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Below canopy radiation divergence in a vineyard: implications on interrow surface energy balance

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Abstract
Vineyards' canopy architecture and row structure pose unique challenges in modeling the radiation partitioning and energy exchange between the vine canopy and the interrow area. The vines are often pruned and manipulated to be strongly clumped, while mechanical harvesting requires wide rows, often with vine height to vine spacing ratio > 1. This paper estimates the intercepted radiation by the canopy, and the effect of this interception on the below canopy surface energy balance and evapotranspiration (ET). Measurements were conducted in an east–west oriented vineyard in CA during intensive observation periods as part of the grape remote sensing atmospheric profile and evapotrnspiration eXperiment (GRAPEX). Below canopy incoming shortwave radiation was measured at multiple positions across the interrow, and the surface energy balance/ET below the vine rows was measured for only one growing season (in 2015) using three micro-Bowen ratio (MBR) systems. These MBR systems were deployed across the interrow, in the north, center, and south of the interrow. A significant spatial and temporal variability in radiation was observed since the vines were not significantly pruned or manipulated and thus grew randomly into the interrow. However, when averaged across the interrow using the radiation sensor array, the values appeared to give reliable mean radiation extinction conditions that agreed with model estimates. The variation in the surface energy fluxes were dominated by the amount of transmitted radiation, while soil moisture was a second order effect. Daily estimates of ET from the three micro-Bowen ratio systems, weighted by their respective representative sampling area, yielded estimates similar to values computed by the correlation-based flux partitioning method, which utilizes high-frequency eddy covariance data measured above the canopy.

Introduction

The architecture of wine grape vineyards is characterized by tall plants reaching on the order of 2 m or more at the peak of the growth cycle, with most of the biomass in the upper one-half to one-third of the plant height, and widely spaced rows on the order of 3 m. The canopy architecture and wide row spacing facilitates sunlight interception, air flow, and field operations. It also results in two distinct management zones: the vines, and the interrow that is often planted with a cover crop. Any water management tool for vineyards must consider how these two systems interact to affect water and energy exchange.

The trellis design as well as ground cover and water management will influence both the radiation and the energy exchange of the interrow with the overstory vine canopy, resulting in the interrow acting as an energy source or sink (Holland et al. 2013). Moreover, with vineyards increasingly being established in arid areas, water becomes a limiting factor and there is much greater interest in understanding and

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Table 1 Dates of the IOPs and associated LAI values collected in concert with below vine canopy radiation observations

Year	IOP1	IOP2	IOP3	IOP4
2013 (LAI)	10–12 April DOY 100–102 (0.50)	10–12 June DOY 161–163 (1.50)	5–7 August DOY 217–219 (1.80)	
2014 (LAI)	26–28 April DOY 116–118 (0.42)	29 June–1 July DOY 180–182 (1.76)	8–10 August DOY 220–222 (2.1)	25–27 September DOY 268–270 (0.96)
2015 (LAI)	21–23 April DOY 111–113 (0.38)	31 May–2 June DOY 151–153 (1.98)	10–12 July DOY 191–193 (2.41)	11–13 August DOY 223–225 (2.10)
2016 (LAI)	1–3 May DOY 122–124 (0.87)	10–12 June DOY 162–164 (2.51)	28–30 July DOY 210–212 (2.74)	

The micro-Bowen ratio measurements were collected only for the 2015 IOPs

quantifying the contribution of evaporation (*E*) relative to transpiration (*T*), which will have a correlation to grape yield and quality (Trambouze et al. 1998), and thus to water use efficiency. Consequently, there have been studies attempting to both model and measure interrow and vine energy exchange and evapotranspiration (ET) (e.g., Holland et al. 2013; Kool et al. 2016; Ortega-Farias et al. 2007).

A key to energy exchange and ET modeling is a reliable description of the radiation divergence through the canopy. Given the hedge row crop design of wine vineyards, the radiation transmission to the surface through the interrow space as well as the radiation transmitted through canopy gaps and through the canopy leaves, is non-random in nature, and changes throughout the day. Evidence is accumulating showing the effect of radiation penetration on grape biochemical processes and consequently fruit quality (Reshef et al. 2017, 2018).

The unique architecture of wine vineyards, that make radiation penetration through the canopy more complex, along with the importance of understanding the radiation dynamics below the vines canopy, call for both experimental research and modeling efforts to better characterize this process. The objective of this work was to describe the radiation reaching the vineyard floor by conducting extensive radiation measurements, and to relate the radiation patterns to below canopy energy fluxes using three micro-Bowen ratio systems (described below).

Materials and methods

To better understand and evaluate model parameterizations of the divergence of radiation through the vine canopy to the interrow floor, radiation measurements in the interrow below the vine canopy were collected in concert with flux tower eddy covariance and radiation measurements at 5 and 6 m, respectively, above ground level during intensive observation periods (IOPs), as part of a multi-scale experiment called the Grape Remote sensing Atmospheric Profile and Evapotranspiration eXperiment (GRAPEX) conducted in California (Kustas et al. 2018a, b). In 2015, micro-Bowen ratio instrumentation was deployed during all four IOPs for evaluating below vine canopy turbulent energy exchange. The IOPs dates [Julian and day of year (DOY)] and ground-based leaf area index (LAI) values from measurements described below are listed in Table 1.

The IOPs were nominally 3-day measurement periods surrounding Landsat 7 and 8 overpasses, where ground-based biophysical, remote sensing and micrometeorological measurements at canopy scale of vine and interrow systems were collected in addition to finer pixel resolution (< 1 m) aerial imagery.

Site description

The experiment was conducted simultaneously in two drip irrigated vineyards, a north and a south vineyard blocks with *Vitis vinifera* (Pinot Noir), which were planted in 2009 and 2011, respectively, near Lodi, CA (38.29°N 121.12°W). The timing and amount of irrigation, pruning activities, cover crop management, and application of agrochemicals—differed from season to season and between the vineyard blocks due to variation in weather and climate conditions.

