



This is a post-peer-review, pre-copyedit version of an article published in Irrigation Science. The final authenticated version is available online at:

<https://doi.org/10.1007/s00271-018-0586-8>

Document downloaded from:



[Click here to view linked References](#)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 Utility of the Two-Source Energy Balance (TSEB) model in vine and interrow flux 2 partitioning over the growing season

3
4 W.P. Kustas¹, J.G. Alfieri¹, H. Nieto², T.G. Wilson¹, F. Gao¹, M.C Anderson¹

5
6 ¹USDA-ARS, Hydrology and Remote Sensing Laboratory, Beltsville, MD

7 ²IRTA-Research & Technology Food & Agriculture, Lleida, Spain

8 9 Abstract

10
11 For monitoring water use in vineyards, it becomes important to evaluate the evapotranspiration
12 (ET) contributions from the two distinct management zones: the vines and the interrow. Often
13 the interrow is not completely bare soil but contains a cover crop that is senescent during the
14 main growing season (nominally May-August), which in Central California is also the dry
15 season. Drip irrigation systems running during the growing season supply water to the vine plant
16 and re-wet some of the surrounding bare soil. However, most of the interrow cover crop is dry
17 stubble by the end of May. This paper analyzes the utility of the thermal-based Two-Source
18 Energy Balance (TSEB) model for estimating daytime ET using tower-based land surface
19 temperature measurements over two Pinot Noir (*Vitis vinifera*) vineyards at different levels of
20 maturity in the Central Valley of California near Lodi, CA. The data were collected as part of
21 the Grape Remote sensing Profile and Evapotranspiration eXperiment (GRAPEX). Local eddy
22 covariance (EC) flux tower measurements are used to evaluate the performance of the TSEB
23 model output of the fluxes and the capability of partitioning the vine and cover crop transpiration
24 (T) from the total ET or T/ET ratio. The results for the 2014-2016 growing seasons indicate that
25 TSEB output of the energy balance components and ET, particularly, over the daytime period
26 yield relative differences with flux tower measurements of less than 15%. However, the TSEB
27 model in comparison with flux partitioning method overestimates T/ET during the winter and
28 spring through bud break, but then underestimates during the growing season. A major factor
29 that appears to affect this temporal behavior in T/ET is the daily LAI used as input to TSEB
30 derived from a remote sensing product.

31
32 **Keywords** vineyards, remote sensing, two source energy balance model, eddy covariance,
33 evapotranspiration, evaporation, transpiration, land surface temperature

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

34 Introduction

35 The typical architecture of wine-grape vineyards in California is characterized by widely
36 spaced rows (~3 m) and tall plants (~2 m) with most of the biomass concentrated in the upper
37 one-third to one-half of the plant. This wide row spacing and canopy architecture facilitates
38 sunlight interception, air flow, and field operations. It also results in two distinct management
39 zones: the vines and the interrow. Often, the treatment of these two management zones is further
40 complicated by a cover crop grown in the interrow. A remote sensing-based land surface model
41 that captures the micro and macro-scale exchanges between the vine, interrow and atmospheric
42 boundary layer is needed to operationally monitor vineyard water use and both vine and interrow
43 plant stress. The Two-Source Energy Balance (TSEB) formulation addresses the key factors
44 affecting the convective and radiative exchange within the soil/substrate–plant canopy–
45 atmosphere system.

46 As water supplies for agricultural production become more restricted due to overuse and
47 drought, particularly in arid regions, there is a concerted effort to improve irrigation methods to
48 reduce the amount of water lost through soil evaporation (E) versus transpiration (T) since for
49 many crops T is correlated to biomass production and ultimately yield while E provides little if
50 any contribution from an agronomic point of view. While a number of measurement techniques
51 have been developed to estimate T and E (Kool et al., 2014), they are very difficult to extrapolate
52 from the local patch scale to field scale and certainly to landscape and regional scales. This study
53 presents an application of the TSEB model for estimating evapotranspiration (ET) that explicitly
54 partitions ET to T and E using land surface temperature (LST), which is also available from
55 satellites, giving it a regional scale application.

56 In this paper, TSEB is applied using local tower LST observations representing conditions
57 surrounding the eddy covariance flux tower. Both the total ET and the partitioned fluxes from
58 vine and interrow systems estimated by TSEB are compared to eddy covariance ET.
59 Additionally, for 2014 and 2015 growing seasons, the T/ET ratio is estimated using the
60 correlation-based flux partitioning method with the high frequency eddy covariance data
61 (Scanlon and Sahu, 2008; Scanlon and Kustas, 2010; 2012). Comparisons in partitioning
62 between E and T on monthly timescales will be used since there were frequent periods lacking
63 convergence with the correlation-based flux partitioning method, but on a monthly time scale
64 there were enough values to compare the partitioning to significant changes in vine and interrow
65 cover crop phenology.

67 Approach

68 The TSEB model has undergone several modifications since it was first presented by
69 Norman et al. (1995). Changes include refinements to the algorithm estimating soil aerodynamic
70 resistance and shortwave and longwave transmittance through the canopy and addition of the

1
2
3
4 71 Priestley-Taylor formulation for canopy transpiration (Kustas and Norman, 1999). Further
5
6 72 improvements have been made incorporating rigorous treatment of radiation modeling for
7
8 73 strongly clumped row crops and accounting for shading effects on soil heat flux (Colaizzi et al.
9
10 74 2012a; 2016a; 2016b) as well as alternative formulations for computing the canopy transpiration
11
12 75 which include Penman-Monteith (PM) or light-use efficiency (LUE) parameterizations (see
13
14 76 Colaizzi et al., 2012b; 2014; 2016c; Anderson et al., 2008).

15 77 Further refinements have been recently made to the within-canopy wind profile (Nieto et al.,
16
17 78 this issue: a) to address the significant vertical variation in vine biomass which is often
18
19 79 concentrated in the upper half of the canopy with a secondary cover-crop biomass in the
20
21 80 interrow. This adjustment involved creating generic canopy profile distributions for four major
22
23 81 seasonal/phenological stages. The first period is just before vine bud break when vines-shoots are
24
25 82 already pruned and there is an actively growing cover crop (March-April). The second period
26
27 83 starts with vine bud break during the spring (April-May); at this time vine development is in the
28
29 84 upper ~1/3 of the canopy between the first cordon where the vine shoots originate (~1.45 m
30
31 85 above ground level (AGL)) and second cordon (~1.90 m AGL) on the vine trellis system. The
32
33 86 cover crop remains vigorous until it is mowed at the end of this period. In the third period, which
34
35 87 exists over an extended growing season and past harvest as the vines go through senescence
36
37 88 (June-November), the foliage distribution is concentrated approximately midway between the
38
39 89 ground and top of the vine canopy with no photosynthetic grass layer. Finally, a fourth
40
41 90 distribution covers the period after vine leaf-off with standing vine shoots and a re-emerging
42
43 91 cover crop (December-February).

44 92 Additionally, a simplified method to derive the clumping index for radiation modeling in
45
46 93 vineyards was derived following the geometric model from Colaizzi et al. (2012a). A rectangular
47
48 94 canopy shape, which simplifies the trigonometric calculations, replaces the elliptical hedgerow
49
50 95 assumption in the original model. Results with this new modeling approach show similar
51
52 96 accuracy to detailed three-dimensional radiation modeling schemes (Parry et al., this issue). A
53
54 97 full description of the model formulations, modified and applied to the vineyard site using tower-
55
56 98 based thermal measurements and aerial imagery, is provided in Nieto et al. (this issue: a & b). A
57
58 99 description of the key TSEB model algorithms is provided in the Appendix and also in Nieto et
59
60 100 al. (this issue; a)

