EFFECT OF TOPOGRAPHY ON VINE EVAPOTRANSPIRATION AND WATER STATUS IN HILLSIDE VINEYARDS

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Abstract:

Context and purpose of the study – Many winegrape regions have hillside vineyards, where vine water use is affected by vine age, density and health, canopy size, row orientation, irrigation practices, and by block slope and aspect. Topography affects the amount of solar radiation the vines receive, which is a major "driving force" of evapotranspiration (ET). Nearly all crop ET studies have been conducted on level ground, where the contributions of weather and crop factors to ET are well known. Information on winegrape ET on hillside terrains is scarce but much needed, as growers seek more resource-efficient production practices and vine water stress monitoring techniques to manage grapes quality, and as future water supplies become increasingly variable, limited and costly. Our UC team measured the seasonal dynamics of actual ET (ETa) and vine water status in two similar vineyard blocks with north and south aspects during three consecutive seasons, with the aim to inform irrigation management decisions.

Material and methods - The vineyard blocks are located in El Dorado County, California, and both are Cabernet sauvignon on 3309 rootstock, planted in 2000 with VSP trellis on approximately 24% (north-facing) and 25% (south-facing) slopes, where the grower managed the irrigation. We determined ETa in the 2016 to 2018 seasons using the residual of energy balance method with a combination of eddy covariance and surface renewal equipment to measure sensible heat flux (H). Reference ET (ETo) data was taken from the nearest weather station to calculate actual crop coefficients (Ka). We also periodically measured midday stem water potential (Ψ_{STEM}).

Results - The north and south blocks had similar seasonal ETa, but the water use dynamic varied with the slope aspect. Until early May, ETa was slightly higher in the south (Ka between 0.5 and 0.9) than the north block (Ka between 0.4 and 0.7). From mid-May to June and mid-July to August, the north block had higher ETa (Ka ~ 0.65 versus 0.55 in the south slope). A progressive decrease in water use was observed from late June onwards in both blocks, with Ka of ~ 0.4 and 0.3 in August and September, respectively. Early and late in the season, we measured lower net radiation in the north block, likely due to the greater incidence angle of the incoming solar radiation. Late in the season, the north block had lower Ψ_{STEM} (more stress) in 2016 and 2017, and the south block had lower Ψ_{STEM} in 2018. Our results show that monitoring ETa and vine water status can inform irrigation and water stress management in hillside vineyards.

Keywords: Energy balance, actual water use, slope, crop coefficient, stem water potential.

1. Introduction

In recent years, many California agricultural production areas faced significant water supply reductions due to periodic droughts and stringent environmental regulations. In this context, the utilization of improved irrigation management practices becomes a necessary strategy to pursue profitable and high quality food production under more pronounced weather vagaries, and with increasingly variable fresh water supplies.

The rapid adoption of pressure-compensating micro-irrigation systems during the last 15 years has enabled California wine grapes growers to expand production in areas with sloping terrains that were unsuited to earlier irrigation methods (e.g., Shapland et al., 2012; Battany and Tindula, 2018). While some degree of slope can be beneficial in a vineyard site because of improved soil drainage, better airflow through the canopy, and faster escape of cold air to reduce the risks of springtime frost damages, the aspect that a vineyard faces can affect micro-climatic conditions, radiation interception and vine water use, and sometime influence grapes ripening.

Several authors indicated that wine grapes quality ties with irrigation management and grapevine water status (see also Jackson and Lombard, 1993; Kennedy et al., 2002; Downey et al., 2004). The amount of irrigation water required to grow quality wine grapes and the frequency of irrigation applications depend on a number of site-specific factors, such as vine growth stage, row and plant spacing, vine density, size of vine's canopy (Williams, 2001), as well as on soil texture and terrain characteristics. Wine grapes growers must consider numerous factors to manage irrigation in vineyards: the winter rainfall preceding a given growing season, the soil water holding capacity, the presence and management of cover crops, the specific rootstock and its rooting depth, the soil and water salinity conditions, the row spacing and type of trellis, as well as the fruit production goals, are all important aspects to account for (Battany and Tindula, 2018).

Regardless of where grapevine is grown, the main questions concerning irrigation management are when to begin irrigating along the crop season, how much water to apply at the different growth stages, with what frequency, and whether to distribute water uniformly or site-specifically across the vineyards and among different blocks.

Wine grapes growers need practical irrigation scheduling methods that enable to limit vegetative growth without reducing photosynthesis, while directing carbon allocation preferentially to fruit. Precise irrigation management is the main tool that growers have to control vineyard vegetative growth (Battany and Tindula, 2018). To this aim, some growers rely on regional estimates of daily reference evapotranspiration (ETo) and generalized crop coefficients (Kc) to determine energy-limited crop ET (ETc=ETo×Kc) and soil water depletions to decide the amount and frequency of water applications needed for efficient irrigation (Allen et al., 1998). Others base their irrigation decisions on periodic measurements of vine water status (by means of leaf or stem water potential), considering that plants integrate the atmospheric water demand with soil-water conditions through the plant physiological processes. Following either irrigation scheduling approach is important to pursue fruit yield and quality targets through managed levels of stress, but both have limitations. While ET and Kc information for wine grapes grown on level terrain are widely published, there is little information on vineyard water use on sloping terrains with different aspects, and even less on the impact of water stress on vine ET. Deficit irrigation is often practiced in wine grapes production vineyards, and the actual ET (ETa) is commonly less than the energy-limited potential crop evapotranspiration (ETc) under well-watered conditions. On the other hand, measuring vine water status is time-consuming and labor intensive. In addition, plant-based irrigation scheduling requires attentive identification of stage-specific and variety-specific thresholds of vine stress for fruit production goals. This article describes a field research study aimed to measure actual grapevine ETa and midday stem water potential (Ψstem) along multiple growing seasons, while keeping track of the applied irrigation water in north and south facing sloped vineyards, in order to evaluate differences in vine water use due to slope and aspect. The overall purpose of this study was to obtain information on grapevine water use for adapting irrigation management based on vineyard topography.