In both vineyards, the vine trellises are 3.35 m apart and run in an east–west direction. An individual vine is planted every ~ 1.5 m, with the two main vine stems attached to the first cordon at a height of 1.45 m above ground level (agl). There is a second cordon at 1.9 m agl where vine shoots are managed. Typically, the vines reach a maximum height of around 2.0–2.5 m agl during the early part of the growing season with the vine biomass concentrated in the upper half of the total canopy height. However, as the season progresses the vines are often left to grow into the interrow and thus the vine canopy often occupies closer to 80% of the upper canopy height. The typical vine canopy width is nominally 1 m mid-season. Pruning of the vines is mainly performed to remove shoots growing significantly into the interrow and depending on the weather conditions, often the vines are used to shade the south facing grapes to prevent overexposure of radiation. Due to irrigation management practices, a grass layer in the interrow is kept in the early stages of the growing season, which is then mowed several times in spring and let cured in summer.

Above canopy measurements

Eddy covariance/energy balance systems were located approximately 20 m inside each vineyard at the east edge to have an adequate fetch for the prevailing winds from the west. A detailed description of the measurements and their post-processing is provided by Alfieri et al. (2018, this issue). Briefly, the tower at each site is instrumented with an infrared gas analyzer (EC150, Campbell Scientific,[1] Logan, Utah) and a sonic anemometer (CSAT3, Campbell Scientific) co-located at 5 m agl to measure the concentrations of water and carbon dioxide and 3D wind velocity, respectively. The full above canopy radiation budget was measured using a four-component net radiometer (CNR-1, Kipp and Zonen, Delft, The Netherlands) mounted at 6 m agl. Air temperature and water vapor pressure at 5 m agl were measured using a Gill shielded temperature and humidity probe (HMP45C, Vaisala, Helsinki, Finland). Subsurface measurements include the soil heat flux measured via a cross-row transect of five plates (HFT-3, Radiation Energy Balance Systems, Bellevue, Washington) buried at a depth of 8 cm, and the heat storage above the plates estimated using self-made copper-constantan thermocouples installed at 6 and 2 cm depths and soil water content measured with HydraProbe (Stevens Water Monitoring System, Portland, Oregon) sensor installed at 5 cm depth.

Radiation measurements in the interrow

During the IOPs, radiation divergence measurements were assessed by placing pyranometers on a levelled board that was laid across the interrow, so that five positions across the interrow were represented: 30 cm north of the southern row, in the middle of the interrow, 30 cm south of the northern row, and two pyranometers halfway between the two at the edges and the one in the interrow (30, 90, 150, 210, and 270 cm from the southern row).

In 2013, only one radiation board was available (see Fig. 1a), comprised of 3 Epply Precision Spectral Pyranometers (PSP; Eppley Laboratory Inc., Newport Rhode Island, USA) and 5 Apogee (AP) pyranometers (CS300 Apogee Instruments Inc., Logan, Utah, USA). The board was rotated between the north and south vineyards (sites 1 and 2, respectively), within the flux tower footprint and ground-based leaf

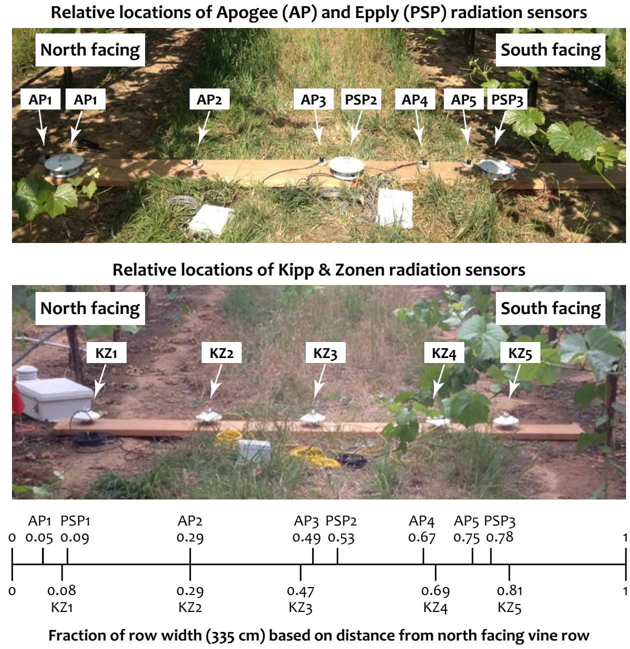

Fig. 1 Eppley PSP and Apogee CS300 radiation board configuration (top) and the Kipp & Zonen (KZ) radiation board sensor arrangement (bottom)

area sampling area. In 2014, an additional radiation board was constructed (Fig. 1b) made up of Kipp and Zonen (KZ) pyranometers (CMP11 and CMP21, Kipp and Zonen). In 2014, an inter-calibration was performed under clear sky conditions. All Apogee, Epply and Kipp & Zonen sensors were calibrated using a linear regression equation fit to the average corresponding to each model version. No attempt was made to calibrate all the sensors to a single standard, although comparisons between different sensor makes and models (once calibrated) were well within manufacturers listed sensor accuracy. Both in 2015 and 2016, both boards were deployed in either the north or south vineyards for making measurements during the IOPs.