61 101

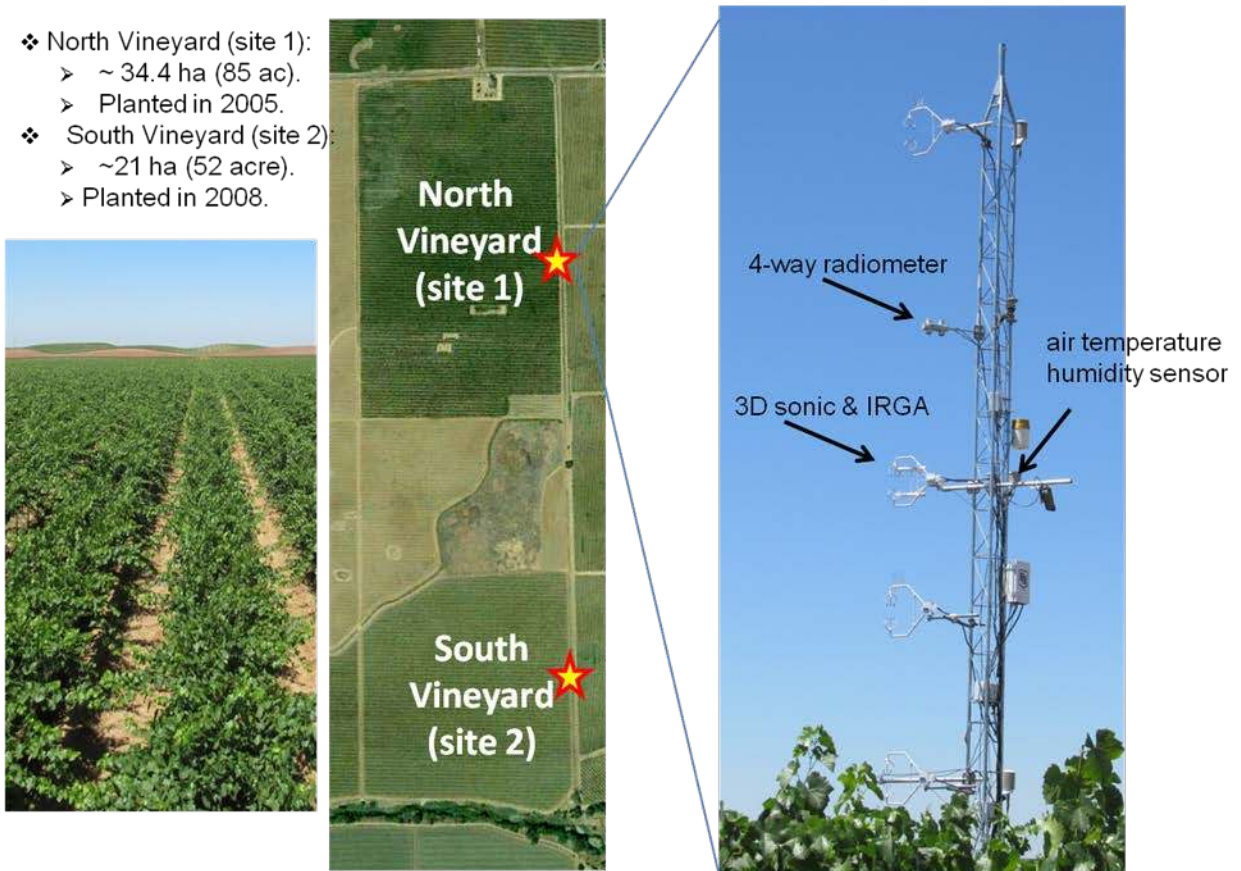
62 102 **Materials and methods**

63 103 The meteorological measurements were obtained from the flux towers located in the north
64
65 104 (site 1) and south (site 2) vineyards (see Figure 1). The vineyards are Pinot Noir (*Vitis vinifera*)
66
67 105 variety with the north vineyard planted in 2009 and the south vineyard planted in 2011. Details
68
69 106 of the flux tower measurements and processing are described by Alfieri et al. (this issue). In both
70
71 107 2014 and 2015, there was nearly a continuous set of high frequency eddy covariance data

1
2
3
4 108 available that allowed for estimates of the monthly T/ET estimates using the correlation-based
5
6 109 flux partitioning eddy covariance (EC) method. Unfortunately, in 2016 there was a loss of the
7
8 110 high frequency data during the main growing season so it could not be used in this analysis. The
9
10 111 input forcing data used in this study include 15-minute wind speed measured at 5 m AGL from a
11
12 112 three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan Utah), air
13
14 113 temperature from a Gill shielded temperature/humidity probe (HMP45C, Vaisala Helsinki,
15
16 114 Finland), and incoming and outgoing shortwave and longwave radiation using a four-component
17
18 115 net radiometer (CNR-1, Kipp and Zonen, Delft, Netherlands) mounted at 6 m AGL. The
19
20 116 upwelling longwave radiation was used to compute a composite hemispherical LST (Norman
21
22 117 and Becker, 1995).

21 119 The measurements were collected in two vineyards located approximately 32
22
23 120 km (~20 mi) northeast of Lodi, CA (38.29°N, 121.12°W).

24 121 East-West Rows spaced ~3.3 m (11 ft). Vines spaced ~1.5 m (5 ft).



56 142 Figure 1. Description of study site and tower sensors used for running TSEB
57 143
58
59 144

1
2
3
4 145 Other key inputs of canopy height, aerodynamic surface roughness, and leaf area index (LAI)
5
6 146 were obtained from ground measurements during intensive observation periods (IOPs) which
7
8 147 occurred during different key vine and cover crop phenological stages, namely April/May,
9
10 148 June/July and August/September. However, the ground measurements required interpolation to
11
12 149 daily values to run TSEB with the meteorological and LST inputs. For LAI, a machine learning
13
14 150 approach (Gao et al., 2012) was applied to generate daily LAI maps at 30 m resolution over the
15
16 151 GRAPEX field sites using Landsat surface reflectance and the MODIS LAI products. Agreement
17
18 152 between the remotely sensed retrieved LAI and ground LAI measurements from 2013 through
19
20 153 2016 yielded an average difference around 25% (Sun et al., 2017). Daily canopy height was
21
22 154 interpolated based on its relationship to LAI from Nieto et al. (this issue; a), and the aerodynamic
23
24 155 roughness parameters were obtained from wind direction relative to vine row orientation (east-
25
26 156 west rows) and their relationship to LAI derived by Alfieri et al. (this issue). Daily green
27
28 157 vegetated fraction (f_G) used in the Priestley-Taylor formulation for canopy transpiration (see
29
30 158 Nieto et al., this issue; a) was estimated based on the day of year when senescence begins
31
32 159 (DOY_S), which was observed from daily phenocam photos. f_G is 1 prior to DOY_S , then from
33
34 160 DOY_S onward f_G follows a linearly decreasing function of LAI:

$$35 \quad f_G(DOY > DOY_S) = \frac{[LAI(DOY) - LAI_{min}]}{[LAI(DOY_S) - LAI_{min}]} \quad (1)$$

36 161
37 162 Here, DOY is day of year and LAI_{min} is the estimated minimum annual value of LAI.

38 163 The value of the hemispherical LST (T_{RH}) can be computed based on the following
39 164 expression:

$$40 \quad T_{RH} = \left(\frac{[R_{L\uparrow} - (1 - \varepsilon_H)R_{L\downarrow} + R_{Latm}]}{\sigma \varepsilon_H} \right)^{1/4}, \quad (2)$$

41 165 where $R_{L\uparrow}$ is the upwelling longwave radiation measurement, $R_{L\downarrow}$ is the downwelling longwave
42 166 radiation, R_{Latm} is the atmospheric longwave contribution from ground to sensor height, σ is
43 167 Stephan-Boltzmann constant and ε_H is the hemispherical emissivity estimated from weighting
44 168 the fractional vegetation cover estimates (f_C) with assumed emissivity of the canopy (0.99) and
45 169 soil/cover crop (0.94) as follows $\varepsilon_H = 0.99(f_C) + 0.94(1 - f_C)$. Given the relatively small path
46 170 length of the longwave sensor from the ground, it was assumed $R_{Latm} \sim 0$.

47 171 **Results**

48 172 For the years 2014-2016, the 15-minute average meteorological and LST forcing data were
49 173 used in TSEB along with daily LAI and aerodynamic roughness parameters to compute surface
50 174 energy fluxes over the daytime period, which is defined when net radiation is greater than 100 W

181 m^{-2} . The TSEB output for years 2014-2016 were computed. Since the focus is on ET and its
 182 partitioning between the vine canopy and the interrow, the model and measured results are
 183 compared using daytime ET and, when available, T/ET estimates using the correlation-based
 184 method with high frequency eddy covariance data. As noted above, comparison of TSEB model
 185 estimates of T/ET with the correlation-based method was conducted on a monthly time scale and
 186 could only be carried out for years 2014 and 2015.

187 The daily daytime latent heat flux, LE or ET, sensible heat flux, H, net radiation, R_n , and soil
 188 heat flux, G, over the course of all three years for the north and south vineyards are illustrated in
 189 Figure 2 using Eq. (1) to determine f_G . TSEB was also run using $f_G = 1$ over the full annual cycle
 190 for years 2014-2016; model results are similar with slightly greater bias. The figure indicates an
 191 overestimate in ET and an underestimate in H and only a slight bias in R_n and G for both
 192 vineyards.

