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Estimation of actual evapotranspiration in winegrape vineyards located on hillside terrain using surface renewal analysis

T. M. Shapland · R. L. Snyder · D. R. Smart · L. E. Williams

Abstract Sensible and latent heat flux densities were estimated in a level vineyard, a northeast aspect vineyard and a southwest aspect vineyard in the Napa Valley of California using the eddy covariance and surface renewal methods. Surface renewal is theoretically not limited to level or extensively homogeneous terrain because it examines a more localized process of scalar exchange as compared with eddy covariance. Surface renewal estimates must be calibrated against eddy covariance data to account for unequal heating of the air parcels under a fixed measurement height. We calibrated surface renewal data against eddy covariance data in a level vineyard, and the calibration factor (α) was applied to the surface renewal measurements on the hillside vineyards. Latent heat flux density was estimated from the residual of the energy balance. In the level vineyard, the average daily actual evapotranspiration (ET_a) for the period of June through September was 2.4 mm per day. In the northeast aspect vineyard, the average daily ET_a was 2.2 mm per day, while in the southwest aspect vineyard it was 2.7 mm per day. The net radiation values for the level vineyard, the northeast aspect vineyard, and the southwest aspect vineyard were compared against the Ecosystem Water Program with good agreement.

Introduction

Grapevine water status and irrigation management are known to be closely tied to winegrape quality (Jackson and Lombard 1993; Downey et al. 2006). Water deprivation is known to enhance red grape quality under some conditions (Kennedy et al. 2002). For this reason, many growers rely on leaf water potential measurements to schedule the first irrigation of the season. These same growers will often rely on gross regional estimates of daily evapotranspiration (ET) and idealized crop coefficients to determine the frequency and quantity of irrigation applications (Allen et al. 1998). The overall objective of this irrigation strategy is to arrest vegetative growth and direct carbon allocation to fruit, although a poorly characterized component apparently involves increasing the amount and typicity of fruit and seed secondary compounds like phenolics (Kennedy et al. 2002).

The crop coefficient (K_c) is a crop- and management-specific multiplier for converting standardized reference evapotranspiration for short canopies (ET_o) into crop evapotranspiration (ET_c) for a well-watered crop without water stress (Eq. 1).

$$ET_o \times K_c = ET_c \tag{1}$$

The ratio of daily ET_c to the ET_o is used to determine the K_c (Allen et al. 1998). The most advanced grapevine K_c values for vineyards were developed from lysimeter measurements of grapevine ET (Williams and Ayars 2005). These K_c values account for the effects of vineyard design and canopy size on ET rates.

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The advent of drip irrigation systems has allowed winegrape vineyards to be planted more extensively on a broad range of slopes and aspects and in marginal soils of diverse water-holding capacities. The current K_c and ET_o model does not account for the effect of hillside terrain on vineyard water demand. An improved method for estimating ET in winegrape production vineyards over a variety of terrains (slope and aspect) would enable growers to refine their irrigation strategies for meeting crop quality goals. It would also allow for adjustments to estimated vineyard ET to account for changes in environmental factors that affect ET demand, like radiation, which can vary by as much as 30 % on slopes with predominantly north-facing versus south-facing aspects.

Evapotranspiration can be obtained from measured components of the energy balance equation. Net radiation (Rn) must be in balance with the ground heat flux density (G), sensible heat flux density (H), latent heat flux density (LE), and other less significant miscellaneous energy terms such as biomass energy storage and photosynthesis. The simplified energy balance equation neglects the miscellaneous terms to provide a mathematical description of energy partitioning at the Earth's surface (Eq. 2).

$$Rn = G + H + LE \tag{2}$$

The simplified energy balance equation is hereafter referred to as the energy balance equation.

Relatively simple thermopiles can be used to measure Rn and G. The measurement of H and LE requires more complex instrumentation because the approach requires a method to observe the boundary-layer turbulence that dominates these two processes (Monteith and Unsworth 1990). The least expensive method to estimate ET is to measure Rn, G, and H and then calculate LE using the residual of the energy balance (Eq. 3).

$$LE = Rn - G - H \tag{3}$$

Latent heat flux density can then be divided by the latent heat of evaporation (L) to obtain the mass flux density of water vapor, and the mass flux density of water can be converted to hourly and daily ET (Eq. 4).

$$ET = LE/L \tag{4}$$

The components of the energy balance were measured in a level vineyard, a northeast (NE) aspect vineyard, and a southwest (SW) aspect vineyard. We hypothesize that the dissimilarity in Rn and H drive the differences in daily ET_a among the three sites. The energy balance residual approach (Eq. 3) was the primary technique used in this study to estimate LE. We measured H using the eddy covariance and surface renewal methods. Both methods are complex, and our introduction of eddy covariance theory and surface renewal theory will be limited to their

application for the measurement of H. Inasmuch as most of the vineyard ET observed in this investigation occurred when heat flux was away from the surface, our introduction of the two methods will be limited to the condition of unstable atmospheric stratification.

The eddy covariance method measures the covariance of the vertical wind speed with sonic temperature averaged over a time interval, for example, a 30-min period (Swinbank 1951). A sonic anemometer is the most common instrument for measuring the 3-dimensional wind velocities and sonic temperature. The velocity fluctuations and sonic temperature fluctuations are assumed to be characteristic of the turbulent fluctuations over the area of interest, which constitutes the flux footprint (Monteith and Unsworth 1990). The footprint of the flux measurements ranges from less than 100 meters to more than 100 km, depending on surface characteristics, instrument height, stability, and other variables that influence boundary-layer observations (Lee et al. 2000, Paw et al. 2004). The eddy covariance method can only detect the vertical turbulent flux into and out of the footprint, so the vertical heat flux is assumed to be equal to the total heat flux. The flux footprint therefore must be level and homogeneous in order to minimize horizontal mass and energy advection. The accounting for horizontal advection over hillside terrain introduces significantly more uncertainty into eddy covariance measurements (Paw et al. 2000).

The surface renewal method measures H by analyzing temperature changes in coherent air parcels that interact directly with the crop surface (Paw et al. 1995). For a brief period after an air parcel comes in contact with the surface, its temperature does not change. This period is called the quiescent period (s). A time trace of the air temperature at the canopy top depicts s as an interval without a change in temperature (Fig. 1). After the quiescent period, the air parcel warms as energy is transported from the canopy to the air parcel. A time trace of the air temperature at the canopy top depicts the warming period (d) as a slow rise in temperature (Fig. 1). The warming of the parcel continues until a cool air parcel sweeps down from aloft and enters the canopy, displacing the heated parcel of air. The time trace of the air temperature depicts the renewal event as an abrupt drop (Fig. 1). The average heating of the air parcel and the number of times the air parcel is renewed at the
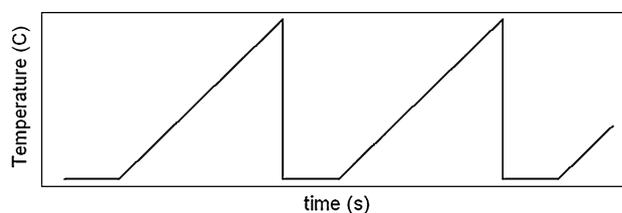

Fig. 1 Schematic showing temperature ramp over time

surface over a sampling period are used to determine H for that period.