Since it is known that the Apogee radiation sensors are not accurate when used below the canopy, three of the Apogee sensors were "co-located" as close as possible without sensor interference with the three Epply PSPs (Fig. 1). They were AP1 with PSP1 under the vines, AP3 with PSP2 around the center of the interrow, and AP5 with PSP3 at three-fourth distance from the north-facing vine row. Since radiation reaching the sensors was highly variable, the comparisons between the PSP and AP sensors were made using the criteria that differences were within 50 W m^{-2}. In addition, to ensure the PSP and AP sensors were shaded during that 15-min period, the ratio of the average of the radiation measured by them to the above canopy incoming solar radiation had to be less than 0.85, while the above canopy incoming solar radiation had to be > 50 W m^{-2} to ensure

[1] The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute official endorsement or approval by the US Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

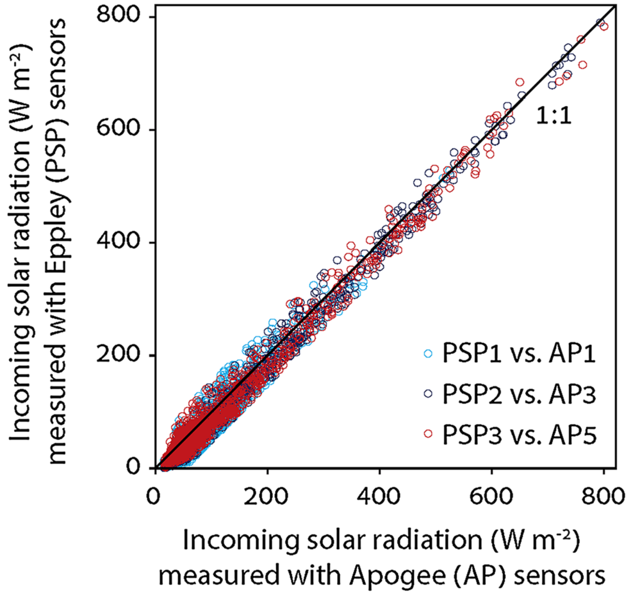

Fig. 2 Comparison of solar radiation measurements from Apogee CS300 pyranometers (AP) collocated with Eppley PSP sensors based on the criteria described in the text. Symbols represent comparison of PSP1 versus AP1 (magenta circle), PSP2 versus AP3 (blue circle) and PSP3 versus AP5 (red circle). See Fig. 1 for sensor locations

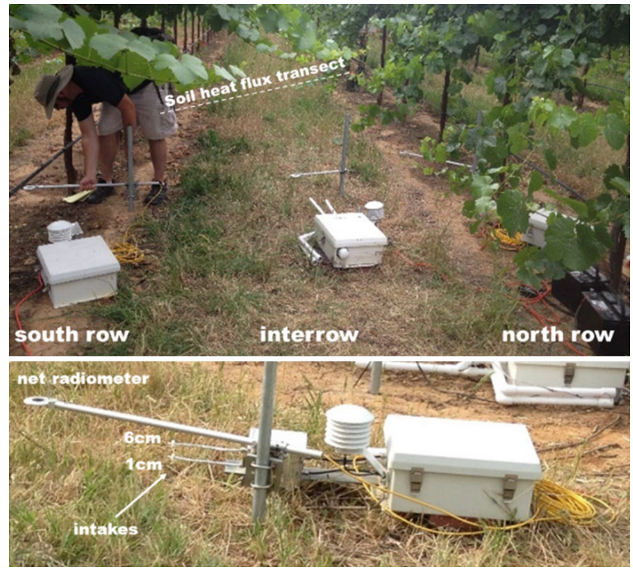

Fig. 3 Photograph of MBR sensor system deployment during IOP 1 in the north vineyard. Net radiometer and MBR intakes are noted as well as relative location of soil heat flux transect. Imbedded figure is the MBR systems deployed during IOP 2 with significantly higher vine LAI

adequate daytime radiation conditions. As is seen in Fig. 2, the agreement between Apogee and Epply PSP is quite satisfactory. There is a bias with the Apogees yielding slightly higher values but with regression slopes between 0.97 and 1. The bias (AP-PSP) was 21 (AP1-PSP1), 14 (AP3-PSP2) and 11 (AP5-PSP3) W m^{-2} and the mean absolute difference (MAD) was 26, 18 and 18 W m^{-2}, respectively.

Below canopy energy balance measurements

Below canopy energy balance components were measured during the three IOPs in 2015 at the north vineyard (site 1) within the footprint of the flux tower using three micro-Bowen Ratio (MBR) systems (Holland et al. 2013). The MBR systems employed a LI-840A CO_2/H_2O gas analyzer (LI-COR, Lincoln, NE, USA) that measures water vapor concentration in air (parts per thousand), which was in turn converted to vapor pressure (kPa) using ambient atmospheric pressure measurements. Each MBR system had two air intakes with a filter (PP Systems, Amesbury, MA, UAS) to remove debris. Air intakes were placed at 1 and 6 cm above the grass/soil surface. Two MBRs were placed underneath the vines, at the northern and southern rows, and one was placed in the center of the interrow (Fig. 3).

The net radiation was measured using a Kipp & Zonen NR Lite, and soil heat flux (*G*) was estimated using the transect consisting of five equally spaced locations across the interrow space as part of the eddy covariance flux tower set up. For a detailed analysis of the *G* measurements see Agam et al. (2019, this issue). The estimates of *G* for each of the MBR systems was computed using the soil heat flux sensors associated with the locations of each MBR system (i.e., north facing under vine, center of interrow, and south facing under vine; see Fig. 3). The MBRs were located within 10 m of the soil heat flux transect and therefore considered representative of soil conditions surrounding these systems.

Leaf area index (LAI) measurements

Indirect leaf area index (LAI) measurements using light bar sensors were collected during the IOPs in 2013–2016, in grids adjacent to both flux towers, where the below canopy radiation and energy balance measurements were conducted. LAI was measured using LI-COR LAI-2000 in 2013 and 2014. In 2014, a newer instrument—LI-COR LAI-2200—was purchased and used as well. In 2014 IOPs 3 and 4, measurements were made using both instruments and found to be comparable. LAI-2200 has the advantage of being useable in a wider range of lighting conditions, and enabling the user to make scattering correction measurements, and was used thereafter.