2. Field Experiment, Methods and Tools

2.1 The Study Site

The study was conducted from 2016 to 2018 in adjacent north (N) and south-facing (S) blocks of a commercial vineyard (Figure 1) near Pilot Hill, El Dorado county, California (38°48'N, -121°01'W; 381 m a.s.l.), approximately 72 km east of Sacramento in the foothills of the Sierra Nevada mountains. El Dorado county is a relatively small but growing California wine grapes production region, falling within California grape pricing district 10, with 2,825 bearing ha recorded in 2017 (USDA National Agricultural Statistics Service, 2019). The top three varieties grown in district 10 are Zinfandel, Cabernet sauvignon, and Syrah.

The planting material in both study blocks was Cabernet sauvignon (clone 15) grafted onto Vitis riparia x Vitis rupestris cv. 3309 Couderc rootstock, planted in 2000 at a density of 3,703 vines ha-1 (spacing 1.8 x 1.5 m.), with vine rows oriented in a north-south direction. Vines were trained in a bilateral cordon vertical shoot positioned system (VSP), and pruned to 14, 2-bud spurs per vine. In 2002 a cover crop mixture of barley, mustard, and clover was sown in the vine row middles; in the study years this mix had been mostly overtaken by a weedy cover including filaree, wild radish, hairy fleabane, common groundsel, and others that was mowed several times each spring before drying down in early summer.

Monthly precipitation and average air temperature values (Tables 1 and 2) were gathered from the nearest automated weather station of the California Irrigation Management Information System (CIMIS, https://cimis.water.ca.gov/) located in Auburn, California, approximately 11 km heading northwest from the study site.

Both the N and S block lie on Auburn series very rocky loam soil with a typical depth to 60 cm, as mapped by the USDA-National Cooperative Soil Survey (SSURGO) (California Soil Resource Lab, 2019). The slope on each block was measured using a Real-time Kinematic (RTK) GPS positioning system unit, and resulted 24.4% and 25.4% in the north-facing and south-facing blocks, respectively.

Table 1. Monthly precipitation (mm) and total precipitation (mm) for the hydrologic year of 2016, 2017, 2018 and long-term average (2005-2018) precipitation recorded at the Auburn weather station #195 of the California Irrigation Management Information System (CIMIS). The hydrologic year accounts for the rainfall events occurred from October of the preceding fall to September of the current year and considers winter precipitation that may be stored in the soil profile.

Year/Month	2015-2016 (mm)	2016-2017 (mm)	2017-2018 (mm)	Long-term Average (2005-2018) (mm)
October	6.9	192.3	13.2	48.6
November	76.9	100.5	165.2	77.7
December	142.7	167.5	17.9	134.3
January	188.4	316.9	93	98.5
February	33	327.3	30.4	114.1
March	196.4	106.9	214.6	117.4
April	41.1	136.6	96	60.9
May	28	7.3	15.9	24.3
June	0	6.6	0	8.2
July	0	0.1	0	0.5
August	0	0	0	0.6
September	0	0	0	4.0
Hydrologic Year Total	713.4	1362	646.2	689.1

Table 2. Monthly average air temperature (°C) recorded at the CIMIS Auburn #195 station during the study years and long-term average (2005-2018).

Month	2015-2016 (°C)	2016-2017 (°C)	2017-2018 (°C)	Long-term Average (2005-2018) (°C)
October	6.9	192.3	13.2	48.6
November	76.9	100.5	165.2	77.7
December	142.7	167.5	17.9	134.3
January	188.4	316.9	93	98.5
February	33	327.3	30.4	114.1
March	196.4	106.9	214.6	117.4
April	41.1	136.6	96	60.9
May	28	7.3	15.9	24.3
June	0	6.6	0	8.2
July	0	0.1	0	0.5
August	0	0	0	0.6
September	0	0	0	4.0

On May 2015, a soil evaluation was performed in the row middle, one vine row over to the east of the ET measurement station on each block using a standard 10cm soil auger. On the S facing slope, augering continued to bedrock at 108cm depth. Evidence of some clay films, mottling and oxidation, indicative of a fluctuating seasonal water table, was observed with fine grape roots at 81cm depth. The N facing slope, presented a different, shallower soil, where augering continued to bedrock at 83cm depth. In the upper 50cm there was less gravel content and more finely textured clay that was visibly moister than in the S slope soil.

