Agricultural and Forest Meteorology 177 (2013) 93–100

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Short communication

Micro-Bowen ratio system for measuring evapotranspiration in a vineyard interrow

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ARTICLE INFO

Article history:
Received 31 December 2012
Received in revised form 9 April 2013
Accepted 16 April 2013

Keywords:
Evapotranspiration
Energy balance
Partitioning
Sparse canopy
Water use

ABSTRACT

Sparse canopy systems such as vineyards are comprised of multiple components (e.g., vines, interrow soil and/or groundcover) that each contribute to system water and energy balance. Understanding component water and energy fluxes is critical for informing management decisions aimed at improving productivity and water use efficiency. Few methods are available to accurately and continuously measure component fluxes. We tested a novel micro-Bowen ratio (MBR) energy balance system for determining interrow evapotranspiration (ET) flux within a vineyard. Our objectives were to develop MBR methodology to measure ET flux from the vineyard interrow and to compare MBR ET measurements for bare soil and fescue interrow conditions to independent ET estimates. MBR methodology utilized measurement of air temperature and water vapor concentration at 1 and 6 cm heights within 2.7 m wide interrows. Measured ET rates were well correlated between MBR systems and micro-lysimeters for both fescue ($R^2 = 0.99$) and bare surface ($R^2 = 0.89$) interrow conditions, though MBR ET rates were larger than those determined from micro-lysimeters in both cases (20 and 60%, respectively). MBR daily ET estimates, determined by compositing measurements from fescue interrows and bare soil under vines, were also well correlated to ($R^2 = 0.70$) and of similar magnitude as vineyard eddy covariance ET measurements during periods when the vines were dormant. Overall, MBR systems appeared to provide a reasonable approach to determine ET for the interrow component within the vineyard. Similar methodology may be useful to better understand components' contributions to water and energy fluxes in other complex or sparse canopy systems.

1. Introduction

Sparse canopy systems involve complex water and energy budgets. Vineyards are globally important sparse canopy systems, generally consisting of two or three components: vines, interrow with or without groundcover, and soil/plants underneath the vine row. All three components influence micrometeorological conditions of the vineyard. Grapevine canopies create an obstacle for water and energy transport between the ground surface and atmosphere (Heilman et al., 1994; Hicks, 1973; Weiss and Allen, 1976a, 1976b). Vines are carefully managed in order to optimize water use, sunlight interception, and canopy humidity, and effects of grapevine canopy on vineyard energy balance are influenced by choice of trellis system (Smart, 1985; Heilman et al., 1996; Williams et al., 2003). The interrow may also be an energy source or sink. Heilman et al. (1994) and Hicks (1973) found that sensible heat flux from the interrow contributed to latent heat flux of the vineyard by providing energy for vine transpiration. Depending on the water regime and groundcover management, the interrow may also contribute directly to vineyard latent heat flux via interrow evapotranspiration (ET) (Yunusa et al., 1997; Centinari et al., 2012; Fandino et al., 2012). Underneath the vine row, soil and/or plants also serve as an energy source or sink and affect the water budget. Vineyard management decisions must be supported by understanding the contribution of each vineyard component to vineyard water and energy budgets.

A variety of techniques are available to assess system-level ET at field and plot scales. Examples include remote sensing (Jackson et al., 1977; Seguin and Itier, 1983; Stone and Horton, 1974; Norman et al., 1995; Bastiaanssen et al., 1998; Allen et al., 2007), lysimetry

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http://dx.doi.org/10.1016/j.agrformet.2013.04.009

(Ritchie and Burnett, 1968), eddy covariance (Wilson et al., 2001), Penman–Monteith or Priestley–Taylor models (Sumner and Jacobs, 2005), and Bowen ratio methods (Bland et al., 1996; Zhang et al., 2007). Far fewer techniques are available to determine ET for individual components within a sparse canopy system. In vineyards, sap flow (Heilman et al., 1994; Braun and Schmid, 1999), chamber, and micro-lysimetry (Centinari et al., 2009) approaches have been utilized. Among these, only sap flow methods have been routinely applied for continuous measurement of component ET. Because the interrow also has important implications for water and energy balance in vineyards, it is valuable to devise a technique for measurement of interrow ET (Yunusa et al., 1997; Lopes et al., 2004; Centinari et al., 2009).

Bowen ratio methods have been used for separating ET flux components within a variety of systems. These studies usually involve application of additional methods such as sap flow gauges (Heilman et al., 1994; Zeggaf et al., 2008), where canopy transpiration or soil water evaporation are found by calculating the difference between either system ET and soil water evaporation or between system ET and canopy transpiration. Challenges of such approaches include reconciling bias amongst different methods and scaling sap flow or chamber data from individual plants to the field scale (Heilman et al., 1994; Zeggaf et al., 2008).

Micro-Bowen ratio (MBR) systems are a relatively new idea that may be used to determine individual ET components within a system (Ashktorab et al., 1989; Zeggaf et al., 2008). A MBR system is a scaled down version of a Bowen ratio system, designed to measure a small footprint. Ashktorab et al. (1989) described the concept of the MBR, but tested its applicability over a bare soil surface only. Zeggaf et al. (2008) showed the potential of the MBR to provide soil evaporation separately from canopy transpiration under a full canopy cover of corn crop. The technique was not tested in sparse canopy conditions, where heterogeneity in micrometeorological conditions is significantly greater. The objective of this work was to test a MBR system for measurement of ET in a vineyard interrow. We considered both grassed and bare soil interrow conditions. We first demonstrate MBR energy balances measured for interrow conditions, and then compare ET determined from MBR systems to estimates obtained from micro-lysimeters, and from a system-integrating eddy covariance system during a period without vine transpiration.

