Estimates of sensible heat flux of heterogeneous canopy crop using different micrometeorological methods

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Abstract: *The paper reports on an experiment over an orange orchard to define the reliability of Surface Renewal (SR) analysis for estimating sensible heat flux, H. The orange orchard was located in Eastern Sicily (Italy) where clear skies, high summer temperatures, light winds, no rainfall and regional advection were typical weather conditions. The technique has the advantage that only requires measurement of the scalar (air temperature) at a point. High-frequency temperature traces showed ramp-like structures, and structure functions were used to determine the mean amplitude and duration of these ramps. The ramp characteristics were used to estimate H. In the study, sensible heat flux values were also obtained from the application of a simplified aerodynamic method (SAM), in which a flux density can be related to the gradient of wind speed and temperature in the atmospheric sub-layer. The reliability of SR and SAM results was evaluated through comparisons with eddy covariance measurements of H.*
The use of SR and SAM sensible heat flux values in the energy balance determination of LE can give results nearly as accurate as those obtained using eddy covariance.
Keywords: *crop water requirement, energy flux exchange, evapotranspiration, micrometeorological method.*

Riassunto: *La sperimentazione, condotta su un agrumeto adulto ubicato nella Sicilia Orientale, è stata finalizzata alla valutazione dell'affidabilità della tecnica micrometeorologica Surface Renewal (SR), utilizzata per la stima dei flussi di calore sensibile (H) scambiati dal sistema vegetazione-atmosfera. L'area in studio presenta tipiche condizioni climatiche mediterranee, caratterizzate da elevate temperature estive, moderata velocità del vento, assenza di precipitazioni estive ed avvezione regionale. La tecnica ha il vantaggio di richiedere, per la stima dei flussi di H, la misura dello scalare considerato (temperatura dell'aria) ad una sola altezza. La misura ad alta frequenza della temperatura dell'aria presenta una tipica struttura denominata "rampa", avente quali grandezze caratteristiche l'ampiezza e la durata, entrambe determinate mediante l'implementazione di "funzioni di struttura". Nello studio, le grandezze caratteristiche delle rampe di temperatura sono state utilizzate per la stima di H. I flussi di calore sensibile sono, inoltre, stati determinati mediante l'applicazione di un modello aerodinamico semplificato (SAM), nel quale la densità del flusso di H è stata messa in relazione con il gradiente di temperatura misurato a fissate altezze al di sopra della vegetazione. L'affidabilità dei metodi SR e SAM è stata, infine, confrontata con la tecnica Eddy Covariance, che consente misure dirette di H. I flussi di H, stimati mediante le tecniche SR e SAM, sono stati utilizzati per risolvere l'equazione di bilancio energetico superficiale, ottenendo come termine residuo il flusso di calore latente LE (o evapotraspirazione). Quest'ultimo è risultato confrontabile con le misure dirette di LE tramite Eddy Covariance.*

Parole chiave: *evapotraspirazione, metodi micrometeorologici, richieste idriche colturali, scambio dei flussi energetici.*

1. INTRODUCTION

The consumptive water use, or evapotranspiration (ET), can be estimated by micrometeorological methods and the energy balance equation, soil depletion techniques, or by using weighing lysimeters. Sap flow in plant trunks can be used to determine transpiration. These methods usually are expensive, difficult to operate, and some of them present problems for measurements in heterogeneous vegetation (Simmons *et al.*, 2007). Therefore, the search for accurate methods for estimating ET fluxes using low-cost, transportable and robust instrumentation is a subject of interest (Castellvì *et al.*, 2006).

The eddy covariance (EC) method is the commonly used micrometeorological technique providing direct measurements of latent heat flux. It uses a sonic anemometer to measure high-frequency vertical wind speed fluctuations about the mean and an infrared gas analyzer to measure high frequency water concentration fluctuations. The fluctuations are paired to determine the mean covariance of the wind speed and humidity fluctuations about the mean to directly estimate latent heat flux (LE). In the EC method, the