2.2.*Measurement of grapevine ET and determination of crop coefficients*

The actual grapevine evapotranspiration (ET_a) was determined with the residual of energy balance (REB) method that calculates the latent heat flux (LE) as the residual from net radiation, ground heat flux, and sensible heat flux measured at the study sites with micro-meteorological sensors, based on Equation 1 below:

$$\mathrm{LE} = \mathrm{R_n} - \mathrm{G} - \mathrm{H} \tag{1}$$

where, LE is the latent heat flux ($\mathrm{MJ\,d^{-1}m^{-2}}$), $\mathrm{R_n}$ is net radiation ($\mathrm{MJ\,d^{-1}m^{-2}}$), G is soil heat flux density ($\mathrm{MJ\,d^{-1}m^{-2}}$), H is sensible heat flux ($\mathrm{MJ\,d^{-1}m^{-2}}$) and λ is the latent heat of vaporization ($\mathrm{MJ\,kg^{-1}}$).

$\mathrm{ET_a}$is calculated via Equation 2 to obtain the actual crop evapotranspiration rates in kg d^{-1} m^{-2}, which is numerically equivalent to mm d^{-1}. The coefficient $\lambda = 2.45\ \mathrm{MJ\,kg^{-1}}$ is the energy required to vaporize 1 kg of water from the liquid state.

$$\mathrm{ET_a} = \frac{\mathrm{LE}}{\lambda} \tag{2}$$

In this field study, one full-flux ET measurement station was installed at each vineyard block (Figure 1). Each ET station included: a) a net radiometer (NRLite2, Kipp & Zonen Inc., Delft, Netherlands) to measure Rn, approximately 1 m above the vine canopy; b) a three-dimensional sonic anemometer (81000RE, RM Young Inc., Traverse City, Michigan) to measure H with the eddy covariance methodology, and two 76.2-µm diameter Chromel-Constantan thermocouples (model FW3 from Campbell Scientific, Logan Utah), both mounted approximately 1 meter above the vine canopy, to measure H at 10Hz frequency with the surface renewal methodology; c) three soil sensor packages to calculate G, each consisting of one soil heat flux plate (HFT3, REBS, Bellevue, Washington), four averaging soil temperature thermocouple probes (Tcav, Campbell Scientific Inc., Logan, Utah), and one volumetric soil moisture sensor (EC5, Decagon Devices, Pullman, Washington). For each package, the ground heat flux plate and soil moisture sensor were installed horizontally at 0.05 m below the soil surface, whereas the probes of the Tcav sensor were installed at an angle from 0.04 to 0.01 m depth and were distributed on both sides of the HFT2 and EC5 sensors in a line perpendicular to the tree rows.

The ground heat flux at the soil surface was estimated using a continuity equation as described by De Vries (1963) utilizing the mean HFT3 measurements, the change in temperature of the 0.04 to 0.01 m temperature measurements, and the volumetric water content.

The half-hourly LE values were computed as: $\mathrm{LE} = \mathrm{Rn} - \mathrm{G} - \mathrm{H}$ using measured net radiation, ground heat flux, and sensible heat flux, while the daily LE was determined by summing the 48 half-hourly values of $\mathrm{LE}\ (\mathrm{MJ\ m^{-2}})$. The calibration procedure between surface renewal and sonic anemometer analysis used in this field research for computing H is described in details in Shapland et al. (2012) and Marino et al. (2019).

At each ET station, all the above-ground individual sensors were installed on a mounting frame consisting of steel posts, driven approximately 1 m into the ground, and steel cross arms. The height of the steel mounting frame was approximately 3.5 m from the vineyard floor, and power for all the sensors was provided by a 40 w solar collector panel connected with a 100 A battery for storage. The micro-meteorological data were collected, stored, and processed with a CR1000 data logger (Campbell Scientific, Logan, Utah). Direct two-way communication with the station was enabled through a cellular phone modem (RavenXT, Sierra Wireless, Richmond, British Columbia).

The values of actual crop coefficients (Ka) at daily and weekly time-steps were calculated by dividing the ETa by time-averaged ETo values (CIMIS station #195) over the corresponding time-steps, according to the relation Ka = ETa/ETo.

The collection period of field data at the two study vineyards varied from year to year, depending on the weather conditions that allowed the installation of field equipment earlier or later in the spring, and on the harvest time.

2.3 *Measurements of Midday SWP*

The midday stem water potential (Ψ_{STEM}) was measured with weekly or bi-weekly frequency during the course of the three growing seasons, using a Scholander-type pressure chamber (model 615, PMS Instrument Co., Corvallis, OR) on six vines randomly selected within the footprint area of each ET station. For each vine, a fully expanded and shaded leaf was selected and covered with light and moisture-impervious Mylar bags at least 20 minutes before performing the measurement (see also Fulton et al., 2011) to equilibrate with branch xylem water potential (e.g. Begg and Turner, 1970). The measurements of Ψ_{STEM} were conducted during clear-sky days between 11:00 am and 2:00 pm.

