# EVALUATION OF A TWO-LAYER MODEL TO ESTIMATE ACTUAL EVAPOTRANSPIRATION FOR VINEYARDS

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## ABSTRACT

The two-layer model of Shuttlerworth and Wallace (SW) was evaluated to estimate actual evapotranspiration (ETa) above a drip-irrigated Merlot vineyard, located in the Talca Valley, Region del Maule, Chile (35º 25' LS; 71º 32' LW ; 136m above the sea level). An automatic weather system was installed in the center of the vineyard to measure climatic variables (air temperature, relative humidity, and wind speed) and energy balance components (solar radiation, net radiation, latent heat flux, sensible heat flux, and soil heat flux) during November and December 2006. Values of ETa estimated by the SW model were tested with latent heat flux measurements obtained from an eddy-covariance system on a 30 minute time interval. Results indicated that SW model was able to predict ETa with a root mean square error (RMSE) of 0.44 mm $d^{-1}$ and mean absolute error (MAE) of 0.36 mm $d^{-1}$. Furthermore, SW model predicted latent heat flux with RMSE and MAE of 32 W $m^{-2}$ and 19W $m^{-1}$, respectively.

## INTRODUCTION

Quantification of the actual evapotranspiration (ETa) is a key to designing strategies for improving water-use efficiency and wine quality of irrigated viticulture (Yunusa et al., 2004; Ortega-Farias et al., 2004a; and McCarthy, 1997). Evapotranspiration modeling over full canopies is common; however, little research has been done on ETa over sparse canopies such as in vineyards. ETa over vineyards is a complex function of water and energy balances of both the vine canopy and the soil surface (Heilman et al., 1994). Vineyards usually contain tall plants and widely spaced rows that produce large diurnal changes in the exposure of plants and soil to solar radiation.

Recent studies have indicated that the two-layer model of Shuttleworth and Wallace (SW) could be used to compute ETa over vineyards. In Chile, Ortega-Farias et al (2007) indicated that SW model was able to compute ETa over a drip irrigated Cabernet Sauvignon vineyard with a root mean square error (RMSE) and mean absolute error (MAE) of 0.42 mm $d^{-1}$ and 0.36 mm $d^{-1}$, respectively. Sene (1994) used the SW model for estimating water consumption of a sparse vine growing under semiarid conditions in southern Spain. In this study, the parameterization of the SW model seemed sufficiently well defined so that, under dry soil conditions the only input data

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required were direct measurements or estimates of the vine growth, solar radiation, air temperature, wind speed, and humidity above the canopy.
The objective of this study is to evaluate the two-layer model of Shuttleworth and Wallace for computing latent heat flux (LE) and actual evapotranspiration (ETa) over a drip-irrigated Merlot vineyard located in the Talca Valley, Region del Maule, Chile.

## THEORY

The SW model combines a one-dimensional model of crop transpiration and a one-dimensional model of soil evaporation. Surface resistances regulate the heat and mass transfer at plant and soil surfaces, and aerodynamic resistances regulate those between the surface and the atmospheric boundary layer (Shuttlerworth and Wallace, 1985):

$$LE = C_c PM_c + C_s PM_s \tag{1}$$

where LE = latent heat flux from the canopy (W m$^{-2}$); $PM_c$ and $PM_s$ are terms (Wm$^{-2}$) similar to those in the Penman-Monteith model that would apply to transpiration from the canopy and evaporation from the soil, respectively; $C_c$ and $C_s$ are the canopy and soil surface resistance coefficients (dimensionless). Values of PMc and PMs, are obtained as follows:

$$PM_C = \frac{\Delta A + \left(\dfrac{\rho_a c_p D - \Delta r_a^c A_s}{r_a^a + r_a^c}\right)}{\Delta + \gamma\left(1 + \dfrac{\left(r_s^c\right)}{\left(r_a^a + r_a^c\right)}\right)} \tag{2}$$

$$PM_S = \frac{\Delta A + \left(\dfrac{\rho_a c_p D - \Delta r_a^s \left(A - A_s\right)}{r_a^a + r_a^s}\right)}{\Delta + \gamma\left(1 + \dfrac{\left(r_s^s\right)}{\left(r_a^a + r_a^s\right)}\right)} \tag{3}$$