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sensible heat flux is also estimated using the covariance of the fluctuations in vertical wind speed and variations in temperature about their means. While the preferred method for measuring turbulent fluxes is the EC, it is known that the closure of the surface energy balance is not guaranteed (Castellvì *et al.*, 2002; 2008). The fact that available energy does not equal the sum of the latent and sensible heat flux is commonly attributed to the lack of fetch and loss of flux by convection (Twine *et al.*, 2000; Wilson *et al.*, 2002). Additionally, the EC equipment is expensive and requires a continuous maintenance and monitoring for accurate measurements. Other energy balance approaches, such as the Bowen ratio and aerodynamic methods, have a sound theoretical basis and can be highly accurate for some surfaces under acceptable conditions. Paw U and Brunet (1991) proposed the Surface Renewal (SR) method for estimating scalar fluxes. The SR method is Lagrangian in nature and is based on the scalar conservation equation (Castellvì *et al.*, 2008). The method has been tested with air temperature data recorded over various crop canopies and it provides good estimates of sensible heat flux (H) regardless of the stability conditions and the flux direction (Paw U *et al.*, 1995; Spano *et al.*, 1997; 2000; Consoli *et al.*, 2006). The approach has the advantages that (i) requires as input only the measurement of scalar trace; (ii) involves lower costs for the experiment set-up, with respect to the EC method; (iii) operates in either the roughness or inertial sub-layers; (iv) avoids levelling, shadowing, and fetch requirements. Snyder *et al.*, (1996) and Spano *et al.*, (1997), however, have indicated the SR method currently requires an appropriate calibration factor that depends on the surface being measured (Chen *et al.*, 1997).

The aerodynamic method is another micrometeorological method used during experimental campaigns where it is necessary to characterize the soil-canopy-atmosphere continuum, and it is based on the assumption that a flux density can be related to the gradient of wind speed and temperature in the atmosphere surface layer. It starts from the logarithmic profile expression of air temperature and wind speed, corrected for atmospheric thermal stability by means of stability functions (Paulson 1970). The accuracy of the aerodynamic metod to measure H depends on the number of measurements levels of wind speed and temperature profiles.

This paper evaluates the performance of surface renewal (SR) and a semplified aerodynamic (SAM) analysis on flux estimates over orange orchard during 1 year period in an experimental site located in the Eastern Sicily (Italy). Uncalibrated surface renewal (SR) sensible heat flux (H_{SR}') values were compared against independent H_{EC} measurements obtained with an eddy covariance system, to determine a calibration factor (α) for estimating H_{EC} from H_{SR}'. The aim of this work was to evaluate alternative micrometeorological methods as reasonable accurate, low-cost and long-term procedure to obtain reliable estimate of latent heat flux (λE, or ET_c) using SR or SAM values of H and the energy balance equation.

2. METHODOLOGY

2.1 Field site experiment

The experiment was carried out over a 120 ha (37° 16' 41"N 14° 53' 01" E) orange orchard (variety navel) located in Eastern Sicily (Italy) from September 2009 to September 2010. The orchard architecture consisted of mature trees, about 3.5 m tall, with a mean leaf area index (LAI) of 4.25 m^2, PAR light interception of 100% within rows and of 50% between rows. Orange orchards were surface drip irrigated with daily frequency during May-October period. The irrigation systems included on-line labyrinth drippers, in a number of four per plant, spaced at 0.80 m, with discharge rate of 4 l/h at a pressure of 100 kPa.

There was 4 meter of distance between trunks within rows and 5.5 m between rows. The field provides an opportunity for micrometeorological studies because of the flat, homogeneous and wide site. The site is located within the agricultural context of the Catania Plain (Eastern Sicily) where clear skies, high summer temperature, light wind, no rainfall during summer and regional advection were the typical weather conditions. Regardless of the wind direction, the fetch was large because the trees were similar for the adjacent plots.

The eddy covariance (EC) technique (Aubinet *et al.* 2000) was used to simultaneously measure the mass and energy exchange flux densities over the orchard field. It encompassed a 3-dimensional sonic anemometer (CSAT3) for measuring the components of wind and a fast-responding open-path gas analyzer *LI-7500* (LI-COR, Lincoln, NE, USA) to measure carbon dioxide and latent heat flux. The EC equipment was mounted at 8 meter above the soil surface.

The net radiation (R_n) over the crop (at 8 meter from soil surface) was determined using two net radiometers (CNR 1 Kippen&Zonen). Net radiation measurements were representative of the average mixed conditions characterizing the heterogeneous context under study.

At the plot, soil heat flux (G) was measured using a network of three soil heat flux plates (HFP01, Campbell Scientific Ltd), which were placed horizontally 0.05 meter below soil surface. Three different measurements of G were selected: in the trunk row (shaded area), at 1/3 distance to the adjacent row, and at 2/3 of the distance to the adjacent row. The soil heat flux was measured as the mean output of three soil heat flux plates. The gradual build up of plant matter changed the thermal properties of the upper layers. Consequently, heat storage (ΔS) was quantified in the upper layer by measuring the time rate of change in temperature. The net storage of energy (ΔS) in the soil column was determined from the temperature profile taken above each soil heat flux plate. Three probes (TCAV) were placed in the soil to sample soil temperature. The sensors were placed 0.01-0.04 m (z) below the surface; the volumetric heat capacity of the soil C_v was estimated from the volumetric fractions of minerals (V_m), organic matter (V_0) and volumetric water content (θ). Therefore, G at the surface is estimated by measuring G' at the depth of 0.05 m and the change in temperature with time of the soil layer above the heat flux plates to determine ΔS.

$$G = G' + \Delta S = G' + C_v \left(\frac{T_f - T_i}{t_f - t_i} \right) \cdot d_g \qquad (1)$$

where G' is the heat flux density measured by the plate, ΔS is the heat storage, T_f is the final temperature at time t_f, T_i is the initial temperature at time t_i (the measurement time interval was of 30 min), d_g is the depth (m) of the heat flux plates, and C_v is the volumetric heat capacity ($J \cdot m^{-3} \cdot K^{-1}$), which depends on the bulk density (ρ_b) of the soil and the volumetric water content (θ) (De Vries 1963).