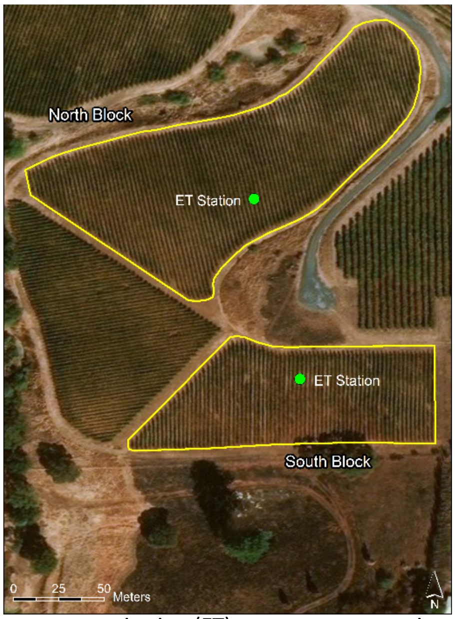

Figure 1: Aerial overview photo of the study vineyard blocks with north (N) and south facing (S) aspect, and locations of the evapotranspiration (ET) measurement stations.

2.4 *Irrigation System Performance and Applied Irrigation Water*

At both the N and S facing vineyard blocks, the micro-irrigation system consisted of single driplines with two Netafim pressure-compensating online button drippers per vine with nominal flowrate of 1.9 l h^{-1}. At the N block, the actual system application rate was 1.73 mm h^{-1} with average emitter's flowrate of $2.4\ \mathrm{l\ h^{-1}}$ and distribution uniformity (DU) of 0.86. At the S block, the actual system application rate was

1.65 mm h^{-1} with average emitter's flowrate of 2.3 $l\ h^{-1}$ and DU of 0.87. These irrigation performance parameters were determined in April 2016 by a professional irrigation system evaluation team (Mobile Lab from the Natural Resource Conservation Service - Resource Conservation District) that used the micro-irrigation evaluation procedure developed by the Irrigation Training and Research Center (ITRC) of CalPoly (Burt, 2004).

In both vineyard blocks, the applied irrigation water was measured using magnetic flowmeters (Sensus iPEARL, Raleigh, NC) installed at the head sections of two driplines, each supplying water to one vine row within the footprint area of the ET stations. The flowmeters were connected with battery-powered dedicated dataloggers that recorded and stored flow data. Table 3 reports the amounts of irrigation water applied in the N and S vineyard blocks, determined from the recorded flowmeter data during the three consecutive crop seasons, and the monthly values of rainfall recorded at the nearby automated CIMIS weather station.

Table 3. Irrigation water applied (mm) in the north (N) and south (S) study vineyards determined from flowmeter records, and monthly cumulative values rainfall (mm) during the 2016-2018 crop seasons from the CIMIS station #195.

	2016			**2017**			**2018**		
Month	**Rainfall (mm)**	**Irrigation N block (mm)**	**Irrigation S block (mm)**	**Rainfall (mm)**	**Irrigation N block (mm)**	**Irrigation S block (mm)**	**Rainfall (mm)**	**Irrigation N block (mm)**	**Irrigation S block (mm)**
March	196.4	--	--	106.9	--	--	214.6	--	--
April	41.1	6.6	6.9	136.6	--	--	96	--	--
May	28	12.3	11.3	7.3	--	--	15.9	--	--
June	0	18.3	17.5	6.6	30.9	15.6	0	44.6	38.5
July	0	48.6	62.4	0.1	54.2	100.5	0	80.7	70.7
August	0	44.2	34.1	0	32.5	118.6	0	70.5	45.3
September	0	11.1	5.8	0	47.6	44.0	0	21.7	19.8
Total	265.5	141.1	138.0	257.5	165.2	287.7	326.5	217.5	174.3

The analysis of flowmeter records showed that irrigation occurred with varying frequency and durations over the different months of the crop seasons. Irrigation scheduling for the two vineyards blocks was mainly dictated by grower's experience and visual observation of the vines, and often constrained by some water supply limitations.

Although the grower reported that irrigations aimed to apply similar amounts of water in the N and S blocks, differences in applied water were noted that probably resulted from different application rates between the blocks, but also from adjustments of irrigation frequency and duration based on visual assessment of vines' performance and appearance. The grower reported that visual observation of the vines and assessment of soil moisture with periodic soil probing were the main criteria guiding irrigation decisions in terms of timing and durations.

2.5*Measurement of Light Interception by Vine Canopy*

Light interception by the vine canopy was measured during the 2018 growing season using the Paso Panel (UCCE, 2019) canopy shade meter (Battany, 2009). It consists of a solar collector panel, a voltage meter, and power switch attached to a portable frame that can be held underneath the grapevine canopy for a few seconds to measure light interception by the vines' canopy. The device measures the amount of current produced by the solar panel, which is proportional to the amount of sunlight striking its surface. The first measurements were taken outside the vineyard to record the amount of current generated by the incoming solar radiation fully lightening the entire panel surface. Afterwards, measurements were taken placing the panel under the vines' canopy that result in varying reductions in current relative to that of full panel lightening, depending on the vines' canopy sizes. Figures 2 illustrates measurements of the light interception by the vine canopy in a commercial production vineyard and at the study vineyard.

Figure 2: Measurement of light interception by vine canopy in A) a commercial production vineyard in the California Central Coast (*courtesy of M. Battany, UC CE Sn Luis Obispo County, CA*), and B) one study vineyard in El Dorado County.