where $\Delta$ = slope of the saturation vapor pressure curve at the mean temperature (kPa ºC$^{-1}$); A = available energy leaving the complete crop (W m$^{-2}$); $c_p$ = specific heat of the air at constant pressure (1013 J kg$^{-1}$ °C$^{-1}$); $\rho_a$ = air density (kg m$^{-3}$); D = water vapor pressure deficit at the reference height (kPa); $r_a^c$ = bulk boundary layer resistance of the vegetative elements in the canopy (s m$^{-1}$); $A_s$ = available energy at the soil surface (W m$^{-2}$); $r_a^a$ = aerodynamic resistance between canopy source height and reference level (s m$^{-1}$); $\gamma$ = psychrometric constant (kPa ºC$^{-1}$); $r_s^c$ = canopy resistance (s m$^{-1}$); $r_a^s$ = aerodynamic resistance between the soil and canopy source height (s m$^{-1}$); and $r_s^s$ = soil resistance (s m$^{-1}$)

A general description of aerodynamic resistances, $C_s$ and $C_c$ is found in Shuttleworth and Wallace (1985) and Ortega-Farias et.al (2007). The available energy at the crop canopy (A) and soil surface (As) is computed as, respectively:

$$A = Rn - G \tag{4}$$

$$As = Rn_s - G \tag{5}$$

where Rn = net radiation ($Wm^{-2}$); G = soil heat flux ($Wm^{-2}$); $Rn_s$ = net radiation at the soil surface, which can be calculated using Beer's law as follows:

$$Rn_s = Rn \exp(-C\,LAI) \tag{6}$$

where LAI = leaf area index ($m^2\ m^{-2}$); C = extinction coefficient of the crop for net radiation (0.5).

The surface canopy resistance, which depends on climatic factors and available soil water, is defined as the resistance to water transfer from the soil and plant to the atmosphere. The combined effect of atmospheric and soil moisture conditions on $r_s^c$ can be expressed as follows (Ortega-Farias et al., 2004b and 2006):

$$r_s^c = \frac{\rho_a \quad C_p \quad D}{\Delta \quad (Rn - G) \quad C_F} \quad F^{-1} \tag{7}$$

where F = normalized soil water (from 0 to 1); $C_F$ = empirical factor (0.066). The F-value can be estimated as (Noilhan and Planton, 1989):

$$F = \frac{\theta_i - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \tag{8}$$

where $\theta_{FC}$ = volumetric soil moisture content at field capacity (fraction); $\theta_{WP}$ = volumetric soil moisture content at wilting point (fraction); $\theta_i$ = volumetric soil moisture content in the root-zone (fraction).

## MATERIALS AND METHODS

Data to evaluate LE and ETa estimated by the Shuttleworh and Wallace (SW) model were collected over a 8-year-old Merlot vineyard located in the Talca Valley, Region del Maule, Chile (35º 25' LS; 71º 32' LW; 136 m above the sea level). The climate in this area is a typical Mediterranean semiarid climate with an average daily temperature of 17.1 $^oC$ between September and March. Average annual rainfall in the region is between 676 mm falling mainly during the winter months. The summer period is usually dry (2.2 % of annual rainfall) and hot while the spring is on average wet (16 % of annual rainfall). The soil at the vineyard is classified as the Talca series (family Fine, mixed, thermic Ultic Haploxeralfs) with a clay loam texture. For the effective rooting depth (0-60 cm), the volumetric soil water content at field capacity ($\theta_{FC}$) and at wilting point ($\theta_{WP}$) were 0.32 $m^3\ m^{-3}$ (192 mm) and 0.20 $m^3\ m^{-3}$ (120 mm), respectively. Also, the total available moisture (TAM) was 0.12 $m^3\ m^{-3}$ (72 mm) at the root zone.

Merlot vines were planted in 1999 in north-south rows 2.5 m apart, with 1.5 m within-row spacing. The vines were trained in standard vertical trellis system with the main wire 0.9 m above the soil surface. The shoots were maintained in a vertical plane by three wires, the highest of which was located 1.9 m above the soil surface. This created a compact hedgerow 2.1 m high and 0.55 m wide with little foliage below the main wire. Typical vine trunk diameters were about 10.6 cm (± 1.7 cm) and soil surface was maintained free of weeds or cover crop during the experiment.

