e.,

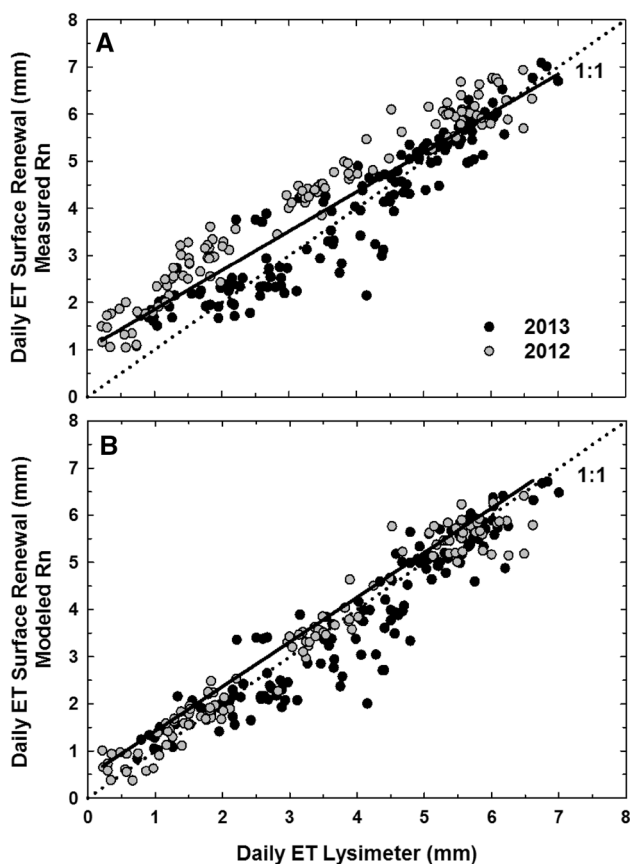


Fig. 2 Relationships between daily lysimeter ET and daily surface renewal ET. ET was determined using the surface energy balance using **a** measured net radiation (root mean square error (RMSE)=0.77 mm, mean bias error (MBE) = -0.40 mm, $r=0.94$) and **b** modeled net radiation (RMSE=0.50 mm, MBE = -0.07 mm, $r=0.96$). Each data point represents daily cumulative value. The sonic anemometer and thermocouple were placed at $z=2.89$ m and 2.09 m, respectively. Data were collected from 29 June to 18 November 2012 and from 13 June to 11 November 2013

more negative) Ψ_{LEAF} values (Fig. 5) and decreasing stomatal conductance (Fig. 6). The results (Figs. 5, 6) in this study are similar to those represented by the linear regressions in Williams et al. (2012). There is more scatter because we are comparing ratios, and small errors in ET or ET_c can lead to big errors in ET/ET_c . During periods when irrigation was withheld in both the lysimeter and surrounding vineyard, the vines in both locations exhibited similar stress as measured by decrease in Ψ_{LEAF} and stomatal conductance (see for example, from 2012 season in Table 3). When irrigation was terminated in 2013 for both the vines growing in the lysimeter and the surrounding vineyard in mid-late August (i.e. DOY 231–237), ET_{LYS} , ET_{SR} , and ET_{EC} all decreased and recovered upon rewatering, however, the magnitude of this change differed across the methods (Fig. 1), which could account for the differences in the stress relationships seen in Fig. 5. Presumably, the limited soil volume occupied by the