2. Materials and methods

2.1. Field sites

The main study was conducted at a commercial vineyard (Fig. 1), located near Dobson, NC (36°21′ N, 80°46′ W). The predominate soil type is the Fairview series (fine, kaolinitic, mesic, Typic Kanhapludult) with a sandy clay loam surface texture. Mean annual precipitation and air temperature are 112 cm and 13 °C, respectively (USDA-NRCS Web Soil Survey). The site is located 366 m above sea level (ASL) on gently rolling hills with an east-facing slope of 2–15%. Vines at the test site were Chardonnay (*Vitis vinifera*) planted in 2001 and were cordon-trained and spur-pruned, with upright shoots vertically shoot-positioned on the trellis with the aid of trellis catch wires. Vine rows were oriented generally north-south with 2.7 m row spacing and approximately 1.8 m spacing between vines within a row. The width of grassed interrow was 1.5–1.9 m (Fig. 2A), which contained weedy fescue (*Festuca arundinacea* Shreb.). The bare soil strip below the vine row was 0.8–1.2 m wide. Grapevine canopy width varied between 0.3 and 0.8 m. Canopy heights from ground and above cordon varied between 0.9–1.9 m and 0.4–1.4 m, respectively. Canopy dimensions varied seasonally as the vines grew and as a result of pruning.

Fig. 1. Vineyard study site near Dobson, NC with standard management conditions (i.e., fescue interrow).

Two treatments (bare soil and fescue) were maintained in the interrow (Fig. 2B). On March 1, 2011 six plots (three plots per treatment) were established, each measuring 7.6 m down the interrow. Because plot length was not constrained by the architecture of the vineyard, plot length was chosen to provide significant fetch (discussed further below), but while still keeping plots relatively small so that they could be co-located with consistent topography, soils, and vine characteristics. Plot width was constrained by the distance between vine rows (2.7 m). A non-selective, contact herbicide, glufosinate, was applied to eliminate vegetation in bare soil plots. With the exception of bare soil interrow plots, plots received standard vineyard management per the host vineyard for the duration of the study, thus the grass plots were bordered by a bare soil strip directly under the vines (Figs. 1 and 2).

A supplementary short-duration bare surface study was conducted at a second site located at NC State University Central Crops Research Station in Clayton, NC. The purpose of this study was to aid in interpretation of data from the bare surface interrow in the vineyard. The site is in the upper coastal plain on relatively flat terrain (2–6% slope), approximately 107 m ASL. The dominant soil types are the Norfolk series (fine-loamy, kaolinitic, thermic Typic Kandiudult) and Varina series (fine, kaolinitic, thermic Plinthic Paleudult), both with a loamy sand surface texture (USDA-NRCS Web Soil Survey). A bare plot (6.1 m × 4.6 m) was maintained, surrounded by a bare tilled field (0.2 ha).

2.2. Micro-Bowen ratio measurement systems

The Bowen ratio (β; Bowen, 1926) can be estimated by measuring differences in water vapor concentration and air temperature at two heights (Arya, 2001):

$$\beta = \frac{H}{LE} = \frac{[P_a C_p(\Delta T)]}{[\lambda \varepsilon(\Delta e)]} \tag{1}$$

where H and LE are sensible and latent heat fluxes (W m^{-2}), respectively, P_a is atmospheric pressure (kPa), C_p is specific heat capacity of air (1004.67 J kg^{-1} K^{-1}), ΔT is air temperature difference between two heights (K), λ is latent heat of vaporization for water (2.45 MJ kg^{-1}), ε is the ratio of molecular weights of air and water (0.622), and Δe is vapor pressure difference between two heights (kPa). LE is calculated from β, R_n, and G:

$$LE = \frac{R_n - G}{1 + \beta} \tag{2}$$

where R_n is net radiation (W m^{-2}) and G is soil heat flux (W m^{-2}). For G, H, and LE, fluxes away from the surface are positive; the opposite sign convention is used for R_n.

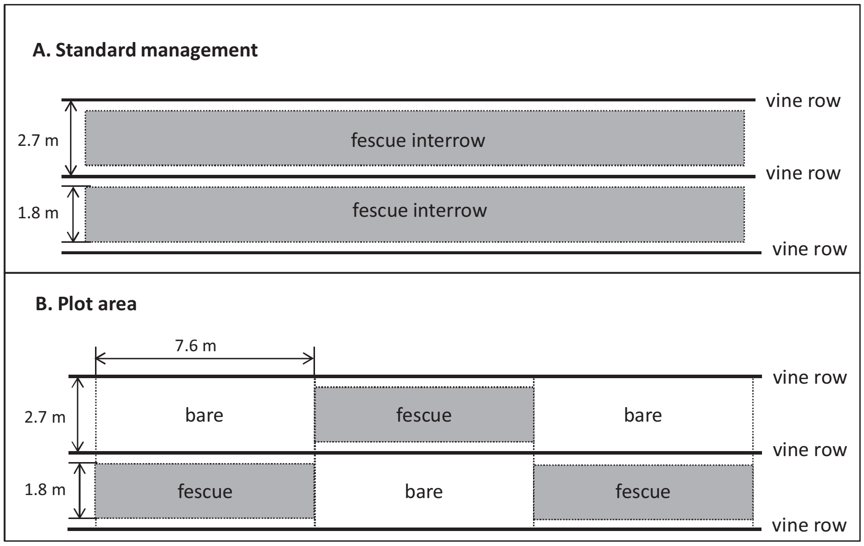

Fig. 2. (A) Standard management in the vineyard at the study site and (B) the plot layout within the vineyard system. Note that standard management conditions existed in the area surrounding the plots. The fescue strip width was 1.5–1.9 m and the bare strip width under the vines was 0.8–1.2 m.

For this study, MBR systems (Fig. 3) employed a LI-840A CO_2/H_2O gas analyzer (LI-COR, Lincoln, NE) that measures water vapor concentration in air (parts per thousand), which was in turn converted to vapor pressure (kPa) using ambient atmospheric pressure measurements. Each MBR system had two air intakes with a filter (PP Systems, Amesbury, MA) to remove debris. Air intakes were placed at 1 and 6 cm above the grass/soil surface. A micro diaphragm gas sampling pump (KNF Neuberger, Inc., Trenton, NJ) was used to draw air through the intakes. The data logger was programmed to switch a solenoid (Numatics, Novi, MI) every 5 min to alternate between top and bottom air intakes. To avoid condensation entering the LI-840A, the data logger was programmed to stop the pump when relative humidity, measured with a HMP60 probe (Vaisala, Woburn, MA) located outside the main enclosure at 30 cm height, was ≥92%. The pump was restarted when relative humidity dropped to ≤88%. Two flow meters (Cole-Parmer Instrument Co., Vernon Hills, IL) were used to control air intake rates at 0.8–1.0 L min^{-1} based on manufacturer recommendations for the LI-840A.