A 3-D sonic anemometer (Windmaster Pro, Gill Instruments Ltd) and two fine wire thermocouples (76.2 μm diameter) were set up at 0.5 meter above the canopy top (4 meter). The SR method to estimate H is based on high frequency temperature measurements. When plotted, the temperature traces show ramp like characteristics, which are used to estimate heat fluxes using a conservation of energy equation (Paw U *et al.*, 1995; Snyder *et al.*, 1996; Spano *et al.*, 1997). The fine-wire thermocouples were, thus, used to measure high frequency (4 Hz) temperature fluctuations and SR estimates of H were computed using a structure function (Van Atta 1977) and time lags of 0.25 and 0.50 seconds for each thermocouple to determine the mean ramp-like temperature trace characteristics.

The three wind components and air temperature were recorded at 10 Hz. Wind components were rotated to force the mean vertical wind speed to zero and to align the horizontal wind speed to the mean streamwise direction (Kaimal and Finningan 1994).

Volumetric water content was measured hourly from 0.3 to 0.6 meter by using the time domain reflectometry theory (TDR) (CS 616, Campbell Scientific, Logan UT, USA). The site was also equipped with an automatic weather station to measure the values of ancillary meteorological features (i.e. solar radiation, precipitation, air temperature, relative humidity, pressure, wind speed and direction).

Air temperature and wind speed profiles were realized within the orchard in order to apply the aerodynamic analysis. Wind speed and air temperature sensors were installed at 4.5, 6.5, 8.0 and 10.0 meter above the soil surface; data were recorded at 30 minute intervals. To monitor canopy temperature and detect stress conditions onset, five infrared thermometers (IRTS-P, Apogee) were installed within the orchard.

2.2 Surface Renewal technique

Consider an air parcel travelling at a given height above the canopy. SR analysis assumes that, at some instant, the parcel suddenly moves downward into the canopy where it remains for a period of time during which it travels horizontally until the parcel is ejected upwards and replaced by another parcel sweeping in from aloft. During the connect time with the canopy, the parcel has been heated (or cooled) because of heat exchange between the air and canopy elements. When high-frequency temperature measurements are collected at fixed point, the renewal process of heated (or cooled) air parcels across a horizontal surface at height z can be visualized in the time as a regular and low frequency ramp-like pattern (asymmetric triangular shape) (Paw *et al.*, 1995) (Fig. 1). A ramp is characterized by an amplitude (a, °C) and the period (l+s, sec).

In Snyder *et al.* (2000) high frequency temperature data were processed in a datalogger to output half-hour means of the 2nd, 3rd, and 5th order moments of the time lag temperature differences. Then the moments were uploaded and analyzed to determine the amplitude (a) and the inverse ramp frequency