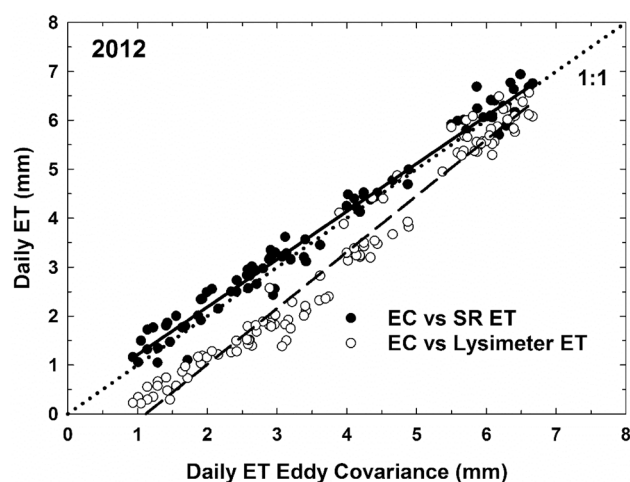


Fig. 3 Relationships between daily ET from the residual of the energy balance ET using surface renewal H versus ET using eddy covariance H (RMSE=0.31 mm, MBE=0.15 mm, $r=0.99$) and the lysimeter ET versus the residual of the energy balance ET with eddy covariance H (RMSE=0.83 mm, MBE = -0.70 mm, $r=0.98$). For the EC and SR ET, measured R_n was used. Each data point represents daily cumulative value

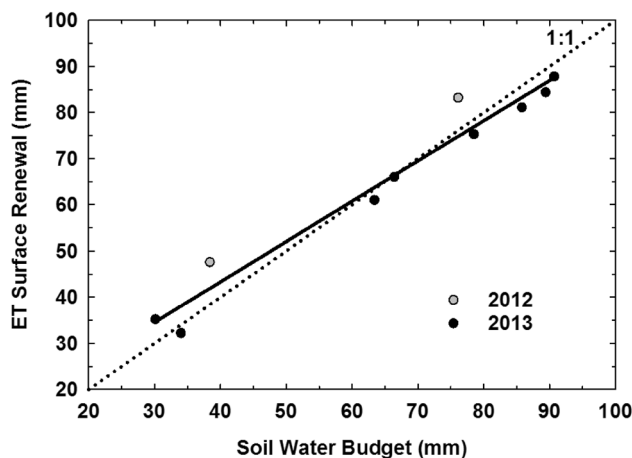


Fig. 4 Relationship between measured surface renewal ET_{SR} and the soil water budget ET (RMSE=4.86 mm, MBE = -0.1 mm, $r=0.98$). Each data point represents ET accumulation over a measurement period determined by soil water content measurement dates (see Supplemental Table 1). Data were collected from 29 June to 17 September 2012 and from 12 June to 18 September 2013

vines in the lysimeter would cause soil water depletion and stress to advance more rapidly than vines in the surrounding vineyard. A comparison of the ET/ET_c stress index to volumetric soil water content revealed a similar pattern with even less data scatter, where indexes derived from ET_{SR} and ET_{LYS} both exhibited a significant decrease as soil water was depleted (Fig. 7). This is consistent with an increase in plant stress as indicated in the previous figures.

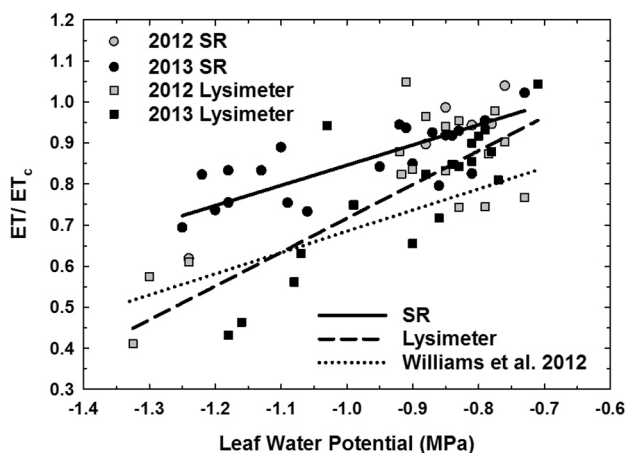


Fig. 5 Relationships between stress ratio (ET_{LYS}/ET_c) and leaf water potential (RMSE=1.73, MBE = -1.72, $r=0.80$) and between stress ratio (ET_{SR}/ET_c) and leaf water potential (RMSE=1.66, MBE = -1.66, $r=0.84$)