The current readings obtained placing the panel under the vines' canopy at multiple locations in the vineyards were then divided by the full-sun current readings to determine the shaded area by the vine canopy, which is a proxy of the fractional canopy cover. All the measurements in the N and S vineyard blocks were taken during clear sky days at solar noon ± 1 hour, and then calibrated against full sun current readings.

The procedure for estimating light interception by the vine canopy is fully described in Battany (2009), and further information can be found at (http://cesanluisobispo.ucanr.edu/Viticulture/Paso_Panel/). The values of shaded percentage of field were used to evaluate comparative differences in canopy growth and size between the N and S blocks.

The measurements were then converted to shaded percentage of field based on the shaded percentage of the panel, the panel length, and row spacing, using the Equations 3 and 4 below.

$$\text{Shaded percentage of solar panel} = [1 - (\text{Shaded reading}/\text{Full Sun reading})] \times 100\% \quad (3)$$

$$\text{Shaded percentage of field} = \text{Shaded percentage of panel} \times (\text{Panel length}/\text{Row spacing}) \quad (4)$$

3. Results and Discussion

3.1 Actual Grapevine Evapotranspiration (ETa)

The datasets presented in this section do not refer to potential evapotranspiration of well-watered grapevine (ETc), but instead to actual evapotranspiration (ETa) obtained from field micro-meteorological measurements collected in the two study vineyard blocks over the course of the growing seasons 2016-2018. The study blocks are commercial production vineyards, where growers commonly implement partial irrigation practices either to achieve fruit quality goals or to cope with water supply limitations. Under these conditions, grapevine faces water stress reducing the actual ET below the maximum potential rates and limiting vegetative growth due to stomata closure and less carbon assimilation. Alongside, vines with smaller canopy size intercept less solar radiation, which in turn reduce water use rates below that of vines with maximum potential canopy grown without water limitations, i.e. ETc. In other words, ETa of commercial production vineyards is often expected to be less than ETc, as suggested by Shapland et al. (2012).

Figure 3 illustrates the seasonal cumulative ETa and ETo for the N and S vineyard blocks in 2016, 2017 and 2018. It can be noticed that the season-long cumulative ETa was very similar for the N and S blocks, but its time course differed between the blocks in all seasons depending on the slope-aspect. A consistent pattern is noted for the N and S blocks in the 2016 and 2018 growing seasons: from April to early June, ETa was slightly higher in the S block than the N block, then in late June ETa of the N and S blocks matched, while afterward the N block had slightly higher ETa from late June until late September to early October.

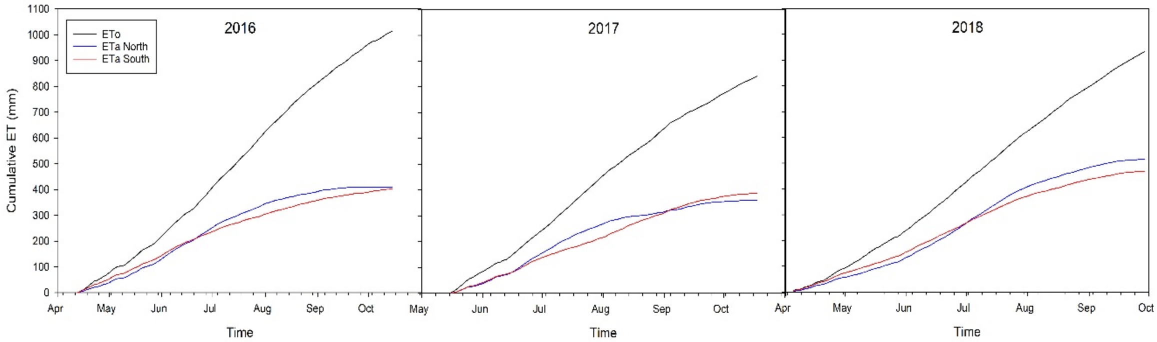

Figure 3: Season-long cumulative actual grapevine evapotranspiration (ETa) measured in the study vineyards and reference evapotranspiration (ETo) obtained from the local CIMIS station (Station #195 - Auburn, CA) for the growing season 2016, 2017 and 2018.

In 2017, the ETa data collection started around mid-May due to very wet winter and spring conditions not allowing installation of field instrumentation earlier. However, the field dataset of 2017 shows very similar seasonal cumulative ETa values for the S and N blocks, but differences in ETa can only be noticed for the period from late June to early September. From late June to early September 2017 the N block had slightly higher ETa than the S block, which is consistent with the pattern of 2016 and 2018. From mid-September to late October 2017, the S block had slightly higher ETa than the N block, which reveals a contrasting pattern to that of 2016 and 2018. In this regard, the higher late season ETa in the N block in 2017 was most likely caused by larger water applications occurred during irrigation events in late July and August in the area surrounding the ET measurement station of the N vineyard, which was probably due to a dripline leak that went unnoticed for more than a month. This problem was reported by the farm manager and the irrigation crew, and it was also noticed from the flowmeter records of 2017 (Table 3).