The water application was done twice a week using 4 L $hr^{-1}$ drippers spaced at intervals of 1.5 m. To check the soil water content ($\theta_m$) at the rooting depth, a portable TDR unit (TRASE, Soil Moisture Corp., Santa Barbara, Calif.) was used twice a week. The management allowed depletion (MAD) was 22 %, which corresponded to 40 % of TAM. The leaf area index (LAI) was measured on 552 vines using a plant canopy analyzer (LAI-2000, LI-COR, Lincold, Nebraska, USA) 2 times during the simulation period. In this case, the average LAI value for the whole vineyard was 0.76 $m^2$ $m^{-2}$

During November and December 2006, an automatic weather system was installed in the central part of the vineyard to measure energy balance components (net radiation (Rn), sensible heat flux (H), latent heat flux (LE) and soil heat flux (G)) and meteorological variables (air temperature (Ta), relative humidity (RH), wind speed (u), wind direction (w) and precipitation (Pp)). Rn was measured by a four-way net radiometer (CNR1, Kipp&Zonen Inc., Delft, Netherlands). LE was measured using an open-path infrared gas analyzer (LI-7500 IRGA; LI-COR, Inc., Lincoln, Nebraska, USA) and H was measured by a three dimensional sonic anemometer (CSAT, Campbell Sci., Logan, UT) both mounted at a height of 4.0 m (Fig.1). The minimum fetch-to-instrument-height ratio was about 200:1, sufficiently large to preclude horizontal advection. Measurements were made at 10 Hz, and means, standard deviations, and covariances were calculated for 30-min periods. Half-hour averages of all signals were recorded on an electronic datalogger (CR 5000).

Soil heat flux was estimated using eight flux plates installed 0.4 m apart on an east-west line between rows. This arrangement takes into account the effect of shade of rows during the course of the day. The flux plates of constant thermal conductivity (HFT3, Campbell Sci., Logan, UT) were placed at a 0.08 m depth. Also, two averaging thermocouple probes (TCAV, Campbell Sci., Logan, UT) were installed above each flux plate at depths of 0.02 and 0.06 m. All these sensors were sampled at 10 second intervals and the data averaged over 30 minute time-steps.

Soil evaporation was measured with microlysimeters which were made from PVC tubes of 75 mm i.d. and 150 mm in depth (Yunusa el at., 2004). Four microlysimeters were installed on either side of the vines into the inter-row and two microlysimeters were installed within the drip-line (one below drip and the other one between drippers) (Fig. 2).

Figure 1. Eddy Covariance and Weather Station

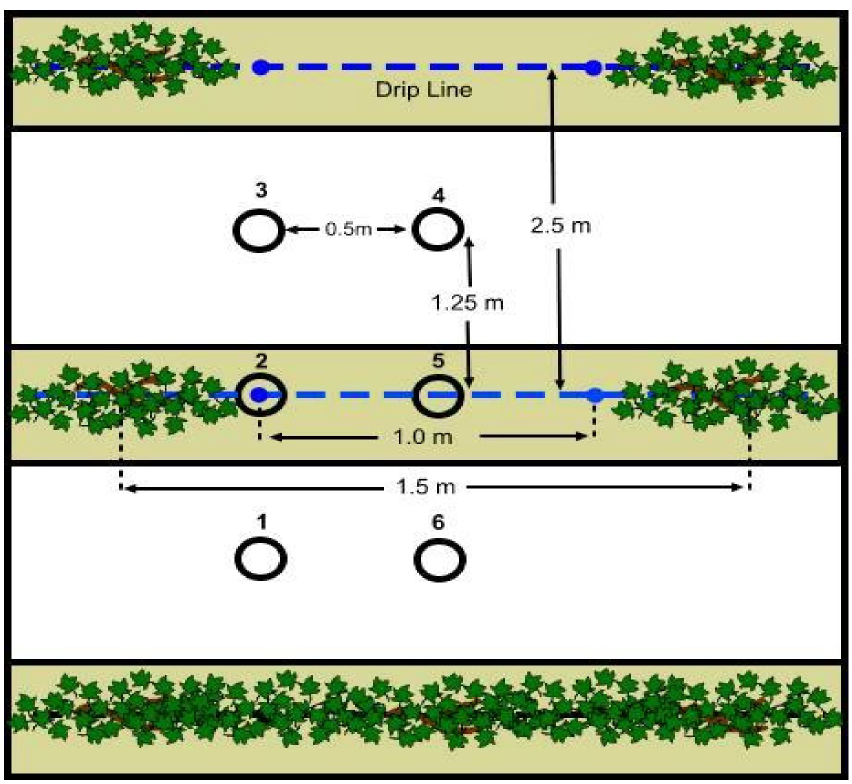


Figure 2. Schematic diagram to illustrate the distribution of microlysimeters.

