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A low-cost portable chamber based on Arduino micro-controller for measuring cover crops water use

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ABSTRACT

Cover crop adoption is growing in sustainable vineyard management to replace tillage and limit its ecosystem disservices. However, water use of such crops must be known and low-cost, yet fast reading, portable and accurate equipment is therefore needed for multipoint measurements in the field. Using an Internet of Things (IoT) approach, in this study we provide details for setup, calibration and operational data of a very low cost (~210 \$), small closed type chamber. Chamber calibration was performed either as instantaneous evaporation (E) rates under laboratory condition (25 runs, 2 min each) and daytime cumulative evapotranspiration (ET) rates performed outside in small pots sown with different cover crops or managed with light tillage. In both cases chamber's derived water loss rates were validated against a gravimetric method. A very close linear relationship between gravimetric vs chamber values was found for lab and outdoor calibration runs ($R^2 = 0.96$ and 0.99, respectively) within ranges of $0\text{--}0.8 \text{ mm h}^{-1}$ (lab) and $0\text{--}23 \text{ mm d}^{-1}$ (outdoor). Ideal measurement time window was estimated at 60 s after "time zero" set at 15 s upon chamber positioning. Under any condition, chamber heating never exceeded 2°C above air temperature. In the warmest hours of the day (i.e. from 11:00 to 16:00) *Festuca arundinacea* hourly ET was 0.56 mm while *Lotus corniculatus* and wet soil tillage registered 0.71 and 0.69 mm h^{-1} , respectively. Dry soil tillage showed ET values between 0.2 and 0.3 mm h^{-1} . The proposed device represents an effective IoT application as total cost of the needed components does not reach a total amount of 200 euros and its size as well as flexibility of use makes it an ideal tool for fast multipoint readings of soil and grass water losses in the field.

1. Introduction

Vineyard cover cropping (i.e. seeded grass cover) is a sustainable soil management practice extensively used in many of the world's viticultural areas (Celette et al., 2008). It is in fact one of the recommended practices to promote environmental sustainability and to face climate change impacts in vineyards (Celette and Gary, 2013; Diti et al., 2020; Schultz and Stoll, 2010; Van Leeuwen et al., 2019). The adoption of cover crops allows for achieving many ecosystem services (ES), including: i) improvement of soil fertility and physical features; ii) better soil water retention capacity and water infiltration rates; iii) improved pest and native weed control together with iv) environmental and social benefits (e.g. carbon sequestration, biodiversity conservation and landscape aesthetics) (Garcia et al., 2018). Thus, cover cropping usage has widely been assessed in a variety of soils and climate conditions across the world and to name a few: Italy (Ferrero et al., 2005; Pardini

et al., 2022)), Spain (Marques et al., 2010; Ruiz-Colmenero et al., 2013) France (Celette and Gary, 2013; Ripon et al., 2010), South Africa (Fourie et al., 2017), Australia (Danne et al., 2010; Nordblom et al., 2021) and United States (Guerra and Steenwerth, 2012).

However, together with ecosystem services, that may lead to a food production promotion, some ecosystem disservices (EDS) may be generated which, contrariwise, tend to hinder it (Von Döhren and Haase, 2015). Competition for soil resources (e.g. water and nutrients) is a good example of cover crop disservice (Celette and Gary, 2013; Klodd et al., 2016). In fact, only a small percentage of farmers are planting cover crops in semi-arid areas due to the disadvantages often outweighing the advantages (Medrano et al., 2015). This happens to be even more important in a viticultural context of climate change where, along with a quite certain global warming, higher frequency of hot spells and slightly reduced total precipitations are expected over most land areas on daily and seasonal timescales (Pachauri et al., 2014). In viticultural areas,

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these changes would lead to a reduction of the water available to plants and, as a likely consequence, occurrence of significant summer drought will increase especially in traditionally non irrigated districts with negative influences on both grape and wine quality (Mirás-Avalos and Intrigliolo, 2017; Pagay et al., 2016). Within such a scenario, the demand for irrigation will rise. To more wisely schedule irrigation events, a more comprehensive knowledge of the dynamic and magnitude of water used by all the vineyard ecosystem components (i.e. vines, grass and soil) is needed (Centinari et al., 2013). The same applies to other agro-ecosystems involving perennial woody crops such as apple orchards (Mobe et al., 2020) and olive groves (Novara et al., 2021).