At each point, a single measurement comprised one above canopy ("A") reading and four below canopy ("B") readings, taken across the row. All readings were taken with the sensor facing along the row. For the most part, measurements were conducted in the morning or early afternoon, so users faced west to keep the sun out of view. "A" readings were

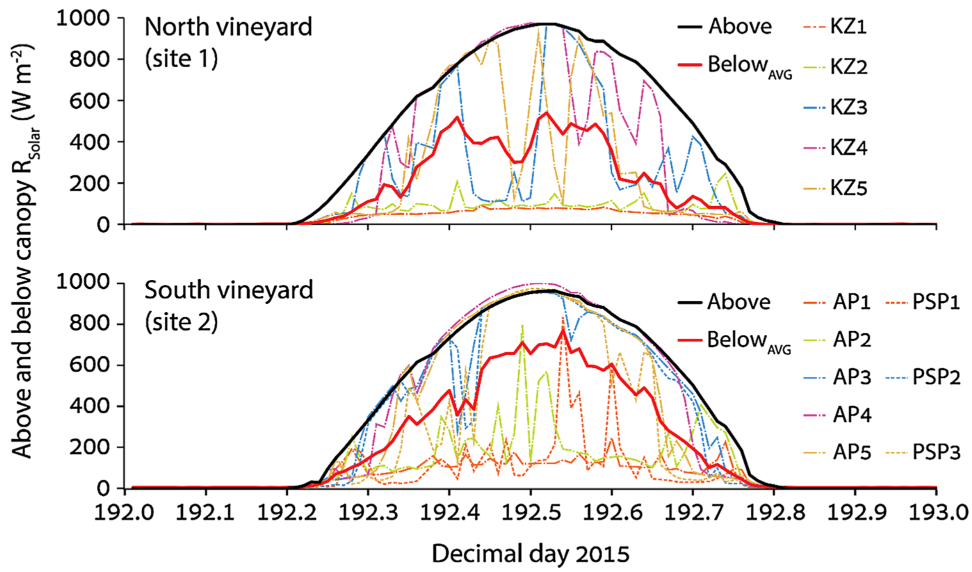

Fig. 4 Example plot of above canopy incoming solar radiation (solid black line), average of radiation reaching the interrow (solid red line) and individual pyranometer measurements using the Kipp & Zonen pyranometer array at site 1 (north vineyard) and the Apogee/Eppley pyranometers at site 2 (south vineyard)

taken with the sensor held above the user's head, above the canopy, facing the sky. "B" readings were taken facing in the same direction as the "A" reading, using a 90° view cap: (1) in-row, (2) ¼-row, (3) ½-row, and (4) ¾-row. In-row readings were taken with the sensor resting on the wire holding the drip line, and the rest were taken with the sensor held just above the grass if measuring vine LAI, or resting on the ground under the grass if measuring vine + cover crop LAI. Each tower grid comprised 25 measurements (5 × 5). Detailed description and analysis of the LAI measurements including an intercomparison of measurement techniques and validation with destructive sampling is given in White et al. (2019, this issue).

Analysis

Radiation divergence

An example of the radiation measurements made by the individual pyranometers for the north and south vineyards for one of the IOPs is illustrated in Fig. 4. This shows the heterogeneous nature of the spatial and temporal variation in the sunlit and shaded areas below the vine canopy. Clearly the vines are not significantly trained and/or pruned for these vineyards and hence the vines growing into the interrow create quite a large variability in shading/canopy cover. An example of the variation in the distribution of vine shoots growing into the interrow and the spatial variability in sunlit and shaded areas underneath the vine canopy is illustrated in Fig. 5.

While there is significant spatial and temporal variability in the 15-min average radiation reaching the surface across the interrow, the average radiation measured from the array of ground pyranometers is assumed to provide reasonable representation of the mean actual direct and diffuse radiation reaching the interrow. One way of evaluating this assumption is to compare, on a daytime basis (incoming solar radiation > 0 W m^{-2}), the ratio of daytime average below and above incoming solar radiation versus the effective leaf area index from the ground measurements for all the IOPs, and see if the relationship follows Beer's law. Although more sophisticated models for transmission of diffuse and direct shortwave radiation have been developed (e.g., Nijssen and Lettenmaier 1999), Campbell and Norman (1998) have shown that using Beer's law to compute the daily fraction of below to above canopy solar radiation (Eq. 1) as suggested earlier by Fuchs et al. (1976) is comparable to detailed model simulations.

$$R_{\text{solar B}}/R_{\text{solar A}} = \mathrm{e}^{-\kappa\,\mathrm{LAI}}, \tag{1}$$

Fig. 5 A west-viewing photograph illustrating the variation of sunlit and shaded areas in the interrow of the south vineyard during June 2015 IOP. Note the sunlit areas illuminating the radiation sensors underneath the vines on the south vine row (left-hand side) and shading even in the center of the interrow

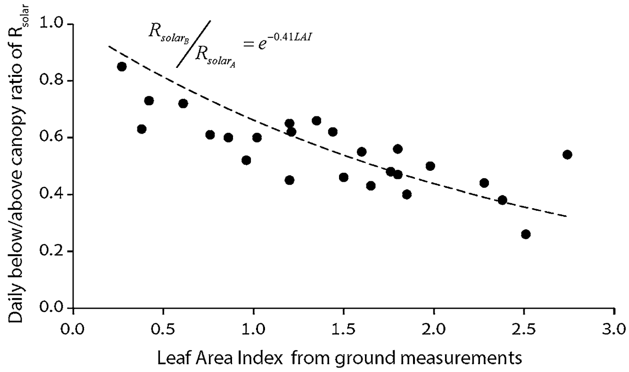

Fig. 6 Comparison of the ratio of below and above solar radiation from the radiation boards for both north and south vineyard sites and all IOPs for 2013–2016 versus the ground-based LAI measurements (White et al. 2018, this issue). The dashed curve is Eq. (1) with $\kappa=0.41$

where $R_{\text{solar B}}$ is the solar radiation below the vine canopy, $R_{\text{solar A}}$ is solar radiation above the canopy, κ is the extinction coefficient typically ranging between 0.3 and 0.6 (Ross 1981), and LAI is the effective leaf area index from the ground measurements. The value from least squares regression, shown as the dashed curve in Fig. 6, is the Beer's law formula for radiation transmission (Eq. 1) yielding an extinction coefficient $\kappa=0.41$, which seems reasonable given the unique canopy architecture and row structure of the vineyard.