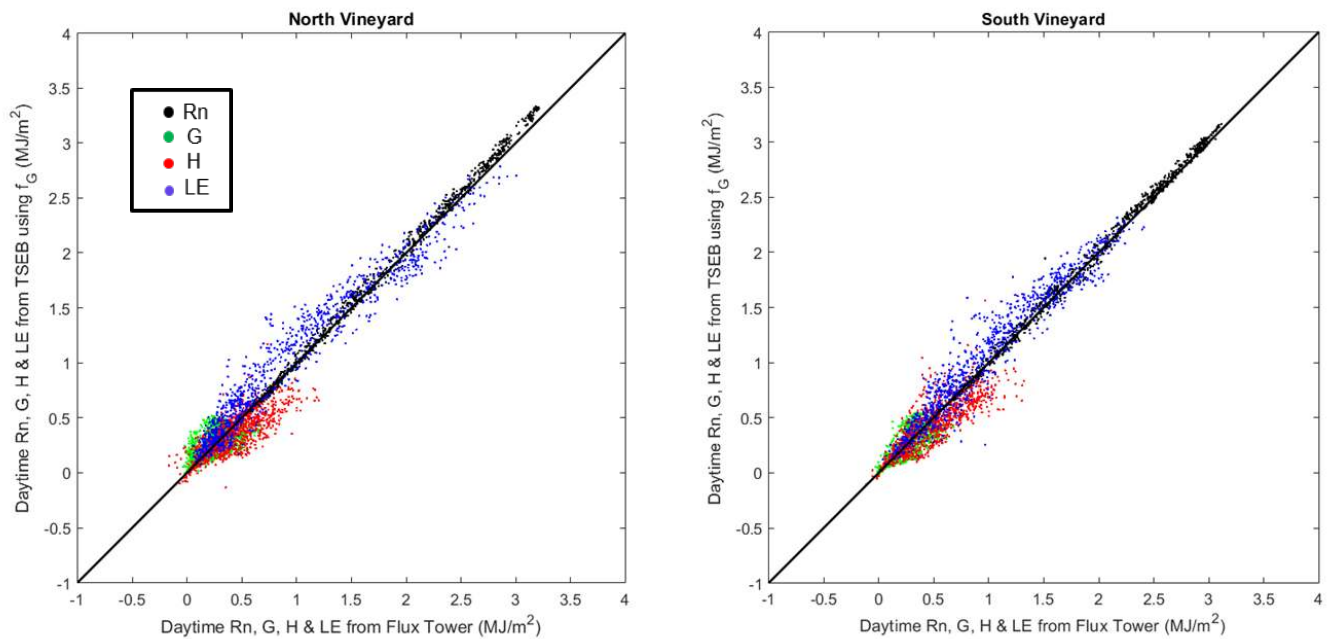


Figure 2. Comparison of daytime net radiation (R_n), soil heat flux (G), sensible heat flux (H) and latent heat flux (LE) computed from hourly flux tower measurements from 2014-2016 for the north and south vineyards versus estimated from TSEB using f_G estimated from Eq. (1).

213 The difference statistics with observed daytime ET (mm) and daytime H (MJ) for the
 214 different foliage distributions are listed in Table 1. Since the leaf-off and bud break statistical
 215 results were virtually the same, those two stages are combined in the table. The mean absolute
 216 percentage difference (MAPD) value, as defined in Table 1, was used as the key performance
 217 metric since it factors in the relative magnitude of the observed flux to the model-measurement
 218 difference. For the north vineyard, the performance of TSEB in LE is notably better over the

growing season through senescence for all years while the spring or the leaf-off through bud break periods produced the greatest errors. However, for H difference statistics, the tendency was to have the largest errors during the growing season when ET is largest and H tends to be relatively small due to frequent irrigations combined with advection of heat from the surrounding mostly dry, arid region. For the south vineyard, MAPD values for LE estimation tended to be largest for leaf-off and bud-break periods, which was also the case for H (except in 2016). Hence for the south vineyard it appears that the largest relative errors in ET have correspondingly the greatest relative errors in H, but this is not the case the north vineyard.

Table 1. Difference statistics between TSEB and measured daily daytime LE or ET (mm) and H (MJ/m²) for the different vine and cover crop phenological conditions

	2014			2015			2016			2014	2015	2016
	December-March leaf-off & bud break	April-May Spring	June-November Growing Season & Senescence	December-March leaf-off & bud break	April-May Spring	June-November Growing Season & Senescence	December-March leaf-off & bud break	April-May Spring	June-November Growing Season & Senescence	Full Year	Full Year	Full Year
Difference Statistics												
North Vineyard												
Evapotranspiration (ET)												
RMSD (mm)	0.25	0.44	0.52	0.37	0.91	0.35	0.39	0.62	0.56	0.42	0.6	0.53
Bias (mm)	0.08	0.21	0.12	0.18	0.8	-0.002	0.28	0.55	0.33	0.13	0.33	0.39
MAPD (%)	21	11	14	34	42	8	40	19	12	12	15	17
Sensible Heat Flux (H)												
RMSD (MJ)	0.1	0.17	0.21	0.1	0.14	0.17	0.06	0.18	0.21	0.17	0.14	0.16
Bias (MJ)	-0.03	-0.11	-0.13	0.003	-0.11	-0.08	-0.003	-0.15	-0.13	-0.1	-0.06	-0.09
MAPD (%)	27	24	34	26	21	31	18	30	39	24	25	27
South Vineyard												
Evapotranspiration (ET)												
RMSD (mm)	0.3	0.31	0.48	0.31	0.46	0.46	0.26	0.61	0.46	0.37	0.41	0.46
Bias (mm)	0.04	0.11	0.19	0.02	0.1	0.33	0.14	0.5	0.28	0.12	0.15	0.31
MAPD (%)	22	9	12	21	12	11	18	18	10	12	13	14
Sensible Heat Flux (H)												
RMSD (MJ)	0.14	0.1	0.16	0.15	0.15	0.21	0.07	0.14	0.2	0.13	0.17	0.15
Bias (MJ)	0.07	0.04	-0.1	0.07	0.004	-0.17	0.03	-0.11	-0.15	0.002	-0.03	-0.08
MAPD (%)	37	14	27	39	15	26	23	21	30	23	24	25

$$\text{BIAS} = \text{Average}[\text{Model} - \text{Observed}]$$

$$\text{RMSD} = \text{Sqrt}[\text{Average}\{(\text{Model} - \text{Observed})^2\}]$$

$$\text{MAPD} = 100 * [\text{Average}\{\text{Absolute}(\text{Model} - \text{Observed})\} / \text{Average}(\text{Model})]$$

The likely reason that the period of greatest errors (in terms of MAPD) in TSEB output for north and south vineyards differ stems from the fact that generally larger H values were measured for the south vineyard during the growing season due to lower biomass/leaf area and less irrigation (see below in the discussion of Figure 6). It is evident from the yearly difference statistics in Table 1 that in general, the TSEB model performs slightly better in the south vineyard than in the north, which agrees with the results from Nieto et al. (this issue; a). Slightly better model-measurement agreement for the south vineyard may to some extent be due to greater variability in vine conditions in the north vineyard; this variability causes the T_{RH} observations to be

generally less representative of the flux measurement footprint of thermal imagery source area (Knipper et al., this issue).

Figure 3 illustrates the effect of phenology-based f_G (Eq. (1)) and temporal trend of LAI on the partitioning of LE between vine canopy or actively transpiring cover crop and the interrow senescent cover crop/bare soil. The ratio of daytime vine/cover crop LE (LE_C or T) in mm to total LE or ET are shown for both north and south vineyards for each of the three study years. As one would expect, the temporal trend in LE_C/LE or T/ET follows the temporal variations in