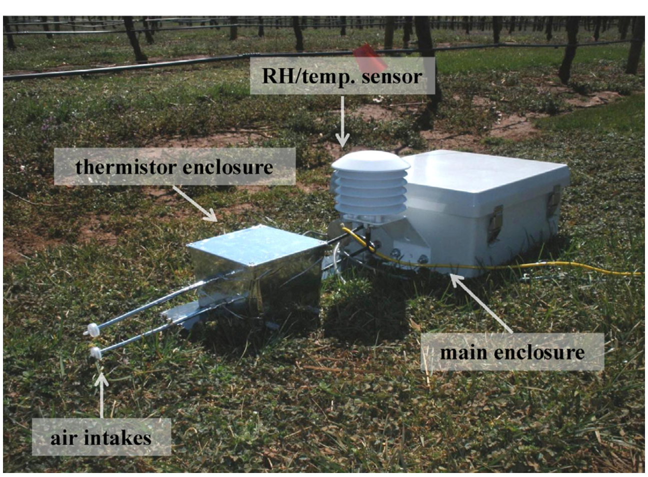

Fig. 3. Micro-Bowen ratio system in the fescue interrow of the vineyard study site. Air intakes are at 1 and 6 cm height above the grass surface. The main enclosure housed the datalogger, pumps, flow meters, and gas analyzer. The relative humidity (RH) and temperature sensor (temp.) was used to shut off the gas analyzer when ambient RH exceeded 92%.

Air traveled from intakes through Synflex® 1300 tubing (0.64 cm O.D., 0.1 cm wall, 22 cm length; Eaton Hydraulics, Eden Prairie, MN) to a thermistor enclosure (Carlon, Memphis, TN). The Synflex® 1300 tubing and thermistor enclosure were wrapped in silver metalized polyester (Mylar®) tape (CS Hyde Company Inc., Lake Villa, IL) to reflect sunlight so air temperature could be accurately measured. In the thermistor enclosure, air traveled from the Synflex® 1300 tubing to Tygon® tubing (Saint-Gobain Performance Plastics, Akron, OH) via a tube fitting (Swagelok, Solon, OH). Air temperature was measured inside a nylon barb tee (Thogus, Avon Lake, OH) containing a thermistor (BetaTHERM USA, LLC, Shrewsbury, MA) covered with epoxy (J-B Weld, Sulphur Springs, TX), placed in-line with the tubing from each air intake; air travel time from the inlet to the thermistor was <0.25 s.

From the thermistor enclosure, air traveled to the main enclosure (Vynckier Enclosure Systems Inc., Houston, TX) via Synflex® 1300 tubing. A water trap was installed in the tubing, built using a borosilicate glass scintillation vial (Fisher Scientific, Pittsburg, PA) and a nylon barb elbow held together with epoxy, as precaution to protect the gas analyzer in case liquid water enters the system. From the water trap, air traveled to the solenoid and then to the gas analyzer through the flow meter. From the gas analyzer, air traveled out of the main enclosure to the outflow via the pump.

A CR10X data logger (Campbell Scientific, Logan, UT) inside the main enclosure recorded all measurements every 10 s, output averages every 5 min, and controlled the MBR system. Additional supporting measurements (R_n, G) are described specific to each of two field campaigns in following sections; data from these measurements were recorded, output, and processed with the same frequency as described for the MBR system. MBR system data for the first minute of each 5-min interval were discarded before averaging to allow time for gas line purging, since the gas analyzer alternated between measurement heights. Thus, a total of six 4-min averages of air temperature and vapor pressure were output each 30-min interval; three 4-min averages were from each measurement height. These data were used to compute average ΔT and Δe for each 30-min interval. Data from MBR systems were rejected when $-1.05 > \beta > -0.95$, because the denominator in Eq. (2) approaches zero, resulting in unreasonably large LE and H. This condition usually occurs around sunset or sunrise when direction of ΔT is opposite direction of Δe (Perez et al., 1999). Specifically, as surface temperature becomes cooler or warmer than above surface temperature around sunset or sunrise, respectively, ΔT typically changes direction before Δe. Additionally, there is less certainty in the direction of ΔT and Δe because their magnitudes become less than the resolution of the sensors (0.02 °C for temperature and 0.018 kPa for vapor pressure) when they change direction around sunset and sunrise. Data were also rejected during precipitation when ET was assumed to be near zero. Wind direction also potentially influenced measurements due to the presence of the data logger and thermistor enclosures; however, we found no clear relationship between MBR performance and above-canopy wind speed or direction. We expect that wind speed near the surface is much lower than above the canopy and also less constant in speed and direction, though no below-canopy wind data were available to make an assessment. No data were specifically screened according to wind speed or direction. After data rejection, the Bowen ratio energy balance was recomputed from 30-min data using a moving average ($n = 3$) to provide hourly values.

Adequate fetch-to-height ratio is necessary to satisfy assumptions of the Bowen ratio method (Fritschen and Fristchen, 2005). Row width dictates fetch across vineyard interrows (typical widths <3 m). Fetch across the interrow may be of less concern, however, because cross row wind speed is lower than down row wind speed near the surface at similar above canopy wind speeds (Heilman et al., 1994). Heilman and Brittin (1989) reported that fetch-to-height ratio ≥20:1 is adequate for the Bowen ratio method. In the present study, fetch-to-height ratio was ≈15:1 across the interrow and >60:1 down the interrow.