In order to assess the validity of the estimation of LE, as computed from the Shuttleworth and Wallace model ($LE_{sw}$), our calculations were compared to latent heat flux obtained from the eddy-covariance method ($LE_{ed}$). Eddy covariance is the most direct micrometeorological technique for measuring turbulent fluxes (H and LE) in the surface of atmospheric boundary layer (Baldocchi et al., 1988). The eddy covariance system compute sensible heat flux (H) (W $m^{-2}$)as the product of the volumetric heat capacity of air ($\rho_a C_p$) and the covariance between vertical wind speed and air temperature ($\overline{w'T'}$).

$$H = \rho_a C_p \overline{w'T'} \qquad (9)$$

Latent heat flux (LE) (W $m^{-2}$) is calculated as the product of the latent heat of vaporization (L) (J $g^{-1}$) and the covariance between vertical wind speed and humidity ($\overline{w'\rho_v'}$).

$$LE = L\overline{w'\rho_v'} \qquad (10)$$

where (w`) = instantaneous deviation of vertical wind speed from the mean (m $s^{-1}$); $\rho_v'$ = instantaneous deviation of the water vapor density from the mean (g $m^{-3}$); $\rho_a$ = density of air (g $m^{-3}$); $C_p$ = heat capacity of air at a constant pressure (J $g^{-1}$ $K^{-1}$); $T'$ = instantaneous deviation of air temperature from the mean (K).

Also, the actual evapotranspiration was computed as a cumulative LE for the 24 hours. A regression model between $LE_{sw}$ and $LE_{ed}$ was performed using fluxes on a 30 minute time interval. The coefficient of determination ($R^2$), root mean square error (RMSE), and mean absolute error (MAE) were all used to evaluate how well the SW model estimates matched the eddy-correlation measurements (Mayer and Butler, 1993).

## RESULTS AND DISCUSSION

Figure 3 shows sensible plus latent heat flux (H+LE) from an open-path infrared gas analyzer and a 3-D sonic anemometer, respectively, versus the available energy (Rn-G) for a drip-irrigated Merlot vineyard. For the closure, values of $R^2$ and b were 0.97 and 0.96, respectively. Also, the slope (0.97) of the regression line was statistically different from 1.0 but the intercept (-4.0 W $m^{-2}$) was significantly equal to 0. Therefore, it is likely that the eddy-covariance method was providing accurate estimates of LE and H. Similar results were found by Ortega-Farias et al (2007) who indicated that the energy balance closure for a drip-irrigated Cabernet Sauvignon vineyard presented $R^2$ and slope values of 0.93 and 1.08, respectively. Similar results were found by Spano (2000) over a flood-irrigated Cabernet Sauvignon vineyard

Results, summarized in Table 1 and Fig. 4, indicate that there was a good agreement between LE measured by the eddy-correlation method ($LE_{ed}$) and that computed by the Shuttleworth and Wallace model ($LE_{sw}$) on a 30 minute basis. $R^2$ and RMSE values were equal to 0.88 and 32 W $m^{-2}$, respectively. Also, the statistical analysis indicated that $LE_{sw}$ tended to be lower than $LE_{ed}$ with a MAE value of 19 W $m^{-2}$. Results of the Z-test indicate that the intercept and slope were

