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Estimation of Carbon Dioxide, Latent Heat and Sensible Heat Fluxes through Surface Renewal Analysis in Vertically Trellised Vineyards.

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Dedication

A Miriam Ruth, mi mamá.

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Chapter I

General Introduction

The exchange of heat, water vapour, and carbon dioxide in the planetary boundary layer (PBL) are critical processes that have been addressed in many ecosystem and atmospheric micrometeorology studies. Following Stull (1988), the atmospheric boundary layer (ABL) is a part of the troposphere that is influenced by earth surface processes on hourly scales and less, and thus, its composition and size constantly varies throughout the day. Surface friction and earth or sea warming rapidly influences ABL, through efficient transmission by turbulent mechanisms.

Following Hatfield et al. (2005), many technological improvements in micrometeorology were made possible, because of agronomic research (soil-plant-water relation and photosynthesis). Also, numerous research projects focus on improving the knowledge of water balances at local, regional, and continental scales. In this sense, the possibility of precise evapotranspiration estimations benefits crop water schedule advances. These advances improve efficiency in water management and use at the water-basin scale, especially in Mediterranean areas, water-scarce areas, or where water demand is greater than supply.

Micrometeorological techniques

The exchange scalars (water vapour, temperature, carbon dioxide, etc.) and vectors (momentum) in ABL have been measured and estimated using different micrometeorological techniques, including eddy covariance (EC), eddy accumulation, horizontal mass flux, and the Bowen ratio (Hatfield et al. 2005).

These methods have been researched and developed over the decades, with large budgets, time demands on data processing and sensor installation, not to mention qualified human resources.

In the agricultural field, micrometeorological methods are preferred because (Meyers and Baldocchi 2005):

- They are not intrusive, meaning that measurements do not affect environment conditions;
- They provide information about vertical fluxes. These fluxes are averaged in aerial spatial scales from meters to kilometres, depending on surface roughness, sensor heights, and atmospheric-stability conditions.

Among all these techniques, eddy covariance (EC) is the predominant one used to independently estimate momentum and sensible heat, latent heat, and carbon dioxide fluxes (Baldocchi 2003).

Eddy covariance

EC is based in the net difference of trace elements between turbulent vertical air fluxes and gas transport that moves between the atmosphere and the surface layer, especially over canopies (Baldocchi 2003; Burba and Anderson 2010).

Turbulence is the main mechanism responsible for momentum, heat, or matter transportation in the boundary layer (Fig. 1). The turbulent exchange quantification is defined by the covariance between scalars (momentum, heat, or mixing ratio) and the vertical wind component (Stull 1988).

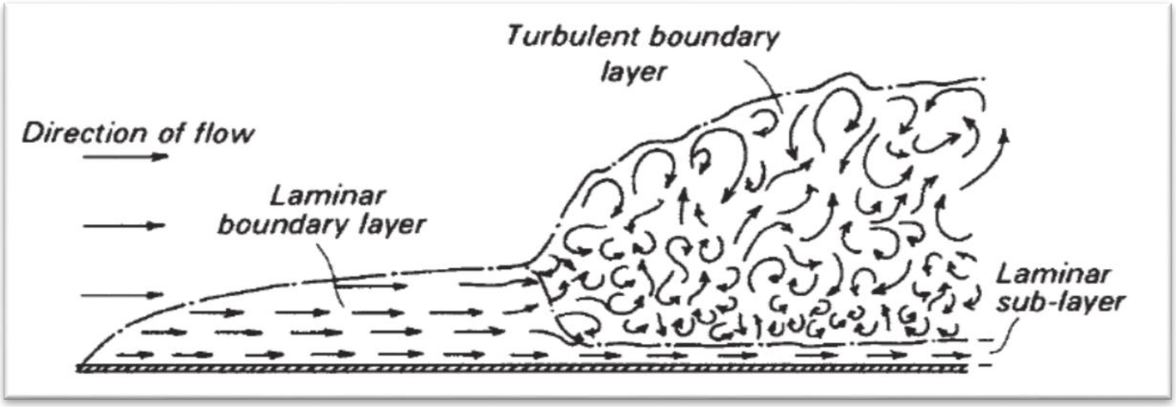

Fig. 1 Eddies of different sizes develop in the turbulent boundary layer. The laminar boundary layer develops over a flat surface and subsequently transitions to turbulent flux. Extracted from Oke (1990).

The carbon dioxide (CO_2), latent heat, and sensible heat fluxes can be measured trough the following equation (Baldocchi et al. 1988):

$$F_c = \rho_d \overline{w'c'} \tag{1}$$

where ρ_d is air dry density (kg m^{-3}), $\overline{w'c'}$ is the mean covariance between deviations in instantaneous vertical wind speed (w in m s^{-1}) and the dry mole fraction as a mixing ratio (c in kg kg^{-1}).

The turbulent fluctuations are random and irregular, so the covariance measurements are calculated as statistical averages, following Reynolds decomposition (Reynolds 1895). This decomposition is achieved only through many observations, so measurement uses high-frequency micrometeorological instrumentation (10 Hz or more), with averages and deviations characterizing the flux on a surface.

The sensible heat flux (H) and latent heat flux (λE) can both be estimated independently through EC. Additionally, with low frequency instruments, net radiation and soil heat flux are estimated. Together, these variables allow us to quantify and study the components of the energy balance of an ecosystem (Wilson et al. 2002; Franssen et al. 2010).

In EC, it is necessary to be cautious with topographic characteristics and the requirements of surface homogeneity (i.e., it should have little or no slope), and the separation between sonic anemometer and gas analyser, among others. (Burba and Anderson 2010). One of the main methods for evaluating EC performance is energy balance closure (EBC), which states that the sum of latent heat and sensible heat fluxes must be quantitatively equal to all other energy sources and sinks (Twine et al. 2000; Wilson et al. 2002), making its application a standard procedure in this methodology (Baldocchi et al. 2001; Wilson et al. 2002; Franssen et al. 2010). The energy balance equation is represented in the following equation:

$$Rn = \lambda E + H + G + S + Q \quad (2)$$

where *Rn* is net radiation (W m^{-2}); *λE* is the latent heat flux, a product of the latent heat of vaporization, λ (2.49 x 106 J Kg^{-1} at 20 °C) and evapotranspiration, *E* (mm m^{-2} s^{-1}); *H* is sensible heat flux (W m^{-2}); *G* is the soil heat flux (W m^{-2}); *S* is the rate of variation of heat storage (air and biomass) between the soil surface and the height from which the measurement is recorded; and *Q* is the sum of all additional energy sources and sinks. In general, the last two terms are quantitatively less important than *λE* and *H*, because their values and influence are typically negligible in the final result of the energy balance equation.

It is often necessary to develop methods that are cheaper and simpler to derive, but that are equally robust. Such methods would permit determining H, λE, and CO_2 fluxes in crops with high precision, while saving time and money and also facilitating the calculations without losing precision in data acquisition. With this intention, Paw U et al. (1995) presented a novel method to estimate scalar fluxes, based on the concepts of Surface Renewal Analysis (SRA).

Surface Renewal Analysis (SRA)

Technically, SRA is based on the theory of turbulence and on the time-space scalar fields, in conjunction with understanding how coherent structures affect the atmospheric surface layer interacting with earth and canopies (Paw U et al. 1992; Snyder et al. 1996; Spano et al. 1997b). Coherent structures are extensive and organized eddies that exchange water vapour, heat, and other scalars in the biosphere (Consoli 2011). The theory of coherent structures indicates that parcels of air that are above the surface penetrate into plant canopies (Gao et al. 1989). Due to the fluctuations caused by coherent structures, when measurements of temperatures (scalar) are plotted against time, forms similar to “ramps” are observed (Snyder et al. 1996), which describes how air parcels interact with a canopy surface (Fig. 2).

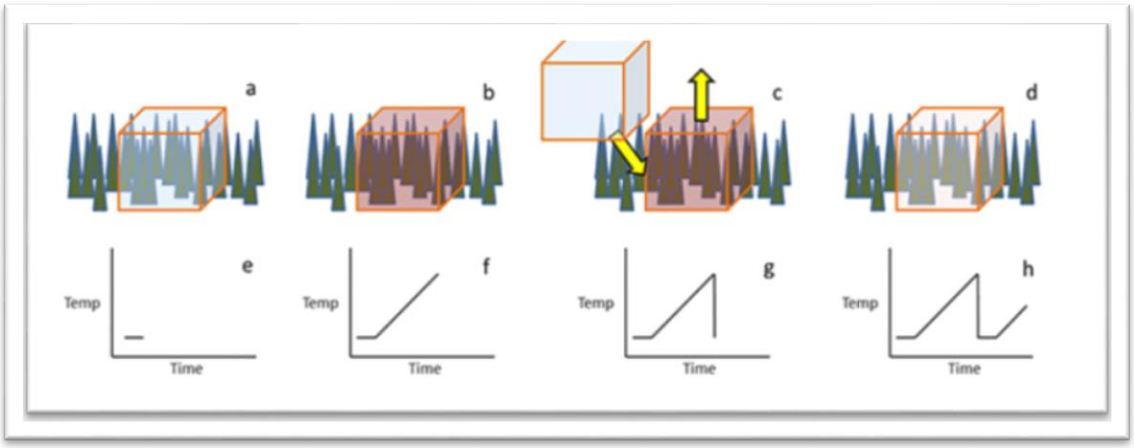

Fig. 2: Temperature ramps, analysis in text. Extracted from McElrone et al. (2013).

Here, after an air parcel comes into contact with a plant surface (Fig. 2a), the parcel experiences a period of inactivity, where small energy exchanges occur and minimal temperature changes over time (Fig. 2e). Eventually the air parcel interacts with the canopy surfaces, exchanging energy and mass. During this time, the air parcel increases in temperature (indicated by the red cube in Fig. 2b), leading to a rise over time (Fig. 2f). Subsequently, a cold air parcel is introduced into the canopy and the hot air parcel is displaced outside (Fig. 2c), resulting in a sharp decrease in the temperature trace (Fig. 2g), where the parcel of cold air replaces the hot air. The cycle then repeats (Figs. 2d, 2h) (Paw U et al. 1995; Katul et al. 1996; McElrone et al. 2013).

Temperature measurements at frequencies of 10 Hz, above or at the surface of the canopy, allow us to observe these “ramp” shapes. The calculation of these ramps dimensions is used in SRA to estimate H (Paw U et al. 1995). SRA has been improved and its use has been gradually intensifying over the past twenty years, because it has shown encouraging results in estimating H and λE using high frequency scalar measurements (4, 10, or 20 Hz), for a variety of terrains and canopies (Snyder et al. 1996; Duce et al. 1997; Spano et al. 1997b; Anandakumar 1999; Castellví et al. 2008; Haymann et al. 2019). Currently, there are three approaches to estimate *H* using SRA: (i) the classical approach analyses structural functions (Paw U et al. 1995; Snyder et al. 1996; Hsieh et al. 1997; Chen et al. 1997), (ii) the empirical method is based on the similarity theory of Monin-Obukhov (Castellví et al. 2002; Castellví 2004), and (iii) the method proposed by Shapland et al. (2012a, b) which takes into account different ramp scales (i.e., smaller ramps and spikes embedded in larger ramps).

In the classical approximation, *H* is calculated using the following equation:

$$H = (\alpha z)\, \rho\, C_p\, \frac{\delta T}{\delta t} \qquad (3)$$

where *H* (W m^{-2}) is related to the correction factor *α* (dimensionless), the specific heat of air C_p (J kg^{-1} °C^{-1}), air density ρ (kg m^{-3}), and $\frac{\delta T}{\delta t}$ (°C s^{-1}), where the high frequency temperature data is taken at a fixed point, *z* (m), and is assumed to represent the total derivative (i.e. the rate of air movement) of air temperature (Paw U et al. 1995; Snyder et al. 1996).

The term $\frac{\delta T}{\delta t}$ in equation (3) is replaced by $\frac{a}{l+s}$ to determine what happens with *H* in over the entire time, namely the time in which the ramp occurs plus the time between ramps. In Fig. 3, *l* is the duration of a ramp, *s* is the resting time between ramp events, and *a* is the amplitude of the scalar of interest. The rest period (*s*) occurs during the time of the transition when the hot and humid air package is expelled from the canopy and a cold and dry air package enters the canopy, in conditions of instability. When we refer to moments of instability (*a > 0*), we refer to the fact that the canopy temperature is higher than the surrounding air; if not, these would be stable conditions (*a < 0*) (Spano et al. 2000). The average temperature amplitude and the time duration (i.e., *l* + *s*) of an average ramp during a sampling interval is used to determine the heat transfer rate (Paw U et al. 1995; Snyder et al. 1996).

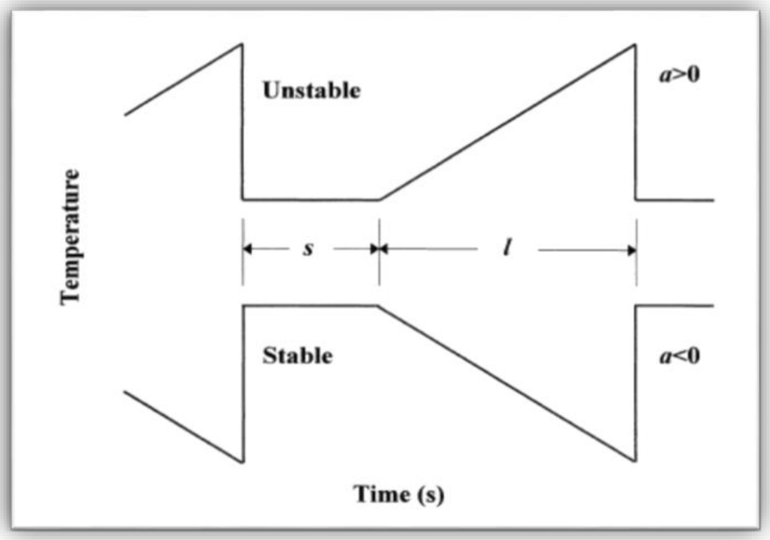

Fig. 3: Ramp model in stable and unstable atmospheric conditions, extracted from Spano et al. (2000).

The parameters of the ramp (*l*, *s*, and *a*) are based on the calculation of structural functions using high frequency temperatures measurements (Van Atta 1977). However, *α* in equation (2) is different. The *α* represents the capacity of the turbulence to mix the scalars within a parcel of air that is about to be renewed (Castellví and Snyder 2009a). A detailed *α* performance under different conditions is reported in Mengistu and Savage (2010). Typically, *α* is calculated as the slope of a regression analysis of *H* fluxes from SRA and EC that is forced through the origin. Castellví (2004) developed an auto-calibration procedure to derive *α* by combining the Monin-Obukhov similarity theory with the classical SRA approach. This approach empirically relates classic SRA (of Lagrangian nature) with the quasi-stationary seasonal diffusion process (Castellví et al. 2002).