Previous studies have mainly focused on quantifying whole vine's transpiration rate using approaches such as sap flow gauges (Braun and Schmid, 1999; Dragoni et al., 2006) or canopy enclosure systems (Poni et al., 2014). However, to determine the total evapotranspiration (ET) of the vineyard ecosystem, the amount of water used by both the bare soil and/or the cover crop needs to be incorporated. The contribution of these two components (i.e. soil and cover crop) to the vineyard water use can be very significant also depending on other interfering factors (e.g. training system, between row distance, etc.). However, data available regarding direct measurements of the amount of water used by a grass cover in a vineyard are still quite limited (Centinari et al., 2012; Lopes et al., 2004; Uliarte et al., 2013). Lopes et al. (2004) used a portable gas exchange system to measure cover crop transpiration rates and showed that contribution to vineyard evapotranspiration can vary from less than $1 \text{ mm d}^{-1} \text{ m}^{-2}$ for *Festuca rubra* subsp. *rubra* to more than $4 \text{ mm d}^{-1} \text{ m}^{-2}$ for *Malva neglecta*.

Several methods can be used to measure ET fluxes, each with advantages and limitations. Cover crop ET can be gravimetrically determined by using a mini-lysimeter (ML), which represents an alternative solution to field lysimeters as it can be used in a limited space situation (such as that available between the vine rows) (Bremer, 2003; Lakso et al., 2019). A ML consists of some kind of container filled with a soil core covered with the same vegetation of the surrounding area and inserted into the ground to the point of being even with the adjacent soil surface. The containers used may be plastic pots (Centinari et al., 2013) provided there are holes at the bottom for the drainage of the water. In this method, MLs are irrigated, allowing time for the extra water to drain and then weighed several times in the following days. Loss in mass during the interval between weighing is attributed to ET.

Micrometeorological techniques, such as the eddy covariance, are other methods that can be used for cover crop ET measurements and have a clear advantage in continuous measurements without disturbing (i.e. indirect method) the micro-environment of the measured field (Muller et al., 2009). However, this method does not apply to small-scale experiments (Baldocchi, 2014).

Conversely, chamber enclosure still holds as a non-invasive method for small scale readings (Steduto et al., 2002). Here, a transparent chamber is placed over vegetation or soil, and gas fluxes are estimated from the concentration changes of the gases through the chamber. Typically, chamber methods are classified into two categories: closed vs open chambers (Garcia et al., 1990; Wagner and Reicosky, 1992).

In an open chamber, the gas is continuously pumped into and out of the chamber through openings. The difference of water vapour concentration between the chamber inlet and outlet is measured and used to determine the ET flux. Measurements can be obtained continuously over a time period from a few days to the whole growing season. However, complex systems are required in order to maintain the micro-climate inside the chamber reasonably close to ambient (Corelli-Grappadelli and Magnanini, 2019; Poni et al., 2014). Moreover, open chambers portability is usually limited and the air flow fed to the chambers needs to be carefully measured.

Even though Centinari et al. (2009) successfully used an open chamber system to determine *Festuca arundinacea* water use in a vineyard, a closed chamber has been designed to better suit the need of portability (Luo et al., 2018) and, as such, it can be quickly moved

among several sampling locations in the field. A closed chamber system estimates gas fluxes by measuring the rate of change in gas concentrations in the chamber air in a short period of time, while the chamber is closed. To minimize chamber-induced canopy micro-climate changes, rapid measurements for brief periods (i.e. 1 min or so) should be used (Nomura et al., 2019).

There is some controversy concerning the accuracy of the closed chamber method when comparisons have been made with other ET measurement techniques. A few studies have shown a good agreement between the daily ET obtained with a closed chamber system and the Energy Balance Bowen Ratio method (Luo et al., 2018; McLeod et al., 2004; Steduto et al., 2002). Contrariwise, other studies have reported that chamber derived water use rates overestimated by about 25% amounts derived from a gravimetric (Grau, 1995) or eddy-covariance (Stannard and Weltz, 2006) approach. However, comparing the results obtained in these studies is complicated because of the different characteristics (e.g. shape, size, etc.) of the closed chambers used.