Figure 4 shows the weekly averaged ETa values (mm d^{-1}) measured in the N and S vineyard blocks during the course of 2016, 2017 and 2018. Also in this case, a clear pattern of the ETa's time course can be identified: slightly higher ETa was observed in the S block early in the season from April to early June in all three years; afterwards, higher ETa occurred in the N block during the central part of the season from early to mid-June through early to mid-August in all three years, whereas slightly higher ETa was observed in the S block relative to the N block in the late part of the season in 2016 and 2017. On the contrary, slightly higher ETa was observed in the N relative to the S block during the late part of the 2018 season. The data from Figure 4 clearly show that vines in the N block expressed higher water use during the central part of the growing season, which is possibly related with higher interception of solar radiation during the period around the summer solstice, when the sun reaches its most northerly excursion relative to the equator.

Higher water use in that period may also be related with the N vines having relatively larger canopy size, or accessing relatively larger soil moisture reserve, thus facing less water restrictions during the hottest part of the growing season.

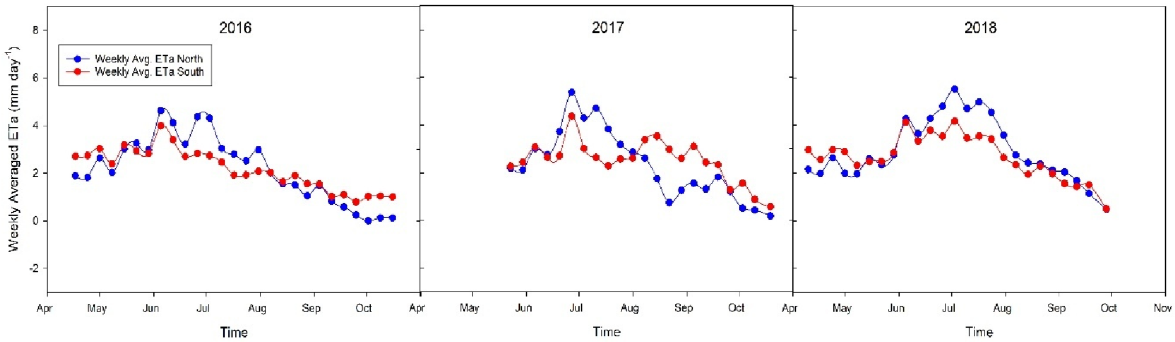

Figure 4: Weekly averaged actual grapevine evapotranspiration (ETa) measured in the north (N) and south (S) facing study vineyards during the 2016, 2017 and 2018 seasons.

Some clear patterns can also be inferred from Figure 5, which shows the weekly cumulative values of Rn (MJ week^{-1} m^{-2}) measured in the N and S blocks during the three study seasons. In details, higher Rn was measured in the S block during the early and late parts of the season in all three years, whereas Rn was similar in both blocks in the central part of the growing season in 2016 and 2018, or slightly higher in the N than the S block in 2017.

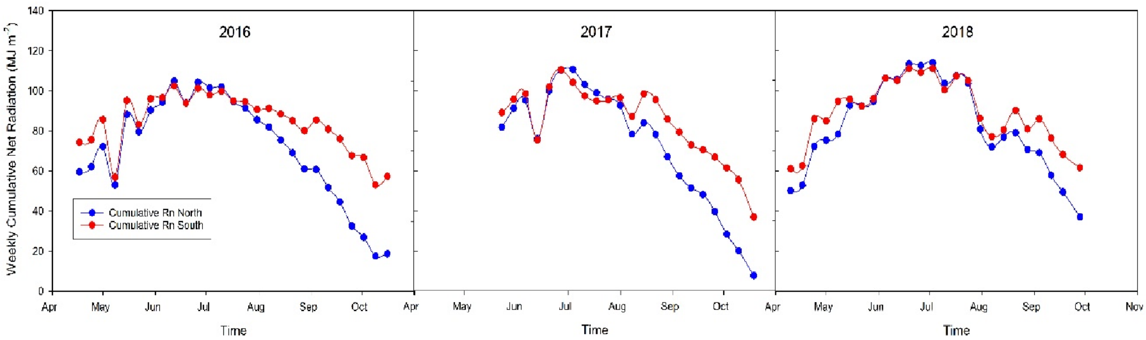

Figure 5: Weekly cumulative values of the net radiation (Rn) measured in the north (N) and south (S) facing study vineyards during the 2016, 2017 and 2018 seasons.

The Rn is the main force driving crop evapotranspiration. However, during the energy limiting crop growth stages, i.e. when soil moisture is abundant and can support vine water use without restrictions, higher Rn leads to higher grapevine ETa, all other factors (vines' canopy size, light interception, available soil moisture) being similar. In the Mediterranean climate of northern California, these conditions normally occur in the period between March and mid-June, when grapevine growth can be supported by abundant residual soil moisture from late winter and early spring rainfall, typically without the need to irrigate. Afterwards, Rn still mostly drives ETa, which is however dynamically regulated by the available soil moisture from irrigation, and by the amount of radiation intercepted by the vines' canopy. As such, the ETa pattern may not necessarily match that of Rn, especially when grapevine face water stress as result of partial irrigation, or because of difference in vines' canopy size or soil moisture available to plants. In other words, multiple factors regulate the actual vine ETa, such as canopy size and row orientation, plant available soil moisture, as well as the angle of incidence of solar radiation, which in turn depends on the position of the sun during the different periods of the crop season and on the vineyard topography.