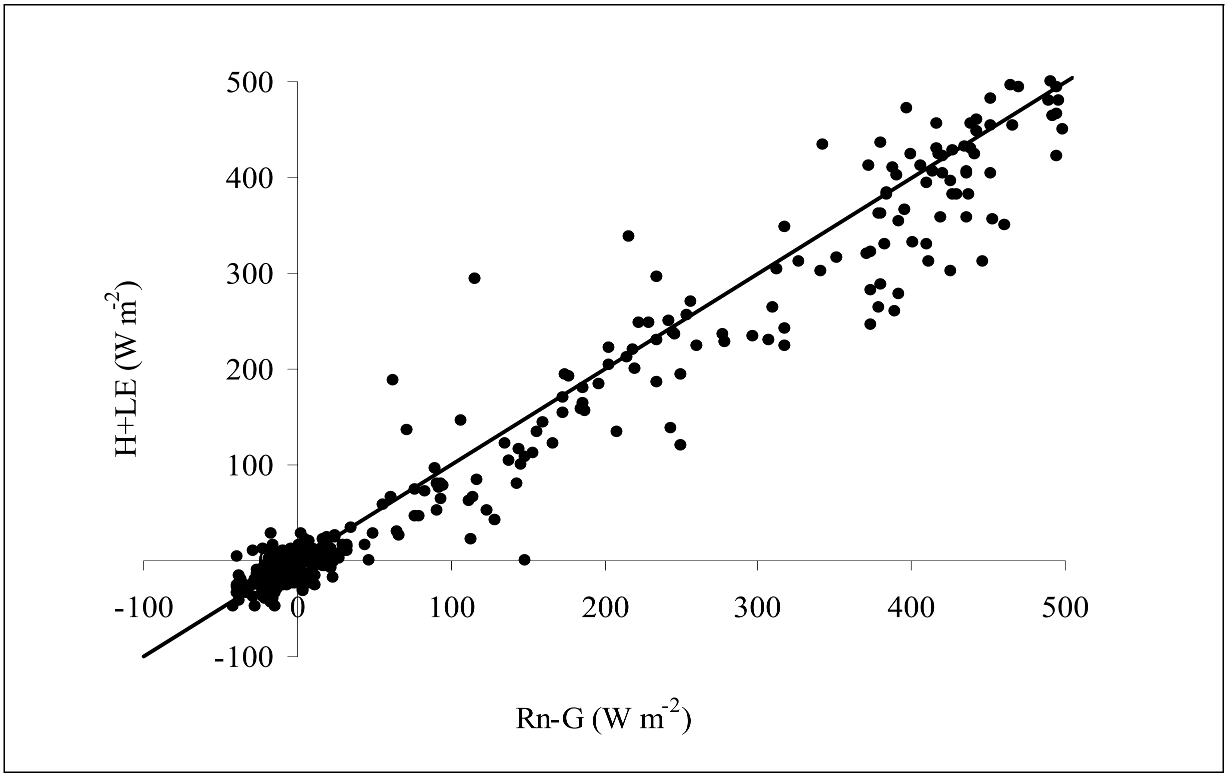


Figure 3. Sensible plus latent heat flux from eddy-covariance (H+LE) versus net radiation minus soil heat flux (Rn-G) for a drip-irrigated Merlot vineyard.

significantly different from 0 and 1.0, respectively. Comparison between both methods (Fig. 4) indicates that $LE_{sw}$ values tended to be lower than $LE_{ed}$ for values above 200 W m$^{-2}$. Furthermore, the SW model was able to simulate ETa, with $R^2$ and RMSE values equal to 0.61 and 0.44 mm d$^{-1}$ (1.1 MJ m$^{-2}$ d$^{-1}$), respectively (Table 1). The Z-test indicated that the intercept and slope were statistically different from 0 and 1.0, respectively. In this case, the SW model tended to underestimate ETa with a MAE value of 0.36 mm d$^{-1}$ (0.88 MJ m$^{-2}$ d$^{-1}$).

Table 1. Statistical validation of latent heat flux (LE) and actual evapotranspiration (ETa) over a drip-irrigated Merlot vineyard estimated by the Shuttleworth and Wallace model.

| | RMSE | MAE | $R^2$ | Intercept | Slope |
|---|---|---|---|---|---|
| LE | 32 W m$^{-2}$ | 19 W m$^{-2}$ | 0.88 | 5.30 W m$^{-2}$ | 0.81 |
| ETa | 0.44 mm d$^{-1}$ | 0.36 mm d$^{-1}$ | 0.61 | 1.10 mm d$^{-1}$ | 0.46 |

RMSE = root mean square error; MAE = mean absolute error; $R^2$ = coefficient of determination

Daytime variation of $LE_{sw}$ and $LE_{ed}$ above the Merlot vineyard for a 10-day period is presented in Fig. 5. Latent heat flux increased from sunrise onwards and peaked between 15:00 and 17:00 h, then declined after that. Maximum values of $LE_{sw}$ and $LE_{ed}$ were between 181 and 278 W m$^{-2}$ and between 189 and 317 W m$^{-2}$, respectively. The top layer of soil (0-10 cm) was dry on these days ($\theta_m$ = 0.09 m$^3$ m$^{-3}$); therefore in this instance, LE was mainly primarily represented by