Eddy covariance measures temperature and wind velocity fluctuations in the fully developed turbulence characteristic of a broad footprint. Surface renewal, on the other hand, measures temperature differences of individual air parcels exchanged locally, in this case immediately above and within the canopy. The fetch requirement for surface renewal seems less than the fetch requirement for eddy covariance (Paw et al. 1995; Qiu et al. 1995). Energy transport to or from sources outside the area of interest were assumed to contribute minimally to the heat exchange of individual air parcels.

Surface renewal must be calibrated against another method for measuring scalar exchange, such as the Bowen ratio or eddy covariance methods, to account for linear bias of the surface renewal measurements (Snyder et al. 1996). This calibration factor, called the alpha calibration (α), is unique for each crop surface and measurement height. A physical explanation of α that is universally applicable has not yet been described; however, it likely accounts for vertical heterogeneity of energy sources within the canopy, which leads to uneven heating of the air parcel (Spano et al. 1997). Alternatively, α may account for differences in the mean parcel size (Spano et al. 2000). For a discontinuous surface such as a vineyard, the canopy architecture effectively changes when the wind moves across the rows in varying directions, which may alter α. At present, α is obtained by simultaneous measurement of H by eddy covariance and by surface renewal. The slope of the least-squares regression forced through the origin of eddy covariance H measurements versus uncalibrated surface renewal H measurements provides an estimate of α.

In this study, α was obtained in the level vineyard using the eddy covariance estimates and subsequently applied to the hillside vineyards for obtaining H by surface renewal. The same coefficient α, which was derived in the level vineyard, was also used on the hillsides because all three vineyards had similar canopy architecture, row spacing, and orientation to the prevailing wind. Due to differences in the turbulence between hillsides and level terrain, α may not be the same at all three sites, despite the similarities in canopy architecture and orientation. Nonetheless, this approach provides a reasonable estimation of H for the hillside vineyards. Latent heat flux density was estimated from the residual of the energy balance. In the level vineyard, the average daily ET_a for the period of June through September was 2.4 mm per day. In the northeast aspect vineyard, the average daily ET_a was 2.2 mm per day, while in the southwest aspect vineyard it was 2.7 mm per day.

Materials and methods

Site description

The level vineyard was located in the central part of the Napa Valley of California (Latitude: 38°23′N, Longitude: 122°19′W, Elevation: 29.1 m). The rows were oriented 40° east of north, the daytime wind direction was predominantly across the rows, and the upwind fetch was 150 m. The vines were trellised with a vertical shoot positioning trellis system, spacing between rows was 2.13 m, spacing between plants was 1.83 m, and the canopy height was approximately 2.00 m. Insect damage to the canopy was minimal. There was a mowed cover crop of dry weedy vegetation between the vine row and a strip of bare soil approximately 0.30 m wide directly beneath the vine row. The vineyard was irrigated approximately once per week using a drip irrigation system and the vineyard owners managed the irrigation timing and amounts. According to the vineyard owner, approximately 30 % of accumulated ET_o was applied on an approximately weekly basis. The estimated irrigation timing and amount data for the level vineyard were supplied by the grower (Table 1). Data were gathered from June 20, 2008, to September 20, 2008, which corresponds to approximately 30 days after anthesis through harvest.

Table 1 Irrigation data by month for the level vineyard, the northeast (NE) aspect vineyard, and the southwest (SW) aspect vineyard

Date (mo./year)	ET_o		Level vineyard		NE vineyard		SW vineyard	
	Monthly (mm)	Season total (mm)	Monthly (mm)	Season total (mm)	Monthly (mm)	Season total (mm)	Monthly (mm)	Season total (mm)
4/2008	124.5	124.5	37.4	37.4	33.2	33.2	46.3	46.3
5/2008	140.3	264.8	42.1	79.5	68.9	102.1	69.8	116.1
6/2008	156.9	421.8	47.1	126.5	37.8	139.9	52.4	168.6
7/2008	157.9	579.6	47.4	173.9	67.7	207.6	93.9	262.4
8/2008	155.9	735.6	46.8	220.7	46.0	253.6	64.0	326.4
9/2008	122.0	857.6	36.6	257.3	29.9	283.5	41.5	367.9

Table 2 Climate data by month

Date (mo./year)	Season Total ET_o (mm)	Rain (mm)	Solar radiation (MJ m^{-2} day^{-1})	Maximum air temp (°C)	Minimum air temp (°C)	Mean air temp (°C)	Dew point temp (°C)	Mean wind speed (m s^{-1})
10/2007	54.6	55.6	12.4	22.6	6.4	14.1	9.0	1.4
11/2007	55.0	15.5	9.2	20.4	4.3	11.2	6.5	1.2
12/2007	44.9	135.8	6.3	13.7	2.2	7.5	3.8	1.5
1/2008	35.6	356.5	5.7	12.6	3.3	7.7	5.0	1.7
2/2008	58.1	125.9	10.5	16.6	3.2	9.2	5.9	1.6
3/2008	96.5	4.1	16.1	19.9	3.4	11.2	5.2	1.8
4/2008	124.5	3.8	21.6	22.4	3.9	13.2	4.7	2.1
5/2008	140.3	6.4	23.7	25.6	7.5	16.7	8.6	2.1
6/2008	156.9	0.0	26.3	29.4	8.7	19.4	8.9	1.8
7/2008	157.9	0.0	28.1	29.6	9.9	19.5	13.4	1.4
8/2008	155.9	0.0	24.8	31.0	10.8	20.0	13.4	1.8
9/2008	122.0	0.0	20.3	29.8	8.1	18.1	9.7	1.5

The NE aspect vineyard was located on a knoll about 1.5 km west of the level vineyard. The slope was approximately 25° and the aspect was 40° east of north (http://websoilsurvey.nrcs.usda.gov/). The vineyard was not terraced. The direction of the predominant wind during the daytime was across the rows and the upwind fetch was roughly 50 m. The canopy architecture was similar to that in the level vineyard. The vines were trellised with a vertical shoot positioning trellis system, the spacing between rows was 1.83 m, the spacing between plants was 1.83 m, and the canopy height was also approximately 2.00 m. There was a mowed cover crop of dry, weedy resident vegetation between the vine row and a strip of bare soil approximately 0.30 m wide directly beneath the vine row. The vineyard was usually irrigated once per week using a drip irrigation system. The irrigation timing and amounts were provided by the vineyard owner (Table 1). Data were collected from June 20, 2008 to September 20, 2008, which corresponded to approximately 30 days after anthesis through harvest.