The rates of change in gas concentrations are frequently assumed to be constant, and the linear regression function (LR) has usually been fit to the measured changes of gas concentrations to estimate gas fluxes in closed chamber systems (Wagner and Reicosky, 1992). However, the non-linear nature of changes in gas concentration, due to the diminishing concentration differences of the gas between the measured subject (e.g. soil, cover crop) and the chamber air during the chamber closure has been recognized (Nomura et al., 2019). Several studies have argued that the use of LR can lead to underestimation of gas fluxes (Kutzbach et al., 2007; Langensiepen et al., 2012). To minimize this flux underestimation Wagner and Reicosky (1992) proposed the quadratic regression function (QR). According to that, the flux can be estimated by the first derivative of the function at time zero (i.e. immediately after the chamber closure).

Although LR and QR might fit well to observed changes of concentration, these conventional regression functions might still be conducive to underestimations of fluxes due to the dynamic characteristics of a concentration sensor (i.e. response lag and dead time) as argued by Nomura et al. (Nomura et al., 2019). This problem is often connected to usage of low cost sensors since rapid-response concentration sensors tend to be expensive and this has limited the applicability of the closed chamber method.

Considering the need to develop low-cost yet reliable and fast-enough concentration sensors, the objectives of this study are to: i) describe a new, custom-built and low-cost closed chamber system for vineyard cover crop ET flux measurements; ii) perform proper calibration; and iii) provide examples of the kind of datasets and degree of accuracy that the system can achieve.

2. Materials and methods

2.1. Chamber description and setup

The chamber design consists of: i) a cylindrical structure made of waterproof 2 mm thick polyvinyl chloride (PVC) sheet; ii) a lower plastic frame and iii) an upper conical lid with a 0.5 cm thick rubber gasket for sealing (Fig. 1).

The chamber has a ground surface of 491 cm^2 and a height of 57 cm, with a total volume of 28L and it is operated as a closed system. It was designed to work on top of a steel collar previously inserted 3 cm onto the soil.

The chamber is made of PVC because of its uniform transmissivity at 400–800 nm wavelength light and because it is lightweight, low-cost and easy to handle and to seal with solvent glue.

Chamber light transmittance properties as well as variation of the diffuse-to-direct light ratio were checked during a summer clear day using a BF2 Sunshine Sensor (Delta-T Devices Ltd, Cambridge, UK) placed horizontally inside and outside the chamber. Recorded values (mean \pm SE, n = 10) for direct and diffuse radiation outside the chamber