Figure 6 reports the weekly cumulative values of H (MJ week^{-1} m^{-2}) measured in the N and S blocks over the course of the three study seasons. The figure shows similar H in the N and S block during the first part of the season until mid-June, then higher H in the S than the N block for the rest of the season in 2016 and 2018. In 2017, higher H was measured in the S block from mid-June to late July, whereas H was higher in the N block from early August to mid-September, and then higher in the S than the N block during the last part of the season.

Higher H reflects a larger effect of the solar radiation on heating the air around the grapevine canopy, and thus indicates the possible occurrence of some water restriction causing lower vine evapotranspiration, and increase in canopy temperature due to partial stomata closure.

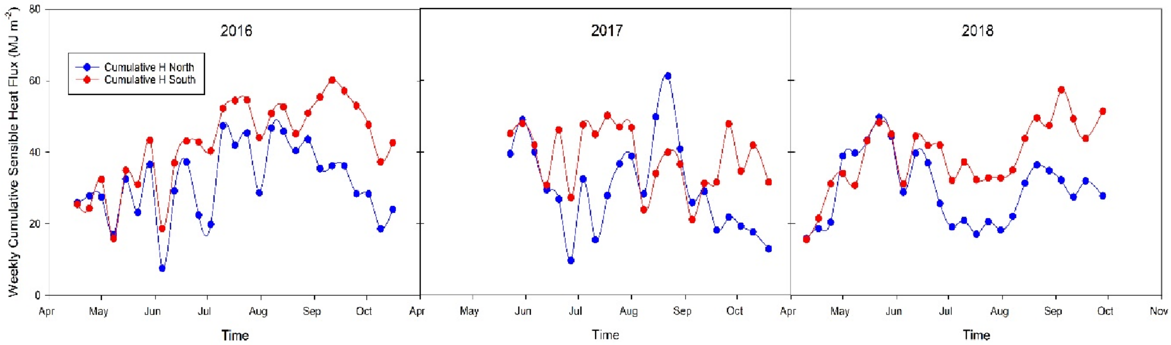

Figure 6: Weekly cumulative values of the sensible heat flux (H) measured in the north (N) and south (S) facing study vineyards during 2016, 2017 and 2018.

A good relative indicator of vine water use is the actual crop coefficient (Ka), which reflects the actual ETa rate relative to the local atmospheric water demand or ETo. Figure 7 shows the weekly average actual crop coefficient (Ka) calculated for the grapevine in the N and S blocks in the three consecutive seasons. Ka integrates the atmospheric water demand with the grapevine physiologic processes regulating actual vine evapotranspiration alongside with the plant available soil moisture. As such, Ka provides synthetic information on actual grapevine water use in the site-specific and plant-specific conditions of the vineyard study blocks.

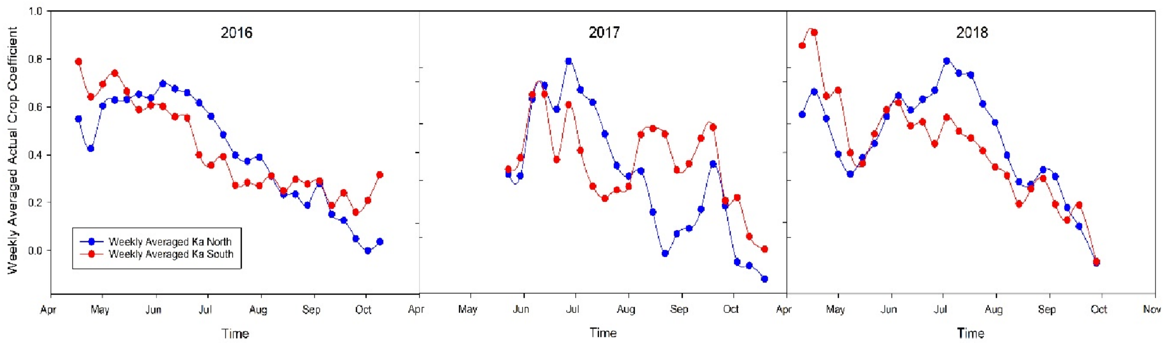

Figure 7: Weekly averaged values of the actual crop coefficient (Ka) calculated for the north (N) and south (S) vineyard blocks during 2016, 2017 and 2018.

Data in Figure 7 show that Ka was higher in the S block early in the season until approximately mid-May in 2016 and 2018, then Ka was higher in the N than S block from early June to early August in all three seasons. Afterwards, Ka was higher in the S block from mid-August to the end of the crop season in 2016 and 2017, whereas it was pretty similar in the N and S blocks from mid-August to the end of the crop season in 2018. The figure also shows that in 2016 and 2018, Ka reached its peak values early in the season between mid-April to early May (whereas in 2017 Ka peaks were measured around late June), and then progressively decreased during the course of the growing season, revealing increasing reduction in vine evapotranspiration.

Following ETa or Ka could provide relevant information for tailoring irrigation management decisions (timing and amounts of water applications) based on actual grapevine water use, especially during periods of water supply restrictions. However, ET-based irrigation scheduling alone may not allow targeting water stress levels that are conducive to reductions of grapevine vegetative growth and to specific fruit yield and quality targets.