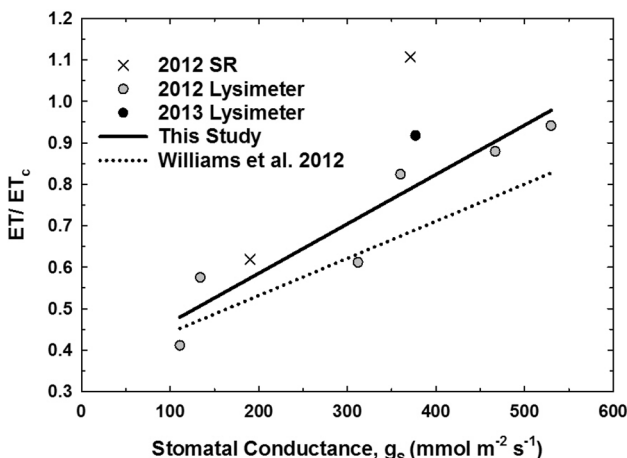


Fig. 6 Relationship between the stress index ET_{LYS}/ET_c and stomatal conductance and ET_{SR}/ET_c and stomatal conductance. The analysis for the current study was run on the combined data from lysimetry and SR ($r=0.85$)

Table 3 Midday leaf water potential (Ψ_l) and stomatal conductance measured during the dry-down period in 2012 for the vines in the lysimeter and those in the vineyard surrounding the lysimeter (outside)

Calendar Date	DOY	Lysimeter Ψ_l (MPa)	Outside Ψ_l (MPa)	Lysimeter g_s ($mmol\ m^{-2}\ s^{-1}$)	Outside g_s ($mmol\ m^{-2}\ s^{-1}$)
24 Aug	237	-0.85	-0.85	530	545
28 Aug	241	-0.82	-0.84	467	453
31 Aug	244	-1.24	-1.24	312	328
5 Sept	249	-1.30b	-1.24a	134b	204a
10 Sept	254	-1.33b	-1.24a	111b	190a
14 Sept	258	-0.92b	-0.87a	360	371

The last day vines were irrigated was 24 August (DOY 237). Irrigation resumed on 11 September (DOY 255). Letters following values within a row (within the Ψ_l or g_s columns) are significantly different at $P < 0.05$. ($n=5-6$ for Ψ_l and 16 for g_s)

Discussion

We derived surface renewal ET_{SRm} using modeled and ET_{SR} using measured R_n , and found that modeled R_n exhibited the tightest relationship with lysimetry (i.e., better statistical fit and slope closer to 1.0). If this relationship holds at other sites, it would allow us to further reduce the cost of a station by eliminating the need for a net radiometer. Microclimatic data needed for the modeled R_n were collected from a CIMIS station located approximately 0.8 km from the lysimeter site. In a growing region like California, clear-sky models can perform very well for much of the growing season (Allen et al. 1998), but more work is needed to confirm optimal distances from SR stations to the nearest weather station for both modeled R_n and ET_o reference estimates (see discussion below). Additionally, work is needed to assess the effectiveness of clear-sky models in other growing regions that experience regularly cloud cover or fog during the growing season. Further efforts to reduce the cost of SR station could involve eliminating G measurements as ground heat flux can be close to zero on a daily basis (Shapland unpublished data; Stoy et al. (2013) Supplemental Fig. 2). ET data needed for irrigation management decisions would rarely need to be finer than daily resolution thus G measurements throughout a day would be unnecessary, and our data from 2012 show a near unity relationship between ET estimated by SR when G was directly measured or assumed to be zero in the energy balance equation (Supplemental Fig. 2). While our current results suggest that daily G could be set to zero, this result may not be universally true and should be tested thoroughly in other experimental settings.