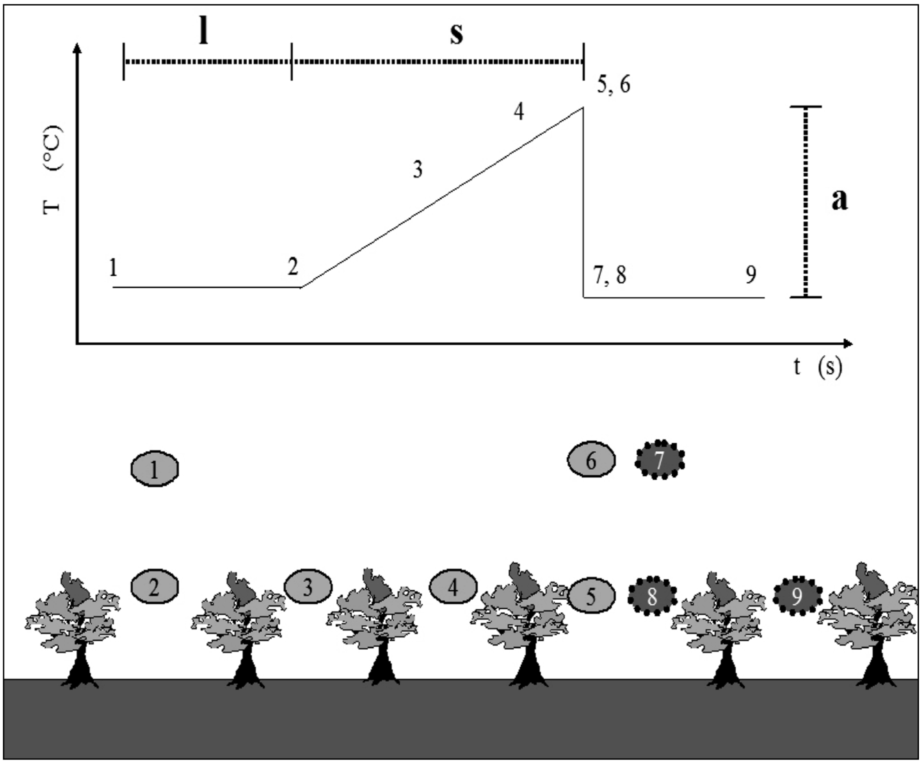

Fig. 1 - Air parcel in the renewal process.
Fig. 1 - Particella d'aria nel processo di rinnovamento.

(l+s) using the Van Atta (1977) structure function methodology.
For temperature recorded at canopy top, the surface renewal equation for sensible heat flux density H is expressed as (Paw U *et al.*, 2005):

$$H = \alpha \rho C_p \frac{a}{l+s} \cdot z \qquad (2)$$

where ρ and C_p are the density and the specific heat of dry air at constant pressure, z is the measurement height and a is a calibration factor embodying temperature variation in the canopy, initially estimated at 0.5 to account for a linear change in temperature with height. If the mean air parcel heats uniformly throughout, then a=1.
In the study sensible heat flux data from SR technique (H_{SR}) were calibrated with independent measurements of H_{EC} by the 3-D sonic anemometer located at the same fine-wire thermocouples level (4 meter). The calibration data subset was used to derive the α value of Eq. 2 by simple linear regression forced through the origin. For this regression, H_{EC} was used as the dependent variable and H_{SR} as the independent one. In this way, the regression slope was the a value looked for, used to correct H from the uncalibrated SR analysis. Calibration was made for stable and unstable cases. For stable cases, samples were split to discriminate surface cooling (R_n-G)≤0 W m^{-2} (i.e., mostly night hours), from daylight hours with (R_n-G) >0 W m^{-2} (i.e., influenced by regional advection of sensible heat flux). For calibration, the datasets selected corresponded to the central 15 days within a 3 months period. Thus, the dataset used for calibration were from day of year 75 to 90, 159 to 172 and 244 to 258, respectively for the corresponding three months period, February-April, May-July and August-October.

2.3 A simplified aerodynamic method

The sensible heat flux H is determined by the flux-gradient relationship:

$$H = -\rho C_p u^* T^* \qquad (3)$$

where u* and T* are, respectively, deduced from the wind and air temperature profile measurements. All the required correction functions for stability are described clearly and systematically by Stull (1988), Kaimal and Finningan (1994) and Arya (2001).
A simplified version of the method has been proposed by Itier (1981) and Riu (1982). In this version, the measurement of Δu and ΔT is only necessary on two levels and the used model avoids the iterative scheme imposed by the conventional functions for stability corrections (Kaimal and Finningan 1994). The method is based on the flux-

gradient relationship and the Monin-Oboukhov similarity theory. Calculation of H is dependent on atmospheric stability which is estimated by means of the Richardson number, R_i:

$$R_i = \frac{g}{T}\frac{\partial T/\partial z}{(\partial u/\partial z)^2} \tag{4}$$

where g (m s-2) is the acceleration due to gravity. On the basis of R_i values, H calculation is made by four equations:

I. Moderate instability condition ($-0.3 \le R_i \le 0$, day situation):

$$H = K\Delta T\Delta u\left(1 - K_R\frac{\Delta T}{\Delta u^2}\right)^{3/4} \tag{5}$$

where *K* e K_R are coefficients depending on the position of the sensors:

$$K = \frac{-\rho C_p k^2}{\left[\ln\left(\frac{z_2}{z_1}\right)\right]^2} \quad K_R = \left(\frac{16g}{T}\right)\sqrt{z_1 z_2}\ln\left(\frac{z_2}{z_1}\right) \tag{6}$$

where *k* is the von Karman constant and z_1 and z_2 are the heights of the first and second sensors, respectively.