The structural functions described by Van Atta (1977) assume that exchanges that occur at the surface layer for the stationary period are represented in the number of ramp repetitions with the same dimension. Shapland et al. (2012a, b) determined that it was important to establish a grade of ramps to estimate coherent structures. By expanding the analysis of structural functions, ramp scales or orders can be identified, with smaller, intermittent or ephemeral coherent structures and a dominant coherent structure with a gradual and persistent increase (Fig. 4).

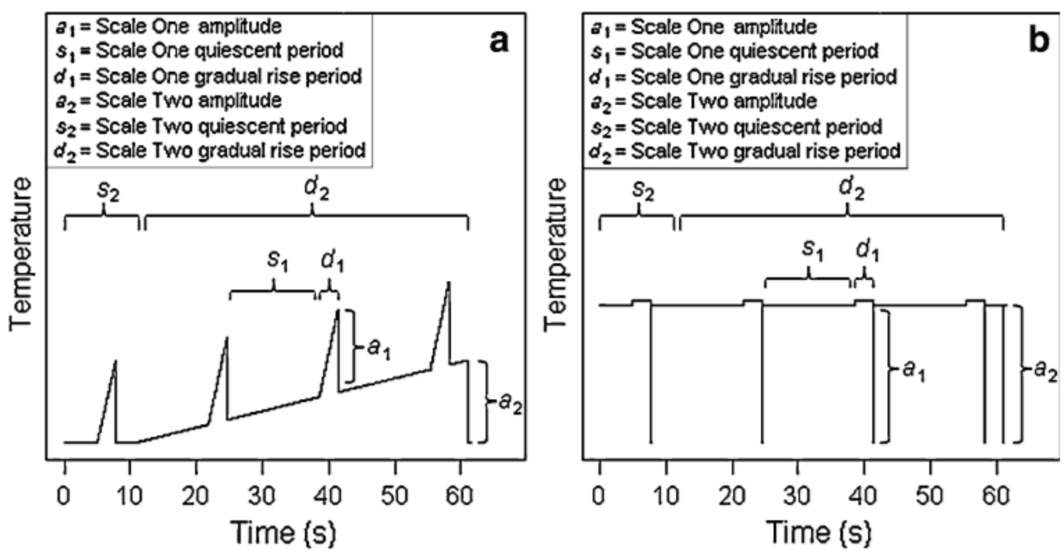

Fig. 4 Ramp models of the Shapland procedure. a) The traces of a two-scale ramp model. b) the first-order structural function of a two-scale ramp model. Extracted from Shapland et al. (2012a).

SRA and EC have similar fetch according to Castellví (2012), but SRA is less demanding and can operate at heights lower than EC, and it performs satisfactorily on sloped surfaces (Shapland et al. 2012c), sparse and dense canopies characteristics (Spano et al. 1997a), low and dense canopies (Duce et al. 1997; Spano et al. 1997b) or heterogeneous canopies like vineyards (Spano et al. 2000; Shapland et al. 2012c; Poblete-Echeverría and Ortega-Farias 2014). Also, using SRA to estimate *H* from the energy balance equation in conjunction with *Rn* and *G* provide an easy and relatively economical method to estimate λE as a residual from the energy balance equation. The main weakness of SRA is that it must be calibrated through EC to obtain α, when using the classic SRA approach (Paw U et al. 1995; Shapland et al. 2012c). Also, when calculating λE as a residual, all calculation errors from the sensors and calculation procedure will be loaded onto it.

During the last 20 years, research has been done to conduct the SRA method without EC, with encouraging results (Castellví 2004; Castellvi and Snyder 2010; Shapland et al. 2012b, a, 2014). In this sense of improvement, Castellví (2004) and Shapland et al. (2012a, b) proposed techniques to avoid the needing the α calibration factor (see equation 2). Suvočarev et al. (2014b) and Castellví et al. (2006) demonstrated that EBC using SRA was as good or better than using EC. In most cases, though, the EC technique is still widely used to estimate the flux exchanges between the atmosphere and the earth's surface, leaving aside SRA.

The SRA should be applied and evaluated in as many canopy plants (naturals and crops), surfaces, and climatic conditions as possible to discover other novel or unknown uses and to improve the technique. In this way, it may be affirmed as a micrometeorological technique with reliable characteristics and relatively low cost. The relative cost refers to the inevitable use of a gas analyser to obtain estimates of carbon dioxide, water vapour, and occasionally methane.

Comparison summary (SRA vs. EC)

• SRA has fewer fetch requirements, meaning that sensors require no particular orientation. The terrain need not be flat. There are no any inconveniences regarding instrument shading or extra difficulties like the separation distance between sensors (time lag between sonic anemometer and EC gas analyser).

• With SRA, the same or better energy balance closure compared to EC (Castellvi et al. 2006; Castellví et al. 2008; Suvočarev et al. 2014b, 2019).

• In SRA, the scalar values (H_2O, CO_2 and T °) are the only necessary inputs, while in EC the value of the scalar of interest and vertical wind speed values are needed (using Castellví's method, a simple anemometer is required for friction velocities).

• SRA can work in the rough layer or inertial sublayer of the atmosphere (Castellví 2012; Paw U et al. 2015) and on sloping terrain (Shapland et al. 2012c).

Proposed research and innovations

Studies and research concerning the literature reviewed do not contemplate the use of the SRA technique to independently estimate H, λE, and CO_2 fluxes on heterogeneous surfaces, such as a trellised vineyard. The studies do not analyse energy balance closures in vineyards using improvements introduced by Shapland et al. (2012a, b) and Castellví (2004). These ideas are novel, not currently developed, and the basis for the present doctoral thesis.

Only three articles were found with respect to CO_2 flux measurement using SRA. Spano et al. (2002) applied the classical approach of Snyder et al. (1996), estimating CO_2 traces through SRA and EC and obtaining the α calibration factor.

Castellví et al. (2008) applied SRA to independently estimate CO_2 on a grassland surface. Suvočarev et al. (2019) estimated CO_2 fluxes using an improved SRA proposed by Castellvi (an approach than could be used when only low frequency wind speed measurements are available) on cotton and rice fields.

Estimating the scalar fluxes by SRA reduce the costs of micrometeorological sensor equipment and avoids using EC and of all its associated methodological concerns, which were discussed previously.

The present doctoral thesis work expands the use of SRA in other crops and heterogeneous surfaces, and helps create a better understanding of coherent structure dynamics (Gao et al. 1989) between vegetation and atmosphere.

Objectives

General objective

Estimate the sensible heat, latent heat, and carbon dioxide fluxes independently using Surface Renewal Analysis in a heterogeneous canopy of Cabernet Sauvignon (vertically trellised vineyard).

Specific objectives

1- Determine the latent heat flux and sensible heat flux using water vapor and temperature values, respectively, through SRA and EC, in a heterogeneous vineyard canopy.

2- Compare, analyse, and describe the results of latent and sensitive heat fluxes and energy balance closures of SRA with the fluxes data obtained with EC.

3- Determine the carbon flux through SRA in a heterogeneous vineyard canopy and compare the data with the carbon dioxide flux obtained with EC.

4- Estimate λE as residual from energy balance equation and compare with λE from EC estimations.

Chapter II

Estimation of Carbon Dioxide, Sensible Heat and Latent Heat Fluxes in a Vertically Trellised Vineyard Using Two Surface Renewal Analysis Approaches

Estimación de flujos de Dióxido de Carbono, Calor Sensible y Calor Latente sobre un viñedo en hilera usando dos métodos de Análisis de Renovación de Superficies

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ABSTRACT

The application and further improvement of surface renewal analysis (SRA) to analyse scalar exchanges in heterogeneous surfaces is the objective of this research. Eddy Covariance (EC) is a widely used technique for estimating turbulent fluxes. However, EC has difficulties and disadvantages that are not present in SRA.

A flux tower was installed in a vertically trellised vineyard to estimate the components of the energy balance equation for all seasons between 2017 and 2018. The type of surface, with partial canopy cover and specific crop architecture, added complexity to the study. The estimation of latent heat (λE), sensible heat (H) and carbon dioxide (Fc) fluxes trough SRA was carried out following methodologies developed by Castellví (2004) (SRA_Cast) and Shapland et al. (2012a) (SRA_Shap) and compared to EC measurements. The slopes of the energy balance closure were 0.70, 0.64, and 0.69, R^2 of 0.95, 0.90, and 0.71 for EC, SRA_Cast, and SRA_Shap, respectively. SRA_Cast outperforms SRA_Shap in estimating λE, H, and Fc. Better results were obtained during unstable atmospheric conditions in comparison to stable conditions. It is concluded that SRA_Cast can be used as an independent methodology to estimate turbulent fluxes in heterogeneous crops, such as vineyards.

Keywords Surface renewal . Eddy covariance . turbulent fluxes . energy balance . coherent structures.

RESUMEN

Expandir el análisis de renovación de superficies (SRA) para analizar intercambios de escalares en superficies heterogéneas motivan esta investigación. La covarianza de torbellinos (EC) es una técnica ampliamente utilizada para estimar flujos turbulentos pero presenta algunas dificultades y desventajas en relación a SRA. Una estación con mediciones de flujos turbulentos fue instalada en un viñedo en espaldero para estimar los componentes de la ecuación de balance de energía durante la temporada (2017-2018) donde la superficie descubierta es mayor que la cubierta y la arquitectura de las plantas añade complejidad al estudio. La estimación de flujos de calor latente (λE), sensible (H) y dióxido de carbono (Fc) por SRA fue realizada siguiendo las metodologías propuestas por Castellvi (2004)(SRA_Cast) y Shapland et al. (2012a)(SRA_Shap) y comparadas con EC. Las pendientes del cierre

de balance de energía (CBE) fueron 0.70, 0.64 y 0.69 y el R^2 0.95, 0.90 y 0.71 para EC, SRA_Cast y SRA_Shap respectivamente. En general presentaron mejores ajustes λE, H y Fc estimados con SRA_Cast que SRA_Shap. Los datos en condiciones atmosféricas inestables presentaron mejores resultados que en condiciones estables. Se concluye que SRA_Cast puede ser utilizado como metodología independiente en viñedos, mientras SRA_Shap no presenta tan buenos resultados.

Palabras clave Renovación de superficie . Covarianza de torbellinos . flujos turbulentos . balance de energía . estructuras coherentes.

INTRODUCTION

Micrometeorological measurements allow us to investigate exchanges and interactions in the biosphere between the earth surface and the atmospheric boundary layer. EC is a widely used method to study energy and mass fluxes (42). However, this technique requires expensive equipment and has several difficulties with respect to installation (i.e., surface must meet certain criteria and have specific characteristics of slope, fetch, and homogeneity) and monitoring that have motivated scientists and practitioners to search for better, easier, and more reliable measurement techniques.

In that sense, SRA represents an interesting alternative, because it eliminates some uncertainties in flux estimation and facilitates data acquisition. Castellví (2012) proved that SRA can have less stringent fetch requirements than EC. Furthermore, Shapland et al. (2012d) estimated fluxes over wine grape vineyards located on hillside terrain, a condition usually not recommended for EC measurements.

SRA analysis was developed by Paw U et al. (1995), who described the performance of a temperature in canopies of maize, walnut, and forest. SRA is based in the concept of coherent structures described for a deciduous forest (12). A coherent structure consists of a weak pulse of air mass that comes from the canopy top being replaced by new air in the canopy. Depending on atmospheric stability conditions, an air mass is cooled (heated) and enriched (depleted) with water vapour or CO_2 as a consequence of the exchange between the canopy and the atmospheric surface layer.

Following this concept, sensible heat flux (H) estimation using SRA has been widely studied (2, 5, 10, 22, 25, 29, 34), while latent heat flux (λE) using SRA has received comparatively less attention (see for instance 37, 38); whereas Castellví et al. (2006). Suvočarev et al. (2019) estimated *H, λE*, and carbon dioxide flux (*Fc*) independently, following the technique proposed by Castellví (2004) in crops with homogenous surfaces, using only a cup anemometer (i.e., not using a sonic anemometer).

Until now, three approaches exist to estimate fluxes using SRA: the classical approach of Paw U (1995) using structure functions developed by Van Atta (1977) where a required calibration factor (α) is calculated by calibrating results SRA against EC values; the approach proposed by Castellví (2004) (SRA_Cast), which combines the classical approach with similarity theory to obtain an empirical α; and the approach proposed by Shapland et al. (2012a, b) (SRA_Shap), which separates the calculation of ramps (a two-model ramp), between flux bearing and isotropic ramps (here α is assumed to be close to 1.00). Exhaustive information about SRA theory and their main characteristics is presented in Mengistu and Savage (2010), Hu et al. (2018) and Paw U et al. (2015).

Suvočarev et al. (2014) estimated H and λE fluxes in heterogeneous crops in orchards in an independent way following Castellví (2004) and Shapland et al. (2012a, b). Vineyards are crops with heterogeneous surfaces and spaced plants that allow air and sunlight to penetrate into the canopy. Under such conditions, soil contribution to the energy balance is considerable, and water use is regulated by both soil and plant characteristics. Heilman et al. (1994) concluded that H generated at the soil surface is an important supplier to the energy balance and transpiration of the canopy in a commercial vineyard. Additionally, Ham and Heilman (1991) determined that energy transport is affected by the aerodynamic and surfaces properties of soil and canopy in cotton.

To the best of our knowledge, no other results have been reported applying SRA to independently estimate λE and CO_2 fluxes on vertically trellised vineyard using SRA_Shap and SRA_Cast approaches. SRA should be tested in all types of surfaces and different crops to verify the feasibility of the technique.

MATERIALS AND METHODS

Site, meteorological conditions, and instrumentation

A flux tower was installed in a 13.14 ha Cabernet Sauvignon (CS) vineyard located in Pirque, Santiago de Chile (lat. 33° 42’ S, 70° 34’ W, elevation 686 m a.s.l.). Data was gathered from November 1, 2017 to

April 13, 2018. The vineyards are north-south oriented in a vertically trellised system and with a 1.94 m crop height during the mean-season period. The space between rows was 2.45 m and space between plants was 1.22 m. During daytime, wind blew from the west and northwest, and at night, mean wind direction was from the southeast. Fetch was calculated following Allen et al. (1996) and reached a value of 312 m in October, 246 m in December 2017, and 229 m in January 2018. The vineyard was irrigated using a drip irrigation system handled by the managers once every 12-15 days until December 30, 2017, after which it was irrigated once every 8-12 days.

Pirque has a typical Mediterranean climate with warm temperatures: 14.2 °C averaged annual temperature, 22.03 °C annual maximum temperature average (warmest month is January) and 5.96 °C annual minimum temperature average (coldest month is July) and precipitation of 470 mm (Pirque station, Dirección General de Aguas) concentrated in the austral winter (June to August).