The southwest aspect vineyard was located on the opposite side of the knoll from the northwest aspect vineyard. The slope was also approximately 25° but the aspect was primarily 220° west of north (http://websoilsurvey.nrcs.usda.gov/). The vineyard was not terraced. The direction of the wind during the daytime was predominantly across the rows and the upwind fetch was around 50 m. The canopy architecture was similar to that of the level and NE aspect vineyards. The vines were trellised with a vertical shoot positioning trellis system, the spacing between rows was 1.83 m, and the spacing between plants was 1.83 m. There was a mowed cover crop of dry, weedy resident vegetation between the vine row and a strip of bare soil approximately 0.30 m wide directly beneath the vine row. The vineyard was

irrigated approximately once per week using a drip irrigation system. The vineyard owners managed the irrigation timing and amounts (Table 1). Data were gathered from June 20, 2008, to September 20, 2008, which corresponds to approximately 30 days after anthesis through harvest.

All three vineyards were located within 2 km of one another. The climate was characteristic of coastal Mediterranean regions during the summer. Typically, the early mornings were foggy, the afternoons were warm and dry, and the evenings were cool. The standardized reference evapotranspiration equation for short canopies was used to calculate ET_o (Allen et al. 1998) with data from the California Irrigation Management Information System (CIMIS), weather station # 77 (Snyder and Pruitt 1992). The CIMIS station #77 is located at the UC-Davis Department of Viticulture and Enology's Oakville field station (Latitude: 38°26′N, Longitude: 122°25′W, Elevation: 57.9 m). Monthly climate data from the CIMIS station are presented in Table 2. The rainfall data in Table 2 were taken from the National Climate Data Center, St. Helena hospital climate station (Latitude: 38°30′N, Longitude: 122°28′W, Elevation: 68.6 m) because the data were collected by hand using a standard rainfall gauge.

Instrumentation and installation

An eddy covariance system was installed in the level vineyard. Wind velocities and water vapor (H_2O) and carbon dioxide (CO_2) densities were sampled at 10 Hz and stored in a datalogger (CR3000, Campbell Scientific Inc., Logan, UT). A sonic anemometer collected 3-dimensional wind velocities and sonic temperature (CSAT3, Campbell Scientific Inc., Logan, UT). An open-path infrared gas analyzer continuously monitored water vapor and carbon

dioxide concentrations (LI-7500, LI-COR, Lincoln, NE). Both instruments were installed at 3.00 m above the ground and approximately 1.5 m above the estimated zero-plane of displacement. The open-path infrared gas analyzer was laterally separated from the sonic anemometer transducers by approximately 0.20 m. For surface renewal analysis in the level vineyard, an unshielded 0.0762 mm diameter Type E thermocouple was installed at 2.13 m above the ground and approximately 0.13 m above the canopy (FW3, Campbell Scientific Inc., Logan, UT). A sampling frequency of 4 Hz was used to gather the temperature data for the surface renewal analysis. For the remaining energy balance terms, a net radiometer (Q*7, REBS, Seattle, WA) was installed at 3 m above the ground directly above the vertically oriented canopy and two ground heat flux plates were buried approximately 0.05 m below the ground surface at 0.6 m on either side of the vine row nearest to the datalogger (HFT-3.1, REBS, Seattle, WA). Two four-probe soil temperature averaging Type E soil thermocouples (TCAV-L, Campbell Scientific Inc., Logan, UT) were installed on either side of each heat flux plate spanning a depth approximately 0.01 to 0.04 m to measure soil energy storage in the soil layer above the ground heat flux plates.

Identical surface renewal systems were installed in the same manner in all three vineyards except for the net radiometers. The net radiometer sensor plates were positioned parallel to the vineyard slope, rather than level, to give the same angle of solar incidence onto the plate as the angle of incidence onto the vineyard surface.

Data processing

H and LE eddy covariance measurements were calculated from the vertical wind velocity, the sonic temperature, and the water vapor concentration sampled at 10 Hz using EdiRe flux statistics software (Mauder et al. 2008). Flux statistics were averaged over 30-min time intervals.

Sensible heat was calculated from the product of the air density, the specific heat of air, and the covariance of the vertical wind and the sonic temperature (Swinbank 1951).

$$H = \rho C_p \left(\overline{w'Ts'} \right) \tag{5}$$

where ρ is the air density (g m^{-3}), C_p is the specific heat of air at constant pressure (J g^{-1} K^{-1}), w is the vertical wind velocity (m s^{-1}), Ts is the sonic temperature (K), and the overbar denotes a time-averaged interval.

Eddy covariance LE, which was used only for the energy balance closure relationship (Eq. 3), was calculated from the product of the latent heat of vaporization and the covariance of the vertical wind and the water vapor density (Swinbank 1951).

$$\lambda E = \lambda \overline{w'q'} \tag{6}$$

where w is the vertical wind velocity (m s^{-1}), q is the water vapor density (g m^{-3}), λ is the latent heat of vaporization (J g^{-1}), and the overbar denotes a time-averaged interval.

Signal spikes between consecutive data points more than 6 standard deviations from the mean and less than 10 scans in duration were removed (Vickers and Mahrt 1997). The wind velocities were rotated into the natural wind coordinate system using the first- and second-rotation algorithms (Lee et al. 2004). The density correction was applied iteratively for both the H and LE until the correction accounted for less than 1 % of the total flux (Webb et al. 1980).

Surface renewal H was calculated from the average heating of the air parcel and the number of times the air parcel was renewed at the surface over 30-min intervals (Eq. 7).

$$H = \alpha \cdot z \cdot \rho C_p \left(\frac{a}{d + s} \right) \tag{7}$$

where α is the calibration factor, z is the measurement height, ρ is the air density (g m^{-3}), C_p is the specific heat of air at constant pressure (J g^{-1} K^{-1}), a is the average ramp amplitude (K), which corresponds to the temperature enhancement of the air parcel, d is the duration of the heating of the air parcel (s), and s is the quiescent period following the sweep-phase of the parcel (s). The sum of d and s is the mean air parcel renewal time over the sampling period (Paw et al. 1995).

The ramp amplitude (a) and duration ($d + s$) were determined using the Van Atta ramp model (Van Atta 1977), which uses 30-min means of the 2nd, 3rd, and 5th moments of the air temperature structure function (Eq. 8).

$$S^n(r) = \frac{1}{m - j} \sum_{i=1+j}^{m} \left(T_i - T_{i-j} \right)^n \tag{8}$$

where m is the number of data points in the 30-min interval measured at frequency (f), n is the order of the structure function, j is a sample lag between data points corresponding to a time lag ($r = j/f$), and T_i is the ith temperature sample (K). The second-, third-, and fifth-order moments were calculated and recorded for $r = 0.25$ s and $r = 0.50$ s. Preliminary H values were calculated separately for each time lag from the mean ramp amplitude and mean ramp period (Eq. 7). The 30-min uncalibrated surface renewal H was obtained from the mean of the H values calculated from the two time lags of $r = 0.25$ and $r = 0.50$ s. The α was obtained from the slope of the least-squares regression of eddy covariance H versus the uncalibrated surface renewal H forced through the origin (Paw et al. 1995).

Thirty-minute average LE for calculating daily ET_a rates for all three sites was obtained from the residual of the energy balance equation (Eq. 3) using H from the surface renewal method. Eddy covariance was used only to calibrate the surface renewal method at the level vineyard. It was assumed that the calibration also applied to the hillside vineyards. Daily ET_a rates were calculated from energy balance and the surface renewal measurements at all three vineyards.