The daily surface renewal ET_{SR} values using the new compensation method had nearly a 1:1 relationship with the daily ET_{EC} from eddy covariance. Similar results were observed previously for 30 min ET values using a calibrated surface renewal approach over grapes (Snyder et al. 1996; Shapland et al. 2012a). While the relationship was similar, slight differences were found when comparing

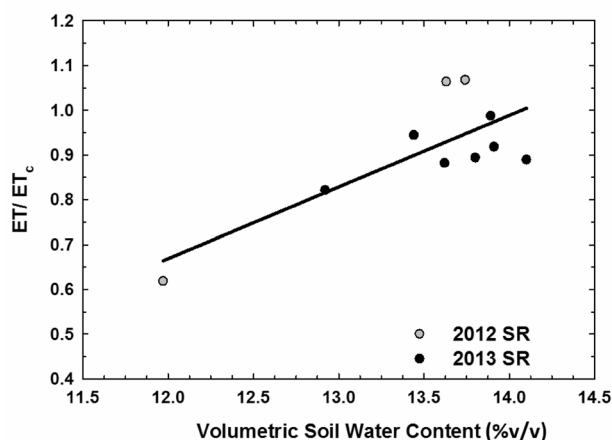


Fig. 7 Relationship between stress index of ET_{SR}/ET_c and volumetric soil water content (θ_v) ($r=0.78$) (%v/v). Williams et al. (2003a) reported volumetric soil water content at field capacity was approximately $22.0 \theta_v$ while that at a soil moisture tension of -1.5 MPa was approximately $8.0 \theta_v$ for this same site

eddy covariance to lysimetry and surface renewal (Fig. 3) that may be due to underlying assumptions associated with each technique. It is difficult to close the energy balance at the earth's surface using experimental data, because the measured available energy in most cases is larger than the sum of estimated sensible and latent heat fluxes (Wilson et al. 2002). Both the SR and eddy covariance methods in this study estimate latent heat flux by residual of the surface energy balance equation, so it assumes that the energy balance is closed. Given that the residual method remains controversial, we compared closure within our study system; regression of the turbulent fluxes (H and LE) against the available energy (i.e., net radiation, R_n , less the energy stored, G) exhibited slopes (Supplemental Fig. 3) of 0.87 and 0.89 for SR and Eddy Covariance, respectively. While these slopes were < 1.0 illustrating that perfect closure was not achieved, it rarely is across most studies and the values found here were nearer to closure than the average values from numerous sites and study years from a FLUXNET dataset that exhibited an average slope of 0.79 (Wilson et al. 2002). In the current study, the residual method may be allocating too much energy to the latent heat flux term of the eddy covariance and SR methods thus causing them to slightly overestimate ET (Fig. 3). However, unpublished lysimeter research on alfalfa has shown that lysimeter ET data exceeds estimates from the residual of the energy balance with H from eddy covariance or SR. In both crops, it is assumed that the lysimeter ET measurements are representative of the footprint being measured by the eddy covariance and surface renewal methods and that the lysimeter measurement is representative of the surrounding field, however, numerous studies have found limitations and discrepancies

between ET measurements from weighing lysimetry and eddy covariance measurements (e.g., Allen et al. 2011; Alfieri et al. 2012; Gebler et al. 2015; Perez-Priego et al. 2017). In fact, our data showed under water deficit conditions that ET of the lysimeter decreased more rapidly than that of the surrounding vineyard as would be expected from the reduced soil volume occupied by the lysimeter vines.

The ET_{SR} was found to be significantly correlated with ET estimated using a soil water budget approach (Fig. 4). Li et al. (2008) showed a good agreement between daily ET measurements from eddy covariance and soil water balance of grapevines in an arid desert region of China. However, the eddy covariance ET in their study was slightly lower than the water balance ET. The surface renewal ET in our experiment was consistently similar to ET from eddy covariance indicating that the H from eddy covariance and surface renewal was similar. Any differences between the observations of the regression curve between our study and Li et al. (2008) is likely due to the difference between the ET accumulation periods (daily versus multiple days).