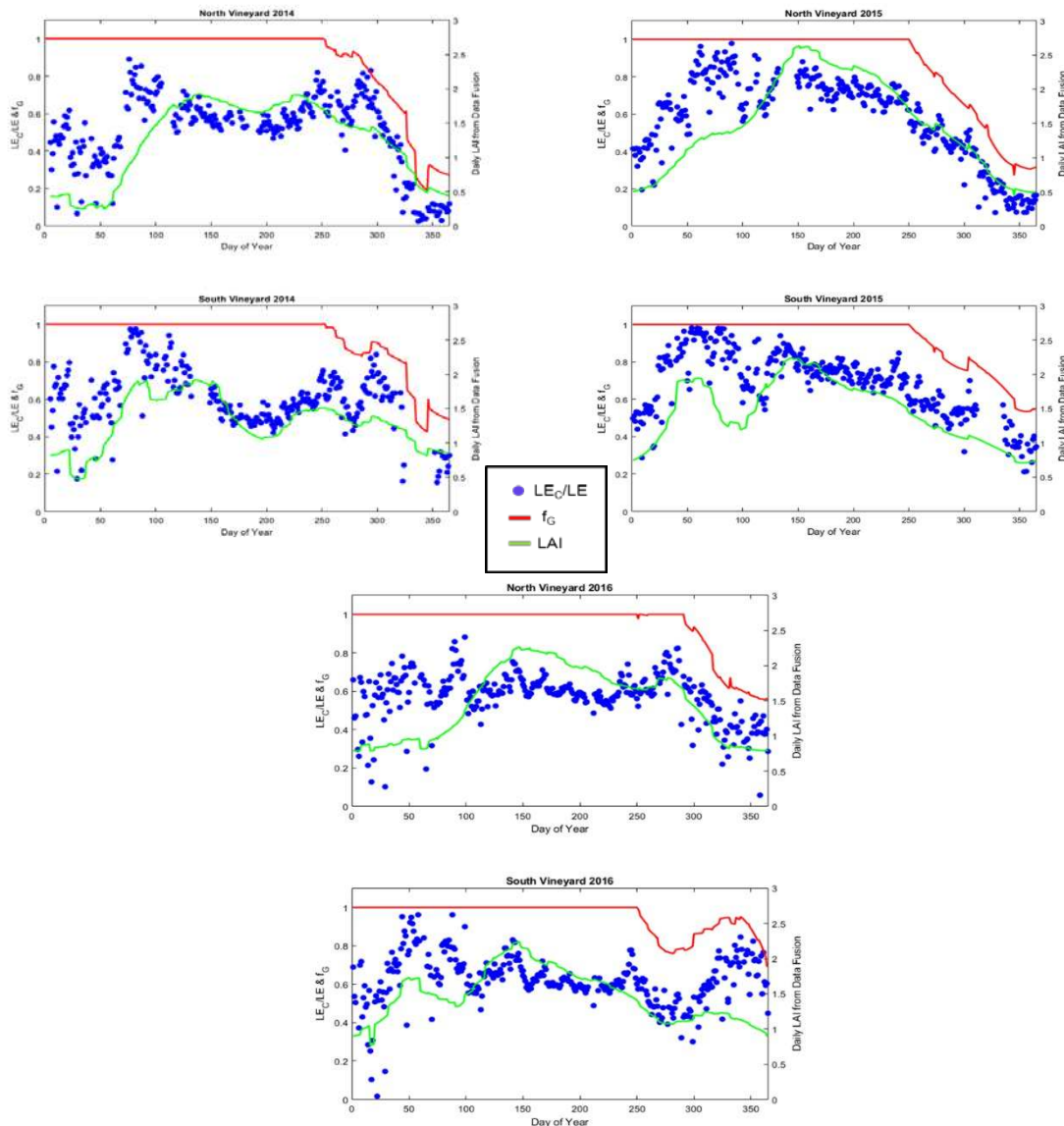
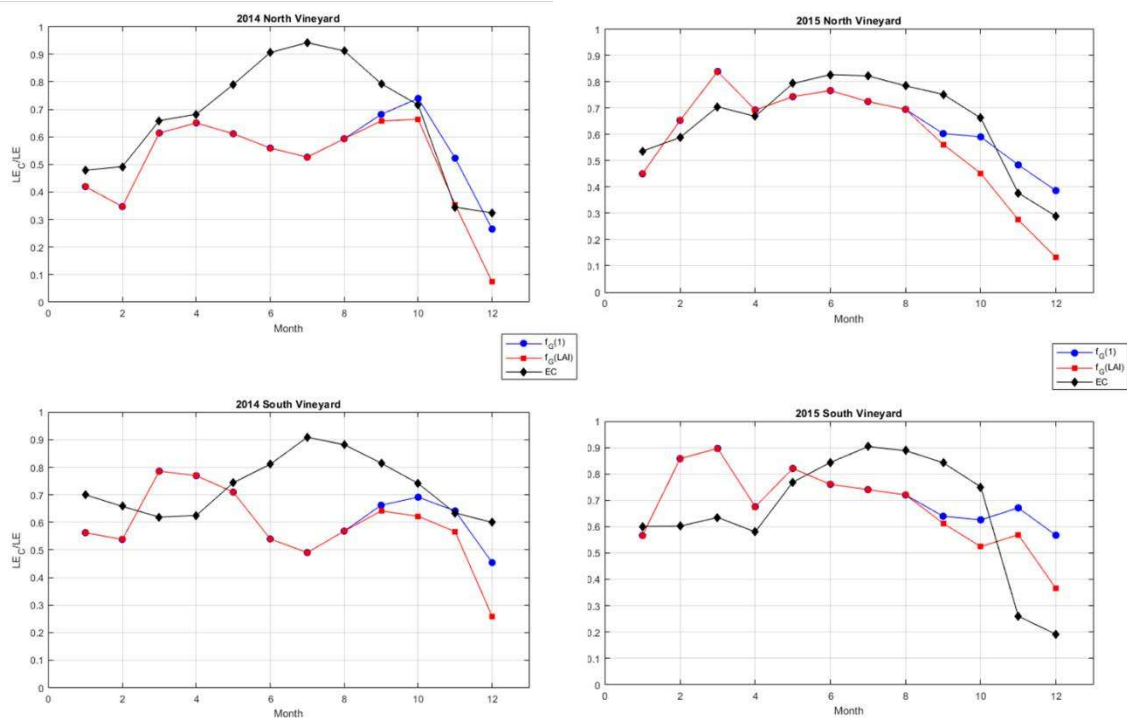


Figure 3. Daytime values of the ratio LE_C/LE or T/ET estimated from TSEB for 2014-2016 using f_G estimated from Eq. (1) and daily LAI from remote sensing retrievals.

1
2
3
4 294 LAI. Early in the year, the cover crop is the primary contributor to T until it is mowed sometime
5
6 295 in the middle of April (~DOY 100), usually soon after bud break. Then, LAI and T/ET increase
7
8 296 as the vine canopy develops. By the end of June (~DOY 180), the vineyard phenology features
9
10 297 transpiring vines and a fully senescent cover crop, and irrigation occurs every 2-3 days. Under
11
12 298 these conditions one would expect T/ET near unity, but instead it decreases through the summer
13
14 300 months as a result of the reduction of LAI through the veraison (July/early August, DOY 180-
15
16 301 T/ET is further amplified after the start of senescence in mid-September (DOY~DOY 260) due
17
18 302 to the decreasing value of f_G .

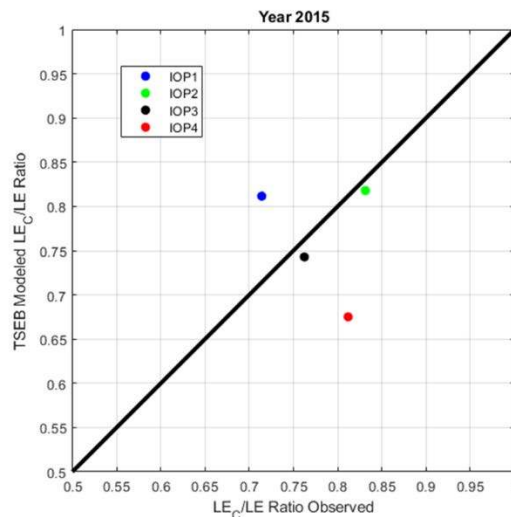
19 303 Figure 4 shows T/ET computed with TSEB and with the EC-based method for 2014 and
20
21 304 2015. In 2014, the T/ET of TSEB is decreasing (concave) during the main months of the growing
22
23 305 season (June-August) while the EC-based method computes an increasing (convex) T/ET. A
24
25 306 decreasing T/ET as the interrow cover crop undergoes senescence and the only source of water is
26
27 307 from drip irrigation along the vine rows, is contradictory to what would be expected and is
28
29 308 supported by the EC-method. However, the TSEB input of LAI from the remote sensing retrieval
30
31 309 also shows a concave relationship over the main growing season (see Fig. 3), which is supported
32
33 310 to some extent by the periodic ground measurements (Sun et al., 2017; White et al., this issue).
34
35 311 However, the actual temporal behavior of LAI may not be as significant or consistent as
36
37 312 estimated by the remote sensing method.



329 Figure 4. The monthly average values of LE_C/LE or T/ET estimated from TSEB for 2014 and
330 2015 using f_G estimated from Eq. (1), $f_G(LAI)$, $f_G=1$, $f_G(1)$ and estimated using the correlation-
331 based flux partitioning method with the high frequency eddy covariance data.

1
 2
 3
 4 332 Better agreement between TSEB-derived T/ET (LE_C/LE) monthly values and the EC method
 5
 6 333 is observed for 2015 versus 2014, particularly for the north vineyard. Additionally, the
 7
 8 334 agreement appears quite good during the senescent periods (October-February) and period up
 9
 10 335 through bud break and flowering (March-May), particularly for 2015 and the north vineyard.
 11
 12 336 Since much of the cover crop is senescent by end of June (DOY ~180), one might expect T/ET
 13
 14 337 to peak in July-August, which is what the estimates using the correlation-based flux partitioning
 15
 16 338 method appear to show. This result needs to be tested with other independent measurements of
 17
 18 339 vine transpiration and interrow cover crop and soil evaporation measurements. However, a major
 19
 20 340 issue with using localized measurements of LST and LAI is the lack of representativeness in
 21
 22 341 relation to the flux tower measurement source area footprint.