2.3. Field campaigns

2.3.1. Vineyard

On April 7, 2011 five MBR systems were installed at the vineyard site. Data were continuously collected through April 2012. Four MBR systems were placed in interrow plots (two MBR systems for each treatment) with the fifth MBR system installed directly underneath the vine row. MBR data from underneath the vine row were used to compute the surface energy balance only during the period when the vines were dormant and without leaves (discussed further below); for this MBR system, fetch-to-height ratio was reduced to 15:1 parallel to the row, due to the presence of vine trunks, and ≈10:1 perpendicular to the row, due to the width of the bare soil strip beneath the vines. Supplemental data used to compute the surface energy balance include net radiation, soil water content, soil temperature, soil heat flux, and atmospheric pressure. Net radiation was measured using NR Lite2 net radiometers (Kipp and Zonen, Bohemia, NY) placed 23.5 cm above the surface in the middle of two plots, one per treatment. A third net radiometer was placed at the same height, directly below the vines in the middle of the bare soil strip. Soil heat flux plates (REBS, Seattle, WA) were installed at 6 cm depth, one per treatment and one directly below the vines. A CS616 soil water content reflectometer (Campbell Scientific) was installed horizontally at 3 cm depth in each treatment and at 6 cm depth under the vines. Soil temperature was measured by two thermocouples (Type E) installed at 2 and 4 cm depths for each treatment and under the vines. Soil volumetric heat capacity, estimated from soil water content measurements, and soil temperatures were used to account for energy storage change above heat flux plates (Sauer and Horton, 2005). The heat storage term was added to the flux measured by the heat flux plate to derive G at the soil surface for use in Eq. (2) via a combination approach. A barometer (Vaisala, model PTB101b) was installed in one MBR system to measure atmospheric pressure (kPa). However, due to logging errors with the sensor, the LI-7500 open path CO_2/H_2O gas analyzer (LI-COR) that was part of the above canopy eddy covariance system (discussed below) provided atmospheric pressure for part of the study. A tipping bucket rain gauge (Texas Electronics, Dallas, TX) provided precipitation measurements (mm).

The MBR systems were compared to the micro-lysimeter (ML) method for both interrow treatments over three different time periods. MLs were built using a design similar to Heitman et al. (2010) and Singer et al. (2010). SDR 21 PVC pipe with 8 cm inside diameter was cut into 10 cm lengths. Each ML was beveled on one end to provide a cutting edge for installation. On March 1, 2011 five MLs were installed in three nests per plot (45 total per treatment). MLs were driven into the ground until their tops were flush with the ground surface.

On June 14, 2011 at approximately 12:00, a ML from two nests in each plot was extracted. In order to disrupt hydraulic contact between soil in the ML and soil underneath, a thin plastic bag was used to cover the ML bottom and held in place by tape. Each ML was weighed with a balance (precision = 0.01 g) and then reinstalled in the same position. After 6 h, the same MLs were extracted, wiped to remove any soil adhering to their exterior, weighed, and reinstalled. The same process was repeated beginning at 6:00 on June 15, 2011. At each 6-h time step, extraction and reinstallation were performed one plot at a time. The same procedure was repeated on July 28–29 and August 15–16, 2011. Data from MBR systems were compared to ML data by integrating fluxes from the MBR systems for corresponding time intervals. Due to power outage and inconsistent measurements from one gas analyzer, only one MBR system was used for each treatment for comparing to MLs. Each ML estimate represents the mean of at least six measurements.

MBR systems ET was also compared to above canopy ET measured with an eddy covariance (EC) system installed 3 m above the ground surface. The EC system consisted of a CSAT3 three-dimensional sonic anemometer (Campbell Scientific) and a LI-7500 open-path CO_2/H_2O gas analyzer (Li-Cor). The EC system was intended to measure the energy fluxes at the system level for the vineyard, which included grassed interrow as standard management. Fetch-to-height ratio was ≥40:1 in all directions. An additional net radiometer was placed at 3 m height to measure vineyard R_n. Data from the EC system were collected at 20 Hz and output as 15-min averages per standard algorithms developed by Campbell Scientific; processing included correction using the Webb–Pearman–Luening correction procedure (Webb et al., 1980) for sensible and latent heat fluxes. Comparisons between MBR and EC measurements were only made when there was no grapevine transpiration (November–February). Daily ET from MBR systems in the fescue interrow and below the vine were spatially weighted and compared to the vineyard daily ET determined with the EC system. Spatial weighting was initially set at 0.67 and 0.33 for interrow and below vine, respectively, based on approximate measured dimensions (Fig. 2A). We also attempted to optimize comparison by adjusting spatial weighting to minimize the sum of square error.

2.3.2. Bare field site

On March 19, 2012 a MBR system was installed in the bare field plot with air intakes placed 1 and 6 cm above the soil surface. The surface energy balance was estimated from March 19 through April 30, 2012. An additional logger was used to record net radiation (NR Lite2), relative humidity and air temperature (HMP60), and soil heat flux. A soil heat flux plate (REBS) was installed at 4 cm depth. A CS616 soil water content reflectometer at 0–4 cm depth and thermocouples at 1.2 and 3.6 cm depths were used to account for energy storage change above the soil heat flux plate. A nearby weather station provided precipitation and wind speed measurements.

A second comparison between MBR systems and MLs was performed using MLs identical to those from the vineyard. At 10:00, 14:00, and 18:00 on March 23 and 26–30, 2012, MLs were extracted, weighed, and reinstalled. A fresh set of MLs was used each day with at least four measurements taken per time interval. On March 26