Additionally, the mean radiation reaching the ground from the sensor arrays was used in a radiation divergence model intercomparison by Parry et al. (2019, this issue) in which they found the most complex three-dimensional model yielded the best results although the performance of less sophisticated algorithms was quite similar, which can be more readily used in two-source energy balance models. Consequently, these ground data are very useful for improving radiation partitioning algorithms which are of key importance for improving two-source energy balance model partitioning between the interrow and vine canopy layers (Kustas et al. 2018, this issue; Nieto et al. 2018, this issue).

Below canopy energy balance

The energy balance components from the MBR systems, namely net radiation (Rn), soil heat flux (*G*), sensible heat flux (*H*) and latent heat flux (LE), for a complete 24-h cycle are illustrated in Fig. 7 for the south and north vine rows and the center of the interrow (see Fig. 3 showing where the MBR systems are located). The day selected for each IOP is representative of the temporal variation in the magnitude of the energy balance components at each MBR location. For IOPs 1–4, the days selected are DOY 113 (April 23), 153 (June 2), 192 (July 11) and 224 (August 12).

For IOP 1, the similar measured Rn at the three locations makes sense given the relatively low LAI (~0.4). The observed G was similar for the north and south vine rows but was significantly damped in the interrow due to the cover crop. While the estimated H was similar between all three positions, LE was generally highest for the interrow due to a still actively transpiring cover crop. LE from the north vine row was less than zero at night and nearly zero all day, likely due to the relatively low volumetric soil moisture (VSM, cm^3/cm^3) measured at 5 cm depth in the north vine row (0.12). Regular irrigation had not yet commenced and so the surface moisture conditions were generally dry, although the VSM measured for the south vine row was significantly higher (0.21). This suggests that due to the relatively small sampling area measured by the MBR systems, variations in surface soil moisture can have a significant effect on MBR-derived H and LE magnitudes under similar radiation conditions.

For IOP 2, a much greater LAI of ~2 significantly affected the available energy, particularly for the south vine row which was largely shaded resulting in overall very small fluxes for all four energy balance components. On the other hand, the recent irrigation on DOY 150 with the high available energy (Rn–*G*) for the north vine row resulted in relatively large LE compared to *H* flux. The interrow was surprisingly intermittently shaded, causing large temporal variations in Rn. With the cover crop senescing and the VSM being ~0.07, there was very little LE and consequently the available energy went into *H*. The observed large oscillations in Rn were reflected in *H* for the interrow and for both *H* and LE for the north vine row; however, *G* did not show much temporal variation, likely due to the cover crop layer insulating and dampening oscillations in the heat transfer into the soil.

From IOP 2 to IOP 3, LAI kept increasing, reaching ~2.4 in IOP 3, thus little available energy was again observed and a corresponding low LE was measured at the south vine row although the soil was wet (VSM ~ 0.30) from irrigations five consecutive days prior to and including on DOY 192. Interestingly, the interrow had higher Rn compared to IOP 2, although still showed significant temporal oscillations in magnitude. The higher Rn may be the result of a reduction of ~0.7 m in the canopy height from pruning while the opening in the interrow was maintained at ~1 m, such that the height-to-width ratio of the opening, which largely determines the radiation penetration to the ground, was significantly smaller. This perhaps explains the large Rn and available energy for evaporation for the north vine row occurring at midday when solar zenith is highest and azimuth is perpendicular to the vine row direction. For *H* and LE, the dry interrow and senescent cover crop meant that most of the available energy went to *H*,