23 342 In 2015, there was a set of interrow flux observations collected using micro-Bowen ratio
 24 343 systems in the north vineyard described in Kustas et al. (this issue). The Bowen ratio, H/LE , is
 25 344 another way to express surface energy partitioning. There are only a handful of reliable
 26 345 measurements available during the four Intensive Observation Periods (IOPs). These were
 27 346 collected on DOY 113, 153, 192 and 224 which are late April (IOP 1) soon after bud break, early
 28 347 June (IOP2) near maximum LAI, mid-July (IOP 3) around the berry setting stage, and mid-
 29 348 August (IOP4) well into the veraison stage along with cane/vine maturation. Estimates of the
 30 349 T/ET ratio for these days were computed using the eddy covariance measurements of the total
 31 350 ET along with the micro-Bowen ratio estimates from the interrow comprising E from the bare
 32 351 soil areas and ET or E from the cover crop, which make up approximately 40% and 60% of the
 33 352 interrow, respectively. The estimated daily ratios of T/ET are compared with the TSEB estimates
 34 353 in Figure 5.



354
 355
 356
 357
 358
 359
 360
 361
 362
 363
 364
 365 Figure 5. Comparison of TSEB model estimated daytime LE_C/LE using f_G estimated from Eq. (1)
 366 versus observed ratio for each of the four IOPs in 2015 (IOP 1=late April; IOP 2 = early June;
 367 IOP 3 = mid-July; IOP 4 = late August) using the tower ET and micro-Bowen ratio
 368 measurements of bare soil and cover crop interrow LE and LE_C from the north vineyard (see
 369 Kustas et al., this issue).

For IOP1, TSEB gives a higher T/ET than the micro-Bowen ratio estimate, while for IOP 2 and 3 the agreement in the T/ET partitioning is very good. However, for IOP 4 in August, the T/ET ratio from TSEB is significantly lower than estimated by the EC flux tower/micro-BR system, which is consistent with the monthly T/ET plots in Figure 4.

Figure 6 illustrates the difference in energy balance between the vine and interrow by way of the evaporative fraction ($EF = LE/(H+LE)$) of the vine/cover crop $EF_C = LE_C/(H_C+LE_C)$ and the interrow bare soil/substrate $EF_S = LE_S/(H_S+LE_S)$. Also plotted are the precipitation and

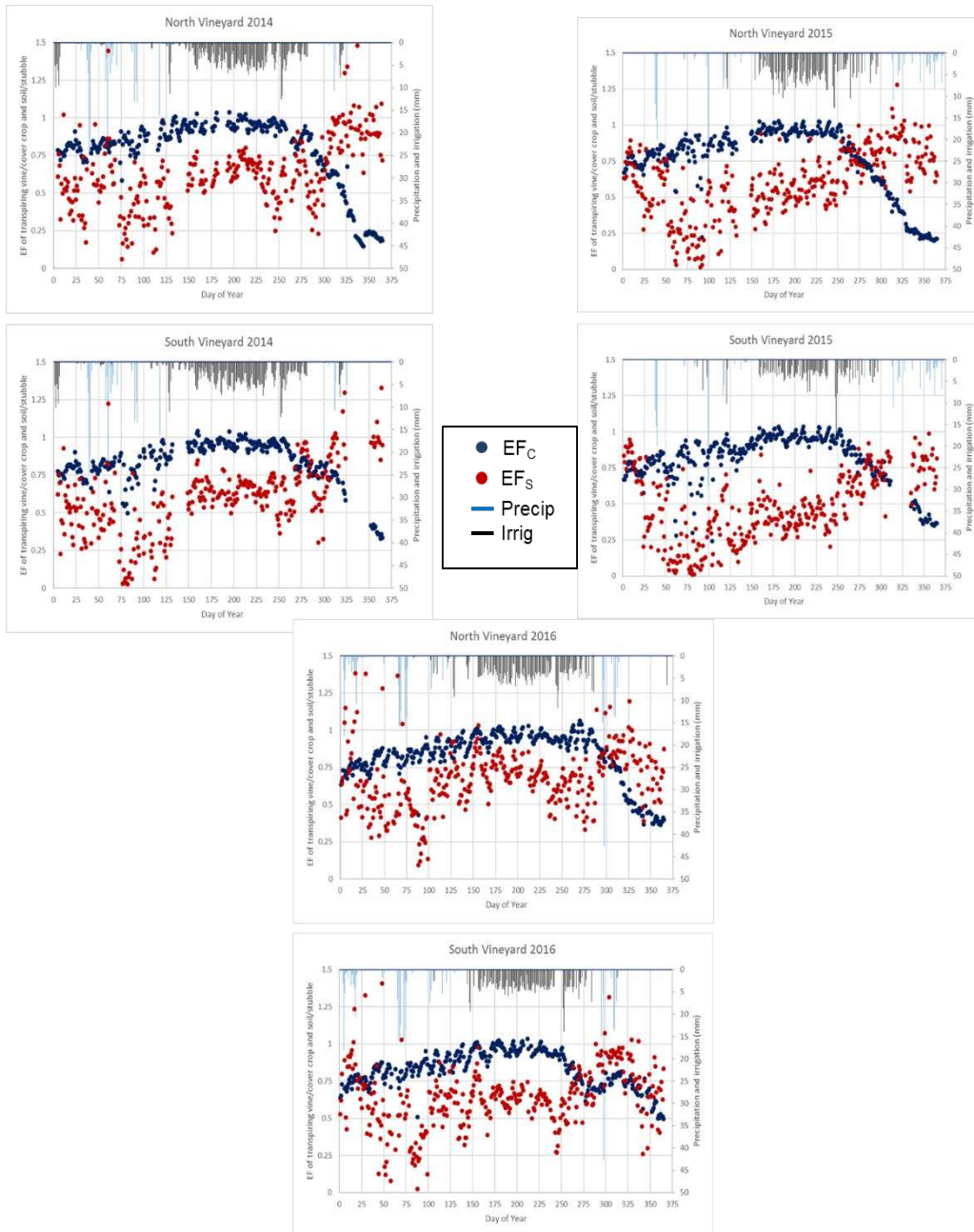


Figure 6. Evaporative fraction (EF) calculated using the TSEB model for the vine/cover crop (EF_C) and the interrow bare soil/senescent cover crop (EF_S).

1
2
3
4 408 irrigation events and amounts in mm and mm/vine, respectively. As expected, under these mostly
5
6 409 well-watered conditions, E_f is near unity except during the period of leaf off through bud
7
8 410 break, nominally the period $DOY < 100$ and $DOY > 275$, January-April and October-December,
9
10 411 respectively. Main vine growth and berry development, concurrent with the majority of vineyard
11
12 412 irrigation, occur from nominally $DOY 125$ through $DOY 250$, May-September.

13
14 414 Values of E_f s tend to be lowest ($E_f < 0.5$) just prior to bud break ($\sim DOY 100$, early April)
15
16 415 and highest (closer to 1) after leaf off, nominally $DOY > 275$, early October. The low E_f s values
17
18 416 prior to bud break may be due to the re-emergence of the cover crop, while the higher values in
19
20 417 E_f s are likely due to irrigation after harvest and leaf off as well as winter precipitation during the
21
22 418 senescence of both vines and cover. Depending on the year, the values of E_f s during the main
23
24 419 vine and berry growth and development period, roughly $DOY 100-250$ (April-early September),
25
26 420 lie between 0.25 and 0.75. However, one would expect for E_f s values to generally be well below
27
28 421 0.5 during the main part of the growing season since $E_f = 0.5$ is equivalent to a Bowen ratio of
29
30 422 order 1, or equal partitioning into H and LE. There are generally lower values of E_f s for the
31
32 423 south vineyard in 2015, which coincides with noticeably lower irrigation amounts; this trend is
33
34 424 also evident to some extent in 2016. Therefore, it may be that the frequent irrigations lead to
35
36 425 higher than expected E_f s values in the summer months; however, it also appears that in the
37
38 426 TSEB formulation may not always properly partitioning E and T, particularly late in the growing
39
40 427 season.

41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65

428 **Summary and Conclusions**

430 Using hemispherical land surface temperature from tower upwelling longwave observations
431
432 from 2014 through 2016, the TSEB model was run over all seasons with available data to
433
434 compute surface energy fluxes with a focus on estimating daytime ET. Several of the original
435
436 TSEB formulations of radiation and wind extinction through the vine canopy layer were
437
438 modified based on the results of Nieto et al. (this issue). The resulting agreement between TSEB-
439
440 estimated daytime sensible (H) and latent heat (LE) fluxes and flux tower observations indicated
441
442 that for the north vineyard, the largest relative differences in LE (MAPD values) occurred in
443
444 either the spring or during leaf-off and bud break periods for both H and LE, with the exception
445
446 of 2016 where the largest differences in H were during the growing and senescent periods. For
447
448 the south vineyard, the largest MAPD values were also from the leaf off and bud break periods,
449
450 while for H it was also leaf off and bud break periods, except in 2016 which was during the
451
452 growing season and senescent period. Since the south vineyard had less irrigated vine biomass, H
453
454 was generally larger over the growing season, making relative errors smaller.