The flux tower was equipped with an integrated open-path gas analyser, 3D sonic anemometer (Campbell Scientific, IRGASON), temperature probe (Campbell Scientific, 107), net radiometer (Kipp & Zonen, NR-Lite), two soil heat flux plates (Huseflux, HFP01), and one set of soil temperature sensors (Campbell Scientific, TCAV). Heat flux plates were buried at 0.1 m, and the temperature probe was buried in pairs at 0.03 m and 0.06 m depth, exactly under the plants (in the row). The net radiometer and the IRGASON were installed above the vineyard, at 2.40 m and 4.58 m, respectively. The IRGASON was pointed toward the northwest, about 270° clockwise from north and the net radiometer was pointed about 22° clockwise from north. A datalogger (Campbell Scientific, CR3000) was used to monitor the sensors and record data.

Ramp calculations

Ramps are signatures of the coherent structures and are visualized when the traces of scalars (temperature, water vapour, carbon dioxide) are plotted versus time. The ramps occur when an air mass enters the canopy and then is ejected (34). Ramps were calculated using structure functions (1), where amplitude (2) and ramp durations ($\tau = l+s$) (3) were estimated following Van Atta (1977):

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

where m is the number of data points in a 30-min interval measured at frequency f in Hz, n is the power function, j is the sample lag between data points corresponding to a time lag ($r = j/f$), and T_i is the ith temperature (in case of H estimation) sample of the interval. Estimated average amplitude (A) is obtained following the following cubic equation searching for real roots:

$$A^3 + pA + q = 0 \tag{2}$$

$$p = 10S^2(r) - \frac{S^5(r)}{S^3(r)} \tag{3}$$

$$q = 10S^3(r) \tag{4}$$

$$\tau = -\frac{A^3 r}{S^3(r)} \tag{5}$$

Shapland procedure

Shapland proposed a two-scale ramp model, where one scale represents the smaller size, non-flux-bearing turbulence, obtained from the Van Atta (1977) procedure for very shorts time lags. The larger scale model represents the main flux-bearing eddies, and the characteristic are calculated by increasing the time lag parameter. Detailed procedure of technique is found in Shapland et al. (2012a, b).

$$H\_SRA\_Shap = z\overline{\rho_a}\overline{C_p}\frac{A_T}{\tau_T} \tag{6}$$

$$\lambda E\_SRA\_Shap = z\bar{\lambda}\frac{A_q}{\tau_q} \tag{7}$$

$$Fc\_SRA\_Shap = z\frac{A_c}{\tau_c} \tag{8}$$

where z is the measurement height in m, $\overline{\rho_a}$ is mean air density (kg m^{-3}), $\overline{C_p}$ is the specific heat of air (J kg^{-1} K), $\bar{\lambda}$ is the latent heat of vaporization (J g^{-1}), and indexes T, q, and c temperature (°C), water vapour (g m^{-3}), and dioxide carbon (mg m^{-3}), respectively, and used to distinguish the amplitude and duration of the different ramps for sensible heat (H_SRA_*Shap*), latent heat (λE_SRA_*Shap*) and carbon dioxide fluxes (*Fc_SRA_Shap*).

Castellví procedure

In this case, Castellví et al. (2002) and Castellví (2004) proposed an empirical technique to calculate α every half hour for each flux within the inertial sublayer, combining SRA and similarity concepts. For this purpose, requiring temperature and wind speed measurements at high frequency (min 10 Hz).

$$H\_SRA\_Cast = z\,\overline{\rho_a}\,\alpha_T\,\overline{C_p}\,\frac{A_{T2}}{\tau_{T2}} \tag{9}$$

$$\lambda E\_SRA\_Cast = z\,\alpha_q\,\bar{\lambda}\,\frac{A_{q2}}{\tau_{q2}} \tag{10}$$

$$Fc\_SRA\_Cast = z\,\alpha_c\,\frac{A_{c2}}{\tau_{c2}} \tag{11}$$

The α_T, α_q, and α_C are the calibraction factors for sensible heat (H_SRA_*Cast*), latent heat (λE_SRA_Cast) and carbon dioxide (*Fc_SRA_Cast*) fluxes for equations (9), (10), and (11) respectively. The α for each flux is calculated by:

$$\alpha = \left[\frac{k}{\pi}\,\frac{(z-d)}{z^2}\,\tau u_* \emptyset^{-1}(\xi)\right]^{1/2} \tag{12}$$

where $k{\sim}0.4$ is the Von Karman constant, d is the zero displacement height in m (calculated as d = 0.67h, where h is canopy height), $u_*$is the friction velocity (m s^{-1}), $\emptyset(\xi)$ is the stability function for scalar transport, calculated as $\xi = (z-d)/\,L_o$.

$$L_o = -\frac{\overline{T_s}\,u_*^3}{kg\,\overline{w'\,T'_s}} \tag{13}$$

where L_o is the Obukhov length in m, g is acceleration of gravity, T_s is sonic temperature in °C, $\overline{w'\,T'_s}$ is the covariance between vertical wind speed w (m s^{-1}) and T_s (°K). Following similarity theory (Högström 1996), the function $\emptyset(\xi)$ for water vapour, temperature, and carbon dioxide is assumed to be similar and is calculated by:

$$\emptyset\,(\xi) = \begin{cases} (0.95+7.8\,\xi) & 0 \le \xi \le 1 \\ 0.95\,(1-11.6\,\xi)^{-1/2} & -2 \le \xi < 0 \end{cases} \tag{14}$$

The second-, third-, and fifth-order moments were calculated and recorded for r = 0.50 s. The Rn and G fluxes were estimated at low frequency, while H, λE, and Fc where sampled at high frequency (10 Hz) from the sonic temperature, water vapour, and carbon dioxide scalars, respectively. These fluxes were averaged over 30-minute intervals.

RESULTS

The general meteorological conditions observed during the study period of study were as follows. For all months, maximum absolute temperatures were above 30°C, except April. Except for January, minimum temperatures were lower than 10 °C and the averaged relative humidity was between 63 % and 69 %. There were only two months (December and March) with precipitation and the amounts were less than 6 mm for each. Averaged wind speed was between 1.4 and 1.8 m s^{-1} for all periods.

Energy Balance Closure

Energy balance closure (EBC) is a standard procedure to analyse the performance of micrometeorological techniques to estimate energy fluxes over surfaces. Theoretically the available energy (Rn-G) must equal the energy associated with turbulent fluxes (LE+H) (25, 42).

Results of EBC for EC, SRA_Cast, and SRA_Shap are presented in

Table **1**. The EBC are classified according to different atmospheric stability conditions, where "all" contains the entire dataset. "Stable" contains values for periods where stability (ξ) was between 0 and 1.0. "Unstable" contains values of ξ between -2.0 and 0. EBC performance is slightly better for EC than SRA_Cast and SRA_Shap. The R^2 values for all the data were higher for EC than SRA_Cast and SRA_Shap (0.95, 0.90, and 0.71, respectively) in both unstable and stable conditions. However, EBC was better in unstable conditions.

The regression analysis slopes for EBC for all atmospheric conditions were 0.70, 0.64, and 0.69 for EC, SRA_Cast, and SRA_Shap respectively. Slopes were higher under unstable atmospheric conditions (0.59, 0.52, and 0.55) than stable ones (0.25, 0.27, and 0.39) for EC, SRA_Cast, and SRA_Shap, respectively.

The RMSE for all stability conditions was lower for EC (99 W m^{-2}) than SRA_Cast (121.38 W m^{-2}) and SRA_Shap (154.72 W m^{-2}). The RMSE for unstable conditions was generally higher than stable conditions. EC had lower RMSE values (137.01 and 28.61 W m^{-2}) than SRA_Cast (168.97 and 41.97 W m^{-2}) and SRA_Shap (202.93 and 47.92 W m^{-2}) for unstable and stable conditions, respectively. Flux values in unstable atmospheric conditions were much larger than in stable conditions.

Note that for all atmospheric conditions, the number of available datapoints is larger for SRA_Cast (6785) than for EC (6731) (

Table **1**), because EC has more restrictions during calculation, requiring data removal (e.g., spike removal, coordinate rotation, frequency response, time delay adjustment).

Table 1. Analysis of energy balance closure using linear regresion for eddy covariance (EC) and surface renewal analysis (SRA) by Castellví (SRA_Cast) and Shapland (SRA_Shap). *Rn-G* is the independent variable and *LE+H* is dependent variable.

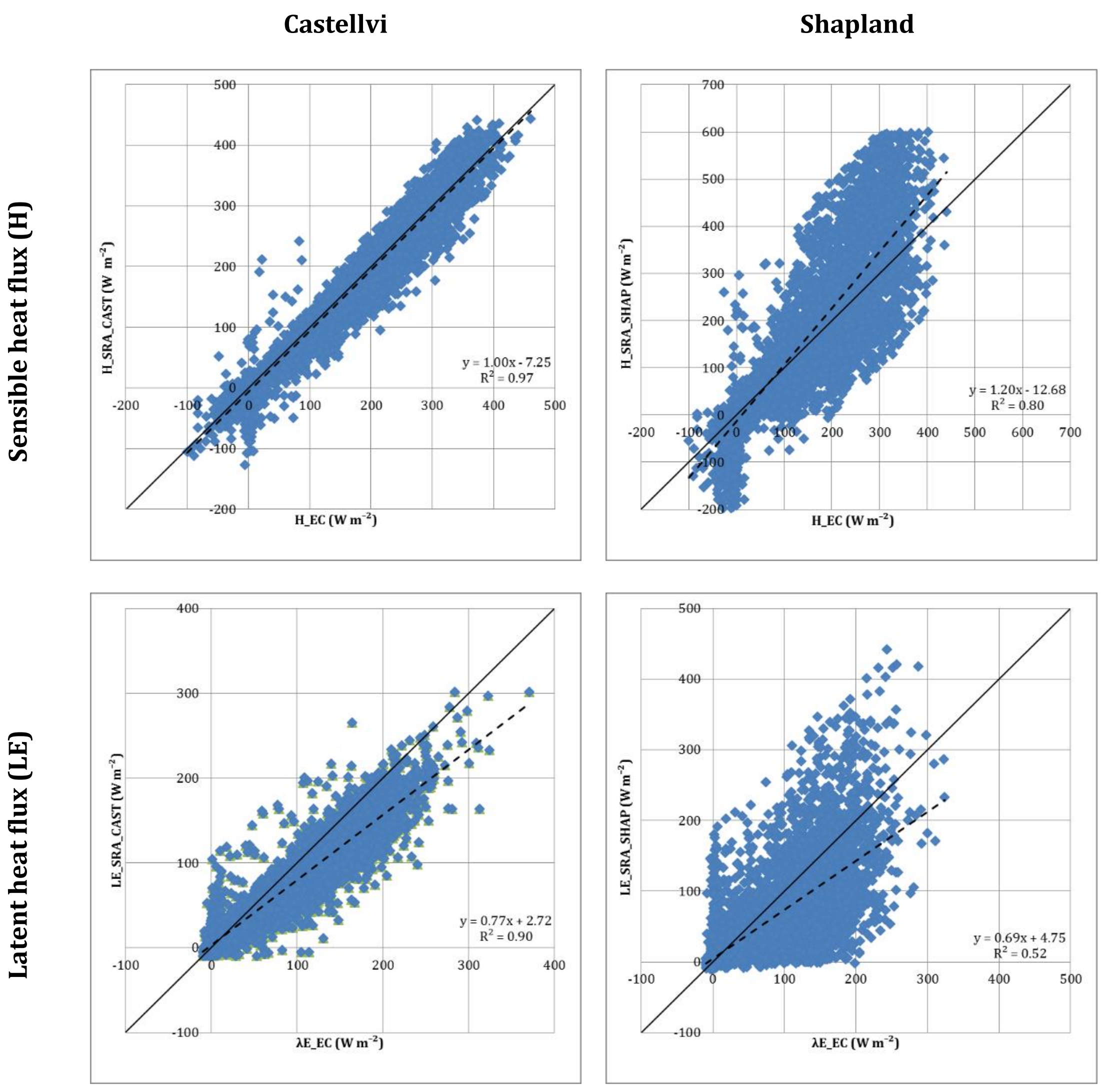
Tabla 1. Cierre de balance de energía a traves de analisis de regresión lineal según covarianza de torbellinos (EC) y analisis de renovación de superficies según Castellví (SRA_Cast) y Shapland (SRA_Shap). *RN-G* es la variable independiente mientras *LE+H* es variable dependiente.

Energy Balance	Stability	Slope	Offset (W m^{-2})	R^2	RMSE (W m^{-2})	N
EC	All	0.7	28.3	0.95	99.16	6731
	Unstable	0.59	84.52	0.86	137.01	3248
	Stable	0.25	4.18	0.23	28.61	2575
SRA_Cast	All	0.64	23.21	0.9	121.38	6785
	Unstable	0.52	90.15	0.75	168.97	3146
	Stable	0.27	2.88	0.05	41.07	3103
SRA_Shap	All	0.69	24.32	0.71	154.72	6229
	Unstable	0.55	102.33	0.37	202.93	2806
	Stable	0.39	1.25	0.02	47.92	2640

N number of available datapoints / **N** cantidad de datos disponibles
RMSE, root mean square error / **RMSE** Error cuadrático medio

Sensible heat, latent heat and carbon dioxide fluxes

Figure 1 shows the sensible heat, latent heat, and carbon dioxide fluxes estimated using EC against SRA_Cast and SRA_Shap. Dotted lines represent the linear regression analysis and solid lines the 1:1 relationship.



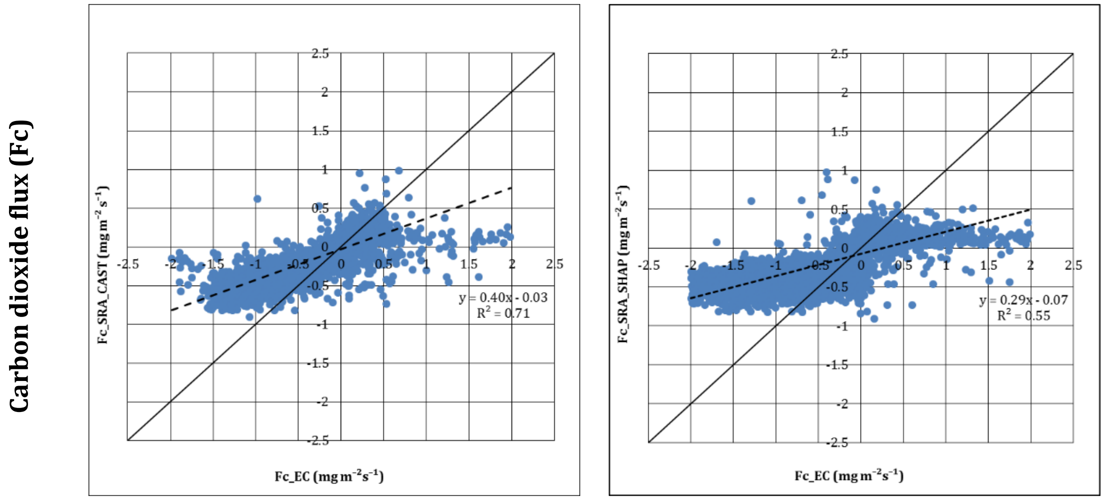


Figure 1. Comparison between sensible heat (*H*), latent heat (λE) and dioxide carbon fluxes (*Fc*) estimation from surface renewal analysis (SRA) using Castellvi method (Cast) and Shapland method (Shap) against eddy covariance (EC). Data was pooled to represent all stability conditions.