The surface renewal analysis failed to resolve ramp characteristics during the majority of stable, nighttime conditions. During these periods, LE appeared to increase dramatically because H values were not available to offset the other energy balance terms. In order to avoid the uncertainties associated with nighttime turbulent flux measurements, LE, and H were assumed to be zero when Rn was less than zero.

Model description

The Ecosystem Water Program (ECOWAT) is a model for estimating ET for non-ideal sites based on the ecosystem water budget (Spano et al. 2009). The model predicts ET_a as a function of the following parameters: irrigation or rainfall amount and frequency, ET_o, microclimate, vegetation, percent ground cover, vegetation water stress, and soil evaporation. Once the input parameters have been applied to the ECOWAT model, the modeled ET_a must be calibrated against measured ET. The ECOWAT calibration accounts for parameters in the water budget that are difficult to obtain, including the contribution of dew, fog, and water tables to the total water balance of the ecosystem.

The microclimate parameter includes a slope and aspect correction. The slope and aspect correction accounts for the effects of day of the year, latitude, slope and aspect to estimate the radiation received by sloped terrain from data collected over level terrain. The ECOWAT slope and aspect correction is based on Lambert's cosine law, which states that the amount of radiation received by a surface depends on the cosine of the angle between the radiation beam and a line normal to the surface (Rosenberg et al. 1983). It is assumed that differences in albedo and long wavelength radiation between level terrain and hillside terrain are negligible.

ECOWAT is based on natural ecosystem water budgets, rainfall depths and frequencies. While ECOWAT was intended ET_a estimation of natural ecosystems, it was only used in this study to test whether the hillside Rn measurements were similar to modeled values based on slope and aspect. The Oakville CIMIS solar radiation data for 2008 were used for the level terrain radiation input parameter in the ECOWAT model, because the model takes incoming solar radiation as its radiation input. The

slope and aspect algorithm of the ECOWAT model was applied, and the model radiation predictions were compared to the measured Rn values for the NE aspect and SW aspect vineyards. The purpose was to determine whether the Rn measurements and the model predictions qualitatively matched.

Results and discussion

Part 1. Quality assurance of flux data and calibration of the surface renewal analysis

Ideally the available energy terms of the energy balance equation (Rn and G) equal the turbulent flux terms of the energy balance equation (H and LE) (Eq. 9).

$$Rn - G = H + LE \tag{9}$$

The percentage of available energy accounted for by the turbulent flux terms is a common method in biometeorology for assessing the quality of the flux data. However, energy balance closure, i.e. when both sides of (Eq. 9) are equal, is infrequently achieved in flux measurement studies (Wilson et al. 2002). In the present study approximately 93 % of the available energy was accounted for by the turbulent flux (Fig. 2). This is a superior result to most energy balance studies reported in the literature, lending confidence to our eddy covariance measurements of H. Because the eddy covariance H was used to calibrate the surface renewal H, the calibrated surface renewal H measurements could also be considered reasonably accurate.

The coefficient of determination (R^2) for the eddy covariance energy balance closure improved when G was excluded (Fig. 3). Poblete-Echeverría and Ortega-Farias 2009 reported similar results in a vineyard. Two heat flux plates and two soil thermocouples were used to estimate
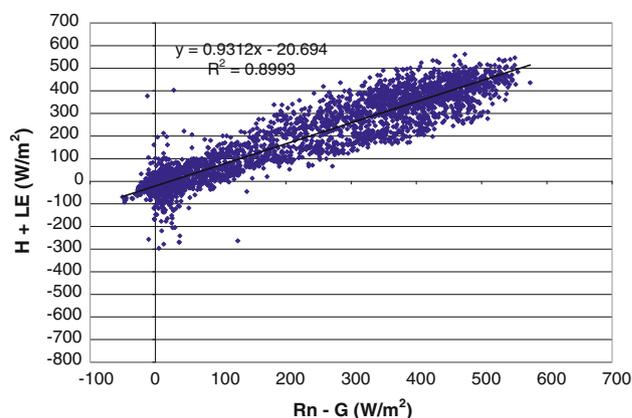
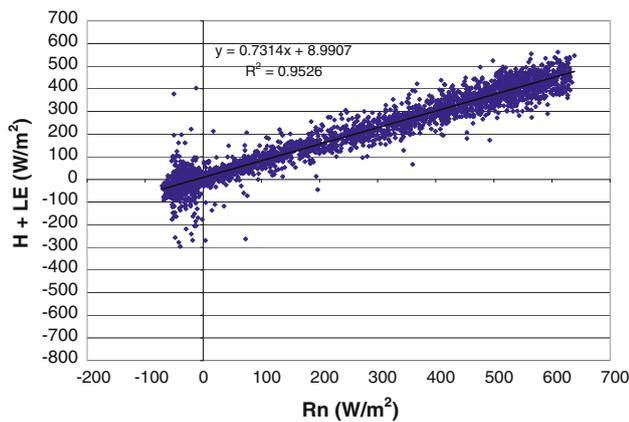Fig. 2 Energy balance closure from 30-min eddy covariance measurements

Fig. 3 Energy balance closure from 30-min eddy covariance data without ground heat flux density estimation

G. It is likely that more sensors were needed for more accurate measurement of *G* below a sparse vineyard canopy. Increasing the number of heat flux sensors, however, would have required a more sophisticated logging system and spatial modeling inasmuch as the vineyard floor is geometrically partitioned into distinct ground covers. This would have dramatically increased equipment costs and interpretation.

In the level vineyard, surface renewal measurements of *H* underestimated eddy covariance *H* by 18 % for the period of study (Fig. 4). Nonetheless, the coefficient of determination of 0.8 is typical for α (Snyder et al. 1996; Spano et al. 1997, 2000), and indicated that in the present study the surface renewal method provided estimates of eddy covariance *H* within general expectations. The α calibration calculated on a daily basis (Fig. 5) varies slightly from one day to the next, but the departures from the mean are small despite the wide range of meteorological conditions met during the course of this study. This
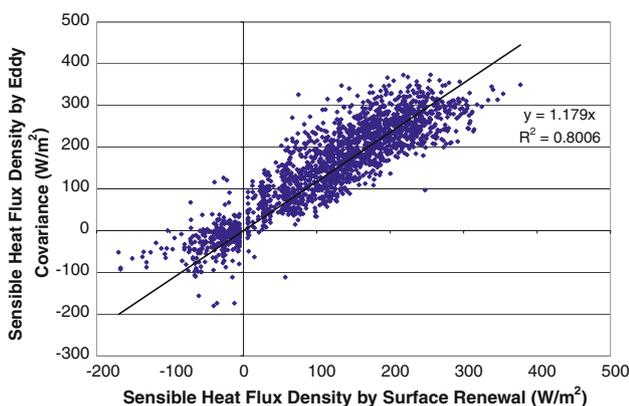
Fig. 4 The α-calibration: the least-squares regression through the origin of 30-min sensible heat flux density obtained by surface renewal versus 30-min sensible heat flux density obtained by eddy covariance

lends further support to the hypothesis that α depends on canopy architecture and sensor height above the canopy top, and not atmospheric variables, justifying the use of the same α values on the level and hillside vineyards to yield reasonable estimates of *H*. All 30-min observations of surface renewal *H* on the level and hillside vineyards were adjusted using the observed correction factor α of 1.18 to obtain a calibrated surface renewal *H*.