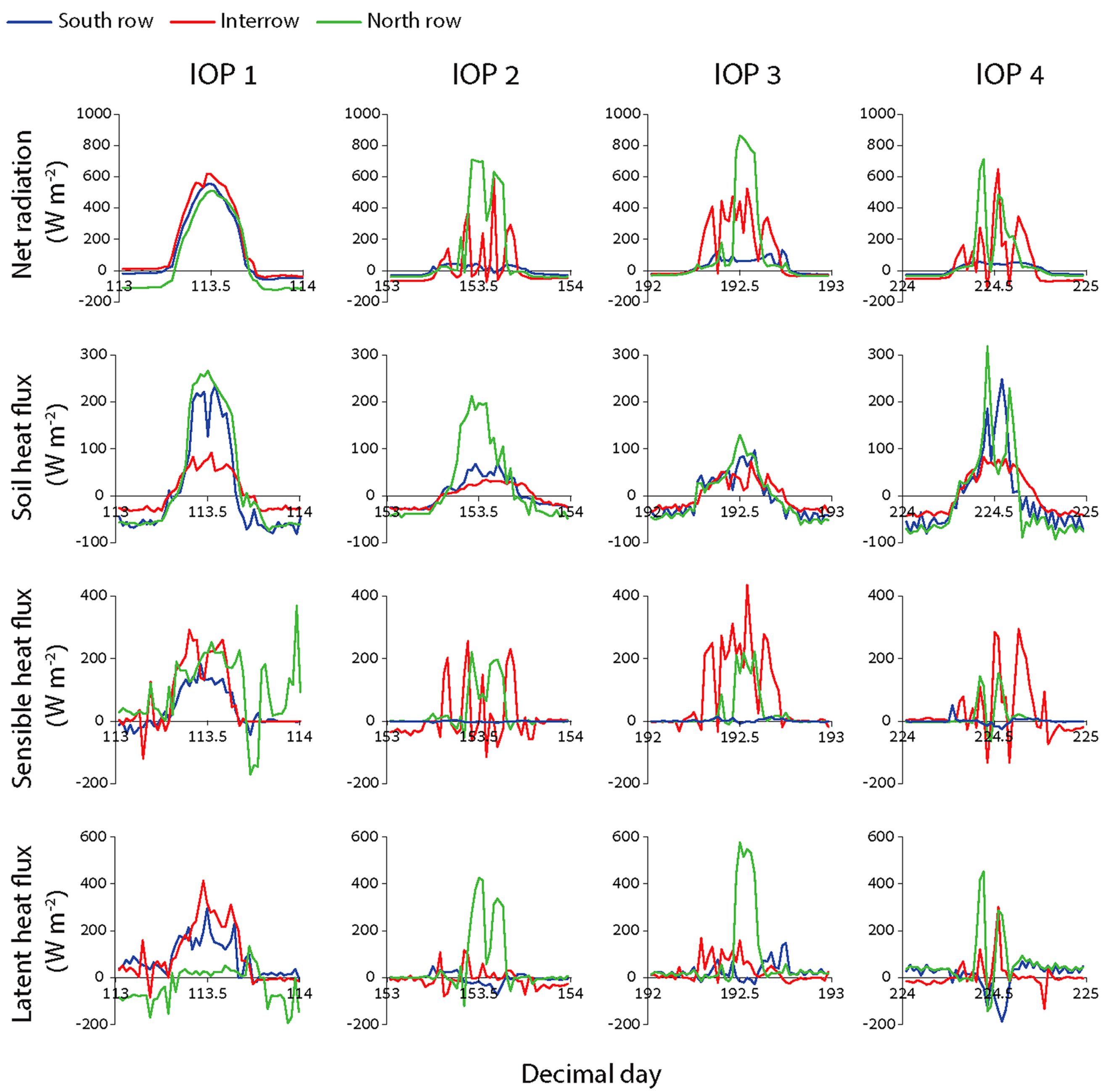

Fig. 7 Energy balance components over a 24-h period from the three MBR systems for each IOP in 2015

while the wet soils (VSM ~ 0.30) for the north vine row yielded a large LE when available energy peaked midday.

Finally, for IOP 4 where the LAI decreased from IOP 3 to ~ 1.9, there was irrigation the prior day and over most of DOY 224, which might explain in part the significant variation in *G* for the north and south vine rows. For IOP 4, however, there is not as a consistently high Rn for the north row as in IOP 2 or 3, while the interrow shows large temporal variability similar to IOP 2. Again the relatively high VSM in the vine rows from irrigation (VSM ~ 0.35) results in high LE values, although dampened at midday due to low Rn.

With radiation playing such a dominant role in affecting the below canopy energy balance components, a comparison of the radiation measurements underneath the south vine row, in the center of the interrow, and underneath the north vine row, to the net radiation measurements from the MBR systems for the days used in Fig. 7 are illustrated in Fig. 8. Although not always a consistency in the temporal variation in transmitted solar radiation and below canopy net radiation, there is generally a good correlation in overall solar radiation received by the MBR situated in each of the three locations and the resulting observation of net radiation. The