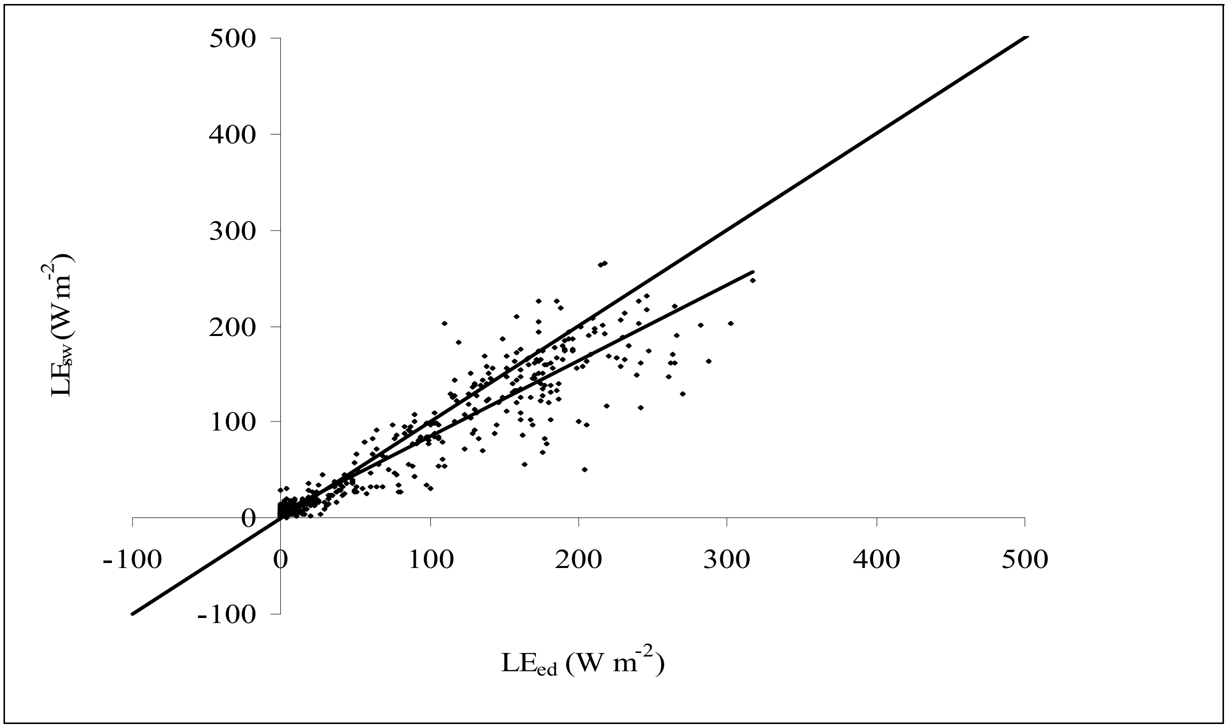


Figure 4. Comparison between latent heat flux obtained by the eddy correlation method ($LE_{ed}$) and computed by Shuttleworth and Wallace model ($LE_{sw}$) over a drip-irrigated Merlot vineyard.