Two sets of data were obtained for LE from the residual of the energy balance. In the first data set LE was obtained from the residual of the energy balance when *H* was calculated by eddy covariance. In the other data set LE was obtained when *H* was calculated from calibrated surface renewal measurements. The correlation between the residual LE calculations was compared in a least-squares regression (Fig. 6). Residual LE by calibrated surface renewal had a nearly 1:1 relationship with the residual LE by eddy covariance. The limited number of ground heat flux plates may partly explain the low coefficient of determination ($R^2 = 0.56$). Nonetheless, a root mean square error of 50.8 (W m^{-2}) was relatively small, indicating that the surface renewal observations of ET were quite accurate (Snyder et al. 1996).

Part 2. Daily actual evapotranspiration

The daily ET presented in this paper are not daily ET_c values, which are only applicable to well-watered crops. The values presented in this paper are ET_a values estimated from micrometeorological approaches. The vineyards in this study were not well-watered because they were production winegrape vineyards and quality goals require that growers practice irrigation deprivation (Jackson and Lombard 1993). Under conditions of moderate to severe water stress, stomatal closure reduces ET_a relative to ET_c Also, water stress reduces plant growth. Since smaller plants intercept less radiation, water stress will delay or prevent attainment of the maximum canopy size and the seasonal maximum K_c value. It is therefore expected that the ET_a rate in a production winegrape vineyard is less than ET_c rate.

Daily ET_a for the study period in the level vineyard averaged 2.4 mm per day while those for the NE and SW aspect vineyards averaged 2.2 and 2.7 mm per day, respectively (Table 3). For the months of June and July, the daily ET_a was highest in the level vineyard, followed by the SW aspect vineyard and the NE aspect vineyard (Fig. 7). For the months of August and September, daily ET_a was highest in the SW aspect vineyard, followed by the level vineyard and the NE vineyard (Fig. 7).

Because the winegrapes were all red varieties, the decrease in daily ET_a at all three sites relative to the ET_c, which should stay constant in the midseason (Allen et al.

Fig. 5 The daily α-calibration
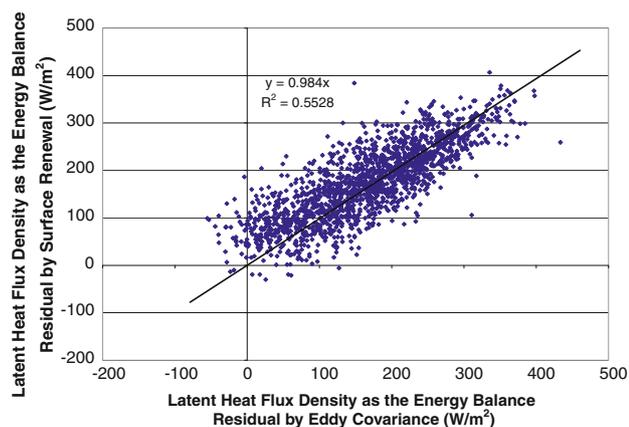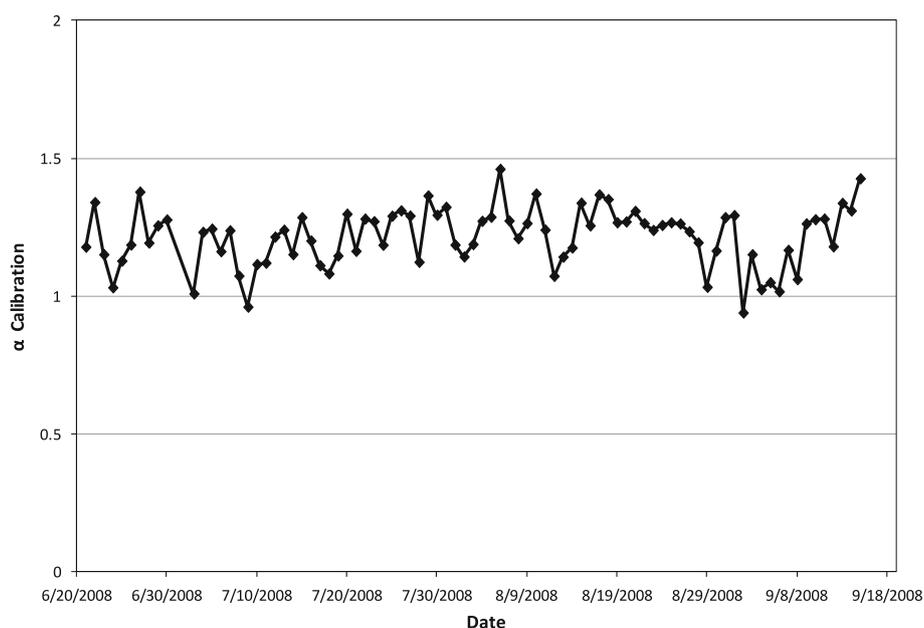
Fig. 6 30-Min surface renewal versus 30-min eddy covariance latent heat flux densities. Both the surface renewal and eddy covariance latent heat flux density values were calculated from the residual of the energy balance

1998), was likely the result of increasing vine water stress leading up to harvest. Considering the SW site received 84 mm more irrigation water than the NE site, it is possible that the NE site experienced more water stress than the SW site, although higher Rn, shallower soils, or other factors could increase stress in the SW site. This cannot be confirmed since vine water status was not monitored in this study.

For water-stressed vineyards, the application of water should cause the daily ET_a to increase relative to ET_o. The level vineyard was irrigated on an approximately weekly basis, but the exact dates and amounts were not recorded. The ratio of daily ET_a to daily ET_o for the level vineyard (Fig. 8) shows increases on an approximately 7–10-day intervals, but it is uncertain whether these increases correspond to irrigation events the due to the lack of irrigation information. In the NE and SW vineyards, the ratio of daily ET_a to daily ET_o increases after most irrigation events (Figs. 9 and 10) presumably because the vine stomata opened as more water became available.