II. Very unstable condition ($Ri < -0.3$, day situation):

$$H = \beta\Delta T^{3/2} \tag{7}$$

with:

$$\beta = \frac{1.3\rho C_p (g/T)^{1/2}}{5.2\left[(z_1 - d)^{-1/3} - (z_2 - d)^{-1/3}\right]^{3/2}} \tag{8}$$

III. Moderate stability condition ($0 < Ri \le 0.15$, night situation):

$$H = K\Delta T\Delta u\left(1 - \frac{\Delta T\Delta z}{6\Delta u^2}\right)^2 \tag{9}$$

IV. Very stable condition ($Ri > 0.15$, end of clear nights):

$$H = K\Delta T\Delta u\left(1 - \frac{\Delta T\Delta z}{6\Delta u^2}\right)^2 \tag{10}$$

In the application of the simplified aerodynamic method (SAM) two elements must be underlined: (i) measurements levels z_1 and z_2 must be chosen so that z_2 is high enough to keep $(z_1 z_2)^{1/2}$ outside the roughness layer; (ii) $(z_2 - z_1)$ must be large enough to measure wind and temperature differences with sufficient accuracy. In the proposed application of the method, z_1 was posed at 4.5 meter and z_2 assumed values of 6.5, 8 and 10 meters, respectively, from the soil surface layer.

2.4 Latent heat flux estimates

When evapotranspiration is considered under the form of latent heat flux density (LE), it is worth considering all the energetic components acting above a vegetated surface, i.e. the energy balance, which can be written as:

$$LEM = R_n - G - H \tag{11}$$

where all the terms are in W m-2, R_n is the net resulting from the balance of all the radiations above the crop and is directly measurable, G is the flux of heat in the soil, also directly measurable, and H is the flux of sensible heat, which was determined in the study from the application of SR, EC and SAM methodologies.

2.5 Performance indicators

Linear regression analysis, L_{RA} (slope, *s*, intercept, *int*, determination coefficient R^2) and the root mean square error, RMSE, were used to compare the sensible heat flux estimates using SR (H_{SR}) and SAM (H_{SAM}) analyses against the eddy covariance (EC) method (H_{EC}). The coefficient $D=\Sigma y/\Sigma x$ which is the sum of the flux estimates (Σy) over the sum of fluxes taken as reference (Σx), where H_{EC} is the reference data, was also determined as an evaluation parameter (Marth 1988). Because regression analysis assumes that H_{EC_8m} (the reference) is free of random sampling errors, the coefficient D was also determined as an integrated evaluation in daily, weekly, monthly, etc. time scales by averaging out errors in the half-hourly estimates (i.e., the bias is times the mean of H_{EC_8m}).

3. RESULTS AND DISCUSSION

Tab. 1 shows for each calibration period, the number of samples, N, available, the calibrated α at 4 meter (α_{4m}) for H_{SR} and the linear regression analysis (slope, *s* and intercept, *int*), R^2 and RMSE comparing H_{EC_4m} versus H_{EC_8m}.

In the paper, the estimates H values from SR and SAM were compared versus the H measured using the EC system deployed at z = 8 m, (i.e., it is the H desired to estimate LE). Fig. 2 shows the energy balance closure at 8 meter.

Case	N	$\alpha_{z=4m}$	Rmse	s	int	R^2	RMSE
P: 75-90							
Unstable	304	0.66	61	**0.85**	**-4**	**0.94**	**35**
Stable⁻	286	0.32	13	**0.67**	**-1**	**0.70**	**12**
P: 159-172							
Unstable	271	0.58	75	**0.81**	**2**	**0.86**	**49**
Stable⁻	108	0.21	17	**0.53**	**-8**	**0.55**	**14**
Stable⁺	29	0.41	14	**0.35**	**-9**	**0.23**	**21**
P: 244-258							
Unstable	183	0.76	51	**0.89**	**2**	**0.86**	**25**
Stable⁻	274	0.25	13	**0.42**	**-7**	**0.29**	**15**
Stable⁺	61	0.38	9	**0.74**	**-3**	**0.38**	**13**

+ and – denotes (Rn-G) positive and negative, respectively.

Tab. 1 - Calibration of parameter α for method SR at height z =4 m ($\alpha_{z=4m}$). In bold, the performance of H_{EC_4m} versus H_{EC_8m}. The Rmse and the *int* are in Wm^{-2}.
Tab. 1 - Calibrazione del parametro α per il metodo SR all'altezza z=4m ($\alpha_{z=4m}$). In grassetto, la performance di H_{EC_4m} rispetto a H_{EC_8m}. I valori di Rmse ed int sono espressi in Wm^{-2}.