Figura 1. Comparación de flujos de calor sensible (*H*), calor latente (λE) y dióxido de carbono (*Fc*) estimados a traves del analisis de renovación de superficies (SRA) según Castellvi (Cast) y Shapland (Shap) respecto a la covarianza de torbellinos (EC). Los datos representados corresponden a toda la temporada y todas las condiciones atmosféricas.

Table 2 presents the results summary of the flux comparisons estimated by EC and SRA. In general, SRA_Cast performs better than SRA_Shap, considering all goodness-of-fit statistics. For *H,* the agreement of H_SRA_Cast against H_EC was very good with a slope of 1.00 and R^2 0.97, while for SRA_Shap we found a slope of 1.20 and an R^2 of 0.80, indicating that *H* was overestimated by SRA_Shap; the RMSE values were 24.99 W m^{-2} and 76.33 W m^{-2}, respectively. Goodness-of-fit was better under unstable conditions, mirroring similar results in peach orchards (38).

The R^2, slope, and RMSE for SRA_Cast (0.90, 0.77, and 28.08 W m^{-2}) estimates of λE were better than those of SRA_Shap (0.69, 0.52, and 53.77 W m^{-2}). The λE RSME values for water depth are 0.04 mm h^{-1} for SRA_Cast and 0.08 mm h^{-1} for SRA_Shap. The outcomes for H_SRA were better than for λE_SRA, considering all statistical values, and λE_SRA performed better than λE_EC in unstable conditions compared to stable conditions.

Fc flux performance under all atmospheric conditions was better for SRA_Cast with R^2, slope, and RMSE of 0.71, 0.40, and 0.40 mg m^{-2} s^{-1}, compared to SRA_Shap with 0.55, 0.29, and 0.53 mg m^{-2} s^{-1}. As in the case of *H* and *λE*, FC_SRA performed better under unstable conditions.

Table 2. Comparison between sensible heat (*H*), latent heat (*λE*), and carbon dioxide (*Fc*) fluxes from surface renewal analysis (SRA)(y variable) by Castellví (Cast), Shapland (Shap), and eddy covariance (EC)(x variable) trough linear regression analysis.

Tabla 2. Comparación entre flujos de calor sensible (*H*), calor latente (*λE*) y flujo de dioxido de carbono(*Fc*) estimados a traves de analisis de renovación de superficies (SRA)(variable y) según Castellvi (Cast) y Shapland (Shap) y covarianza de torbellinos (variable x) para analisis de regresión lineal.

Flux	**Stability**	**Slope**	**Offset ($W\ m^{-2}$)**	**R^2**	**RMSE ($W\ m^{-2}$)**	**N**
H_Cast	All	1	-7.25	0.97	24.99	6890
	Unstable	1.02	-11.83	0.89	32.21	2875
	Stable	0.69	-9.12	0.28	15.77	3161
λE_Cast	All	0.77	2.72	0.90	28.08	5954
	Unstable	0.79	-0.04	0.76	37.81	2795
	Stable	0.76	2.80	0.20	9.61	2069
Fc_Cast	All	0.40	-0.03	0.71	0.40	5501
	Unstable	0.29	-0.13	0.46	0.47	3439
	Stable	0.08	0.10	0.03	0.22	1821
H_Shap	All	1.20	-12.68	0.80	76.33	6834
	Unstable	1.20	-16.60	0.51	108.12	2875
	Stable	0.19	-9.42	0.14	33.04	3355
λE_Shap	All	0.69	4.75	0.52	53.77	6014
	Unstable	0.82	-15.16	0.31	74	2685
	Stable	0.92	11.19	0.05	43.47	2443
Fc_Cast	All	0.29	-0.07	0.55	0.53	5380
	Unstable	0.16	-0.21	0.25	0.47	3171
	Stable	0.03	0.11	0.01	0.41	1558

RMSE, root mean square error (W m^{-2} for H and λE, mg m^{-2} s^{-1} for Fc) and N, number of half hourly samples.

RMSE, error cuadrático medio (W m^{-2} para H y λE, mg m^{-2} s^{-1} para Fc) y N, número de muestras cada media hora.

Soil heat flux

Figure 2 shows *G* averaged by hour for the entire season. Plates were buried at 8 cm, directly beneath the vineyards plants. The averaged *G* for the entire period was between -50 W m^{-2} (8 am) and 150 W m-

^{2} (12 pm), with a difference of 200 W m^{-2}. The coloured lines represent different months; note that higher *G* values are in December 2018 and lower values are in March and April 2018.

Also note that there are two peaks: one at 12:00 and another at 15:00 hours. This is explained by vineyard orientation (north-south) and soil surface radiation during the day. Since the plates were located directly beneath the plants, they were shaded when the sun was at zenith and started to receive sunlight later in the afternoon, leading to the second peak. However, the G flux between these peaks does not represent what is really happening in the whole system.

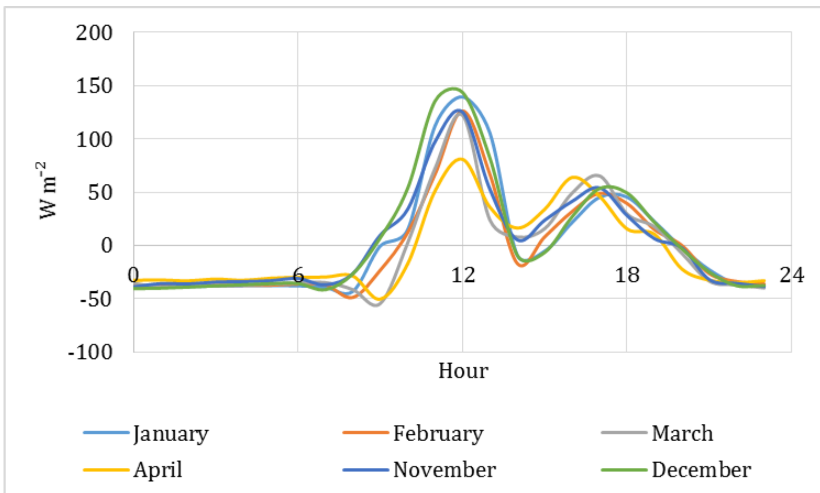


Figure 2. Averaged soil heat flux (in W m $^{-2}$) by hour for different months in the period under study.

Figura 2. Flujo promedio de calor en el suelo (en W m $^{-2}$) por hora, para distintos meses del período bajo estudio.

DISCUSSION

Based on R^2, RMSE, and slopes, H_SRA_Cast performs better against H_EC for all stability conditions than H_SRA_Shap, and unstable conditions show better performance than stable conditions. Similar results are found in Suvočarev et al. (2014) in peaches, Castellvi et. al (2006) in rice plantations, and Castellvi et al. (2008) in grasslands. For λE, SRA_Cast also performed better than SRA_Shap, with RMSE lower than 28.08 Wm^{-2} (equal to 0.04 mm h^{-1}) and 53.77 W m^{-2} (equal to 0.08 mm h $^{-1}$), respectively for all atmospheric conditions. Again, unstable conditions had better results than stable conditions.

SRA_Cast performs better than SRA_Shap for H and λE, and H_SRA has a better fit than λE_SRA for both techniques, which is similar to findings by Suvočarev et al. (2014). Flux differences could be explained by some dissimilarity grade of transference between scalars. This situation has been reported to occasionally occur when advection conditions are present (19).

Considering all the statistics, the energy balance closure was slightly better for EC (R^2: 0.95, slope: 0.70, RMSE: 99.16 W m^{-2}) than SRA_Cast (R^2: 0.90, slope: 0.64, RMSE: 121.38 W m^{-2}) and much better than SRA_Shap (R^2: 0.71, slope: 0.69, RMSE: 154.72 W m^{-2}) for all atmospheric conditions. Shapland et al. (2012c) and Poblete-Echeverría and Ortega-Farias (2014) had better EBC in vineyards under similar conditions, with R^2 of 0.90 and 0.92 and slopes 0.93 and 0.97, respectively. Conversely, Spano et al. (2004) showed R^2 of 0.82 and slope of 0.84, while Wilson et al. (2002) showed slopes ranging between 0.59 and 0.99 (average of 0.79) and R^2 between 0.64 and 0.96 (average of 0.86) for fifty micrometeorological study sites.

This behaviour of EBC is partially explained by footprint variability, because the sampled area does not always match the area corresponding to the footprint (an area that depends on wind speed and direction) in stable atmospheric conditions. Also during prevalent night-time wind directions came from the east (rear of the IRGASON). Another explanation for the lack of closure could be the presence of advection conditions, the soil heat fluxes, and the height measurements sensors.

Advection is inconvenient in EC and SRA measurements, but is considered equal for all the samples estimated under the same atmospheric conditions and fetch (18, 39, 42). Vertical advection could be eliminated when the coordinate system are rotated, so that vertical wind velocity is zero (21). However, heterogenic surfaces can promote circulations and vertical movements than compromise this assertion (41). In this case, poor night-time energy balance closure is expected, especially when turbulent conditions are missing and friction wind speeds are lower (3).

Wilson et al. (2002) detailed how G is an important factor in EBC, and G performance has been investigated in vertically trellised vineyards (1, 14) and shown to represent up to 30% of net radiation. Agam et al. (2019) verified spatial and temporal variability in eleven locations and determined that net radiation is the primary source causing variability in G values in an east-west oriented vineyard. As shown in Figure 2, average G values showed two peaks, so it would be interesting to evaluate how to place G plates in a north-south oriented vineyard and how this impacts EBC.

Finally, the IRGASON was installed at 4.58 m (structure was fixed to ground) over the soil and 2.28 m above the vineyard canopy. In other studies (25, 29, 34) sensors were installed at most 1 m above the canopy to better capture ramp formation. Also, Poblete-Echeverría et al. (2014) evaluated how height measurements affect SRA performance and concluded that 0.5 m above the canopy provided better estimations. Another study (32) concluded that higher measurements are inconvenient for ramp formation, because wind shear has less impact on coherent structure formation.

Estimating H, λE, and EBC using SRA_Shap and SRA_Cast techniques performed poorly in stable atmospheric conditions, when fetch requirements are more demanding and footprints are larger than unstable conditions. These mirror similar conclusions from other studies (11, 38). Fc is more difficult to estimate and evaluate than H and λE. Terms related with convection, storages and atmospheric drainage are needed to evaluate properly Fc flux performance. However, if the EBC is unacceptable or very poor, because scalar conservation principles are not achieved, then Fc measurements could also be incorrect (4).

To our knowledge, the only studies estimating Fc fluxes using SRA are Spano et al. (2002, 2008) and Snyder et al. (1996) using the classical SRA approach, Castellví et al. (2008), using the SRA_Cast approach, and Suvočarev et al. (2019) using the SRA_Cast approach but without a sonic anemometer. In rangelands, Castellví et al (2008) found R^2 values of 0.93 and 0.97 and slopes of 1.09 and 1.06 for unstable conditions and R^2 values of 0.70 and 0.62 and slopes of 0.81 and 0.76 in stable conditions. In the present study, Fc performance was better for SRA_Cast (R^2: 0.71, slope: 0.40) than SRA_Shap (R^2 0.55, slope: 0.29) for all atmospheric conditions. The comparatively lower R^2 values for Fc_SRA_Cast and Fc_SRA_Shap in the present study could have been due to thermal stratification during the night, which would not would not have been detected by sensors, given their height. Insufficient turbulent situations and CO_2 losses by convection could be reasons for Fc underestimation (20, 36).

CONCLUSIONS

This research shows the performance of SRA following Castellvi (2004) and Shapland et al. (2012a, b) to independently estimate sensible heat, latent heat, and carbon dioxide fluxes and analyse the energy balance closure in a vertically trellised vineyard for nearly an entire season (2017-2018), avoiding the use of EC.

SRA_Cast outperforms SRA Shap in estimating H and λE, but more research should be done for SRA_Shap and Fc fluxes to understand the performance of the method and its potential applicability. Also, we recommend measuring fluxes near the canopy to better estimate ramp formation and, in the case for G in vertically trellised vineyards, more points to measure soil heat fluxes are required.

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Chapter III

Independent Estimation of Sensible and Latent Fluxes in a Vineyard Using Improved Surface Renewal Analysis

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This chapter will be sent to *Theoretical and applied Climatology*

Abstract

Turbulent fluxes are key components of the surface energy balance. Micrometeorological techniques, such as eddy covariance (EC), are usually preferred to estimate sensible (*H*) and latent (*LE*) heat fluxes, because they provide direct estimates and do not interfere with the normal crop canopy development. However, EC has technical difficulties, strict size and surface homogeneity requirements, and is relatively expensive. Surface renewal analysis (SRA) is a promising EC alternative, because it is more economic, has less stringent fetch requirements, and can be deployed in heterogeneous canopies or marked sloped surfaces. Castellví (2004) (SRA_Cast) presented a methodology to estimate *H* using SRA, avoiding the high-frequency wind-speed records necessary for determining stability and friction velocity, which are used to calibrate the α parameter. Instead, an iterative procedure using wind speed recorded using a simple cup anemometer, can be used.

We estimated *H*, *LE*, and *LE* as residual from the energy-balance equation (LEres_SRA) using SRA_Cast and compared results with EC measurements in a vertically trellised vineyard (heterogeneous canopy). Values of *H* and *LE* through SRA_Cast present a high agreement with EC, with slopes (b) of 1.11 and 0.88 and coefficients of determination (R^2) of 0.97 and 0.89, respectively. LE_SRA_res showed values of 1.60 and 0.80 for b and R^2, respectively. Energy balance closure was slightly better for SRA than for EC (b: 0.73 and 0.71, R^2: 0.94 and 0.95) proving to be a decent and simpler alternative for turbulent flux estimation. Also, flux estimated using the SRA method showed better results under unstable atmospheric conditions.

Keywords: Surface Renewal. Eddy covariance. Evapotranspiration. Sensible heat flux. Latent Heat Flux. Vineyard

Introduction

The correct determination of crop water requirements for irrigation operation and scheduling is a critical step for sustainable water resource use, particularly under restricted conditions. Actual crop evapotranspiration estimation through latent heat measurements, either directly or as residuals of an energy balance equation, represents a valid alternative to provide accurate and robust data for irrigation scheduling. When selecting methodologies for estimating evapotranspiration, micrometeorological techniques are preferred, because they offer direct estimate of the observed fluxes and are non-intrusive (Hatfield et al. 2005). Eddy covariance is one broadly used technique for estimating mass and energy fluxes in the atmospheric boundary layer (Wilson et al. 2002). However, applying the EC method in heterogeneous, tall canopies, or sloping surfaces is difficult, as it has specific instrument installation requirements, it is an expensive technique (sensor costs), and usually presents a lack of energy balance closure which results in serious implementation drawbacks (Twine et al. 2000; Wilson et al. 2002).