455
456
457
458
459
460
461
462
463
464
465

443 The TSEB model estimates the daytime source of LE or ET is primarily from the vine
444 canopy during the growing season, although the model still estimates a significant contribution to

1
2
3
4 445 LE from the bare soil/senescent cover crop. During periods of no or insignificant vine biomass,
5
6 446 the transpiring interrow cover crop and bare soil mainly contributes to ET. Evaluation of the
7
8 447 partitioning between soil and vegetation sources of LE shows that LE_c/LE or T/ET starts around
9
10 448 1 in early spring when the cover crop is rapidly growing and transpiring, decreases after cover
11
12 449 crop mowing, increases again from bud break until peak LAI, gradually declines through harvest,
13
14 450 and finally increases in late autumn as the cover crop rebounds. This partitioning between E and
15
16 451 T is controlled in large part by the remotely sensed LAI estimates (see Fig. 3), which generally
17
18 452 indicated a peak LAI in late May/early June followed by a gradual decline over the course of the
19
20 453 growing season.

21 454 In 2014 and 2015, a near complete and continuous record of high frequency eddy covariance
22
23 455 data allowed the estimation of monthly T/ET partitioning based on the correlation-based flux
24
25 456 partitioning method. The comparison with monthly values from TSEB indicates that the 2015
26
27 457 growing season TSEB-derived T/ET agreed more closely with the correlation-based flux
28
29 458 partitioning method than in 2014. In addition, selected days during the IOPs have T/ET estimates
30
31 459 using micro-Bowen ratio measurements of E and ET components for the interrow cover crop and
32
33 460 bare soil together with total ET from the flux towers. The agreement in the T/ET ratios was good
34
35 461 for IOP 2 and 3, which were early June and mid-July but over and underestimated for IOPs 1 and
36
37 462 4 in late April and mid-August.

38 463 The partitioning ratios of LE_c/LE and T/ET for the soil/substrate and vine canopy, calculated
39
40 464 by TSEB, tend to be higher than the values from the correlation-based flux partitioning EC
41
42 465 method during the leaf-off and bud burst periods but lower than the EC method values during the
43
44 466 growing season through senescence. This temporal trend in T/ET partitioning estimated from
45
46 467 TSEB is significantly affected by the temporal trend in LAI, which from the remote sensing
47
48 468 method generally shows an increase in LAI in response to growth of the cover crop in the spring
49
50 469 followed by a decline after cover crop mowing, and then an increase after bud burst in March
51
52 470 until end of May/early June. This behavior is followed by a general decline over the growing
53
54 471 season as the cover crop undergoes senescence and the vines are managed/pruned, and then after
55
56 472 harvest the trend in T/ET continues to decrease as both the cover crop and vines are dormant
57
58 473 during winter rains and cooler temperatures (Fig. 3).

59
60
61 474 The magnitude of the evaporative fraction of the soil/substrate (EF_s) estimated by TSEB is
62
63 475 generally scattered around 0.5 (± 0.25) during the growing season; $EF_s = 0.5$ indicates a Bowen
64
65 476 ratio of 1, or equal partitioning of the available energy between H and LE. This LEs component
66
67 477 seems too large for the underlying non-irrigated senescent cover crop interrow, albeit
68
69 478 approximately 40% of the interrow is composed of irrigated bare soil. The response of higher
70
71 479 EF_s values for the north vineyard, which tended to receive higher irrigation amounts, is
72
73 480 plausible. However, one would still not expect EF_s values to exceed 0.5.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

481 Clearly, more detailed measurements are needed to better determine whether the errors in
482 partitioning are the result of biases or errors in the inputs to TSEB, principally in estimates of the
483 leaf area and hemispherical land surface temperature. This study should include applying several
484 methods for estimating the partitioning of ET into vine transpiration using sapflow gages and
485 perhaps microlysimeters as well as more detailed below canopy measurements following the
486 below canopy measurement design of Kool et al. (2016) for estimating E and when appropriate T
487 contributions from the interrow.

488 Reliable estimates of vine transpiration relative to the total ET is valuable information for
489 determining vine water use and stress, both of which influence grape yield and quality. This has
490 led others to develop crop water stress indices using very high resolution aerial thermal imagery
491 to define vine only stress and water potential for irrigation scheduling (Bellvert et al., 2016).
492 With coarser resolution thermal imagery routinely available from satellites (Semmens et al.,
493 2016; Knipper et al., this issue), reliable partitioning of ET into T and E, particularly during the
494 vine growing season, could be used to define a stress index which could relate to the crop/vine
495 water stress index and lead to estimating leaf/vine water potential for irrigation scheduling at the
496 field scale.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

518 Acknowledgements

519 Funding provided by E.&J. Gallo Winery contributed towards the acquisition and processing of
520 the ground truth data collected during GRAPEX IOPs. In addition, we would like to thank the
521 staff of Viticulture, Chemistry and Enology Division of E.&J. Gallo Winery for the assistance in
522 the collection and processing of field data during GRAPEX IOPs. Finally, this project would not
523 have been possible without the cooperation of Mr. Ernie Dosio of Pacific Agri Lands
524 Management, along with the Borden vineyard staff, for logistical support of GRAPEX field and
525 research activities. The senior author would like to acknowledge financial support for this
526 research from NASA Applied Sciences-Water Resources Program [Announcement number
527 NNH16ZDA001N-WATER]. Proposal No. 16-WATER16_2-0005, Request Number:
528 NNH17AE39I. USDA is an equal opportunity provider and employer.

529
530 On behalf of all authors, the corresponding author states that there is no conflict of interest.

1
2
3
4 **531 References**

5 532
6 533 Alfieri J, Kustas W, Gao F, Prueger J, Nieto H, Hipps L (this issue) Influence of wind direction
7 534 on the effective surface roughness of vineyards. *Irrigation Science*

8 535
9 536 Anderson MC, Norman JM, Kustas WP, Houborg JM, Starks PJ, Agam N (2008) thermal-based
10 537 remote sensing technique for routine mapping of land-surface carbon, water and energy fluxes
11 538 from field to regional scales. *Remote Sens. Environ.*, 112:4227–4241.

12 539
13 540 Bellvert J, Zarco-Tejada P, Marsal J, Girona J, Gonzalez-Dugo V, Fereres E (2016) Vineyard
14 541 irrigation scheduling based on airborne thermal imagery and water potential thresholds.
15 542 *Australian Journal of Grape and Wine Research* 22(2):307{315, DOI 10.1111/ajgw.12173}

16 543
17 544 Brutsaert W (1999) Aspects of bulk atmospheric boundary layer similarity under free-convective
18 545 conditions. *Rev. Geophys.* 37(4):439–451

19 546
20 547 Brutsaert W (2005) *Hydrology. An Introduction*. ISBN-13 978-0-521-82479-8, Cambridge
21 548 University Press

22 549
23 550 Colaizzi PD, Evett SR, Howell TA, Li F, Kustas WP, Anderson MC (2012a) Radiation model
24 551 for row crops: I. Geometric view factors and parameter optimization. *Agron. J.* 104:225-240.

25 552
26 553 Colaizzi PD, Agam N, Tolck JA, Evett SR, Howell TA, Gowda PH, O’Shaughnessy SA,
27 554 Kustas WP, Anderson MC (2014) Two-source energy balance model to calculate E, T, and ET:
28 555 Comparison of Priestley-Taylor and Penman-Monteith formulations and two time scaling
29 556 methods. *Trans. ASABE*, 57(2):479-498.

30 557
31 558 Colaizzi PD, Kustas WP, Anderson MC, Agam N, Tolck JA, Evett SR, Howell TA, Gowda PH,
32 559 O’Shaughnessy SA (2012b) Two-source energy balance model estimates of evapotranspiration
33 560 using component and composite surface temperatures. *Adv. Water Resour.*, 50:134-151.

34 561
35 562 Colaizzi PD, Agam N, Tolck JA, Evett SR, Howell TA, O’Shaughnessy SA, Gowda PH,
36 563 Kustas WP, Anderson MC (2016c) Advances in a two-source energy balance model :
37 564 Partitioning of evaporation and transpiration for cotton using component and composite surface
38 565 temperatures. *Trans. ASABE* 59(1): 181-197. Doi 10.13031/trans.59.11215.

39 566
40 567 Colaizzi PD, Evett SR, Agam N, Schwartz RC, Kustas WP (2016a) Soil heat flux calculation for
41 568 sunlit and shaded surfaces under row crops: 1. model development and sensitivity analysis.
42 569 *Agric. Forest Meteorol.* 216:115–128.