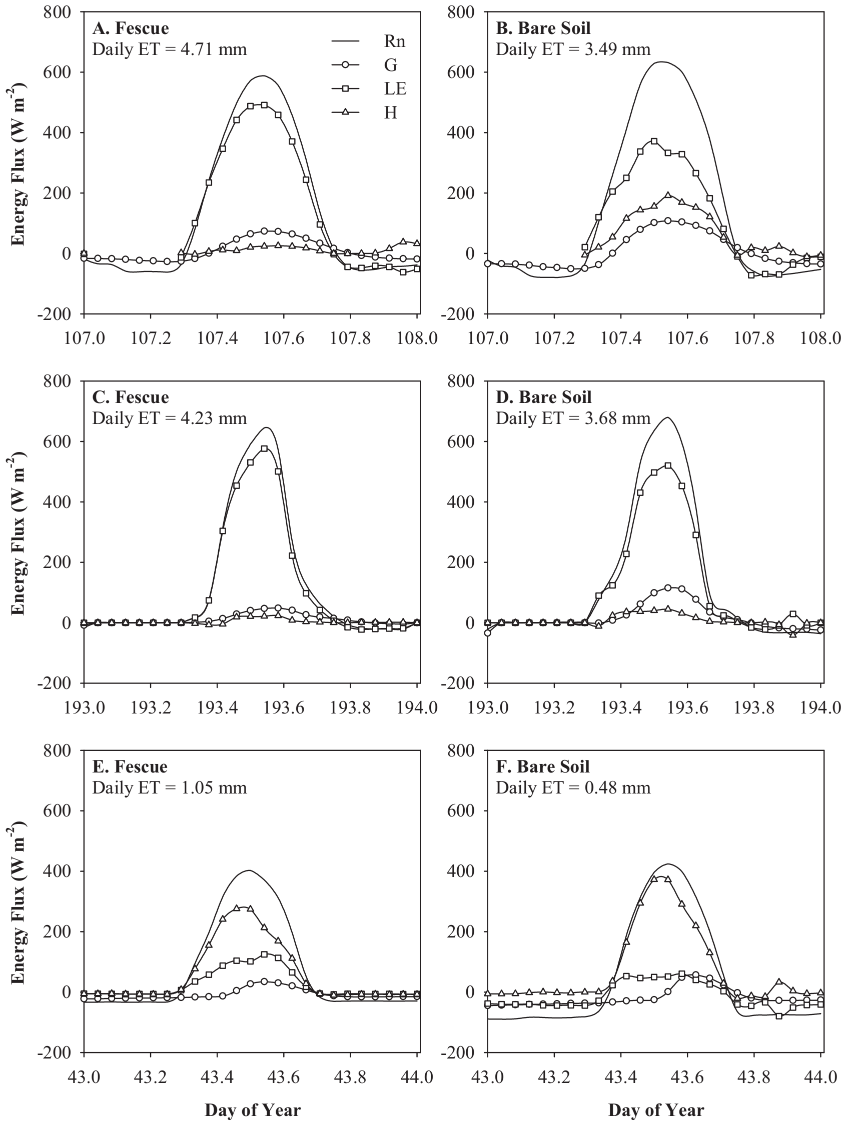

Fig. 4. Bowen ratio energy balance for fescue (left column) and bare soil (right column) interrow conditions at the vineyard on selected representative clear sky days. Panels A–D are from 2011 and panels E and F are from 2012. R_n (net radiation), G (soil heat flux), LE (latent heat flux), H (sensible heat flux), ET (evapotranspiration).

and 27, MLs were also extracted at 6:00 to measure ET between 6:00 and 10:00. ET during this interval was found to be near zero, so the interval was excluded thereafter.

3. Results and discussion

3.1. Surface energy balance and ET in the vineyard interrow

In the vineyard interrow, surface energy balances were computed for fescue and bare soil conditions on representative clear sky days (Fig. 4). Energy fluxes were near zero during the night. Beginning around sunrise, when incoming radiation gradually became greater than outgoing radiation, energy fluxes became positive. Throughout the day, energy fluxes followed a similar trend to R_n in that they increased and usually peaked around solar noon and then decreased to $\leq 0\,W\,m^{-2}$ as the sun set.

Seasonal changes in the energy fluxes are also observed by comparing panels in Fig. 4. Net radiation was greatest during spring and summer (Fig. 4A–D) and then decreased during fall and winter (Fig. 4E and F). Duration of positive R_n became shorter as the grapevine canopy began to develop, providing morning and afternoon shading (Fig. 4C and D). Magnitude of peak R_n also decreased as intensity and duration of daytime incoming radiation decreased in winter (Fig. 4E and F). Table 1 shows the fraction of R_n partitioned to LE and H between 8:00 and 18:00 for both treatments on representative days. The fraction of R_n partitioned to LE decreased during winter due to grass entering winter dormancy and because of less atmospheric evaporative demand (i.e., lower potential evapotranspiration). Only H increased during winter, when less energy was partitioned to LE and G (Fig. 4E and F). Soil heat flux differed considerably between treatments during the study period. For bare soil, daily G ranged from −0.6 to $3.3\,MJ\,m^{-2}$ (ave. = $1.42\,MJ\,m^{-2}$). For fescue, daily G ranged from

Table 1
Fraction of net radiation (R_n) partitioned to latent (LE) and sensible (H) heat for the vineyard interrow with fescue and bare soil conditions.

DOY	LE/R_n		H/R_n	
	Fescue	Bare soil	Fescue	Bare soil
43	0.31	0.14	0.67	0.84
107	0.85	0.56	0.04	0.28
193	0.89	0.77	0.03	0.07

Table 2
Evapotranspiration rates for fescue interrows of vineyards in North Carolina and New York. New York data after Centinari et al. (2009).

DOY	Evapotranspiration rate (mm d^{-1})	
	New York[a]	North Carolina
198	2.5	3.3
221	2.4	3.6
234	2.0	2.7
243	1.6	2.8
251	1.8	3.0
253	1.3	2.7

[a] Approximate values; exact values were not reported.

−0.3 to 1.8 MJ m^{-2} (ave. = 0.59 MJ m^{-2}). This difference is not surprising due to the direct effect of soil cover on reflected radiation, where R_n was slightly higher for bare soil, and also because less energy was partitioned to *LE* for bare soil.

Both daily and seasonal trends in energy fluxes appear reasonable with a few small anomalies (Fig. 4). Because β is based primarily on ΔT and Δe and these are measured at close vertical spacing by the MBR system, any subtle disturbance can be reflected in the computed surface energy balance. This may result in irregular fluctuations as observed for bare soil (Fig. 4D and F), particularly during the night when strong winds and overcast skies create near-neutral conditions (Arya, 2001). For example, a strong gust of wind may cause ΔT and Δe to be less pronounced causing uncertainty in the computed direction (i.e. positive or negative) and magnitude of *LE* and *H*, even with adequate fetch.

Comparison of the present experiment to estimates of interrow ET from other studies helps contextualize our results. Centinari et al. (2009) measured ET in the fescue interrow of a vineyard located in Geneva, New York (NY) using MLs. The range in ET for the NY vineyard was 1.3–2.5 mm d^{-1}, compared to 2.7–3.6 mm d^{-1} at the NC vineyard (Table 2). Heilman et al. (1994) measured daily evaporation above a bare-soil interrow in a west Texas (TX) vineyard over an eight day period beginning on May 31 (DOY 152). The range in evaporation was 1.3–2.7 mm d^{-1}, which was estimated between 6:00 and 20:00 each day. This range is similar, but lower than that estimated for daily evaporation at the NC vineyard during the same time of year over the bare soil interrow; 1.9–3.4 mm d^{-1}. It is reasonable for the NC vineyard to have greater ET than the NY vineyard because NC conditions provide greater evaporative demand and adequate soil moisture. The difference between ET at the TX and NC vineyards is likely due to differences in soils (i.e., soil texture, moisture). In general, the results of these studies are similar to ET rates measured in our study by MBR systems.