Part 3. Energy balance comparisons

The ensemble average of hourly values for each energy balance term during the period of record was used to construct an ensemble average diurnal energy balance for each site (Figs. 11, 12 and 13). The hourly ensemble values of each energy balance term were averaged to obtain the

Table 3 Summary of average daily actual evapotranspiration rates by month for the level vineyard, the northeast (NE) aspect vineyard, and the southwest (SW) aspect vineyard

Date	June ET_a (mm day^{-1})	July ET_a (mm day^{-1})	August ET_a (mm day^{-1})	September ET_a (mm day^{-1})	Season ET_a (mm day^{-1})
Level vineyard	2.6	3.1	2.3	1.6	2.4
NE vineyard	3.1	2.7	1.9	1.3	2.2
SW vineyard	2.9	2.7	2.6	2.6	2.7

Fig. 7 Estimated daily evapotranspiration rates for the level vineyard, the northeast aspect vineyard, and the southwest aspect vineyard
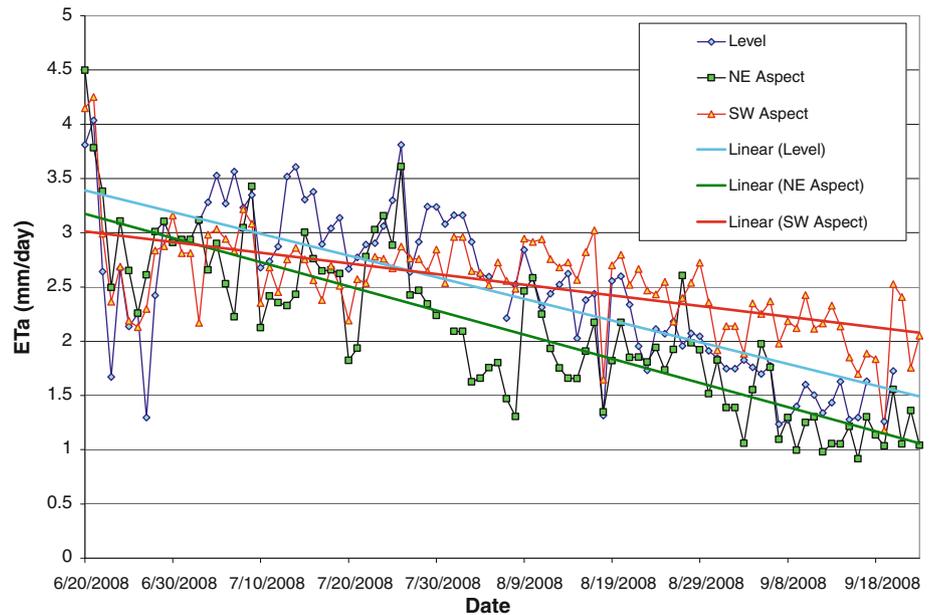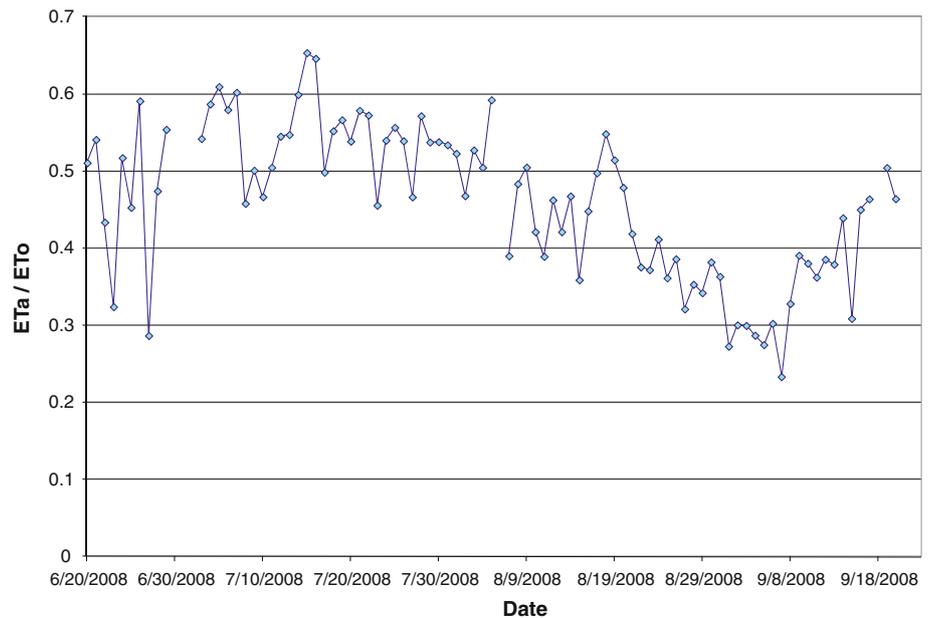

Fig. 8 Daily actual evapotranspiration rates divided by the reference evapotranspiration rates for the level vineyard

daily mean values of each term (Table 4). Note that, the terms in Table 4 do not balance because turbulent fluxes were set to zero during nighttime periods to avoid uncertainty associated with nighttime flux measurement.

The average daily Rn is the mean amount of solar and terrestrial energy impinging upon the surface minus that reflected or emitted away from the surface over the course of a day. During the summer in California, the mean daily Rn is positive over all vegetation. The seasonal average daily Rn was highest in the SW vineyard, intermediate in the level vineyard, and lowest in the NE vineyard

(Table 4). According to Lambert's cosine law, the amount of energy received by a surface is proportional to the angle of incidence, i.e., the angle between the incoming radiation and the surface (Rosenberg et al. 1993), and therefore a south-facing slope in the northern hemisphere usually intercepts more solar radiation than a north-facing slope. The daily mean Rn for the NE aspect vineyard was consistently lower than Rn for the level vineyard. For the months of June and July, Rn was slightly higher for the level than the SW aspect vineyard presumably because of the difference in angle of incidence as shown in the

Fig. 9 Daily actual evapotranspiration rates divided by the reference evapotranspiration rates for the northeast aspect vineyard
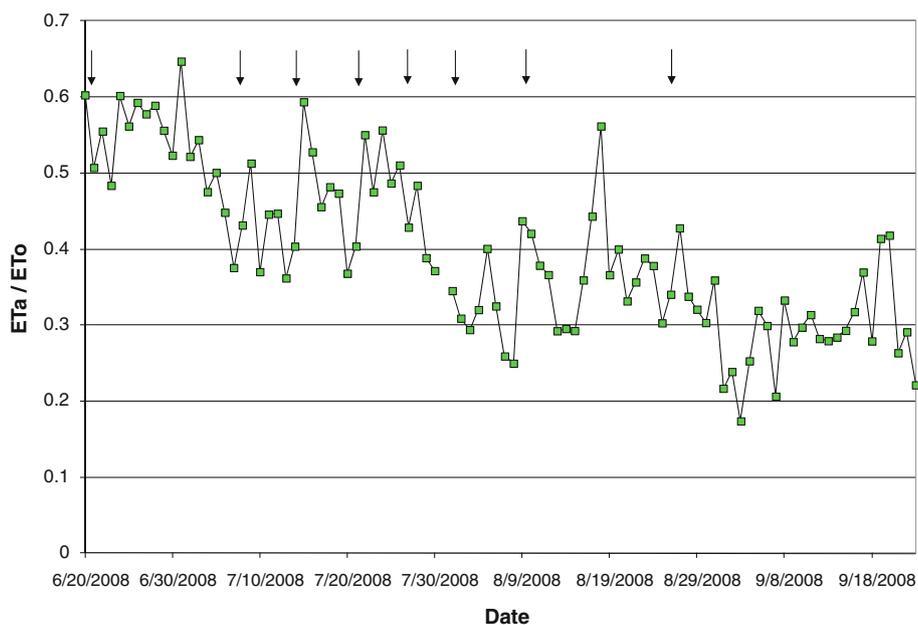