Surface renewal analysis, developed by Paw U et al. (1995) and improved by Castellví (2004), is an alternative and attractive method to estimate latent heat (*LE*) and sensible heat (*H*) fluxes, because it require no specific instrument orientation and height or instrumentation separation (Paw U et al. 2015), has comparatively less-stringent fetch requirements, works properly over heterogeneous surfaces (Castellví 2012; Suvočarev et al. 2014a; Haymann et al. 2019), and functions over marked slopes (Shapland et al. 2012c).

Paw U et al. (1995) calculated *H*, combining the concept of coherent structures (Gao et al. 1989) and the procedure developed by Van Atta (1977). Coherent structures are associated with an air mass that interacts with the surface, exchanging mass and energy (Paw U et al. 1991). When plotted on a graph of a particular scalar value against time, coherent structures describe ramp-like behaviours. The time of the ramp (τ) is represented by the duration of the contact between the air mass (air parcel) passing and the surface acting as source (sink). The amplitude (A) corresponds to the scalar (water vapour, temperature, or carbon dioxide) depletion or enrichment in the air mass. Initially, SRA estimated H using high-frequency temperature data in maize, a walnut orchard, and a forest canopy (Paw U et al. 1995). Sensible heat flux was calculated trough the following equation (1). In this method it is necessary to calculate a calibration parameter (α), because of the uneven heating of the air parcel (Spano et al. 1997b):

$$H = (\alpha z)\, \rho\, C_p \frac{A}{\tau} \tag{1}$$

where z in m is the sensor height (measurement height), ρ is air density in kg m^{-3}, C_p is the specific heat of air in J kg^{-1}K^{-1}, and τ and A are defined above.

The α factor is a calibration value that varies with measurement height, canopy type, crop architecture, data acquisition frequency, and atmospheric stability conditions, among others (Poblete-Echeverría et al. 2014; Paw U et al. 2015). This parameter can be calculated using another independent measurement, such as EC (Snyder et al. 1996; Shapland et al. 2012c) or empirical techniques that combine SRA with Monin-Obukhov similarity concepts (Castellví 2004). However, this latter approach requires high frequency temperature data and mean horizontal wind speed measurements to avoid using EC for α calibration.

Two methodologies have been developed to facilitate the use of SRA becoming independent of EC. Castellví (2004) (SRA_Cast) used mean wind velocity at a reference height and high-frequency temperature data from a simple cup anemometer and a thermocouple (for instance FW3, Campbell Scientific Inc.) respectively, avoiding the use of a sonic anemometer. Shapland et al. (2012b, a) (SRA_Shap) proposed a two-ramp model that discriminates larger turbulent coherent structures from smaller isotropic turbulence. SRA_Shap performance is better under unstable atmospheric conditions, while SRA_Cast works properly in stable and unstable atmospheric conditions (Shapland et al. 2012b; Suvočarev et al. 2014b).

Subsequently, Suvočarev et al. (2014a) applied SRA_Cast (using high frequency temperature and wind speed values) and SRA_Shap techniques to independently estimate *H* and *LE* fluxes, and the energy balance closure on heterogeneous cropping systems such as peach orchards. Castellví and Snyder (2009c) and Suvočarev et al. (2019) applied SRA_Cast using an iterative processes to obtain friction velocity and the stability parameters required for Obukhov length estimation. Castellví et al. (2008) estimated *LE*, *H*, and carbon dioxide fluxes over rangeland grass surfaces and Suvočarev et al. (2019) estimated the same fluxes on rice and cotton fields (homogenous surfaces). The results showed a high correlation with EC fluxes across the growing season. Elsewhere Spano et al. (2000) estimate *H* using the classical approach and *LE* as residual of the energy balance equation in a vertically trellised vineyard (Net Radiation (*Rn*) - Soil Heat Flux (*G*) – *H* = LEres_SRA).

Despite these various studies, SRA needs improvements to increase the feasibility of this technique, namely making micrometeorological techniques less expensive, simplifying the calculation of micrometeorological measurements, and decreasing the magnitude of error in flux estimates.

In this study, we use a vertically trellised vineyard to estimate *H* and *LE* by applying SRA_Cast for turbulent fluxes and estimate *LE* as a residual of the energy balance equation. Vertically trellised vineyards have a particular architecture, where canopy heterogeneity plays an important role in the energy balance partition (Heilman et al. 1996; Agam et al. 2019).

Materials and methods

Experimental site and climatic characteristics

A micrometeorological station was installed in a 13.14 ha trellised vineyard of Cabernet Sauvignon (CS) in Fundo Lo Arcaya, in Pirque, Chile (latitude 33° 42’ S, 70° 34’, elevation 686 m a.s.l.). The data was recorded between November 1, 2017 and April 13, 2018. We selected data obtained in January 2018 as it had a better footprint, thus avoiding errors associated with fluxes that do not properly represent the surface under study (Fig 1).

The red polygon in Fig. 1 represents the footprint in the CS plantation under unstable atmospheric conditions for January 2018, (DOYs 1 to 31). The fetch requirement for the full development of a boundary layer was 237 m and was calculated following Allen et al. (1996). The vineyards are north-south oriented in a vertically trellised system and approximately 1.9 m tall. The space between rows is 2.45 m and between plants is 1.20 m. The vineyard was irrigated using a drip system on three dates: December 29, 2017 and January 13 and 22, 2018. The maximum, minimum, and mean monthly temperatures were 34.8, 10.5, and 21.9 °C respectively, mean relative humidity was 66.7%, and mean wind speed was 1.5 m s^{-1}.

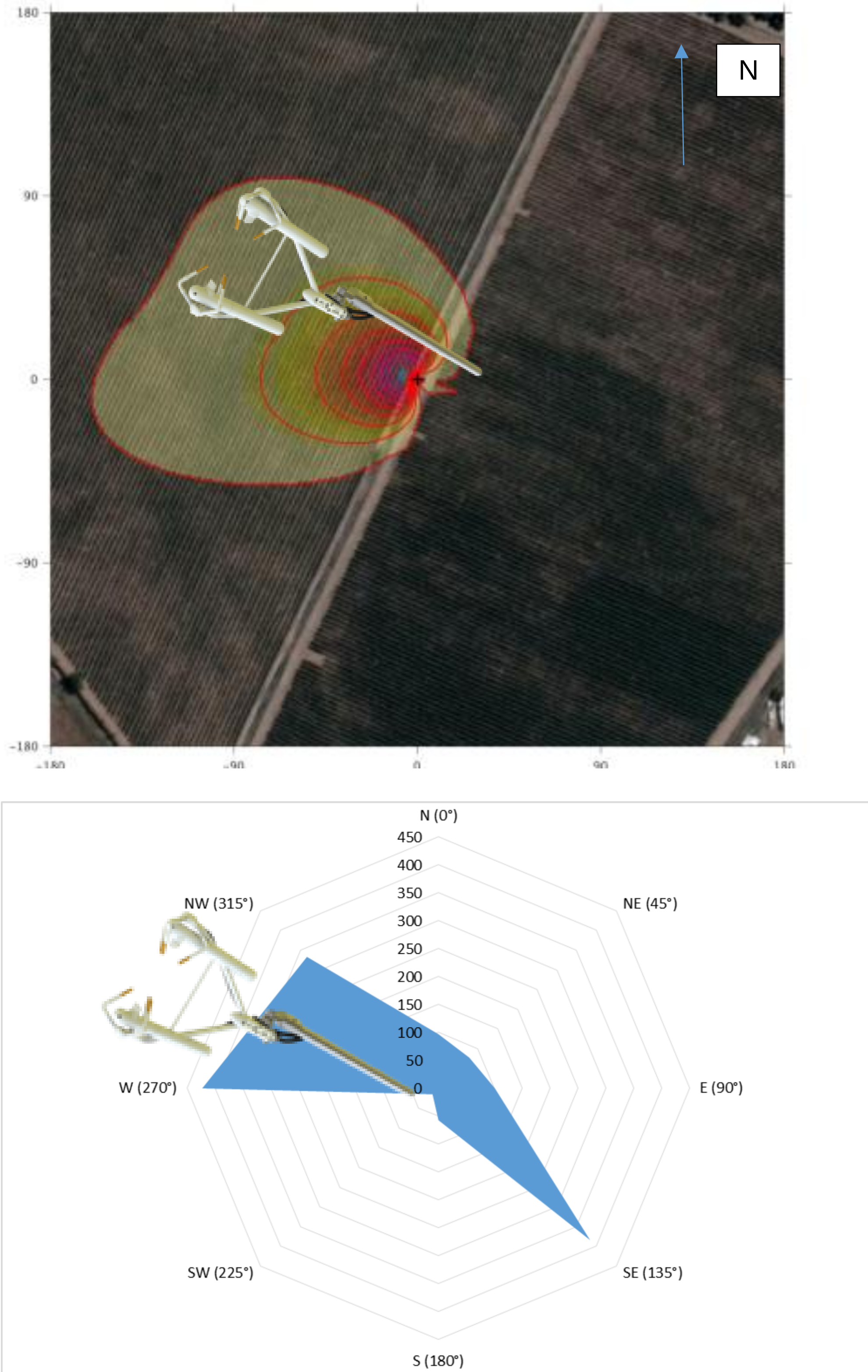

Fig.1. Top: Footprint generated using data gathered in unstable atmospheric conditions using Kljun et al. (2015). IRGASON real orientation (azimuth 270°). Bottom: Wind rose for January 2018 using all atmospheric conditions, numbers indicate number of events from that direction.

Instrumentation

The micrometeorological station was fixed to the soil and equipped with sensors to measure all the energy balance components: *H*, *LE*, *Rn*, and *G*. An integrated Open-Path CO_2/H_2O gas analyser with a 3-D sonic anemometer (Campbell Scientific, IRGASON) was used to measure *H* and *LE*. An IRGASON was mounted at 4.58 from the ground surface (270° of azimuth). A net radiometer (Kipp & Zonen, NR-Lite) was placed 2.40 m above the soil, pointing almost north (22° from azimuth). Soil heat flux (*G*) was measured using two heat flux plates (Huseflux, HFP01), buried at 0.08 m directly beneath the plants; the corresponding thermocouples (Campbell Scientific, TCAV) were installed under each plate at depths of 0.02 and 0.06 m., to measure soil temperature.

SRA calculation

Sensible heat flux (H ; W m^{-2}) in SRA is calculated with equation (1), which uses the structure function (S^n) methodology for estimating A and τ, following Van Atta (1977):

$$S^n(r) = \frac{1}{m-j} \sum_{i=1+j}^{m} (T_i - T_{i-j})^n \tag{2}$$

where m is the number of data points in a 30-min interval measured at frequency (f) in Hz, n is the power function, j is the sample lag between data points corresponding to a time lag ($r=j/f$) and T_i is the ith temperature sample in the interval in the case of H estimation (water vapour concentration for LE). An estimation of an averaged A value is obtained using equation (2):

$$A^3 + pA + q = 0 \tag{3}$$

where

$$p = 10S^2(r) - \frac{S^5(r)}{S^3(r)} \tag{4}$$

$$q = 10S^3(r) \tag{5}$$

Finally, the ramp duration τ in seconds is solved using equation (5):

$$\tau = -\frac{A^3 r}{S^3(r)} \tag{6}$$

The estimation of α was made following Castellvi (2004). The procedure combines SRA with a diffusion equation and concepts of similarity theory that are valid for the atmospheric inertial sublayer using the equation:

$$\alpha = \left[\frac{k}{\pi}\,\frac{(z-d)}{z^2}\,\tau u_* \emptyset^{-1}(\varsigma)\right]^{1/2} \tag{7}$$

where k~0.4 is the Von Karman constant, d (m) is zero plane-displacement (estimated as d=0.67 h, where h is canopy height in m), u_* is friction velocity (m s^{-1}), $\emptyset(\varsigma)$ is the stability function for scalar transport, where the stability parameter ς is defined as z-d/Lo and Lo(m) is the Obukhov length defined by Businger (1988):

$$L_o = -\frac{u_*^3}{kg\,\overline{w'T'_s}}\,T_s \tag{8}$$

where g is gravitational acceleration and T_s is sonic temperature, which can be substituted with temperature estimated with a thermocouple. The mean term ($\overline{w'T'_s}$) represents the covariance between w (vertical wind speed in m s^{-1}) and T_s in °K and can be replaced by $\frac{H}{\rho\, C_p}$ (Paw U et al. 1995).

The equation for estimating $\emptyset(\varsigma)$ was described by Foken (2006) and Högström (1988):

$$\emptyset(\varsigma) = \begin{cases} (0.95 + 7.8\,\varsigma) & 0 \le \varsigma \le 1 \\ 0.95\,(1 - 11.6\,\varsigma)^{-1/2} & -2 \le \varsigma \le 0 \end{cases} \tag{9}$$

Appendix B of Castellvi et al. (2008) describes the procedure for determining SRA fluxes, replacing the sonic anemometer with a simple cup anemometer. The current study uses wind speed values from the installed IRGASON. Through the wind profile law, the friction velocity u_* could be calculated using the subsequent equation (Brutsaert 1982):

$$u_* = \frac{ku_r}{ln((z_r - d)/z_o) - \Psi_m(\varsigma)} \tag{10}$$

where u_r is wind speed in m s^{-1} at reference height z_r in m, z_0 is aerodynamic surface roughness length in m and is calculated as $z_0 = 0.12h$, and $\Psi_m(\varsigma)$ is the diabatic profile function for momentum (Paulson 1970):

$$\Psi_m(\varsigma) = \begin{cases} 2ln\big(0.5(1+x)\big) + ln\big(0.5(1+x^2)\big) - 2arctan(x) + o.5\pi & \varsigma \leq 0 \\ -4.7\varsigma & \varsigma > 0 \end{cases} \tag{11}$$

where $x = (1 - 16\varsigma)^{1/4}$.

The iterative procedure for its calculation uses the following steps:

1. Calculate the amplitude ramp sign of temperature using equations (2), (2), (4), and (5).
2. Estimate $\Psi_m(\varsigma)$ from equation (11) and $\emptyset(\varsigma)$ from equation (9) (positive amplitude implies negative stability and vice versa).
3. Use equations (9) and (10) to obtain a first approximation value of u_* (atmospheric neutral conditions are initially assumed, thus use $\varsigma = 0$ to start).
4. Use u_* in equation (12) to get the first α value to be used in find H from equation (1).