3.2. Comparisons of MBR measurements to other methods

3.2.1. Lysimetry

Correlation between ET rates from MLs and MBR systems for the interrow at the vineyard site was slightly stronger for fescue (R^2 = 0.99, Fig. 5A) than for bare soil (R^2 = 0.89, Fig. 5B) interrow. Simple linear regression intercepts were slightly less than zero in both cases. MBR measurements increasingly overestimated ML measurements as ET increased, particularly for bare soil (fescue slope = 1.17, bare soil slope = 1.60). If ML estimates are assumed accurate, greater overestimation in the bare soil plots may be due to limited plot size. This possibly resulted in influence from fescue ET in the surrounding vineyard on MBR measured ET rates in the bare soil plots (Fig. 2). Since ET was lower for the bare soil, and the MLs only capture the local conditions, if the fetch for the MBR in the bare soil plot is too small and the fescue contributes to the measured fluxes, ET is overestimated. Also, there is possibly greater surface roughness for bare soil compared to the evenly-mowed

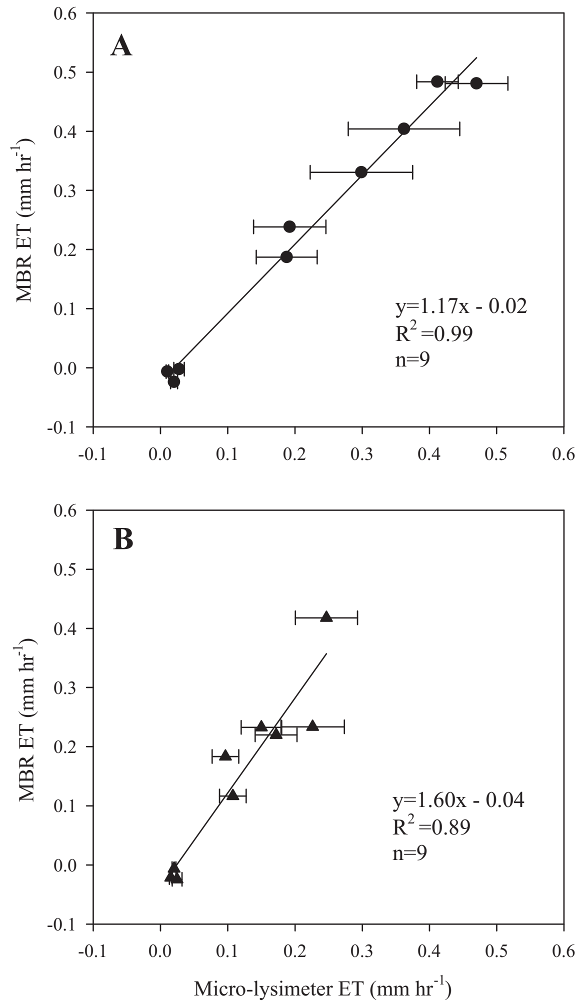

Fig. 5. Micro-lysimeter vs. micro-Bowen ratio (MBR) system evapotranspiration (ET) for fescue (A) and bare soil (B) interrow conditions. Each micro-lysimeter value is the mean of at least six measurements; error bars indicate one standard deviation.

fescue. The MBR systems are sensitive to surface roughness because as surface roughness increases, turbulence may cause ΔT and Δe to become less pronounced.

Correlation between MBR and ML measurements at the bare field site (Fig. 6) was not as strong (R^2 = 0.66) as that at the vineyard site (Fig. 5). One reason for this could be greater wind speed. Strong wind gusts can create error in measured ΔT and Δe. Average wind speed during the observation period at the bare field site was 2.9 m s^{-1} at 2 m height. The average wind speed at the vineyard, corrected for 2 m height (Allen et al., 1998), was much less (1.0 m s^{-1}). The slope (0.98) and near zero intercept of the linear regression, however, indicate that MBR evaporation rates measured in a large bare soil area were less biased toward overestimation, compared to bare vineyard interrow measurements. Observations at the bare soil site support the interpretation that measured vineyard bare soil evaporation rates were elevated due to ET from grassed interrows in the surrounding vineyard rather than because of specific characteristics of the bare soil.

Previous studies have compared MBR approaches with lysimeters for non-vineyard systems. Ashktorab et al. (1989) compared evaporation from a similar MBR system with a 6.1 m diameter, 90 cm deep weighing lysimeter for a bare loam soil in California. They found a strong correlation (R^2 = 0.83) with regression slope = 0.82, implying that the MBR system underestimated evaporation. Zeggaf et al. (2008) used a similar MBR system to

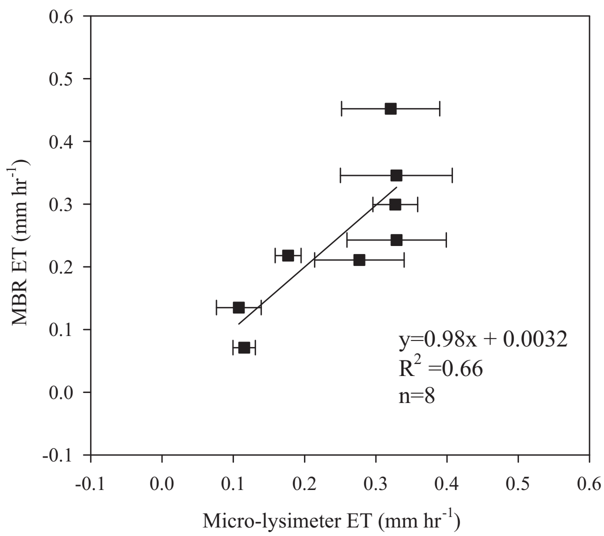

Fig. 6. Micro-lysimeter vs. micro-Bowen ratio (MBR) system evapotranspiration (ET) at the bare surface field site. Each micro-lysimeter value is the mean of at least four measurements; error bars indicate one standard deviation.