To precisely manage irrigation requirements, growers need to know how much water to apply and when to apply it based on plant water status. Irrigation requirements based on ET_c models are commonly used to estimate vineyard water needs using crop coefficients and ET_0 of a well-watered reference crop surface as described above (Doorenbos and Pruitt 1977; Allen et al. 1998, 2006). While this method is relatively simple to apply, it can lack accuracy compared to direct measurements due to the distance between the target field site and the ET_0 station, poor maintenance of the ET_0 station, physiological and disease status of the plant, etc. (Jones 2004; English et al. 2008). Inaccuracies in ET_c estimations caused by the above problems can result in over- or under-estimations of irrigation needs and timing based on modeled stress indices. Here we found that ET_c in 2013 was consistently higher than SR and lysimeter-based estimates of ET. This is particularly surprising for the lysimeter, since this is the same site where the K_c was developed for vineyards. This may be due to difference in the age and disease levels in the lysimeter and surrounding vineyard compared to when the data were originally developed. Any inaccuracies in the ET_c could also contribute to variability in a stress index that uses this measure to compare ET_{SR} from a given crop to that of a model grass under these same conditions.

The significant relationship between lysimeter ET/ET_c and Ψ_{LEAF} found here (Fig. 5) is similar to the one observed by Williams et al. (2012). This relationship suggests that SR could be used as a tool to provide growers with information about how much and when to irrigate based on triggers associated with physiological stress under water deficit. Lower stress index values were associated with decrease in stomatal conductance and Ψ_{LEAF} that are commonly used measurements that trigger timing of vineyard

irrigation (Williams and Araujo 2002). In a previous study at the same vineyard, the coefficient of determination for ET_{LYS}/ET_o and Ψ_{LEAF} was 0.90, similar to the 0.96 coefficient of determination for stomatal conductance and Ψ_{LEAF} (Williams et al. 2012). In the current study, the coefficient of determination for ET_{LYS}/ET_c and Ψ_{LEAF} , as well as ET_{SR}/ET_c and Ψ_{LEAF} , was lower (0.66 and 0.66, respectively). The cause of the lower coefficient of variation in this study is unclear (i.e., source of error could come from either measurement method). Although our study did not have as many data points as Williams et al. (2012) for the lysimeter ET_{LYS}/ET_c and stomatal conductance comparison, they both had similar coefficients of determination (0.84 versus 0.79) (Fig. 6). Unfortunately, most of the stomatal conductance measurements were made when ET_{SR} estimates were not available, so this comparison could not be made. Soil water status is also often used as an indicator of crop water status. A comparison of the ET/ET_c stress index using both the lysimeter and SR estimates to volumetric soil water content revealed a positive correlation for both relationships (Fig. 7).

Despite the age of the vines in the lysimeter and surrounding vineyard (25 years old in 2012; vines planted in 1987), the mid-season daily values of ET measured by SR and lysimetry were similar to daily values of ET_c measured from 1991 to 1993 (Williams et al. 2003b) and 1998–1999 (Williams and Ayars 2005). While the maximum K_c used to irrigate the vineyard in this study was 0.96 (taken from Williams et al. 2003b), the ET_{SR}/ET_c ratio was similar to that value for the few days SR measurements were taken in 2012, but both the lysimeter ET_{LYS}/ET_c ratios in 2012 and 2013 and the ET_{SR}/ET_c ratio in 2013 were less. It should be pointed out that the mid-season K_c values from Williams et al. (2003b) across the three growing seasons did vary from 0.8 to 1.0. Therefore, the ET_{SR}/ET_c and ET_{LYS}/ET_c ratios reported herein are reasonable and probably reflect differences in canopy coverage from year to year in this vineyard. In fact, the K_c values estimated from the measurement of shaded area beneath the vines at solar noon are similar to the measured ET_a/ET_o ratios of SR and lysimetry. That data along with the results of Williams and Ayars (2005), López-Urrea et al. (2012), and Picón-Toro et al. (2012) would indicate the usefulness of measuring canopy shaded area (fraction of ground cover) to provide an estimate of the seasonal crop coefficients.