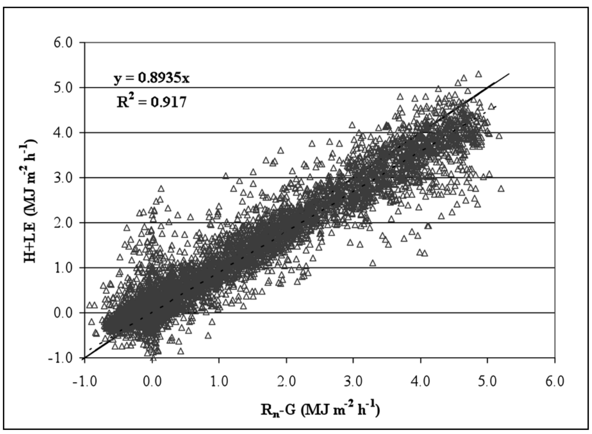

Fig. 2 - Energy balance closure at 8 meter.
Fig. 2 - Chiusura del bilancio energetico a 8 metri.

The H values estimated from SR and SAM (with z_2=10 meter) were close to H from EC method. Fig. 3 and 4 show that the hourly H_{SR} and H_{SAM} versus H_{EC} were similar for a wide range of H. When the simplified aerodynamic method (SAM) was applied with z_2 at 8 or 6.5 meter, H_{SAM} resulted quite different from H_{EC}. Most likely (z_2-z_1) wasn't large enough to measure wind and temperature differences with sufficient accuracy. In fact, when the atmospheric surface boundary layer is moderate or quite unstable, similar studies indicate that the roughness sub-layer depth mostly varies from 1 to 2

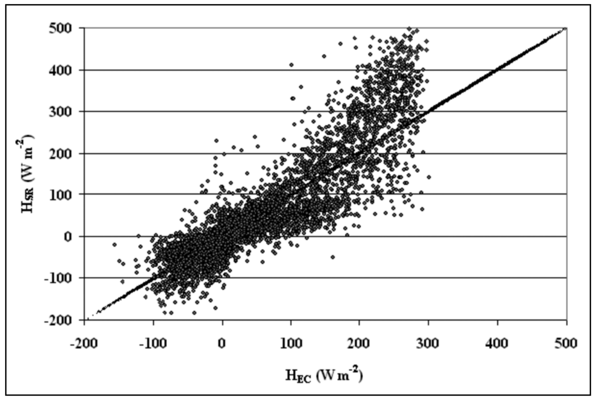

Fig. 3 - Hourly H estimates using SR analysis, H_{SR}, versus the measured using the EC method at 8 meter, H_{EC}.
Fig. 3 - Confronto tra le stime orarie di H ottenute attraverso il metodo di analisi SR, H_{SR}, ed i valori misurati utilizzando il metodo EC a 8 metri, H_{EC}.

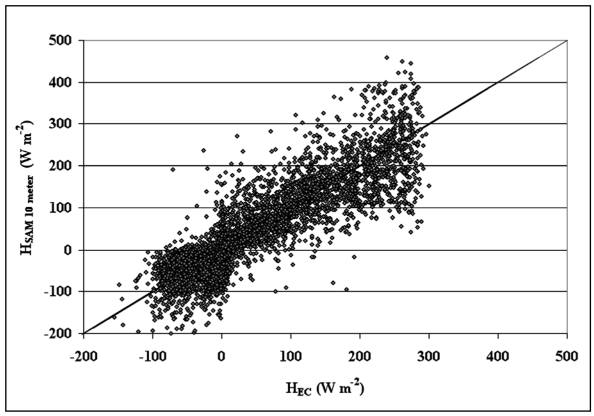

Fig. 4 - Hourly H estimates using SAM with z_2=10 meter, H_{SAM}, versus the measured using the EC method at 8 meter, H_{EC}.
Fig. 4 - Confronto tra le stime orarie di H ottenute attraverso il metodo SAM con z_2=10 metri, H_{SAM}, ed i valori misurati utilizzando il metodo EC a 8 metri, H_{EC}.

times the canopy height (Castellvì and Snyder 2009). Fig. 5 shows the frequency of z = 8 m to be above the roughness sublayer versus time (GMT) Castellvì *et al.* 2012). In general, it is shown that for hours with negative (Rn-G), the measurement height mainly remained within the inertial sub-layer. For positive (Rn-G) the roughness sublayer depth was oscillating around the upper level for about the 50% of the samples from sunrise until about two hours after noon, and late afternoon the upper level tended to remain in the inertial sublayer. Furthermore, some spurious H estimates were obtained from SAM during moderate and very stable atmospheric conditions, thus reducing the available data set for the comparison. In particular, the number of samples gathered under unstable atmospheric conditions was higher than from stable conditions.