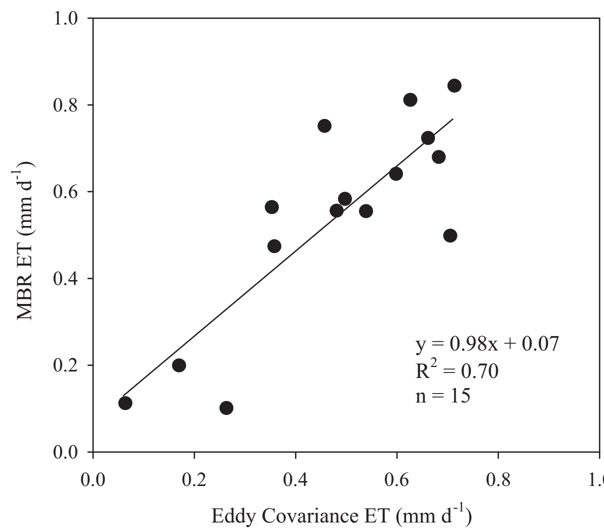

Fig. 7. Eddy covariance vs. micro-Bowen ratio (MBR) systems evapotranspiration (ET). MBR estimates are based on spatially weighted means of two MBR systems, one under the vines and one in the fescue interrow. Spatial weighting was based on measured row dimensions.

measure evaporation underneath a maize canopy. A 1.5 m diameter, 1.5 m deep weighing lysimeter was used to measure ET from the maize field. Below-canopy evaporation was assumed to be the difference between ET and transpiration from the maize itself, which was measured with sap flow gauges. Their observed correlation between estimated evaporation and MBR evaporation was weak ($R^2 = 0.36$). This may be due, however, to the indirect measurements of evaporation used for comparison to the MBR measurements. Although the system in the Ashktorab et al. (1989) studies was not a vineyard, their observed correlation, together with correlation observed in the present study, provides a favorable comparison between MBR measurements and lysimetry. The overestimation of ET in the present study and the underestimation of ET in the Ashktorab et al. (1989) study, when MBR is compared to lysimetry, suggest that further testing is warranted to reduce uncertainty in the MBR approach.

3.2.2. Eddy covariance

Correlation for daily ET rates from the EC and MBR systems is shown for 15 clear days during the vines' dormant season (November–February) in Fig. 7 ($R^2 = 0.70$). The average ET rate from the EC system was lower than that from the MBR systems by 11%. To rule out the possibility that the difference is attributed to inaccurate spatial weighting of the fescue vs. bare soil strips, an optimization test was performed by changing the weights and comparing the correlation strength. No weight combination was found to improve the correlation, indicating that the weight did not affect the correlation significantly.

Differences in measured ET may be due to the EC system representing a much larger area than the MBR systems, with EC providing integration of within footprint variability, which affects more localized MBR estimates. Differences may also be associated with differences in EC and Bowen ratio measurement approaches that are not scale dependent. While the BREB forces closure, the average energy balance residual (residual = $R_n - G - H - LE$) for EC data presented in Fig. 7 was 20 W m^{-2} (30% bias). This bias can be considered acceptable (Twine et al., 2000), but the residual represents a significant portion of the winter energy balance (see Fig. 4E and F). Others have observed similar (or worse) agreement when comparing traditional Bowen ratio measurements with EC. Dugas et al. (1991) compared EC with Bowen ratio systems over an irrigated spring wheat crop in Arizona. On average, *LE* from the EC system underestimated that from the Bowen ratio system by 28%. Fritschen et al. (1992) compared hourly *LE* from EC with a Bowen ratio system over a freshly burned field and over a grass field. Average correlation was modest ($R^2 = 0.49$) in the burned field, but stronger ($R^2 = 0.76$) in the grass. Given some lack of certainty in spatial weighting and energy balance closure here, comparisons between MBR and EC measurements generally appear favorable.

4. Summary and conclusion

Understanding how vineyard interrows contribute to water and energy budgets is useful for supporting vineyard management decisions. Few methods are available to continuously and accurately measure ET under and between sparse canopies. We tested a novel MBR system to measure interrow ET in a vineyard. Energy fluxes estimated by MBR systems provided reasonable patterns both within days and between seasons. Measured ET rates were similar to those reported by other researchers for similar conditions in the vineyard interrow. ET rates were well correlated both between MBR systems and MLs and between MBR and EC systems, though ET rates determined by MBR were up to 60% larger than those determined by MLs for bare soil interrows. Overall, MBR systems provided a viable approach for estimating vineyard interrow ET patterns and dynamics. Further testing and adaptation may be necessary to correct overestimation of ET magnitude before the approach is broadly adopted. MBR systems may also be useful to separate energy fluxes of individual components in other sparse canopy or mixed systems, although additional investigation is needed to test limitations particular to a given environment.

Acknowledgements

This study was supported by the Binational Agricultural Research and Development Fund (BARD US-4262-09). The authors thank Shelton Vineyards for providing the vineyard study site and assisting with site maintenance.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper No. 56. FAO, Rome.

Allen, R.G., Tasumi, M., Trezza, R., 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—model. J. Irrig. Drain. Eng. ASCE 133 (4), 380–394.

Arya, S.P., 2001. Introduction to Micrometeorology, second ed. Academic Press, CA.

Ashktorab, H., Pruitt, W.O., Paw, U.K.T., George, W.V., 1989. Energy balance determinations close to the soil surface using a micro-Bowen ratio system. Agric. For. Meteorol. 46, 259–274.

Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A., Holtslag, A.A.M., 1998. A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. J. Hydrol. 212–213, 198–212.

Bland, W.L., Loew, J.T., Norman, J.M., 1996. Evaporation from cranberry. Agric. For. Meteorol. 81, 1–12.

Bowen, I.S., 1926. The ratio of heat losses by conduction and evaporation from any surface. Phys. Rev. 27, 779–789.

Braun, P., Schmid, J., 1999. Sap flow measurements in grapevines (*Vitis vinifera* L.) 2. Granier measurements. Plant Soil 215, 47–55.

Centinari, M., Poni, S., Filippetti, I., Magnanini, E., Intrieri, C., 2009. Evaluation of an open portable chamber system for measuring cover crop water use in a vineyard and comparison with a mini-lysimeter approach. Agric. For. Meteorol. 149, 1975–1982.