Conclusion

While further validation is needed for the SR method for other crops, the results presented here for grapevines are promising for the development of SR as a user-friendly and

cost-effective technique for estimating crop surface energy fluxes. Our results showed statistically significant correlations between estimates of ET from the new stand-alone SR technique, weighing lysimetry, residual of the energy balance with eddy covariance H, and soil water budgeting in a mature Thompson Seedless vineyard. Changing water availability conditions in the lysimeter and surrounding vineyard were reflected in the ET measured with the various methods. Until recently, SR has required simultaneous use of eddy covariance H to derive an alpha calibration factor, which varied depending on the crop, measurement height, etc. Working with turbulence data over bare soil and sorghum and a meta-analysis of SR data from the literature, Shapland et al. (2014) demonstrated that the alpha calibration converges close to the theoretically predicted value once the measurement thermocouple has been compensated for its frequency response characteristics. Previous comparisons of ET estimated for grass using SR and weighing lysimetry at a different experimental site showed similarly strong correlations to those recorded here ($R^2=0.97$; Castellví and Snyder 2010a). There were several periods when these measurements diverged significantly in both growing seasons, and more work is needed to resolve what factors contributed to these differences (Zeri et al. 2013), and whether this would be exacerbated by utilizing modeled R_n and assumptions about G. Due to different physiological responses to drought and surrounding meteorological conditions that species and even varieties have, it will be necessary to determine if the improved SR method gives similar results over other crop species and varieties to those found in this study.

Compliance with ethical standards

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

References

- Alfieri JG, Kustas WP, Prueger JH, Hipps LE, Evett SR, Basara JB, Neale CMU, French AN, Colaizzi P, Agam N, Cosh MH, Chavez JL, Howell TA (2012) On the discrepancy between eddy covariance and lysimetry-based surface flux measurements under strongly advective conditions. *Adv Water Resour* 50:62–78
- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, vol 300. FAO, Rome
- Allen RG, Walter IA, Elliott RL, Howell TA, Itenfisu D, Jensen ME, Snyder RL (2005) The ASCE standardized reference evapotranspiration equation. Task committee on standardization of reference evapotranspiration American Society of Civil Engineers. Appendices A-F and Index, Reston VA, p 69