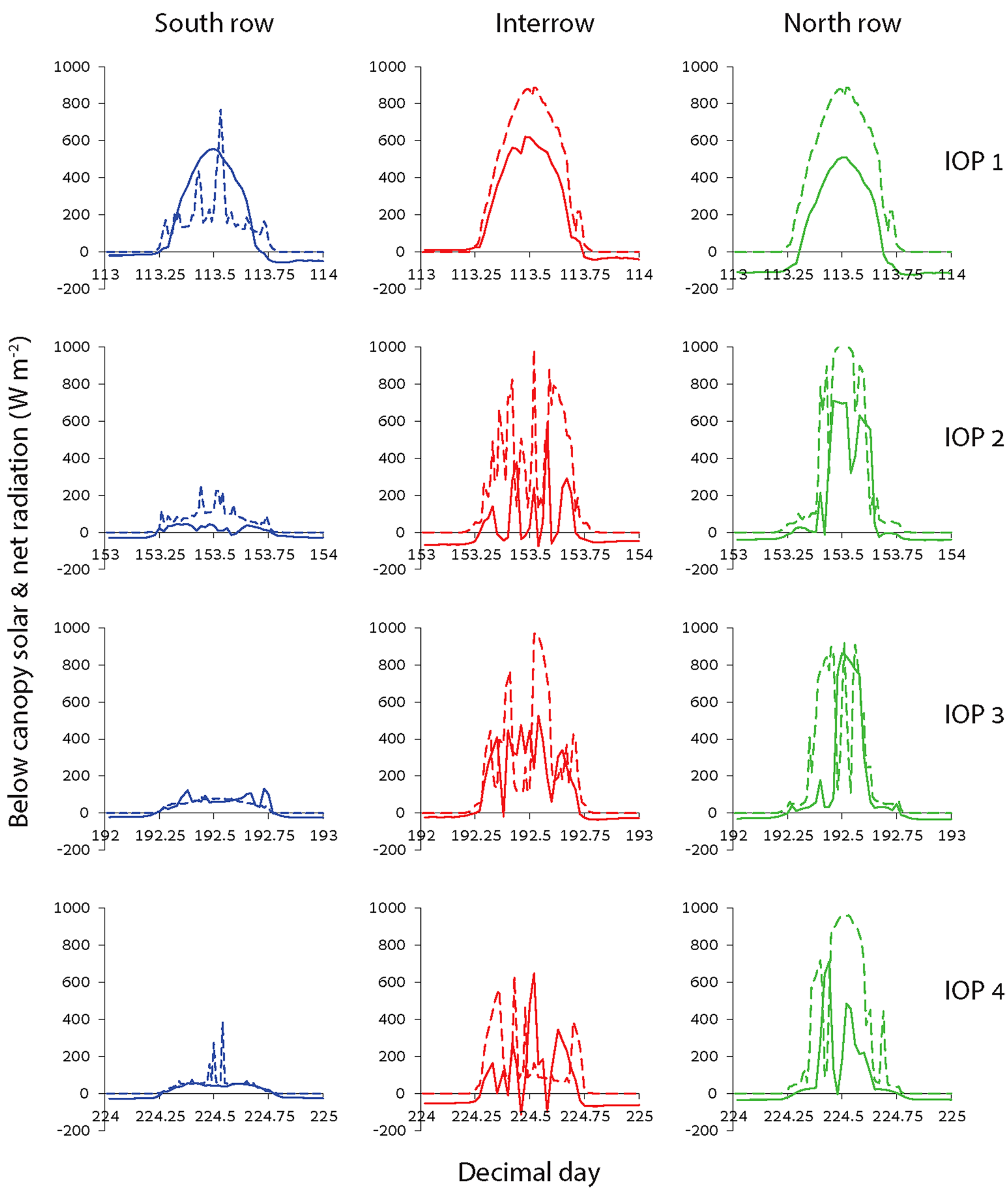

Fig. 8 Temporal variation in transmitted solar radiation (dashed line) and MBR-observed net radiation (solid line) from the south vine row (blue), the center of the interrow (red) and north vine row (green) for all four IOPs

radiation reaching the ground is clearly the main driver in the magnitude of the turbulent fluxes, particularly between the north and south vine row, while the partitioning between *H* and LE for the interrow versus north row is affected by near surface soil moisture.

To support this conclusion of the dominant role of radiation in determining the magnitude of LE, a plot of daily ET from the three MBR systems for the four IOPs and the associated VSM values is illustrated in Fig. 9. Except for IOP 1, which had nearly the same radiation input for the three MBR systems (due to the low LAI), there is a first-order effect or impact of VSM on daily ET from the south versus north vine row (the interrow had high ET due to a still very active cover crop). What follows for IOPs 2–4 is that while VSM is similar for the north and south vine rows, significantly different daily ET fluxes are observed, with an

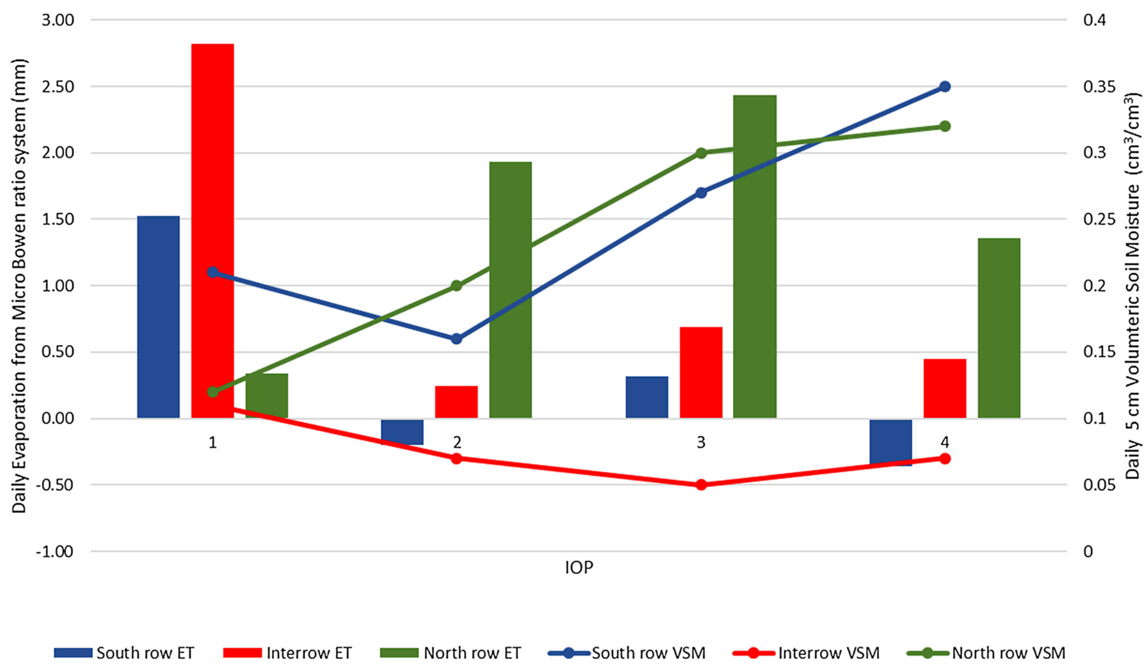

Fig. 9 IOP 1–4 daily estimates of ET for the three MBR systems and associated VSM values

emphasis on the small negative values for the south vine row in IOPs 2 and 4. The small negative *E* values for the south vine row are caused by a combination of measurement error due to very small vapor pressure gradients, negligible daytime E and nighttime condensation (i.e., $E < 0$). The interrow has low ET due to senescent cover crop and low VSM but is still surprisingly larger than the south row.

With such significant variability in transmitted radiation affecting the below canopy energy balance fluxes, one might conclude it is not reasonable to obtain representative estimates of the *E* and *T* flux contributions from the bare soil and cover crop system in the interrow for the vine conditions at this site. Yet, on a daily basis, the MBR estimates appeared to yield reasonable estimates of ET flux from the interrow, except, perhaps for the small negative values estimated by the MBR in the south vine row for IOPs 2 and 4 (see Fig. 9). To evaluate the utility of MBR observations, daily above canopy ET partitioning to *E* and *T* was estimated using the correlation-based flux partitioning method that utilizes the high-frequency eddy covariance (EC) data (Scanlon and Sahu 2008; Scanlon and Kustas 2010, 2012).