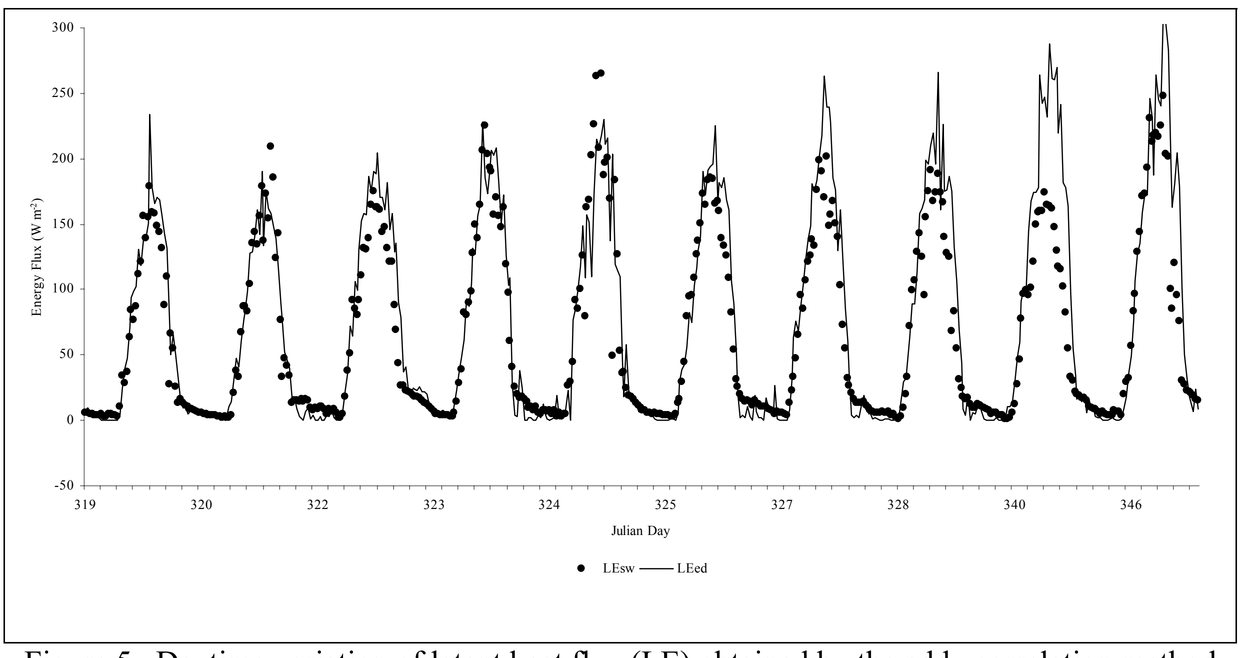


Figure 5. Daytime variation of latent heat flux (LE) obtained by the eddy correlation method ($LE_{ed}$) and computed by Shuttleworth and Wallace model ($LE_{sw}$) over a drip-irrigated Merlot vineyard.

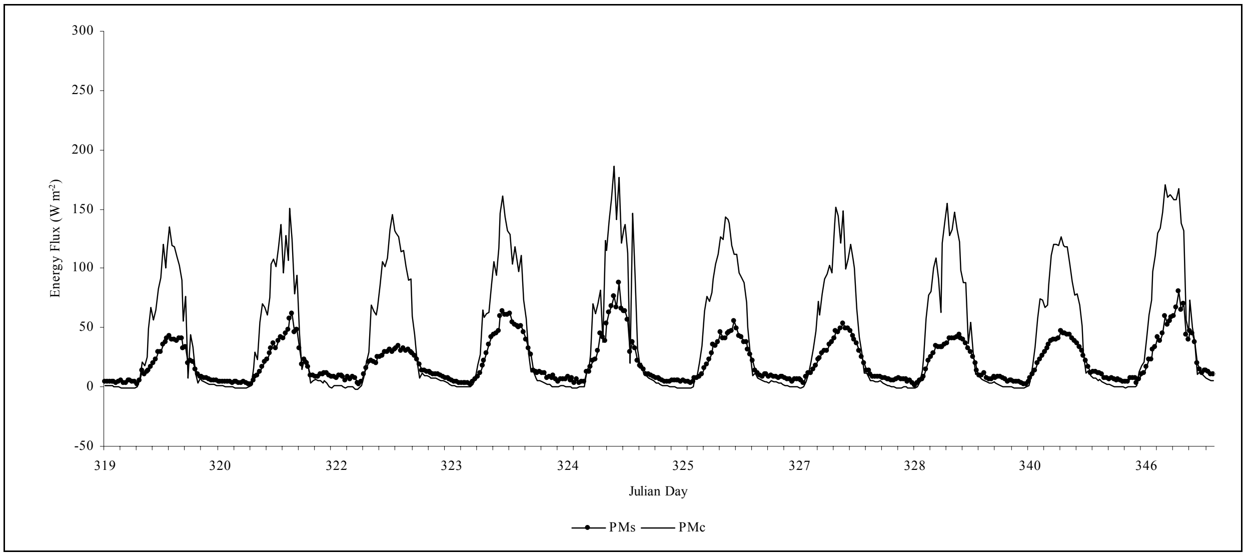


Figure 6. Daytime variation of transpiration (PMc) and evaporation (PMs) computed by Shuttleworth and Wallace model over a drip-irrigated Merlot vineyard.