Some additional considerations can be drawn observing Figure 8, which shows the values of stem water potential (Ψ_{STEM}) measured in the N and S blocks over the course of the crop seasons. In all three years,

Ψ_{STEM} (bars) values decreased progressively from maximum values between -2:-4 bars early in the season to minimum values between -12:-15 towards the final part of the season, revealing that vines in both the N and S blocks were exposed to increasing water stress.

Vines in the S blocks had relatively lower Ψ_{STEM} values from April to early or mid-August in 2016, 2017 and 2018. Ψ_{STEM} values were lower in the N block from early August to the end of the season in 2016 and 2017, whereas vines in the N and S blocks had pretty similar Ψ_{STEM} values from mid-August to the end of the season in 2018.

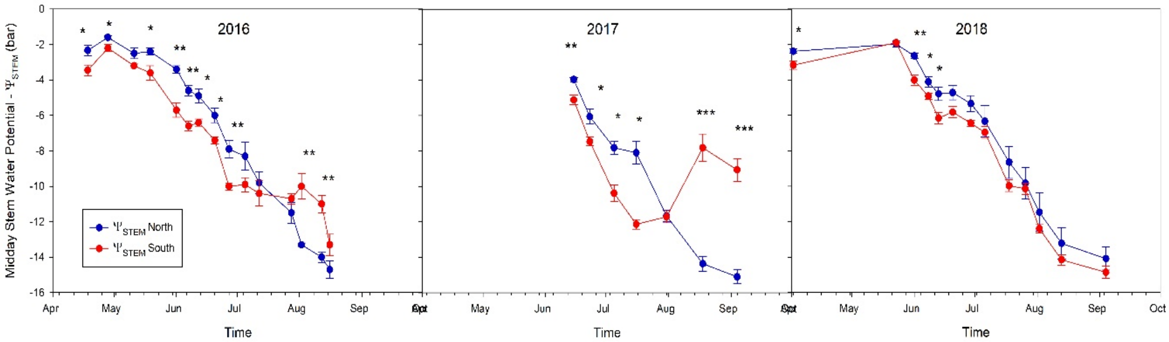

Figure 8: Stem water potential (Ψ_{STEM}) values measured at the north (N) and south (S) study vineyards during the 2016, 2017 and 2018 grapevine growing seasons.

As far as plant water status is concerned, the relatively lower Ψ_{STEM} values of vines in the S block in the first half of the crop season for all three seasons could possibly be due to higher environmental water demand on those vines, i.e. higher Rn. Similarly, the lower Ψ_{STEM} values of N vines during the central part of the season was possibly related to higher environmental water demand in the N block due to similar incidence of solar radiation between the two blocks but higher light interception by the vines in the N block. Alongside, the flow meter records showed larger irrigation water applications in the S block in late July and August 2016 and 2017, which possibly relieved some water stress on the S vines.

Table 4 reports the values of light interception by the vines' canopy measured during the course of the 2018 season in the N and S blocks. Data from the table show slightly faster vegetative growth and larger vines' canopy size in the N than the S block during the crop season 2018. According to Kurtural et al. (2007), faster canopy growth and larger canopy size in north-facing vineyards in Mediterranean climate can be expected as a result of relatively earlier bud-break and due to relatively lower impact of heat stress on vines relative to south facing slopes. All other factors being equal, in south facing slopes heat can increase during daytime above stress threshold levels, thus causing reductions of stomata conductance, less carbon assimilation and slower growth.

Table 4. Light interception by vines' canopy measured with the Paso Panel in the north (N) and south (S) study vineyard blocks during the growing season 2018.

Date	Light interception N block (%)	Light interception S block (%)
April 2	18.0	16.5
May 17	36.5	31.0
May 23	43.5	35.5
June 1	53.5	44.0
June 8	57.0	47.5
June 13	39.0	31.0
June 20	41.0	34.0
June 29	41.0	31.5

July 6	43.5	40.0
July 18	46.5	33.0
July 26	42.5	34.0
August 2	44.5	34.0
August 13	42.5	33.5
August 24	44.0	32.5
September 4	43.5	31.0

4. Conclusive remarks

Irrigation scheduling of wine grapes production vineyards must consider multiple factors that regulate the actual grapevine water use, in order to maintain vine water status at specific target levels for restricting vegetative growth while pursuing fruit yield and quality objectives. Among others, vines' canopy size, row orientation and available soil moisture to plants are major factors.

The data presented in this article show that vineyard topography, i.e. slope and aspect, are additional factors that may play a significant role in regulating ETa in hillside vineyards. As such, following an ET-based irrigation scheduling with generalized crop coefficients from other locations and vineyard conditions may not be appropriate. Following ETa and Ka that result from the site-specific vineyard conditions could provide some relevant information for irrigation scheduling decisions, but may not enable growers to pursue vine water stress levels that are desirable in specific stages of the growing season for fruit yield and quality objectives.

Integrating weather-based and plant-based irrigation scheduling approaches could enable higher level of control on grapevine water status that is necessary for quality purposes. For instance, following ETa and Ka, while keeping track of Ψ_{STEM} values could possibly provide more integrative information on actual vine evapotranspiration and water status for more precise irrigation management decisions. In details, Ψ_{STEM} values can help decide the proper irrigation timing, while at the same time ETa and Ka allow determining adequate irrigation amounts to maintain the desired water deficit levels for balancing vegetative growth with production goals.

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