43 570
44 571 Colaizz PD, Evett SR, Agam N, Schwartz RC, Kustas WP, Cosh, MH, McKee LG (2016b) Soil
45 572 heat flux calculation for sunlit and shaded surfaces under row crops: 2. model test. *Agric.Forest*
46 573 *Meteorol.* 216: 129–140.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Gao F, Anderson MC, Kustas WP, Wang Y (2012) A simple method for retrieving Leaf Area Index from Landsat using MODIS LAI products as reference. *J. Appl. Remote Sens.* 6, DOI: 10.1117/JRS.1116.063554.

Goudriaan J (1977) *Crop micrometeorology: A simulation stud.* Tech. rep., Center for Agricultural Publications and Documentation, Wageningen

Hillel D (1998) *Environmental Soil Physics.* Academic Press

Knipper KR, Kustas WP, Anderson MC, Aleri JG, Prueger JH, Hain CR, Gao F, Yang Y, McKee LG, Nieto H, Hipps LE, Alsina MM, Sanchez L (this issue) Evapotranspiration estimates derived using thermal-based satellite remote sensing and data fusion for irrigation management in California vineyards. *Irrigation Science*

Kondo J, Ishida S (1997) Sensible heat flux from the earth's surface under natural convective conditions. *J. Atmos. Sci.* 54(4):498–509

Kool D, Agam N, Lazarovitch N, Heitman JL, Sauer TJ, Ben-Gal A (2014) A review of approaches for evapotranspiration partitioning. *Agric. For. Meteorol.* 184:56–70.

Kool D, Kustas WP, Ben-Gal A, Lazarovitch N, Heitman JL, Sauer TJ, Agam N (2016) Energy and evapotranspiration partitioning in a desert vineyard. *Agric. For. Meteorol.* 218–219: 277–287.

Kustas WP, Norman JM (1999) Evaluation of soil and vegetation heat flux predictions using a simple two-source model with radiometric temperatures for partial canopy cover. *Agric. For. Meteorol.* 94:13-29.

Kustas W, Norman JM (2000) A two-source energy balance approach using directional radiometric temperature observations for sparse canopy covered surfaces. *Agron. J.* 92(5):847–854.

Kustas WP, Nieto H, Morillas L, Anderson MC, Alfieri JG, Hipps LE, Villagarcía L, Domingo F, García M (2016) Revisiting the paper “using radiometric surface temperature for surface energy flux estimation in mediterranean drylands from a two-source perspective”. *Remote Sens. Environ.* 184:645–653

Massman W (1987) A comparative study of some mathematical models of the mean wind structure and aerodynamic drag of plant canopies. *Bound.-Layer Meteorol.* 40(1):179–197

Massman W, Forthofer J, Finney M (2017) An improved canopy wind model for predicting wind adjustment factors and wildland fire behavior. *Canadian J. Forest Res.* 47(5):594–603

Nieto H, Kustas W, Gao F, Alfieri J, Torres A, Hipps L (this issue a) Impact of different within-canopy wind attenuation formulations on modelling evapotranspiration using TSEB. *Irrigation Science*

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

621 Nieto H, Kustas WP, Torres-Rúa A, Alfieri JG, Gao F, Anderson MC, White WA, Song L, del
622 Mar Alsina M, Prueger JH, McKee M, Elarab M, McKee LG (this issue b) Evaluation of TSEB
623 turbulent fluxes using different methods for the retrieval of soil and canopy component
624 temperatures from UAV thermal and multispectral imagery. *Irrigation Science*
625

626 Norman JM, Becker F (1995) Terminology in thermal infrared remote sensing of natural
627 surfaces, *Remote Sens. Rev.*, 12:159–173.
628

629 Norman JM, Kustas WP, Humes KS (1995) Source approach for estimating soil and vegetation
630 energy fluxes in observations of directional radiometric surface temperature. *Agric. Forest*
631 *Meteorol.* 77(3-4):263–293.
632

633 Parry CK, Nieto H, Guillevic P, Agam N, Kustas WP, Alfieri J, McKee L, McElrone AJ (this
634 issue) An intercomparison of radiation partitioning models in vineyard row structured canopies.
635 *Irrigation Science*
636

637 Priestley CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using
638 large-scale parameters. *Monthly Weather Review* 100(2):81–92
639

640 Sauer TJ, Norman JM, Tanner CB, Wilson TB (1995) Measurement of heat and vapor transfer
641 coefficients at the soil surface beneath a maize canopy using source plates. *Agric. Forest*
642 *Meteorol.* 75(1-3):161 – 189.
643

644 Santanello Jr J, Friedl M (2003) Diurnal covariation in soil heat flux and net radiation. *J.*
645 *Applied Meteorol.* 42(6):851–862.
646

647 Scanlon TM, Kustas WP (2010) Partitioning carbon dioxide and water vapor fluxes using
648 correlation analysis. *Agric. For. Meteorol.* 150:89-99.
649

650 Scanlon TM, Kustas WP (2012) Partitioning evapotranspiration using an eddy covariance-based
651 technique: Improved assessment of soil moisture and land-atmosphere exchange dynamics.
652 *Vadose Zone J.*, 11, DOI: 10.2136/vzj2012.0025
653

654 Scanlon TM, Sahu P (2008) On the correlation structure of water vapor and carbon dioxide in the
655 atmospheric surface layer: A basis for flux partitioning. *Water Resour. Res.* 44, W10418. URL:
656 <http://onlinelibrary.wiley.com/doi/10.1029/2008WR006932/abstract>,
657 doi:10.1029/2008WR006932.
658

659 Semmens KA, Anderson MC, Kustas WP, Gao F, Alfieri JG, McKee L, Prueger JH, Hain CR,
660 Cammalleri C, Yang Y, Xia T, Sanchez L, Alsina MM, Vélez M (2016) Monitoring daily
661 evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion
662 approach. *Remote Sens. Environ.* 185:155 – 170, DOI 10.1016/j.rse.2015.10.025
663

664 Sun L, Gao F, Anderson MC, Kustas WP, Alsina M, Sanchez L, Sams B, McKee LG, Dulaney
665 WP, White A, Alfieri JG, Prueger JH, Melton F, Post K (2017) Daily mapping of 30 m LAI,

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

666 NDVI for grape yield prediction in California vineyard. Rem. Sens., 9, 317; 18 pp.
667 doi:10.3390/rs9040317

668
669 White AW, Alsina M, Nieto H, McKee L., Gao F, Kustas WP (this issue) Indirect measurement
670 of leaf area index in California vineyards: Utility for validation of remote sensing-based
671 retrievals. Irrigation Science.
672

Appendix A TSEB model

The basic equation of the energy balance at the surface can be expressed following Eq. A1.

$$\begin{aligned} R_n &\approx H + LE + G \\ R_{n,S} &\approx H_S + LE_S + G \quad (A1) \\ R_{n,C} &\approx H_C + LE_C \end{aligned}$$

with R_n being the net radiation, H the sensible heat flux, LE the latent heat flux or evapotranspiration, and G the soil heat flux. “C” and “S” subscripts refer to canopy and soil layers respectively. The symbol “ \approx ” appears since there are additional components of the energy balance that are usually neglected, such as heat advection, storage of energy in the canopy layer or energy for the fixation of CO₂ (Hillel, 1998)

The key in TSEB models is the partition of sensible heat flux into the canopy and soil layers, which depends on the soil and canopy temperatures (T_S and T_C respectively). If we assume that there is an interaction between the fluxes of canopy and soil, due to an expected heating of the in-canopy air by heat transport coming from the soil, the resistances network in TSEB is considered in series. In that case H can be estimated as in Eq. A2 (Norman et al, 1995, Eqs. A1-A3)

$$\begin{aligned} H = H_C + H_S &= \rho_{air} C_p \frac{T_{AC} - T_A}{R_a} \\ &= \rho_{air} C_p \left[\frac{T_C - T_{AC}}{R_x} + \frac{T_S - T_{AC}}{R_s} \right] \quad (A2) \end{aligned}$$

where ρ_{air} is the density of air (kg m⁻³), C_p is the heat capacity of air at constant pressure (J kg⁻¹ K⁻¹), T_{AC} is the air temperature at the canopy interface, equivalent to the aerodynamic temperature T_0 , computed as follows (Norman et al., 1995, Eq. 4):

$$T_{AC} = \frac{\frac{T_A}{R_a} + \frac{T_C}{R_x} + \frac{T_S}{R_s}}{\frac{1}{R_a} + \frac{1}{R_x} + \frac{1}{R_s}} \quad (A3).$$