Fig. 10 Daily actual evapotranspiration rates divided by the reference evapotranspiration rates for the southwest aspect vineyard
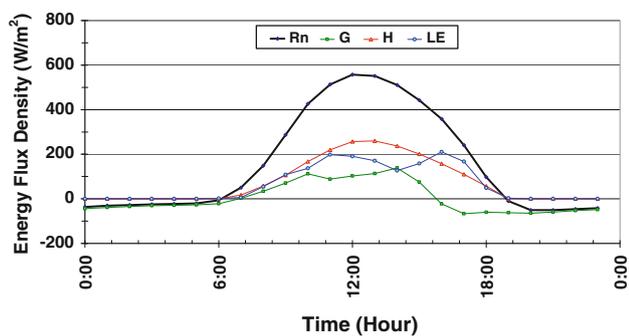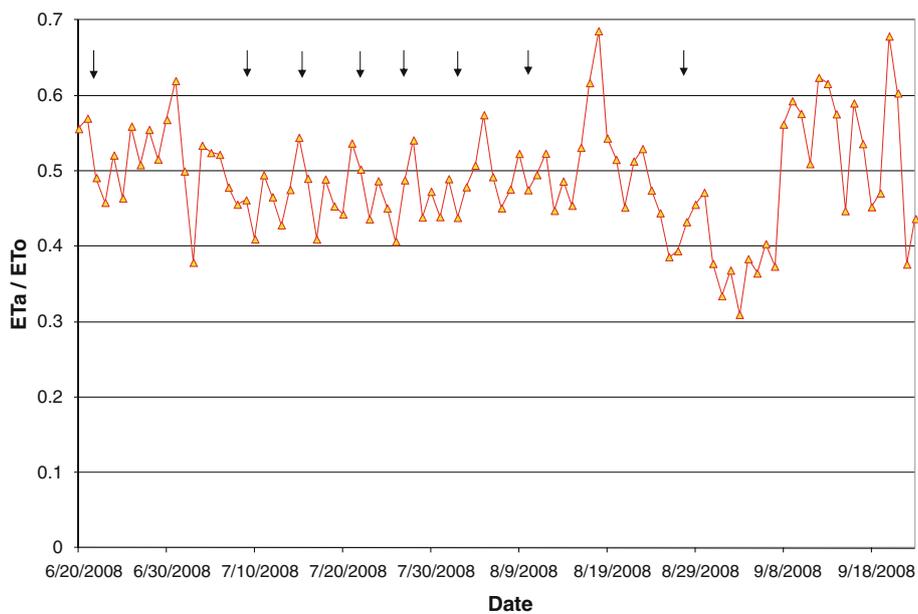

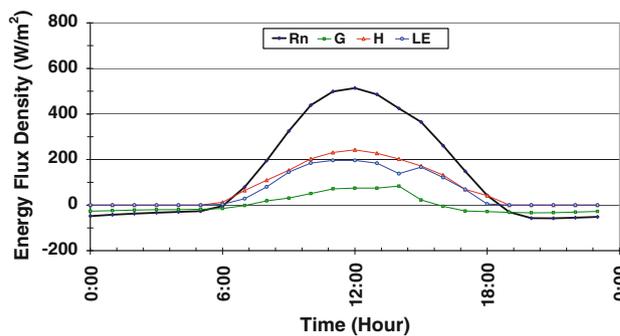**Fig. 11** Level vineyard average diurnal energy balance

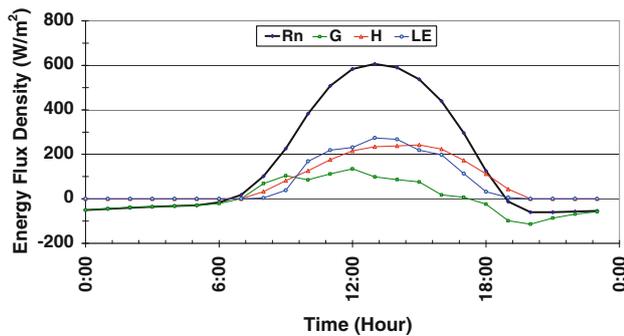**Fig. 12** Northeast aspect vineyard average diurnal energy balance

Fig. 13 Southwest aspect vineyard average diurnal energy balance

comparison with the ECOWAT model. During the months of August and September, however, Rn was highest at the SW aspect vineyard.

The daily duration of positive Rn differed among the sites due to the shadowing effects of the mountain ranges on both sides of the valley. Daily duration of positive Rn was approximately 30 min longer on the level vineyard than the NE vineyard, whereas positive Rn was approximately 1 h longer on the level vineyard than the SW vineyard. Because Rn values are near to zero around dawn and dusk, the variation in daylight duration probably had a negligible effect on daily ET_a.

The average daily G is the average amount of energy conducting into or out of the earth over the course of the day. During the summer in California more energy is conducted into the earth and away from the surface than energy conducted out of the earth and toward the surface, so average daily G is positive. The NE aspect vineyard had

the lowest average daily G (Table 4). The net radiation was lowest at the NE aspect vineyard, so there was less energy available to contribute to G in comparison to the other sites. The SW aspect vineyard had the highest average daily G relative to the other sites because it had the highest midday Rn. The level vineyard had a relatively intermediate average daily Rn, and commensurate with this observation, the average daily G was also intermediate at this site. The G was the lowest energy component of the energy balance, so the differences in G had less influence on the estimation of daily ET_a.

The average daily sensible heat flux density, H, is the mean amount of energy transported between the surface and the air over the course of the day. During the summer in California over a discontinuous crop surface that is warmer than the air, more energy is transported from the surface to the air than from the air to the surface, so average daily H is positive. For a given daily mean available energy (Rn − G), increases in positive average daily H are related to a reduction in the energy used for LE and hence ET_a. The relative differences in average daily H among the sites did not follow the same pattern of relative differences in average daily Rn among the sites. The average daily H was highest in the SW aspect vineyard, intermediate in the NE vineyard and lowest in the level vineyard (Table 4). There is a dependence of H on the surface roughness, the wind speed, and the difference in temperature between the surface and the air. The canopies were similar at each site, so it is unlikely that there were significant differences in surface roughness among the sites. Compared to the other sites, the NE site experienced

Table 4 Summary of average daily energy flux densities for the level vineyard, the northeast (NE) aspect vineyard, and the southwest (SW) aspect vineyard