The correlation-based flux partitioning method (Scanlon and Kustas 2010) makes use of Monin–Obukhov similarity theory indicating that high-frequency time series for scalars, such as the water vapor (q) and carbon dioxide (c) concentrations, will have perfect correlation when measured at the same point within the atmospheric surface layer. For q and c, one source/sink arises from the exchange of water vapor and carbon dioxide across leaf stomata during transpiration and photosynthesis, while a second from non-stomatal direct evaporation and respiration. If only *T* occurs, the similarity theory predicts a correlation of -1 (a negative correlation because transpiration is a water vapor source and photosynthesis is a carbon sink). If only *E* occurs, the theory suggests a correlation of 1 (evaporation and respiration are sources for water vapor and carbon, respectively). Consequently, the q–c correlation will depart from the expected -1 correlation as *E* contribution increases or the ratio *T*/ET decreases from unity. The fundamental principle of the correlation-based flux partitioning method technique is that the degree of deviation from the expected -1 correlation can be used to infer the relative amounts of *T* and *E* fluxes to the total ET. Recent improvements in the partitioning algorithm have enhanced the robustness of this technique for partitioning ET into *T* and *E* (Skaggs et al. 2018).

During the first IOP, with the vines still at initial stages of development, the source for *T* was assumed mainly from the actively transpiring cover crop; and for the consecutive IOPs, the interrow cover crop was assumed senescent, thus at any given time only two contributing sources were assumed: bare soil *E* and either cover crop or vine *T*. The *E* from the bare soil area was area weighted: ~40% from the average of MBR E from the vine north and south rows, and 60% for the MBR interrow measurements of *E* (when cover crop is senescent) or ET (when the cover crop is active in the Spring). In Fig. 10, the comparison of *E* and *T* derived from the eddy covariance high-frequency data and the MBR estimates of *T* (for IOP 1 only) and *E*, indicates a fairly good agreement except the *E* estimates for IOP 4, where

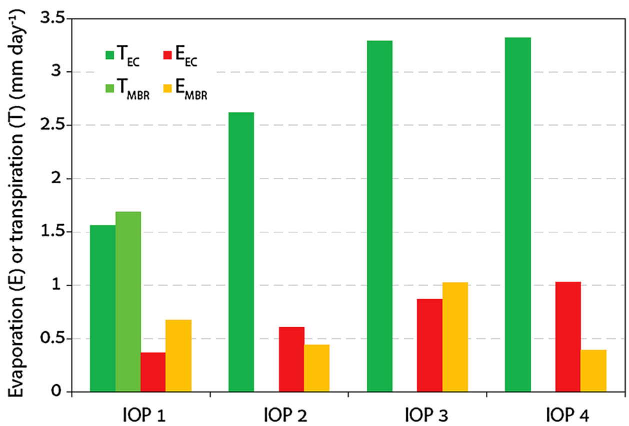

Fig. 10 Estimates of daily vine/cover crop transpiration (*T*) and soil evaporation (*E*) derived by the correlation-based flux partitioning method with the high-frequency eddy covariance data (EC) and from the MBR systems (MBR)

Fig. 11 Photographs taken during IOP 4 at the north vineyard showing the interrow within the EC flux tower footprint (top) and the specific position of the MBR systems (bottom)

the EC-derived *E* is on the order of 1 mm/day while MBR estimate is less than 0.5 mm.

This divergence may be the result of overirrigation that was occurring in some areas of the vineyard prior to and during IOP 4, as is evident from the photograph shown in Fig. 11 where the cover crop in places within the EC flux tower footprint that re-emerged in the center of the interrow and was actively transpiring. This indicates that soil water content in areas of the interrow normally very dry in August were being re-wetted and were sources of both *E* and *T* that were reflected in the eddy covariance high-frequency data. On the other hand, in the immediate vicinity of the MBR systems there was no green actively transpiring cover crop anywhere in the interrow. Consequently, a lower daily *E* from the MBR systems would be expected indicating footprint differences between the EC and MBR systems is contributing to the discrepancy in the *E* estimates.

Summary and conclusions

To better understand and evaluate model parameterizations for the divergence of radiation through the vine canopy to the interrow floor, and to model below vine canopy turbulent exchange, the intercepted radiation by the canopy, and the effect of this interception on the below canopy surface energy balance and evapotranspiration (ET), were assessed. Radiation and micro-Bowen ratio measurements in the interrow below the vine canopy were collected in concert with above canopy eddy covariance flux tower measurements. Through these set of measurements, although limited in quantity, it is apparent that there are strong micro-climate effects on both radiation divergence and turbulent fluxes. In particular, the spatial and temporal variability in radiation strongly affects the magnitude of the energy fluxes across the interrow with soil moisture having a secondary level of influence. This suggests that when modeling or using remote sensing data at resolutions that can distinguish vine canopy and interrow sunlit and shaded areas, the resulting radiances and fluxes are greatly affected.

In fact, the effects of shadows on spectral and thermal-infrared measurements and remotely sensed variables such as normalized difference vegetation index (NDVI), and LAI as well as land surface temperature using high-resolution imagery from unmanned aerial vehicles (UAVs) were examined by Aboutalebi et al. (2019, this issue). Their analysis showed that the impact of shadowed pixels in the canopy led to significant differences in calculated NDVI and LAI and, as well as strongly affecting the retrieval of the land surface temperature. This in turn strongly affected the thermal-based land surface model estimates of energy fluxes and ET for the shaded area using such high-resolution imagery.

Although these microscale measurements of radiation and water and energy exchange are not readily extrapolated to the field scale or correlate well to standard micrometeorological measurements, they do provide an insight to the relative importance of radiation and local soil water and plant dynamics in the exchange of water and heat from the vine canopy and interrow systems. In future projects, we plan to collect a significantly longer time series in below canopy radiation and micro-Bowen ratio measurements to capture a greater range in the influence of vine and cover crop growth and development on the energy exchange between vine canopy and interrow systems.

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Compliance with ethical standards

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

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