5. Use equation (13) to obtain the first L_o (replace the term $\overline{w'T'_s}$ with $\frac{H}{\rho\, C_p}$).

6. The first ς is determined.

7. Repeat procedure until convergence is achieved.

The process was concluded when differences between the ς values were less than 0.0001, the same criteria used in Suvočarev et al. (2019).

Then, *LE* is calculated with the following equation, where *q* represents water vapour:

$$LE_{SRA} = (\alpha z)\, \lambda \frac{A_q}{\tau_q} \tag{12}$$

The values used for u_* and ς are the same as those obtained for calculating *H*. Meanwhile, ramp dimensions and α are calculated using equations (2) and (12), respectively.

Data processing

The raw data for turbulent fluxes (water vapour concentration for *LE* and sonic corrected-temperature for *H*) were estimated at 10 Hz by a datalogger CR3000 (Campbell Scientific Inc.) and stored in a 2 GB memory card. Then, the data was processed and corrected, and 30-min averages were stored in the laboratory. *G* and *Rn* were measured at lower frequencies and stored every 30-min. The second-, third-, and fifth-order moments for equation (2) were calculated and recorded for r = 0.50 s. Finally, eddy covariance results were used to evaluate SRA performance.

Results and discussion

Sensible heat and latent heat fluxes

Table 1 summarizes the performance of *H* (H_SRA) and *LE* (LE_SRA) fluxes and *LE* residuals (LEres_SRA) estimated using SRA, against these same metrics estimated using EC. Performance is evaluated using regression analyses, where the respective SRA estimates are the dependent variables and the corresponding EC estimates are the independent variables. Data was also classified by atmospheric stability, with stable ($0 \leq \varsigma \leq 1$), and unstable ($-2 \leq \varsigma \leq 0$) conditions.

Table 1: Regression analysis of sensible heat (*H*), latent heat (*LE*), and LE as residual (LE_res) calculated by SRA as the dependent variable against eddy covariance fluxes as independent variables for all atmospheric conditions for January 2018 in a vertically trellised vineyard. Statistics include slope (b), intercept (a), coeficient of determination (R^2), root mean square error (RMSE), and number of half-hourly samples (N).

	Stability	b	a ($W\ m^{-2}$)	R^2	RMSE ($W\ m^{-2}$)	N
H_SRA	All	1.11	-2.77	0.97	29.40	1480
	Stable	0.20	-6.60	0.08	9.77	701
	Unstable	0.84	16.36	0.94	39.00	772
LE_SRA	All	0.88	0.85	0.89	27.38	1430
	Stable	0.54	2.82	0.10	17.27	654
	Unstable	0.91	-4.43	0.87	28.28	762
LEres_SRA	All	1.66	-28.62	0.80	89.26	1278
	Stable	0.28	-18.79	0.02	33.69	640
	Unstable	1.78	-44.83	0.67	111.12	756

The H_SRA and LE_Cast estimations performed better than LEres_SRA, with lower RMSE and higher R^2. H_SRA had higher goodness-of-fit statistics compared to H_EC, with R^2 of 0.97, slope of 1.11 and RMSE of 29.4 W m^{-2} for all atmospheric conditions, with H_EC overestimating by 11% with respect to H_SRA (Fig. 2). The correlation was poor for stable conditions (R^2: 0.08, slope: 0.20, RMSE: 9.8 W m^{-2}) and relatively high for unstable conditions (R^2: 0.94, slope: 0.84, RMSE: 39.0 W m^{-2}). Poblete-Echeverría et al. (2014) reported RMSE of 52.2 W m^{-2} at 0.5 m above the vineyard canopy and r = 0.7 s for the whole season using the classical SRA approach in a drip irrigated Merlot. Castellvi (2004) reported RMSE values ranging from 22.5 to 167.0 W m^{-2} for *H* using a combination of SRA with similarity theory in grapevines in Napa Valley (USA).

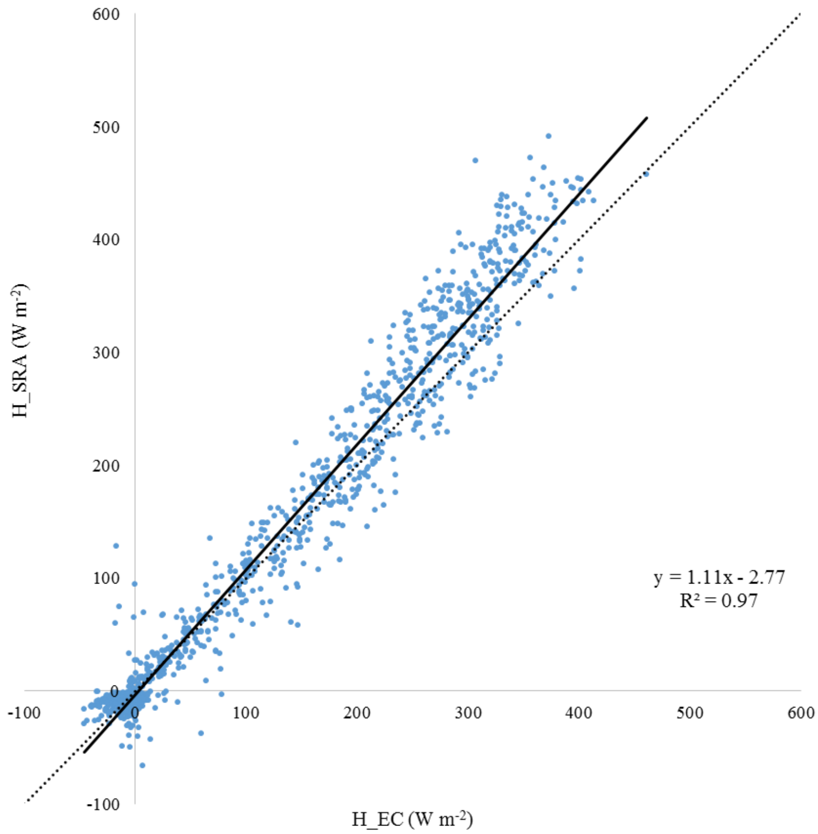

Fig. 2 Comparison between sensible heat flux (*H*) estimated by eddy covariance (H_EC) and surface renewal anlaysis (H_SRA) for all stability conditions. The solid line indictes the linear regression analysis and dotted line the 1:1 relationship.

LE_SRA underestimated with respect to LE_EC (Fig. 3), but it has good performance (R^2: 0.89, slope: 0.88, RMSE: 27.4 W m^{-2}). The agreement was better for unstable atmospheric conditions (R^2: 0.86, slope: 0.91, RMSE: 28.3 W m^{-2}) than stable conditions (R^2: 0.10, slope: 0.54, RMSE: 17.3 W m^{-2}). The RMSE for water depth was 0.04 mm h^{-1} for all data, 0.04 mm h^{-1} for unstable, and 0.03 mm h^{-1} for stable atmospheric conditions. Suvočarev et al. (2019) overestimated LE values and estimated RMSE between 51.1 and 77.4 W m^{-2} in cotton and rice fields.

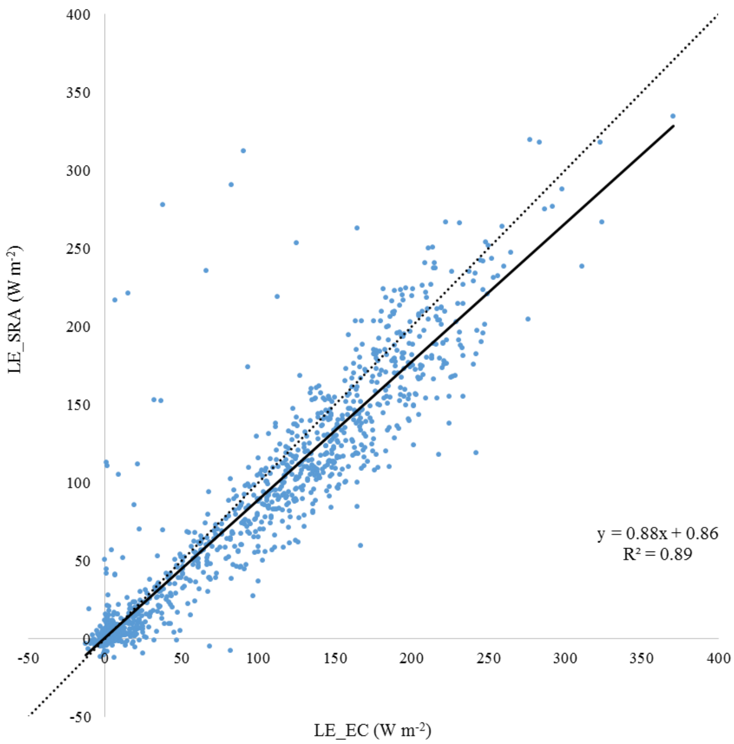

Fig. 3 Comparison between latent heat flux (*LE*) estimated by eddy covariance (LE_EC) and surface renewal anlaysis (LE_SRA), for all stability conditions. The solid lines represents the linear regression analysis and the dotted line the 1:1 relationship.

LEres_SRA overestimated the fluxes with respect to LE_EC (R^2: 0.80, slope: 1.66, RMSE: 89.3 W m^{-2}, Fig. 4). Unstable atmospheric conditions also overestimated fluxes (R^2: 0.67, slope: 1.78, RMSE 33.7 W m^{-2}), while stable conditions greatly underestimated fluxes (R^2: 0.02, slope: 0.28, RMSE: 111.1 W m^{-2}). Since LEres_SRA is calculated as a residual from the energy balance equation, all errors from *H*, *G*, and *Rn* are added to LEres. In estimating latent heat flux as energy balance equation residuals using the classical SRA approach to estimate *H*, Rosa et al. (2013) reported a strong agreement in tomato crops (R^2: 0.99, slope: 0.94), Spano et al. (2000) also reported good correlations in grapevine canopies (R^2: 0.78, slope: 0.94, RMSE =58 W m^{-2}).

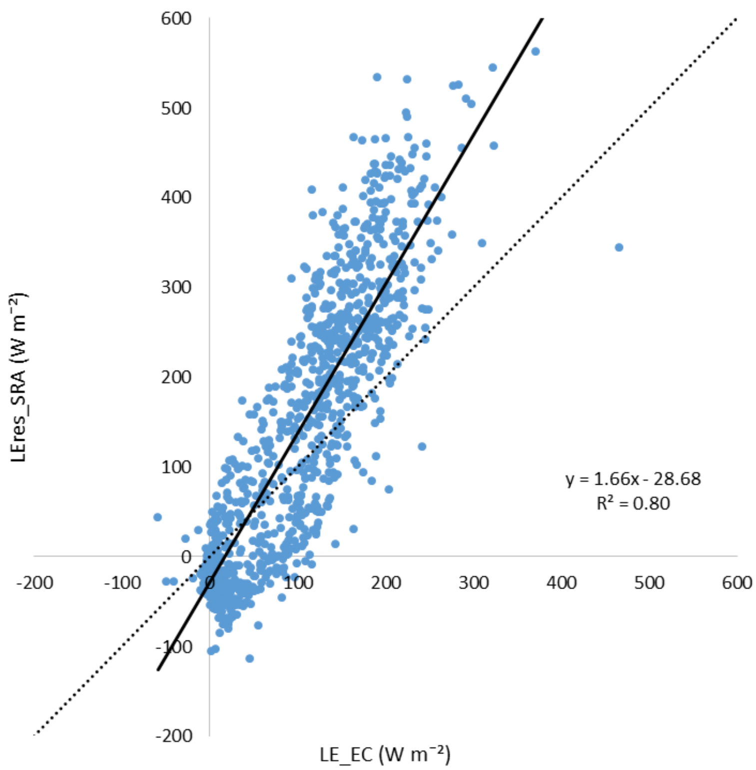

Fig. 4 Comparison between latent heat flux (LE) estimated by eddy covariance (LE_EC) and by surface renewal anlaysis as residual from energy balance equation (LEres_SRA), for all stability conditions. The solid line represents the linear regression analysis and dotted line the 1:1 relationship.

Fig. 5 shows the comparison between LEres_SRA and LEres_EC (*LE* estimation as residuals from the energy balance equation using *H* estimated by EC) with good agreement

(R^2: 0.97, slope: 0.91). The lack of energy balance closure is important when *LE* is calculated as residuals, because the value of all uncertainties are added to *LE*.

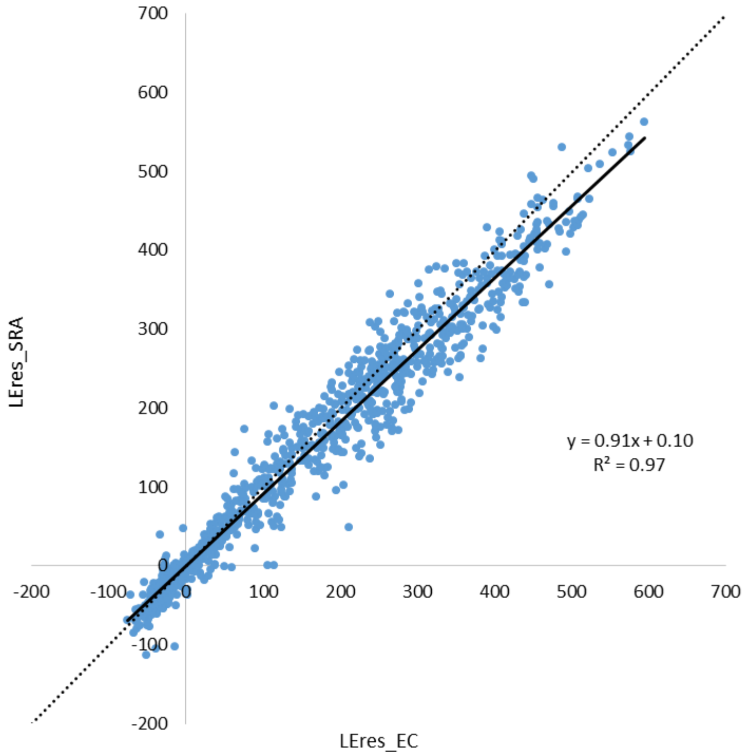

Fig. 5: Comparison between latent heat flux estimated as residual from energy balance equation by eddy covariance (LEres_EC) and surface renewal anlaysis (LEres_SRA), for all stability conditions. The solid line represents the linear regression analysis and dotted line the 1:1 relationship.

Energy balance closure

Energy balance closure (EBC) is a standard procedure to evaluate the performance of turbulent flux estimations using micrometeorological techniques (Twine et al. 2000; Wilson et al. 2002; Burba 2013). If the sum of *H* and *LE* equals the difference between *Rn* and *G*, all energy transfers have been successfully accounted.

The EBC of EC and SRA were evaluated using RMSE and linear regression analysis. In this sense *RN* – *G* was considered as an independent variable and LE_EC + H_EC and LE_SRA + H_SRA were considered as dependent variables (Fig. 6).