Here, R_a is the aerodynamic resistance to heat transport (s m⁻¹), R_s is the resistance to heat flow in the boundary layer immediately above the soil surface (s m⁻¹), and R_x is the boundary layer resistance of the canopy of leaves (s m⁻¹). The mathematical expressions of these resistances are detailed in Norman et al. (1995) and Kustas and Norman (2000), discussed in Kustas et al. (2016), and shown below:

$$\begin{aligned} R_a &= \frac{\ln\left(\frac{z_T - d_0}{z_{0H}}\right) - \psi_h\left(\frac{z_T - d_0}{L}\right) + \psi_h\left(\frac{z_{0H}}{L}\right)}{\kappa' u_*} \\ R_s &= \frac{1}{c(T_S - T_A)^{1/3} + b u_s} \quad (A4), \\ R_x &= \frac{C'}{LAI} \left(\frac{l_w}{U_{d_0 + z_{0M}}} \right)^{1/2} \end{aligned}$$

where u_* is the friction velocity (m s⁻¹) computed as:

$$u_* = \frac{\kappa' u}{\left[\ln\left(\frac{z_u - d_0}{z_{0M}}\right) - \psi_m\left(\frac{z_u - d_0}{L}\right) + \psi_m\left(\frac{z_{0M}}{L}\right) \right]} \quad (A5).$$

1
2
3
4 699 In Eq. A5, z_u and z_T are the measurement heights for wind speed u (m s^{-1}) and air temperature
5
6 700 T_A (K), respectively. d_0 is the zero-plane displacement height, z_{0M} and z_{0H} are the roughness
7
8 701 length for momentum and heat transport respectively (all those magnitudes expressed in m), with
9
10 702 $z_{0H} = z_{0M} \exp(-kB^{-1})$. In the series version of TSEB z_{0H} is assumed to be equal to z_{0M} since
11
12 703 the term R_x already accounts for the different efficiency between heat and momentum transport
13
14 704 (Norman et al., 1995), and therefore $kB^{-1} = 0$. The value of $\kappa' = 0.4$ is the von Karman's
15
16 705 constant. The Ψ_m and Ψ_h terms in Eqs. A4 and A5 are the adiabatic correction factors for
17
18 706 momentum and heat, respectively, whose formulations are described in Brutsaert (1999, 2005)
19
20 707 and are functions of the atmospheric stability. The stability is expressed using the Monin-
21
22 708 Obukhov length L (m), which has the following form:

$$20 \quad 709 \quad L = \frac{-u_*^3 \rho_{air}}{kg[H/(T_A C_p) + 0.61E]} \quad (\text{A6})$$

21
22 710 where H is the bulk sensible heat flux (W m^{-2}), E is the rate of surface evaporation (kg s^{-1}), and g
23
24 711 the acceleration of gravity (m s^{-2}).

25 712 The coefficients b and c in Eq. A4 depend on turbulent length scale in the canopy, soil-
26
27 713 surface roughness and turbulence intensity in the canopy, which are discussed in Sauer et al
28
29 714 (1995), Kondo and Ishida(1997) and Kustas et al.(2016). C' is assumed to be $90 \text{ s}^{1/2} \text{ m}^{-1}$ and l_w is
30
31 715 the average leaf width (m).

32 716 Wind speed at the heat source-sink ($z_{0M} + d_0$) and near the soil surface was originally
33
34 717 estimated in TSEB using the Goudriaan (1977) wind attenuation model:

$$35 \quad 719 \quad \begin{aligned} U(z) &= U_c \exp[-a_G(1 - z/h_c)] \\ a_G &= 0.28LAI^{2/3} h_c^{1/3} l_w^{-1/3} \end{aligned} \quad (\text{A7}).$$

36
37
38 720
39 721 For the vineyards, Nieto et al. (this issue) utilized a new wind profile formulation developed by
40
41 722 Massman et al. (2017). This canopy wind profile model is a more physically-based method for
42
43 723 calculating wind speed attenuation for the canopies of vertically non-uniform foliage distribution
44
45 724 and leaf area that often exist in orchards and vineyards.

46 725 When only a single observation of T_{rad} is available (i.e. measurement at a single angle),
47
48 726 partitioning of T_{rad} into canopy and soil components (T_C and T_S) is required to estimate
49
50 727 component sensible heat fluxes via Eq. A2. The approach developed for TSEB (Norman et al.,
51
52 728 1995) starts with an initial estimate of plant transpiration (λE_C), as defined by the Priestley and
53
54 729 Taylor(1972) relationship, applied to the canopy divergence of net radiation ($R_{n,c}$)

$$53 \quad 729 \quad LE_C = \alpha_{PT} f_g \frac{\Delta}{\Delta + \gamma} R_{n,c} \quad (\text{A8}).$$

54
55 730 Here, α_{PT} is the Priestley-Taylor coefficient, initially set to 1.26, f_g is the fraction of vegetation
56
57 731 that is green and hence capable of transpiring, Δ is the slope of the saturation vapor pressure
58
59 732 versus temperature curve, and γ is the psychrometric constant. This method allows the canopy
60
61 733 sensible heat flux to be calculated using the energy-balance at the canopy layer ($H_c = R_{n,c} -$

1
2
3
4 734 LE_C) and hence an estimate of T_C to be obtained by rewriting Eq. A8 to have the following form
5
6 735 (Norman et al, 1995):
7 736

$$8 \quad T_{Ci} = T_a + \frac{R_{n,c}R_a}{\rho C_p} \left[1 - \alpha_{PT} f_G \frac{\Delta}{\Delta + \gamma} \right] \quad (A9),$$

10 737
11
12 738 where T_{Ci} is the initial estimate of canopy temperature. Alternatively, T_{Ci} can be derived with
13
14 739 the linearization approximation to the series resistance approach described in Appendix A of
15 740 Norman et al. (1995), specifically Eqs. A7, A11 and A12. Then, T_S is the derived from the
16 741 following using T_{rad} , T_C , and an estimate of $f_c(\theta)$, the fraction of vegetation observed by the
17 742 sensor view zenith angle θ :
18 743
19 744

$$20 \quad T_{rad}^4(\theta) = f_c(\theta)T_C^4 + [1 - f_c(\theta)]T_S^4 \quad (A10)$$

21 745
22
23 746 The value of $f_c(\theta)$ is typically estimated as an exponential function of the leaf area index
24 747 (LAI), which includes a clumping factor or index Ω for canopies where the LAI is concentrated
25 748 for sparsely distributed plants or for organized canopies such as row crops (Kustas and Norman,
26 749 1999; Anderson et al., 2005), and has the following form:
27 750

$$28 \quad f_c(\theta) = 1 - \exp\left(\frac{-0.5\Omega LAI}{\cos\theta}\right) \quad (A11)$$

29 751
30 752 However due, to the unique vertical canopy structure and wide row width relative to canopy
31 753 height of vineyards, a new method to derive Ω had to be developed that was both based on the
32 754 geometric model of Colaizzi et al.(2012a) and simple enough to be incorporated into TSEB.
33 755 Parry et al. (this issue) compared radiation extinction models of different complexities and found
34 756 the simplified geometric model developed by Nieto et al (this issue) was a robust modified
35 757 radiation scheme. The resulting effective LAI , $LAI_{eff} = \Omega LAI$, was then used as input in the
36 758 Campbell and Norman (1998) canopy radiative transfer model to estimate soil and canopy net
37 759 radiation, $R_{n,s}$ and $R_{n,c}$, respectively (see also Kustas and Norman (2000) for details).
38 760

39 761 The final energy balance component of soil heat flux, G , is typically estimated by TSEB as a
40 762 fraction of the net radiation at the soil surface, $R_{n,s}$. However, over the daytime period, the
41 763 assumption of a constant ratio between G and $R_{n,s}$ is unreliable (Santanello and Friedl, 2003;
42 764 Colaizzi et al., 2016a, b). Based on observations between the measured soil heat flux and the
43 765 estimated $R_{n,s}$ in Nieto et al (this issue; a), a modified formulation estimating G as a function of
44 766 $R_{n,s}$ was adopted that accounts for the temporal behavior of the $G / R_{n,s}$ ratio over the daytime
45 767 period using a double asymmetric sigmoid function; this estimate was a significantly better fit to
46 768 the observations than the sinusoidal function proposed by Santanello and Friedl (2003).
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

769 With $R_{n,S}$ and G estimated and H_S computed via T_S estimated from Eqs. A9-A11, iteratively
770 solving for Eqs. A2-A7 results in LE_s solved as a residual via Eq. A1 for the soil layer, namely
771 $LE_s = R_{n,S} - G - H_S$.

772 In some cases, the initial T_C implied by the Priestley-Taylor approximation (Eq. A9) results in
773 deriving a relatively high value of T_S for a given observed T_{rad} and $f_c(\theta)$ condition. This high T_S
774 can cause a significant overestimate in H_S and therefore produce unrealistic estimates of LE_s
775 (i.e., negative values during daytime; $LE_s < 0$) solved by residual. In this case, the α_{PT} coefficient
776 is iteratively reduced at 0.1 intervals from its initial value ~ 1.3 , effectively assuming the canopy
777 is stressed and transpiring at sub-potential levels until $LE_s \geq 0$.
778