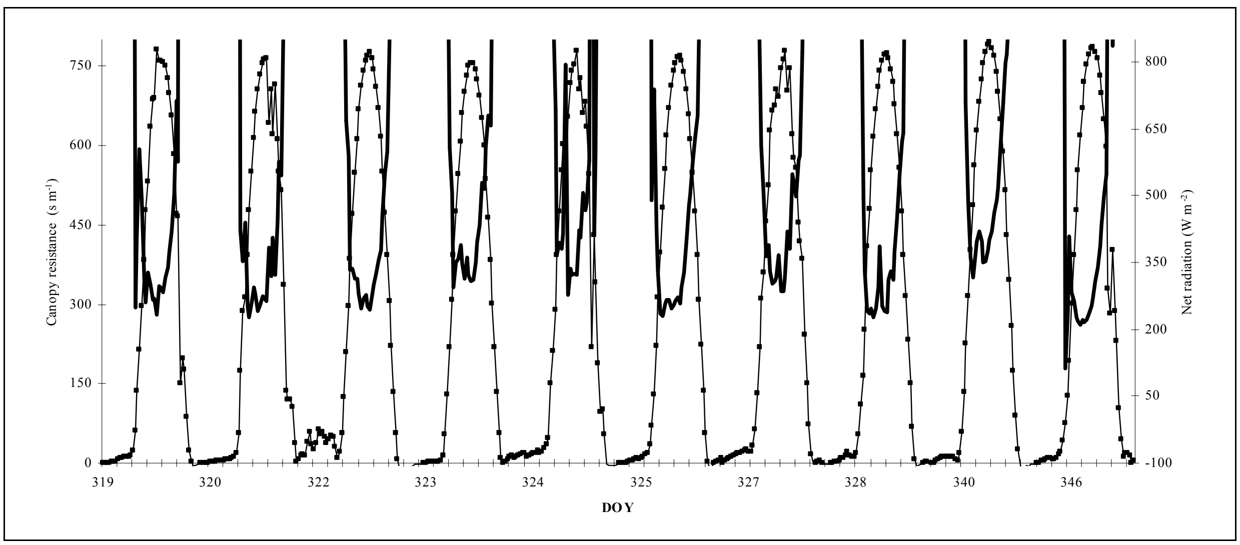


Figure 7. Daytime variation of canopy resistance ( $r_s^c$ ) (average values from 10:00 to 15:00 h) for well-irrigated Merlot vineyard. The net radiation (Rn) is included as reference.

transpiration (Fig. 6). In this case, maximum values of PMc and PMs were 136-187 W m$^{-2}$ and 33-86 W m$^{-2}$, respectively. The average PMc and PMs during the simulation period (10 days) were 1.7 mm day$^{-1}$ and 0.7 mm day$^{-1}$, respectively (Fig. 6). On the other hand, soil evaporation measured by the microlysimeters ranged between 0.28 and 0.39 mm day$^{-1}$. The overestimation of soil evaporation by the SW model may be associated with the soil resistance which was set up as a constant during this study (2000 s m$^{-1}$). Also, it is important to indicate that the soil water content (SWC) in the root zone was maintained near field capacity ($\theta_i$ = 29%) and F was 0.73. For this level of SWC, the surface canopy resistance (average values from 10:00 to 15:00 h) ranged between 292 and 420 s m$^{-1}$ (Fig. 7). The lowest value of $r_c$ was observed on DOY 346, which presented measured and estimated values of ETa equal to 3.4 mm $day^{-1}$ and 2.8 mm $day^{-1}$, respectively.

Best agreements between $LE_{ed}$ and $LE_{sw}$ at the Talca site were observed on DOY 320 where the regression slope was not significantly different from 1.0 and intercept was equal to 0 indicating that values of $LE_{ed}$ were similar to those of $LE_{sw}$. Greatest disagreements were observed on DOY 340 (Fig. 5), where the SW model tended to underestimate LE with a MAE of 24 W $m^{-2}$ and RMSE of 56 W $m^{-2}$. On this day, estimated and measured values of ETa were 2.5 mm $d^{-1}$ (6.2 MJ $m^{-2}d^{-1}$) and 3.4 mm $d^{-1}$ (8.4 MJ $m^{-2}$ $d^{-1}$), respectively. Major disagreements were observed during the afternoon (between 16:00 and 18:00 h), where values of $LE_{sw}$ were less than those of $LE_{ed}$ with a maximum difference of 140 W $m^{-2}$.

## CONCLUSIONS

The purpose of this study was to use the Shuttleworth and Wallace (SW) model to compute latent heat flux over a well-irrigated Merlot vineyard. The SW model ($LE_{sw}$) calculations were compared to those of the eddy-covariance method ($LE_{ed}$) on a 30 minute time interval. Model performance was good for the study period with the mean root square (RMSE) and mean absolute error (MAE) of 32 $Wm^{-2}$ and 19 W $m^{-2}$, respectively. For the actual evapotranspiration, RMSE was 0.44 mm $d^{-1}$ and MAE was 0.36 mm $d^{-1}$. Further research will be performed on modeling of the soil and canopy resistances to improve the estimation of soil evaporation and transpiration for vineyards under soil water stress.

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