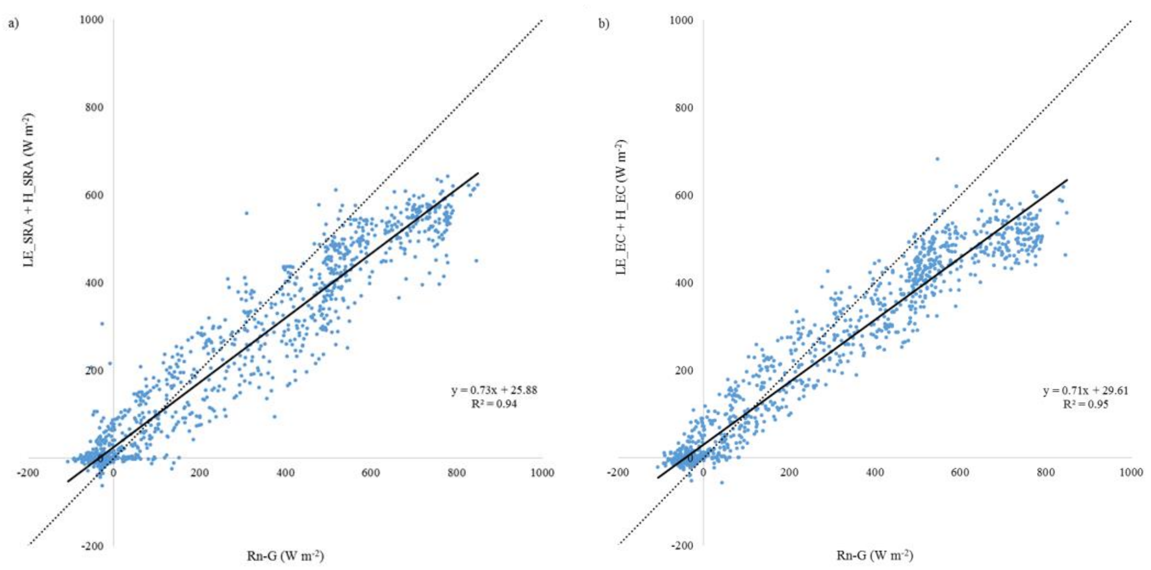

Fig. 6 Energy balance closure for surface renewal analysis (a) and eddy covariance (b) for January 2018 in a vertically trellised vineyard for all stability conditions. The solid lines represent the linear regression analysis and dotted lines the 1:1 relationship.

Table 2 shows that EC and SRA underestimated the (*H* + *LE*) fluxes by 29% and 27%, respectively for all atmospheric conditions, but R^2 values were higher (0.95 and 0.94) and RMSE were similar (102.2 and 96.2 W m^{-2}). Wilson et al. (2002) showed variations between 1% and 47%, with a mean of 21%. Better EBCs over vineyards have been achieved, with Shapland et al. (2012c) presenting a lack-of-closure of 7% (R^2: 0.90) and Ortega-Farias et al. (2007) demonstrating 3% (R^2: 0.92) in drip-irrigated Merlot.

Table 2: Regression analysis for energy balance closure (*H* + *LE* as dependent variable vs *Rn* – *G* as independent variable) using eddy covariance (EC) and surface renewal anlysis (SRA) during January 2018 for different atmospheric conditions. Statistics include slope (b), intercept (a), coeficient of determination (R^2), root mean square error (RMSE), and number of half-hourly samples (N).

	Stability	b	a ($W\ m^{-2}$)	R^2	RMSE ($W\ m^{-2}$)	N
EC	All	0.71	29.61	0.95	102.22	1281
	Stable	0.06	-0.10	0.02	35.42	426
	Unstable	0.68	45.64	0.92	122.43	855
SRA	All	0.73	25.88	0.94	96.21	1423
	Stable	0.19	-28.56	0.02	35.86	520
	Unstable	0.72	35.78	0.90	117.39	904

EBC agreement was better under unstable atmospheric conditions than stable conditions, with similar performance for EC (R^2: 0.92, slope: 0.68, RMSE: 122.43) and SRA (R^2: 0.90, slope: 0.72, RMSE: 117.39). Stable atmospheric conditions showed very poor EBC agreement for both techniques, with R^2 less than 0.1 and slopes lower than 0.20. Suvočarev et al. (2014a) report similar EBC performance, in that unstable atmospheric conditions had a better fit than stable conditions.

Fig. 1 presented the wind rose showing that winds primarily arrived at the IRGASON from the front and back. The wind direction during unstable atmospheric conditions (daytime) came from the research zone, but during stable conditions (night-time) the fluxes mainly came from behind the sensor (time-of-day data not shown). The micrometeorological station was fixed to ground and could not be installed in a better position, because it would interfere with farm activity. Other locations in the vineyard were suboptimal for flux estimation, due to vineyard architecture creating terrain heterogeneity, due to the impacts of covered and uncovered surfaces (Heilman et al. 1994, 1996). In addition, the vertically trellised system creates an unusual pattern of net radiation distribution in the soil heat flux, creating two peaks, one at midmorning and another at mid-afternoon. The wind direction distribution, the vineyard architecture, and the *G* performance can help explain the lack of closure for the EC and SRA methodologies.

Ramp duration

Fig. 7 shows the hourly average τ duration of water vapour (solid line), used to calculate *H*, and temperature (dotted line), used to calculate *LE*, with different ramp durations during day (unstable conditions) and night (stable conditions). Average daytime and night-time τ values for *H* were 25-50 seconds and 50-200 seconds, while *LE* values were 50-75 seconds and 75-225 seconds, respectively.

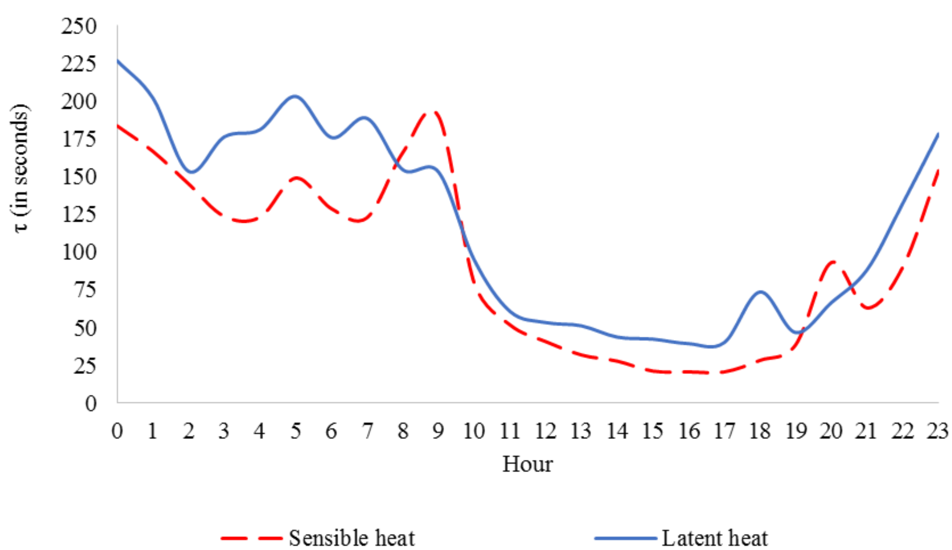

Fig. 7. Averages of the 30 min values for ramp duration (τ) by hour for latent heat (solid line) and sensible heat (dotted line) fluxes for January 2018.

There is solid agreement between both fluxes, however *H* generally has slightly lower values than *LE* for τ estimations, except during sunrise and sunset, when atmospheric stability conditions are changing. The estimation of τ and A of H and LE show the signatures of the coherent structures defined by Gao et al. (1989). The amplitude depends on the scalar value, but ramp duration depends on contact time between air mass and target surface. Fig. 7 shows some disagreement between τ values for H and LE, so the similarity theory for scalar transport applied for stability parameter calculation could be not satisfied in heterogeneous surfaces. Similar conclusions were found by Suvočarev et al. (2014a).

Friction velocity

Fig. 8 shows the friction velocity measured with the sonic anemometer (u_{*c}) from the IRGASON vs the friction velocity estimated by equations (9) and (10) (u_{*e}). Although u_{*e} underestimates u_{*c} (b=0.67), R^2 is very good (0.92) across all the data. Roughly 34% of the data were greater than 0.2 m s^{-1}, while roughly 65% of unstable atmospheric conditions samples (R^2: 0.80, slope: 0.59) were greater than 0.2 m s^{-1}, compared with only 3% of stable condition samples (R^2: 0.34, slope: 0.34). In studies over grass surfaces influenced by regional advection, u_{*e} systematically overestimated u_{*c} (Castellví and Snyder 2009c).

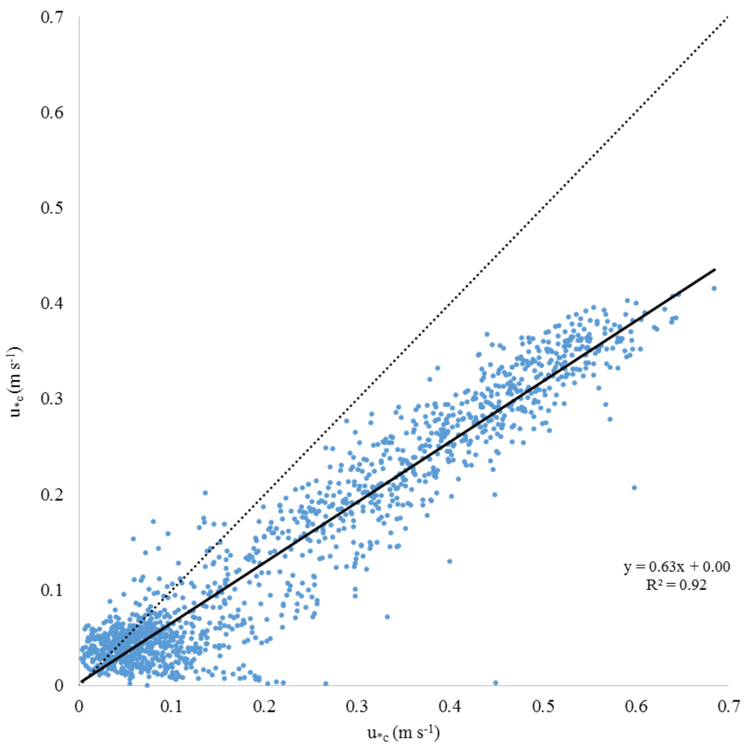

Fig. 8 Friction velocity measured with IRGASON (u_{*c}) vs estimates by equation (10) (u_{*e}). The solid line represents the linear regression analysis and the dotted line the 1:1 relationship.

The IRGASON was installed at 4.58 m above the soil surface, and a lower height was not feasible, because of maintaining field access by machine, and the risk of damage was too great at lower heights. The lower speeds at night and sensor height help explain the lack of closure during stable atmospheric conditions.

Conclusions

The estimation of sensible heat, latent heat, and latent heat as a residual of the energy balance equation, using the surface renewal analysis method proposed by Castellvi (2004) and avoiding EC use, was applied on a vertically trellised vineyard in January 2018.

The *H* and *LE* were estimated in SRA using the scalar value and a novel method that calculated α using low frequency wind velocities values and an iterative process to obtain u_*, L_o and ς. The results demonstrate that H_SRA and LE_SRA present good agreement with EC fluxes, and are consequently recommended for micrometeorological measurement.

Also, SRA presents slightly better EBC than EC (slopes: 0.73 and 0.71 and R^2: 0.94 and 0.95, respectively). The lack of EBC is a recurrent shortcoming in EC estimations; here, more points to calculate soil heat fluxes are needed, since a single system is insufficient in to characterized *G* in vertically trellised vineyards (Heilman et al. 1994; Agam et al. 2019).

LEres_SRA shows a good correlation against LE_EC_res but overestimated against LE_EC by 66% between values. SRA is an economic technique (avoids using a sonic anemometer) and estimates feasible evapotranspiration requirements more easily than EC. However, good EBC achievement is needed, otherwise all errors are placed on LEres_SRA.

Future research should focus on other flux estimations (e.g., carbon dioxide flux) in heterogeneous crops, which present more complexity, especially during stable atmospheric conditions.

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General discussion

This research demonstrates the performance of SRA to independently estimate sensible heat, latent heat, and carbon dioxide fluxes and analyse the energy balance closure in a vertically trellised vineyard of Cabernet Sauvignon during the growing 2017-2018 season, following the differing methods of Castellvi (2004) and Shapland et al. (2012a, b). Heterogeneous surface conditions with bare soil, plants exceeding 2m in height, and vineyard orientations generating large daily changes in solar radiation to soil and plants are all factors make this study a challenge for micrometeorological research.

Sensible heat flux analysis using SRA (H_SRA) has been widely studied, with a large number of publications (Paw U et al. 1995; Snyder et al. 1996; Spano et al. 1997b, 2000; Anandakumar 1999; Castellvi and Martínez-Cob 2005; Rosa et al. 2013).Sensible heat flux estimated with the Castellvi (2004) method (H_SRA_Cast) showed good results for the entire period and for all atmospheric conditions, compared to EC-estimated sensible heat flux (H_EC). Unstable atmospheric conditions produced excellent performances compared to stable conditions. Similar conclusions of sensible heat flux using SRA (H_SRA) were documented for peaches (Suvočarev et al. 2014b), rice plantations (Castellvi et al. 2006), and pastures (Castellví et al. 2008) under different atmospheric conditions.

The latent heat flux using the Castellvi (2004) method (λE_SRA_Cast) demonstrated more than acceptable values, compared EC estimates (λE_EC) for the whole period and all atmospheric conditions, and unstable conditions showed values of R^2 of 0.7, slope of 0.79, ad RMSE of 37.81 $W.m^{-2}$ (equivalent to 0.056

mm / hour). Suvočarev et al. (2014b) reported similar λE_SRA_Cast values in peach plantations.

The sensible heat estimates using the Shapland et al. (2012a, b) method (H_SRA_Shap) compared to H_EC was poorer than H_SRA_Cast. However, the R^2 values of 0.80, slope of 1.20 and RMSE of 76.33 $W.m^{-2}$ for the entire period and all atmospheric conditions show a more-than-acceptable performance. Under stable conditions, though, H_SRA_Shap performed worse than H_SRA_Cast.

The behaviour of latent heat flux by Shapland (λE_SRA_Shap) reached values of R^2 of 0.52, pending of 0.69 and RMSE of 53.77 $W.m^{-2}$ (equivalent to 0.08 $mm.hour^{-1}$) for the whole period and all atmospheric conditions. Compared to λE_EC, the λE_SRA_Shap present results not so consistent as those obtained with λE_SRA_Cast. In Shapland et al. (Shapland et al. 2012b) it is concluded that the method performs better in unstable conditions than in stable conditions.