- Allen RG, Pruitt WO, Wright JL, Howell TA, Ventura F, Snyder RL, Itenfisu D, Steduto P, Berengena J, Baselga Yrisarry J, Smith M, Pereira LS, Raes D, Perrier A, Alves I, Walter I, Elliott R (2006) A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman–Monteith method. *Agric Water Manag* 81:1–22
- Allen RG, Pereira LS, Howell TA, Jensen ME (2011) Evapotranspiration information reporting: I. Factors governing measurement accuracy. *Agric Water Manag* 98:899–920
- Blonquist JM, Allen RG, Bugbee B (2010) An evaluation of the net radiation sub-model in the ASCE standardized reference evapotranspiration equation: Implications for evapotranspiration prediction. *Agric Water Manag* 97:1026–1038
- Bryla DR, Trout TJ, Ayars JE (2010) Weighing lysimeters for developing crop coefficients and efficient irrigation practices for vegetable crops. *HortScience* 45(11):1597–1604
- Castellví F, Snyder RL (2010a) A comparison between latent heat fluxes over grass using a weighing lysimeter and surface renewal analysis. *J Hydrol* 381:213–220
- Castellví F, Snyder RL (2010b) A new procedure based on surface renewal analysis to estimate sensible heat flux: a case study over grapevines. *J Hydrometeorol* 11:496–498. <https://doi.org/10.1175/2009JHM1151.1>
- Castellví F, Consoli S, Papa R (2012) Sensible heat flux estimates using two different methods based on surface renewal analysis. A study case over an orange orchard in Sicily. *Agric For Meteorol* 152:58–64
- de Vries DA (1963) Thermal properties of soils. In: van Wijk WR (ed) *Physics of plant environment*. North-Holland Publishing Co, Amsterdam, pp 210–235
- Doorenbos J, Pruitt W (1977) Crop water requirements. FAO irrigation and drainage. Paper 24. Land and Water Development Division, FAO, Rome
- English M, Sayde C, Gitelman A, El Khoury L (2008) A feedback system to optimize crop water use estimates in irrigation scheduling, world environmental and water resources congress. ASCE, Reston, pp. 1–10
- Gallardo M, Snyder RL, Schulbach K, Jackson LE (1996) Crop growth and water use model for lettuce. *J Irrig Drain Eng* 122(6):354–359
- Gebler S, Hendricks Franssen H-J, Pütz T, Post H, Schmidt M, Vereecken H (2015) Actual evapotranspiration and precipitation measured by lysimeters: a comparison with eddy covariance and tipping bucket. *Hydrol Earth Syst Sci* 19:2145–2161
- Hanson B, Putnam D, Snyder RL (2007) Deficit irrigation of alfalfa as a strategy for providing water for non-agricultural uses. *Agric Water Manag* 93:73–80
- Jensen ME, Burman RD, Allen RG (1990) Evapotranspiration and irrigation water requirements. ASCE manuals and reports on engineering practices, No 70. American Society of Civil Engineers, New York
- Jones HG (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods. *J Exp Bot* 55:2427–2436
- Li S, Kang SZ, Li FS, Zhang L, Zhang BZ (2008) Vineyard evaporative fraction based on eddy covariance in a desert region of Northwest China. *Agric Water Manag* 95:937–948
- Linquist B, Snyder RL, Anderson F, Espino L, Inglese G, Marras S, Moratier R, Mutters R, Nicolosi P, Rejmanek H, Russo A, Shapland TM, Song Z, Swelam A, Tindula G, Hill J (2015) Water balances and evapotranspiration in water- and dry-seeded rice systems. *Irrig Sci*. <https://doi.org/10.1007/s00271-015-0474-4>
- López-Urrea R, Montoro A, Mañas F, López-Fuster P, Ferreres E (2012) Evapotranspiration and crop coefficients from lysimeter measurements of mature ‘Tempranillo’ wine grapes. *Agric Water Manag* 112:13–20
- McElrone AJ, Shapland TM, Calderon A, Paw U KT, Snyder RL (2013) Surface renewal: an advanced micrometeorological method for measuring and processing field-scale energy flux density data. *J Vis Exp*. <https://doi.org/10.3791/50666>
- Paw U KT, Brunet Y (1991) A surface renewal measure of sensible heat flux density. Preprints, 20th Conference on Agricultural and Forest Meteorology, pp. 52–53
- Paw U KT, Qiu J, Su HB, Watanabe T, Brunet Y (1995) Surface renewal analysis: a new method to obtain scalar fluxes without velocity data. *Agric For Meteorol* 74:119–137
- Perez-Priego O, El-Madany TS, Migliavaca M, Kowalski A, Jung M, Carrara A, Kolle O, Martín M, Pacheco-Labrador J, Moreno G, Reichstein M (2017) Evaluation of eddy covariance latent heat fluxes with independent lysimeter and sapflow estimates in a Mediterranean savannah ecosystem. *Agric For Meteorol* 236:87–99
- Picón-Toro J, González-Dugo V, Uriarte D, Mancha LA, Testi L (2012) Effects of canopy size and water stress over the crop coefficient of a “Tempranillo” vineyard in south-western Spain. *Irrig Sci* 30:419–432
- Rana G, Katerji N (2000) Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. *Eur J Agron* 13:125–153
- Shapland TM, Snyder RL, Smart DR, Williams LE (2012a) Estimation of actual evapotranspiration in winegrape vineyards located on hillside terrain using surface renewal analysis. *Irrig Sci* 30:471–484
- Shapland TM, McElrone AJ, Snyder RL, Paw U KT (2012b) Structure function analysis of two-scale scalar ramps. Part I: theory and modelling. *Bound Layer Meteorol* 145:5–25
- Shapland TM, McElrone AJ, Snyder RL, Paw U KT (2012c) Structure function analysis of two-scale scalar ramps. Part II: ramp characteristics and surface renewal flux estimation. *Bound Layer Meteorol* 145:27–44
- Shapland TM, McElrone AJ, Paw U KT, Snyder RL (2013) A turnkey data logger program for field-scale energy flux density measurements using eddy covariance and surface renewal. *Ital J Agrometeorol* 1:1–9
- Shapland TM, Snyder RL, Paw U KT, McElrone AJ (2014) Thermocouple frequency response compensation leads to convergence of the surface renewal alpha calibration. *Agric For Meteorol* 189:36–47
- Snyder RL, Spano D, Paw U KT (1996) Surface renewal analysis for sensible and latent heat flux density. *Bound Layer Meteorol* 77:249–266
- Spano D, Snyder RL, Duce P, Paw U KT (1997) Surface renewal analysis for sensible heat flux density using structure functions. *Agric For Meteorol* 86:259–271
- Stoy PC, Mauder M, Foken T, Marcolla B, Boegh E, Ibrom A, Arain MA, Arneth A, Aurelai M, Bernhofer C, Cescatti A, Dellwik E, Duce P, Gianelle D, van Gorsel E, Kiely G, Knohl A, Margolis H, McCaughey H, Merbold L, Montagnani L, Papale D, Reichstein M, Saunders M, Serrano-Ortiz P, Sottocornola M, Spano D, Vaccari F, Varlagin A (2013) A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity. *Agric For Meteorol* 171–172:137–152
- Suvocarev K, Shapland TM, Snyder RL, Martinez-Cob A (2014) Surface renewal performance to independently estimate sensible and latent heat fluxes in heterogeneous crop surfaces. *J Hydrol* 509:83–93
- Williams LE (2014) Determination of evapotranspiration and crop coefficients for a Chardonnay vineyard located in a cool climate. *Am J Enol Vitic* 65:159–169
- Williams LE, Araujo FJ (2002) Correlations among predawn leaf, midday leaf, and midday stem water potential and their correlations with other measures of soil and plant water status in *Vitis vinifera*. *J Am Soc Hortic Sci* 127:448–454