Date	June (MJ m^{-2} day^{-1})	July (MJ m^{-2} day^{-1})	August (MJ m^{-2} day^{-1})	September (MJ m^{-2} day^{-1})	Season (MJ m^{-2} day^{-1})
Flux density	Rn	Rn	Rn	Rn	Rn
Level vineyard	14.1	15.5	14.0	11.3	13.7
NE vineyard	13.4	13.6	11.9	8.6	11.9
SW vineyard	13.8	14.9	14.7	13.0	14.1
Flux density	G	G	G	G	G
Level vineyard	0.3	0.3	0.3	0.1	0.3
NE vineyard	0.3	0.3	0.2	0.1	0.2
SW vineyard	0.1	0.5	0.4	0.3	0.3
Flux density	H	H	H	H	H
Level vineyard	5.1	5.5	5.9	4.1	5.2
NE vineyard	6.1	7.5	7.4	5.8	6.7
SW vineyard	5.6	7.5	7.5	6.8	6.9
Flux density	LE	LE	LE	LE	LE
Level vineyard	5.8	7.5	5.7	3.8	5.7
NE vineyard	7.5	6.4	4.6	3.2	5.4
SW vineyard	7.1	6.6	6.4	5.4	6.4

Fig. 14 Net radiation for the level vineyard, the northeast aspect vineyard, and a southwest aspect vineyard
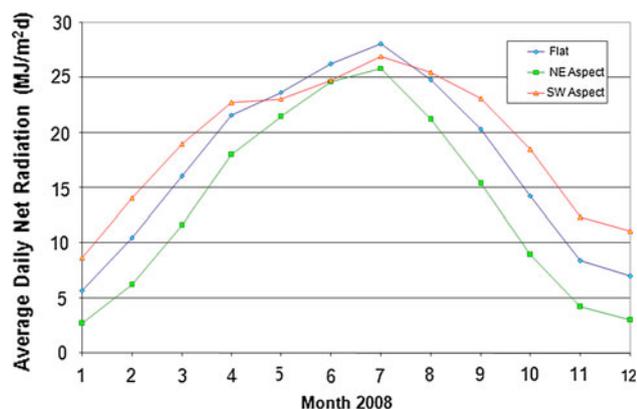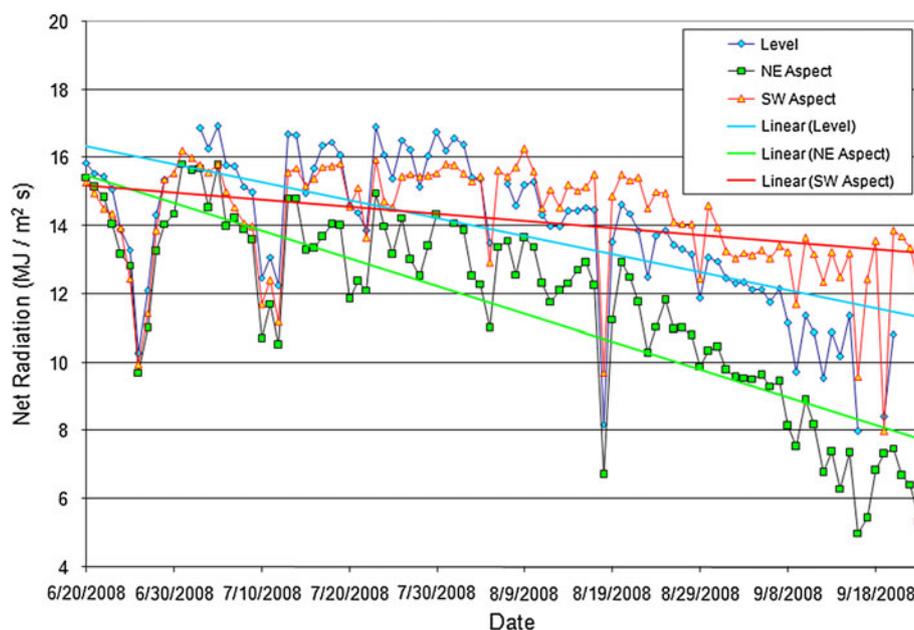

Fig. 15 Modeled net radiation for the level vineyard, the northeast aspect vineyard, and a southwest aspect vineyard

higher Rn earlier in the day when air temperatures were cooler. The relatively higher positive H at the NE site implies a greater temperature lapse condition relative to the other sites in the mornings. Although the average daily Rn was lowest at the NE aspect site, the relatively high H, experienced only at this site in the mornings, increased its average daily H values relative to the level vineyard. The increase in average daily H at the NE site is related to a decrease in daily energy used for LE, and thus daily ET_a. Although the SW site experienced higher Rn later in the day when air temperatures were warmer, the afternoon H values at the SW site nonetheless were the highest relative to the other sites.

Average daily LE is the mean amount of energy used to vaporize water from the ecosystem surface including crop foliage over the course of the day. During the summer in California over a discontinuous crop surface, which is mostly bare dry ground, more water is vaporized than condensed, so average daily LE is positive. Evapotranspiration was highest in the SW aspect vineyard, where Rn was highest. It was lowest in the NE aspect vineyard, where the Rn was the lowest. The LE was highest during the afternoon at the level and SW sites. It was highest during midday at the NE site. For vineyards on level terrain with VSP trellising oriented NE-SW, it was reported that the highest LE occurred during the 2 h following peak net radiation (Poblete-Echeverría and Ortega-Farias 2009). The authors suggested this was due to the effect of heat storage in the soil and biomass. Even though the NE vineyard had the same trellis system and row orientation as the other sites, daily LE was less there than at the other sites and this is a likely consequence of lower Rn in the afternoon and higher H in the morning. The daily differences in Rn were more closely related to daily average LE than the daily differences in H and G among the sites (Table 4). The ET_a rates consistently tracked Rn at all sites throughout the period of study (Fig. 14). Because Rn was the primary source of energy for LE, the effect of the slope and aspect on Rn may have been the most important factor contributing to the differences in daily ET_a among the sites. Plant responses to water availability also likely affected daily ET_a among the sites, but this cannot be confirmed since vine water status was not monitored in this study.

Part 4. Model comparison

Monthly radiation was modeled on the level vineyard and the hillside vineyards using the ECOWAT model to predict the effects of slope and aspect on measured Rn (Spano

et al. 2009). The measured Rn follows the same pattern as the modeled radiation at all three sites (Figs. 14, 15; Table 4). Both the modeled radiation data and the measured Rn data for the NE aspect vineyard were consistently lower than the modeled radiation data and measured Rn data for the level vineyard. For the months of June and July, the modeled radiation data and the measured Rn data were highest at the level vineyard. During the months of August and September, however, the modeled radiation and the measured Rn data were highest at the SW aspect vineyard. Due to the similarity between the modeled radiation data and the measured radiation data, it seems that the slope and aspect differences among the sites contributed to the differences in average daily Rn.

Conclusions

Vineyard ET_c rates and K_c values are based on ET measurements of grapevines planted on level terrain and managed without water stress. This paper presents typical ET_a rates for production winegrape vineyards located on varying terrain. The variation in the energy balance among the differing terrains explains the variation in ET_a.

The authors suggest that irrigation managers adjust ET_o according to the local slope and aspect prior to applying the K_c and stress factors in order to obtain more accurate information on crop water demands. The ECOWAT is a convenient and effective model for adjusting the regional solar radiation for the local slope and aspect. A more accurate estimate of ET_c for vineyards located on hillsides may help growers manage canopy development and winegrape quality throughout the growing season.

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