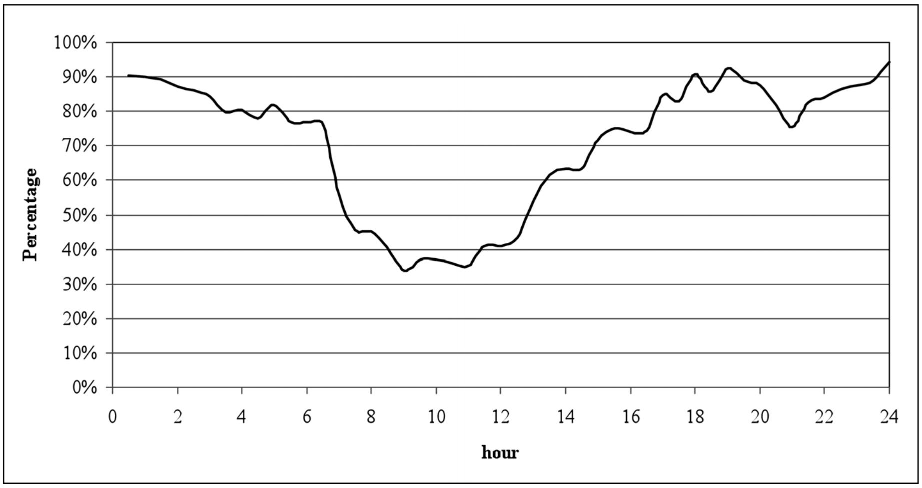

Fig. 5 - Percentage of cases when z=8 m falls above z*.
Fig. 5 - Percentuale di casi in cui z=8 m ricade al di sopra di z.*

Tab. 2 shows the results of the linear regression analysis (slope, intercept and coefficient of determination, R^2), root square mean error, RMSE, and D obtained for the analyzed data set. The largest RMSE values were obtained using the simplified aerodynamic method applied at 8 and 10 meter. In a review of experiments where the measurements were taken in the roughness sublayer, the RMSE values found to adjust surface renewal method where lower than that in Table 1 (Paw U *et al.*, 1995; 2005; Castellvì *et al.*, 2004). However these experiments are not direclty comparable because H was measured using a one dimensional sonic anemometer.

Slight underestimations by the proposed alternative methods (SR and SAM) were observed. A 3.8% underestimation was found by SR for the whole data set including both stable and unstable cases; as a result that for small fluxes the ramp amplitude was often not in accord with the sign of H_{EC}. RMSE values from SR and SAM were not high. SR and SAM linear regression analyses showed slopes of, respectively, 1.12 and 0.95 very close to unit and high coefficients of determination.

For optimized drip irrigation, hourly LE estimates are desired. The best LE estimates from eq.11 are attained when all the terms are averaged hourly. A better closure may be achieved when turbulent fluxes are determined using longer block averages than half-hourly because lower frequencies are captured as well (Finningan *et al.*, 2003). However, SR is based on the analysis of organized motion near the canopy-atmosphere interface. The continuous ramp patternexhibited in the scalar trace is a canopy-scale coherent structure, which is not associated with large circulations. Therefore, the H_{SR} is best determined half-hourly. Comparisons of LE_{EC} using hourly block averages versus hourly L_{SR} and L_{SAM} (obtained from the residual energy balance method) were slightly worse than that between H values obtained from the different micrometeorological techniques. The hourly LE_{SR} and LE_{SAM} were closer to LE_{EC} mainly under unstable cases.

	H_{SR} versus H_{EC}	H_{SAM} (z_2= 10 m) versus H_{EC}	H_{SAM} (z_2= 8 m) versus H_{EC}	H_{SAM} (z_2= 6.5 m) versus H_{EC}
a	1.12	0.95	1.20	1.87
b (W m^{-2})	-5.80	-2.33	2.96	-4.58
R^2	0.80	0.77	0.63	0.75
RMSE (W m^{-2})	50.19	44.52	58.92	117.11
D	0.96	0.88	1.11	1.72

Tab. 2 - Linear regression analysis, RMSE, D, comparing the hourly H_{SR} and H_{SAM} (with different z_2) versus H_{EC} for the whole data set.
Tab. 2 - Analisi di regressione lineare, RMSE, D, relativi al confronto dei valori orari di H_{SR} e H_{SAM} (con diverso z_2) con quelli di H_{EC} per l'intero set di dati.

	H_{EC} (W m^{-2})	H_{SR} (W m^{-2})	H_{SAM} (W m^{-2})	R_N-G (W m^{-2})	LE_{EC} (W m^{-2})	LE_{SR} (W m^{-2})	LE_{SAM} (W m^{-2})	u (m s^{-1}) z_1=4.5	z_2=6.5	z_2=8	z_2=10
M	105.0	114.2	102.1	226.8	145.6	112.6	124.7	1,5	1,9	2,1	2,3
σ	92.1	125.1	96.6	182.1	102.0	107.1	119.6	1,1	1,3	1,5	1,6

Tab. 3 - Means (M) and standard deviations (σ) of the main energy fluxes and wind speed characteristics along the vertical profile. Fluxes are determined for unstable atmospheric condition cases.
Tab. 3 - Medie (M) e deviazioni standard (σ) dei principali flussi energetici e caratteristiche della velocità del vento lungo il profilo verticale. I flussi sono determinati per i casi di instabilità atmosferica.