Evapotranspiration over the entire season were 316, 255, and 230 mm H_2O for EC, SRA_Cast, and SRA_Shap respectively. Suvočarev et al. (2014b) found similar values, that the H_EC values were overestimated and the RMSE increased in comparison with H_SRA_Cast.

Therefore, the performance of SRA_Cast and SRA_Shap in estimating latent heat and sensible heat fluxes in relation to EC is similar to that described by Suvočarev et al. (2014b), where better results are obtained with SRA_Cast, and H_SRA performed better than LE_SRA. No explanation was found to explain this phenomenon in the behaviour of either flux, but it coincides with an explanation given by Castellví et al. (2008) where there is some degree of dissimilarity between the scalar measurements, meaning that the stability functions used to estimate the scalar transfers sometimes fail under advection conditions (Lee et al. 2004).

If we consider R^2, slope, and RMSE, the best energy balance closure was obtained for EC and SRA_Cast in January and in February for SRA_Shap for all atmospheric conditions (data not shown in document). This is because there was a better footprint in these months, since we found the best relationship between fetch and footprint in January compared to the other months, especially in unstable atmospheric conditions, when the footprint was located exactly in the area of interest (i.e., the CS vineyard).

The latent heat flux estimated as a residual from the energy blance closure (LEres_SRA) overestimated the fluxes with respect to LE_EC in January 2018 (R^2: 0.80, slope: 1.66, RMSE: 89.3 W m^{-2}). Unstable atmospheric conditions also overestimated fluxes (R^2: 0.67, slope: 1.78, RMSE 33.7 W m^{-2}), while stable conditions greatly underestimated fluxes (R^2: 0.02, slope: 0.28, RMSE: 111.1 W m^{-2}). Since LEres_SRA is calculated as a residual from the energy balance equation, all errors from *H, G*, and *Rn* are added to LEres. In estimating latent heat flux as energy balance equation residuals using the classical SRA approach to estimate *H*, Rosa et al. (2013) reported a strong agreement in tomato crops (R^2: 0.99, slope: 0.94), Spano et al. (2000) also reported good correlations in grapevine canopies (R^2: 0.78, slope: 0.94, RMSE =58 W m^{-2}).

Likewise, for all atmospheric conditions and for the entire period studied, energy balance closure was slightly better for EC (R^2: 0.95, slope: 0.7, RMSE: 102.37 W

m^{-2}) than SRA_Cast (R^2: 0.93, slope: 0.67, RMSE: 116.88 W m^{-2}), and both were better than SRA_Shap (R^2: 0.71, slope: 0.69, RMSE: 154.72 W m^{-2}). Shapland et al. (2012c) and Poblete-Echeverría et al. (2009) obtained better energy balance closure in vineyards of similar characteristics (R^2: 0.90 and 0.92, slope: 0.93 and 0.97, respectively), as did Spano et al. (2004) (R^2: 0.82, slope: 0.84). However, Wilson et al. (2002) showed slope fluctuations between 0.53 and 0.99 (average of 0.79) and R^2 between 0.64 and 0.96 (average of 0.86) for fifty study sites. Therefore, our research presents an acceptable energy balance closure. Other explanations can also explain the performance on the energy balance closures, including advection conditions, soil heat flux, and the measuring height of the sensors.

Advection should be the same for all samples estimated under the same atmospheric and fetch conditions (Laubach and Teichmann 1999; Twine et al. 2000; Falge et al. 2002). Vertical advection can be eliminated by rotating the coordinate system, so the average vertical speed is always zero (McMillen 1988). However, in heterogeneous terrain conditions, vertical circulations and movements that compromise the previous statement can be promoted (Vidale et al. 1997). Therefore, the poor performance of energy balance closures during stable conditions is a fact, especially in conditions of turbulence and low friction speeds (Aubinet et al. 1999).

In several studies it has been shown that soil heat flux (*G*) is an important factor when assessing energy balance closure (Wilson et al. 2002). The performance of *G* in vertically trellised vineyards was investigated by Heilman et al. (1994), who concluded that *G* can represent up to 30% of net radiation, and Agam et al. (2019), who experimentally demonstrated the spatial and temporal variability of *G* and concluded that the variability of *Rn* is the primary source of differences in measuring *G*. This latter study was conducted in vineyards with east-west row orientation. In our study, the row orientation was north-south, and we found that placing the measurement sensors directly beneath the canopy generated two peaks of *G* throughout the day. It would be interesting to conduct more exhaustive research in the future about the behaviour of *G* in north-south oriented vineyards to examine how this impacts energy balance closures.

The input needed to estimate *H* through the ramps is temperature, and water vapour is the input needed to estimate *λE*. At the start of this research, thermocouples were proposed to estimate temperature, but throughout the data collection period these instruments frequently broke. Consequently, sonic temperature was used (with later correction), estimated with the IRGASON to calculate *H* across the entire season. The IRGASON was installed 4.58 m above the ground and approximately 2.28 m above the vineyard foliage, because the support structure of the sensors was fixed. It could not be installed in the row, because of the constant passage of tractors for farm work. Spano et al. (2000), Shapland et al. (2012c), and Poblete-Echeverría and Ortega-Farias (2014) installed sensors at a maximum distance of 1 m above the vineyard canopy to effectively capture ramp formations. In addition, Poblete-Echeverría and Ortega-Farias (2014) made measurements at different canopy heights and estimated that the best SRA performance was 0.5 m above it. In a study of different canopy types, Spano et al. (1997a) concluded that ramp formation becomes more difficult with increasing height, because the shear effect of the wind loses strength. These points about measurement height can partially explain why SRA_Cast and SRA_Shap had a poor performance when calculating sensible and latent heat fluxes and the energy balance closure in stable atmospheric conditions. However, other studies showed that poor performance is expected during night-time conditions, since fetch requirements are more demanding and the footprint increases considerably.

The performance of the carbon dioxide flux estimatations deserves a separate explanation. To our knowledge, only a couple of publications on estimating CO_2 fluxes using SRA have been published. Castellví et al. (2008) and Suvočarev et al. (2019) both use the Castellvi (2004) SRA, and a brief communication by Spano et al. (2002) who used the traditional method (Snyder et al. 1996). Therefore the bibliography consulted relates only to the use of EC for CO_2 flux estimation.

Better CO_2 flux values were obtained with CO_2_SRA_Cast (R^2: 0.71, slope: 0.40) than with CO_2_SRA_Shap (R^2: 0.55, slope: 0.29) for the entire period and all atmospheric conditions. Castellví et al. (2008) presented R^2 values of 0.93 and 0.97 and slopes of 1.09 and 1.06 for unstable conditions. In stable conditions they presented R^2 values of 0.70 and 0.62 and slopes of 0.81 and 0.76 for a pasture. The CO_2 estimated by SRA_Cast and SRA_Shap doubled and even tripled those estimated by EC.

Under stable conditions, the R^2 values were less than 0.1 for both CO_2_SRA_Cast and CO_2_SRA_Shap. Perhaps if the IRGASON had been installed closer to the canopy, better results could have been obtained at night. Night-time thermal stratification may not allow CO_2 output from the foliage to reach our sensor height. Insufficient turbulence conditions and CO_2 loss by convection can be reasons for underestimating the CO_2 flux in EC (Lindroth et al. 1998; Sun et al. 1998).

However, the behaviour of CO_2 fluxes is more difficult to quantify and evaluate than latent heat and sensible heat fluxes. To improve the estimations, it would be necessary to measure factors related to convection, storage, and atmospheric drainage. However, if the energy balance closures are not acceptable because the principles of scalar conservation are not fulfilled (Baldocchi et al. 2001) or there are advection conditions, the measurement of carbon dioxide fluxes will also be poor.

As demonstrated in this thesis and raised in other documents (Castellví et al. 2008; Suvočarev et al. 2014b, 2019; Hu et al. 2018) SRA can estimate fluxes without the need of EC to calibrate it. The use of SRA_Cast is recommended to estimate latent and sensitive heat fluxes. However, more research is needed for SRA_Shap flux estimations under stable atmospheric conditions and for carbon dioxide fluxes. Also, the sensors should be mounted close to the foliage to accurately estimate ramp formation; in the case of vineyards, several *G* measurement systems should be installed to more precisely compute what happens in the soil.

Conclusions

The conclusions are divided by chapter for organizational purposes.

Chapter II

This research shows the performance of SRA following Castellvi (2004) and Shapland et al. (2012a, b) to independently estimate sensible heat, latent heat, and carbon dioxide fluxes and analyse the energy balance closure in a vertically trellised vineyard for nearly an entire season (2017-2018), avoiding the use of EC.

SRA_Cast outperforms SRA Shap in estimating H and λE, but more research should be done for SRA_Shap and Fc fluxes to understand the performance of the method and its potential applicability. Also, we recommend measuring fluxes near the canopy to better estimate ramp formation and, in the case for G in vertically trellised vineyards, more points to measure soil heat fluxes are required.

Chapter III

The estimation of sensible heat, latent heat, and latent heat as a residual of the energy balance equation, using the surface renewal analysis method proposed by Castellvi (2004) and avoiding EC use, was applied on a vertically trellised vineyard in January 2018.

The H and LE were estimated in SRA using the scalar value and a novel method that calculated α using low frequency wind velocities values and an iterative process to obtain u_*, Lo and ς. The results demonstrate that H_SRA and LE_SRA present good agreement with EC fluxes, and are consequently recommended for micrometeorological measurement.

Future research should focus on other flux estimations (e.g., carbon dioxide flux) in heterogeneous crops, which present more complexity, especially during stable atmospheric conditions.

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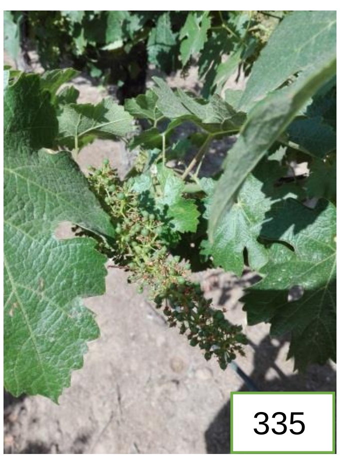
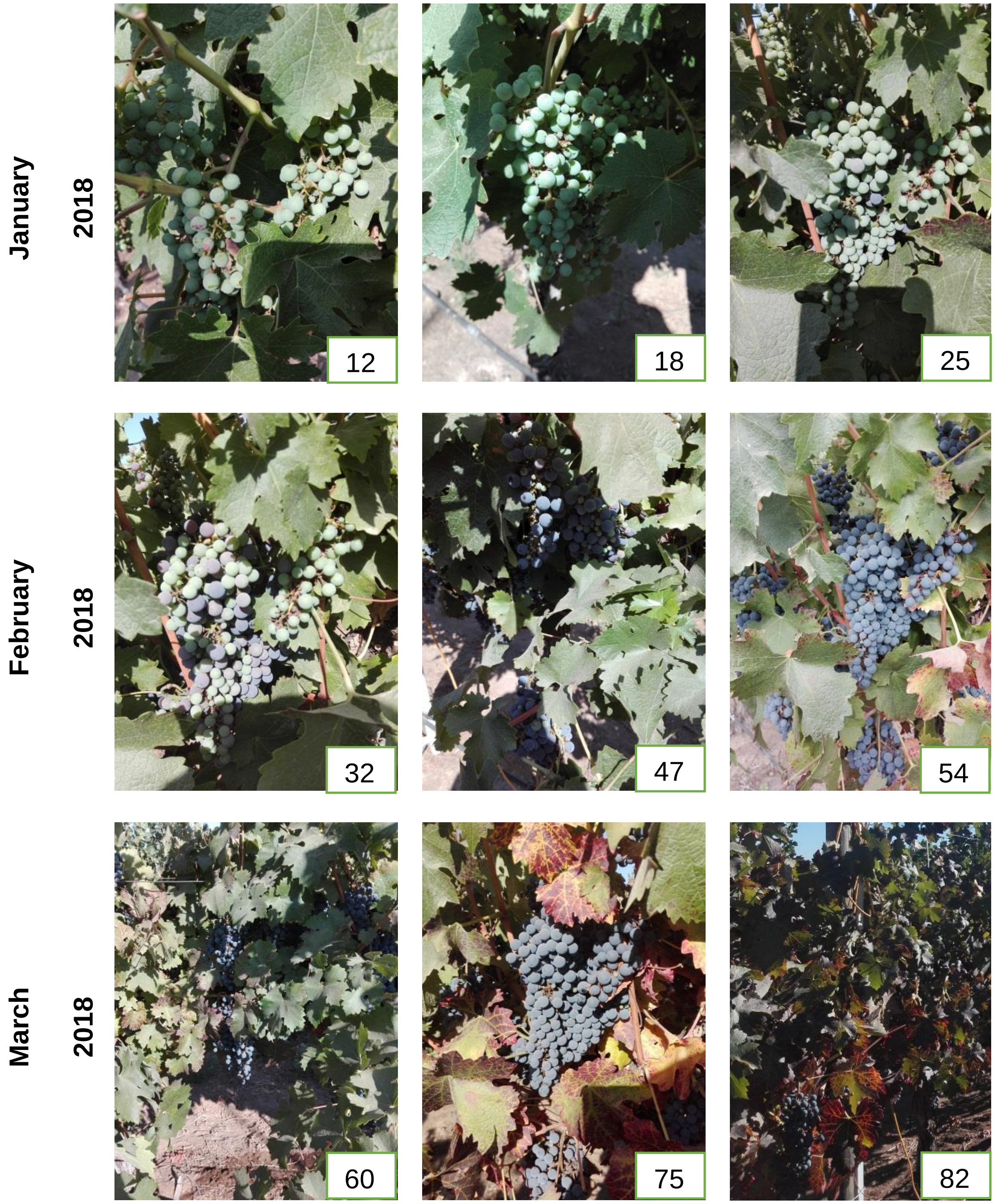
Appendix

Cabernet Photo Tracking

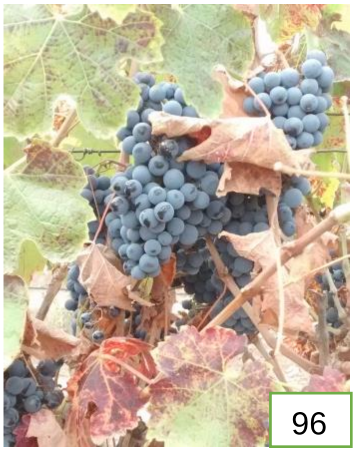
In the following photographs track the evolution of the vineyard. The sequence begins in November 2017 and ends in April 2018.

Table 3: Evolution of Cabernet Sauvignon vineyard. The numbers in the images indicate day-of-year.

Month	**Year**	**I**	**II**	**III**
November	**2017**			
December	**2017**			


January
2018
12
18
25
February
2018
32
47
54
March
2018
60
75
82

April 2018



96

103

Seminar Poster

Presented in “Hacia una Agricultura Sustentable: Avances y Desafíos en áreas claves para Chile y California” in Santiago, Chile.