Centinari, M., Poni, S., Intrigliolo, D.S., Dragoni, D., Lakso, A.N., 2012. Cover crop evapotranspiration in a northeastern US Concord (*Vitis labruscana*) vineyard. Aust. J. Grape Wine Res. 18, 73–79.

Dugas, W.A., Fritschen, L.J., Gay, L.W., Held, A.A., Matthias, A.D., Reicosky, D.C., Steduto, P., Steiner, J.L., 1991. Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat. Agric. For. Meteorol. 56, 1–20.

Fandino, M., Cancela, J.J., Rey, B.J., Martinez, E.M., Rosa, R.G., Pereira, L.S., 2012. Using the dual-K_c approach to model evapotranspiration of Albarino vineyards (*Vitis vinifera* L. cv. Albarino) with consideration of active ground cover. Agric. Water Manage. 112, 75–87.

Fritschen, L.J., Qian, P., Kanemasu, E.T., Nie, D., Smith, E.A., Stewart, J.B., Verma, S.B., Wesely, M.L., 1992. Comparisons of surface flux measurement systems used in FIFE 1989. J. Geophys. Res. 97, 18,697–18,713.

Fritschen, L.J., Fristchen, C.L., 2005. Bowen ratio energy balance method. In: Viney, M.K., Hatfield, J.L., Baker, J.M. (Eds.), Micrometeorology in Agricultural Systems. ASA/CSSA/SSSA Inc., Madison, WI, pp. 97–405.

Heilman, J.L., Brittin, C.L., 1989. Fetch requirements for Bowen ratio measurements of latent and sensible heat fluxes. Agric. For. Meteorol. 44, 261–273.

Heilman, J.L., McInnes, K.J., Savage, M.J., Gesch, R.W., Lascano, R.J., 1994. Soil and canopy energy balances in a west Texas vineyard. Agric. For. Meteorol. 71, 99–114.

Heilman, J.L., McInnes, K.J., Gesch, R.W., Lascano, R.J., Savage, M.J., 1996. Effects of trellising on the energy balance of a vineyard. Agric. For. Meteorol. 81, 79–93.

Heitman, J.L., Horton, R., Sauer, T.J., Ren, T.S., Xiao, X., 2010. Latent heat in soil heat flux measurements. Agric. For. Meteorol. 150, 1147–1153.

Hicks, B.B., 1973. Eddy fluxes over a vineyard. Agric. Meteorol. 12, 203–215.

Jackson, R.D., Reginato, R.J., Idso, S.B., 1977. Wheat canopy temperature: a practical tool for evaluating water requirements. Water Resour. Res. 13, 651–656.

Lopes, C., Monteiro, A., Ruckert, F.E., Gruber, B., Steinberg, B., Schultz, H.R., 2004. Transpiration of grapevines and co-habitating cover crop and weed species in a vineyard. A “snapshot” at diurnal trends. Vitis 43, 111–117.

Norman, J.M., Kustas, W.P., Humes, K.S., 1995. Source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature. Agric. For. Meteorol. 77, 263–293.

Perez, P.J., Castellvi, F., Ibanez, M., Rosell, J.I., 1999. Assessment of reliability of Bowen ratio method for partitioning fluxes. Agric. For. Meteorol. 97, 141–150.

Ritchie, J.T., Burnett, E., 1968. A precision weighing lysimeter for row crop water use studies. Agron. J. 60, 545–549.

Sauer, T.J., Horton, R., 2005. Soil heat flux. In: Viney, M.K., Hatfield, J.L., Baker, J.M. (Eds.), Micrometeorology in Agricultural Systems. ASA/CSSA/SSSA Inc., WI, pp. 131–154.

Seguin, B., Itier, B., 1983. Using midday surface temperature to estimate daily evaporation from satellite thermal IR data. Int. J. Remote Sens. 4, 371–383.

Singer, J.W., Heitman, J.L., Hernandez-Ramirez, G., Sauer, T.J., Prueger, J.H., Hatfield, J.L., 2010. Contrasting methods for estimating evapotranspiration in soybean. Agric. Water Manage. 98, 157–163.

Smart, R.E., 1985. Principles of grapevine canopy microclimate manipulation with implications for yield and quality. A review. Am. J. Enol. Viticult. 36, 230–239.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available from: http://websoilsurvey.nrcs.usda.gov/ (accessed 14.11.11).

Stone, L.R., Horton, M.L., 1974. Estimating evapotranspiration using canopy temperatures: field evaluation. Agron. J. 66, 450–454.

Sumner, D.M., Jacobs, J.M., 2005. Utility of Penman–Monteith, Priestley–Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. J. Hydrol. 308, 81–104.

Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., Houser, P.R., Meyers, T.P., Prueger, J.H., Starks, P.J., Wesely, M.L., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agric. For. Meteorol. 103, 279–300.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Q. J. R. Meteorol. Soc. 106, 85–100.

Weiss, A., Allen Jr., L.H., 1976a. Air-flow patterns in vineyard rows. Agric. Meteorol. 16, 329–342.

Weiss, A., Allen Jr., L.H., 1976b. Vertical and horizontal air flow above rows of a vineyard. Agric. Meteorol. 17, 433–452.

Williams, L.E., Phene, C.J., Grimes, D.W., Trout, T.J., 2003. Water use of mature Thompson Seedless grapevines in California. Irrig. Sci. 22, 11–18.

Wilson, K.B., Hanson, P.J., Mulholland, P.J., Baldocchi, D.D., Wullschleger, S.D., 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. Agric. For. Meteorol. 106, 153–168.

Yunusa, I.A.M., Walker, R.R., Guy, J.R., 1997. Partitioning of seasonal evapotranspiration from a commercial furrow-irrigated Sultana vineyard. Irrig. Sci. 18, 45–54.

Zeggaf, A.T., Takeuchi, S., Dehghanisanij, H., Anyoji, H., 2008. A Bowen ratio technique for partitioning energy fluxes between maize transpiration and soil surface evaporation. Agron. J. 100, 988–996.

Zhang, B.Z., Kang, S.Z., Zhang, L., Du, T.S., Li, S.E., Yang, X.Y., 2007. Estimation of seasonal crop water consumption in a vineyard using Bowen ratio-energy balance method. Hydrol. Process. 21, 3635–3641.