For the unstable atmospheric conditions, Tab. 3 shows the main statistics of the estimated and measured energy fluxes. The mean wind speed values from 4.5 to 10 meters were also reported. During the irrigation season (May-October period), latent heat flux density averaged 8.5, 7.0, and 7.6 MJ m^{-2} d^{-1} for the EC, SR and SAM, respectively.
The mean (about 0.90) of daytime evaporative fraction (EF) during summer, which characterizes the partition of the energy budget at the daily time scale, varied little (0.06) based on average cloudiness. The temporal variability of the partitioning, expressed in terms of EF daily standard deviation, reached a maximum of 14%. The experiment showed that the evaporative fraction computed from flux measurements at 4 hours past sunrise tends to increase very slowly, thus to assume that the underestimation in daytime average would be not significant.
Actual crop ET (ET_a) was computed by dividing LE by the latent heat of vaporization: L = 2.45 MJ m^{-2} mm^{-1}. Generally, crop coefficients are determined by calculating the ratio $K_{co}=ET_c/ET_o$, where ET_c is the evapotranspiration of a well-watered crop. Since these orchards are well managed, it is assumed that there was little or no transpiration reducing water stress and $ET_a \approx ET_c$. Hourly variations of crop coefficient (K_{co}) values, during the monitoring period, were determined using ET_c and reference evapotranspiration (ET_o) for a short canopy (Allen *et al.*, 1998). Weather data used to calculate ET_o came from the SIAS station (the agro-meteorological service of the Sicilian region) which is located 4 km far from the site. Hourly ET_o values were summed over 24-hour periods to obtain daily ET_o.
During May-October period, average daily values of ET_c were of 3.5, 2.9 and 3.1 respectively from EC, SR and SAM, with corresponding values of the hourly crop coefficient of 0.54, 0.51, and 0.62.
H_{EC_4m} and H_{EC_8m} were rather well correlated

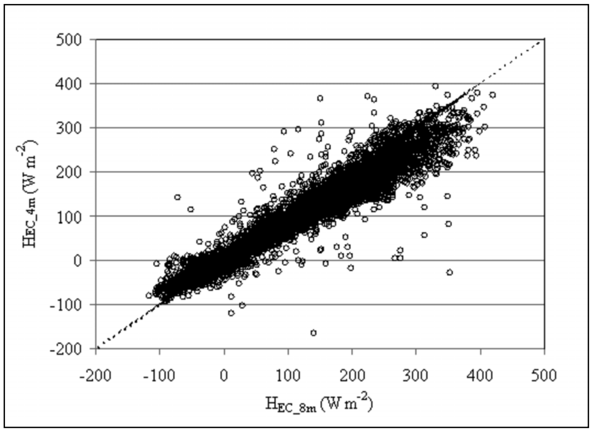

Fig. 6 - Sensible heat flux measurements using the EC method at z=4 m, H_{EC_4m} versus at z=8 m, H_{EC_8m} for all the data.
Fig. 6 - Confronto tra le misure del flusso di calore sensibile ottenute attraverso il metodo EC a z=4 m, H_{EC_4m}, e quelle a z=8 m, H_{EC_8m}, per l'intero set di dati.

(R^2=0.93) considering the different amount of small eddies (much higher close to the canopy top) that cannot be properly sampled by sonic anemometer. Fig. 6 shows H_{EC_4m} versus H_{EC_8m} for all the campaign. In general H_{EC_4m} underestimated H_{EC_8m} of 18%. For unstable cases, the a values for unequal heating was of 0.61 at 4 meter and of 0.68 at 8 meter.

CONCLUSIONS

This paper reports on an experiment in orange orchard to study the reliability of alternative micrometeorlogical techniques, such as surface renewal (SR) and a simplified aerodynamic method (SAM), for estimating sensible heat fluxes. The SAM analysis was accomplished by coupling different equations based on simple gradient flux expressions to account for atmospheric changes depending on stability or unstability conditions. H estimates using the alternative techniques were compared with H data directly measured by eddy covariance at the same site.
In general H_{SR} and H_{SAM} were similar to H_{EC}

regardless of the atmospheric stability conditions, demonstrating the potential of SR and SAM analyses as methods applicable to estimate sensible heat flux. The SAM was more sensitive to moderate and very stable atmospheric conditions, thus resulting in some spurious data.

SR technique appears in advantage with respect to SAM and EC because it may operate close to the canopy, thus minimizing fetch requirements, which make it a useful micrometeorological method where fetch requirements limit the application of other techniques.

The combination of the SR procedure and the simplified surface energy balance equation appears to be an affordable alternative to be considered for estimating water use in agriculture.

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