- Williams LE, Ayars JE (2005) Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy. *Agric For Meteorol* 132:201–211
- Williams LE, Matthews MA (1990) Grapevine. In: Stewart BA, Nielsen DR (eds), *Irrigation of agricultural crops—agronomy monograph No. 30*. ASA-CSSA-SSA, Madison, pp. 1019–1059
- Williams LE, Phene CJ, Grimes DW, Trout TJ (2003a) Water use of young Thompson Seedless grapevines in California. *Irrig Sci* 22:1–9
- Williams LE, Phene CJ, Grimes DW, Trout TJ (2003b) Water use of mature Thompson Seedless grapevines in California. *Irrig Sci* 22:11–18
- Williams LE, Grimes DW, Phene CJ (2010) The effects of applied water at various fractions of measured evapotranspiration on water relations and vegetative growth of Thompson Seedless. *Irrig Sci* 28:221–232
- Williams L, Baeza P, Vaughn P (2012) Midday measurements of leaf water potential and stomatal conductance are highly correlated with daily water use of Thompson Seedless grapevines. *Irrig Sci* 30:201–212
- Wilson K, Goldstein A, Falgec E, Aubinet M, Baldocchi D, Berbigier P, Bernhofer C, Ceulemans R, Dolman H, Field C, Grelle A, Ibrom A, Lawl BE, Kowalski A, Meyers T, Moncrieff J, Monson R, Oechel W, Tenhunen J, Valentini R, Verma S (2002) Energy balance closure at FLUXNET sites. *Agric For Meteorol* 113:223–243
- Zeri M, Sá LDA, Nobre CA (2013) Estimating buoyancy heat flux using the surface renewal technique over four amazonian forest sites in Brazil. *Boundary Layer Meteorology* 149:179–196

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.