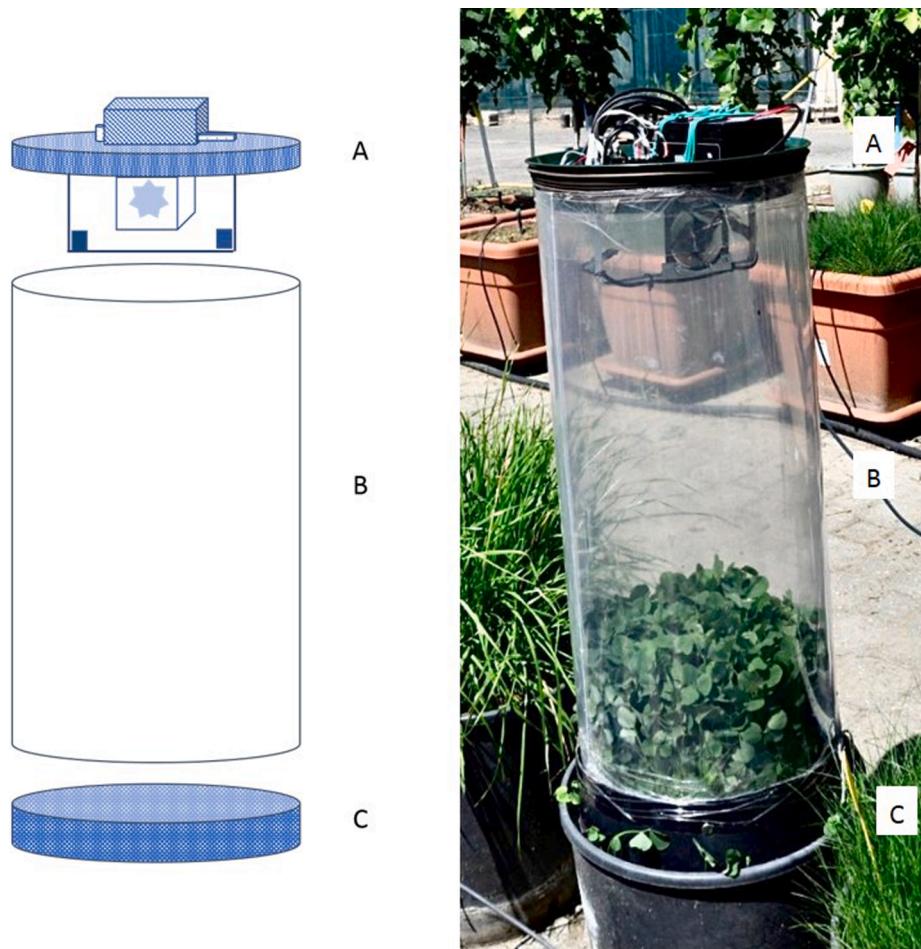


Fig. 1. Portable closed chamber whose main components are: A) upper conical lid on which electronics and sensors are mounted; B) cylindrical polyvinyl chloride structure; C) lower plastic frame.

were 1368 ± 2.80 and $580 \pm 1.35 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively, and 1128 ± 6.98 and $486 \pm 1.87 \mu\text{mol m}^{-2} \text{s}^{-1}$ inside it. Therefore, light transmission through the chamber was reduced by 17% whereas the diffuse-to-direct light ratio remained unchanged at around 43%.

The lid was designed flat instead of the spherical shape used in other commercial chambers, for easier manufacturing and handling in the field, and to reduce the measurement time due to a lower chamber volume (Ladrón De Guevara et al., 2015).

All the chamber components were fixed on the lid and connected to the Arduino1 Rev3 micro-controller (Smart Projects, Ivrea, TO, Italy). Actual components (A) and the wiring (B) of the chamber electronic system are shown in Fig. 2.

For a more flexible field operation, the electrical and electronics systems were designed to be of low current drain, compatible with being powered from a rechargeable battery or directly from a tablet or a computer. The software was developed using Arduino platform (1.6.11 version). After turning on the micro-controller and the brushless fan, with the chamber temporarily kept at about 50 cm above the ground, chamber humidity stabilisation has to be reached, usually taking no more than 45 s. Then, the chamber is lowered on the pot (perfect fit is needed) or on the steel frame, previously inserted onto the soil. Data recording was programmed at 15 s interval and the duration of the calculation window was set at a maximum of 120 s. The initial lag and mixing time was estimated as 15 s (i.e. 15 s from the chamber closure) from which the calculation time window (TW) started.

Current cost of each item needed to build and configure the chamber is shown in Table 1.

2.2. Evapotranspiration calculation

The chamber sensor GY BME280 (Bosch Sensortech, Milan, Italy) measures pressure (p), temperature (T) and relative humidity (RH).

Relative humidity is defined as the ratio, expressed as a percentage, of the actual water vapour pressure (p_w) to the saturation water vapour pressure (p_{ws}) at a given temperature:

$$RH = \frac{p_w}{p_{ws}} \quad (1)$$

While RH (%) is given by the sensor every 15 s interval, p_{ws} (Pa) can be calculated from the Antoine equation:

$$p_{ws} = \exp[A - \frac{B}{T + 273.15} - C \ln(T + 273.15)] \quad (2)$$

$$A = 65.81 \quad B = 7066.27 \quad C = 5.976$$

where T is the chamber temperature ($^{\circ}\text{C}$) given by the sensor and A, B and C are constant values. The p_{ws} value at the chamber micro-climate condition is calculated every 15 s.

Both RH and p_{ws} are known and from Eq. (1) and the actual water vapour pressure (p_w) can be calculated as:

$$p_w = p_{ws} * \frac{RH}{100} \quad (3)$$

Then, according to Dalton's law of partial pressures, the partial pressure water moles (n_w) is obtained from the relation:

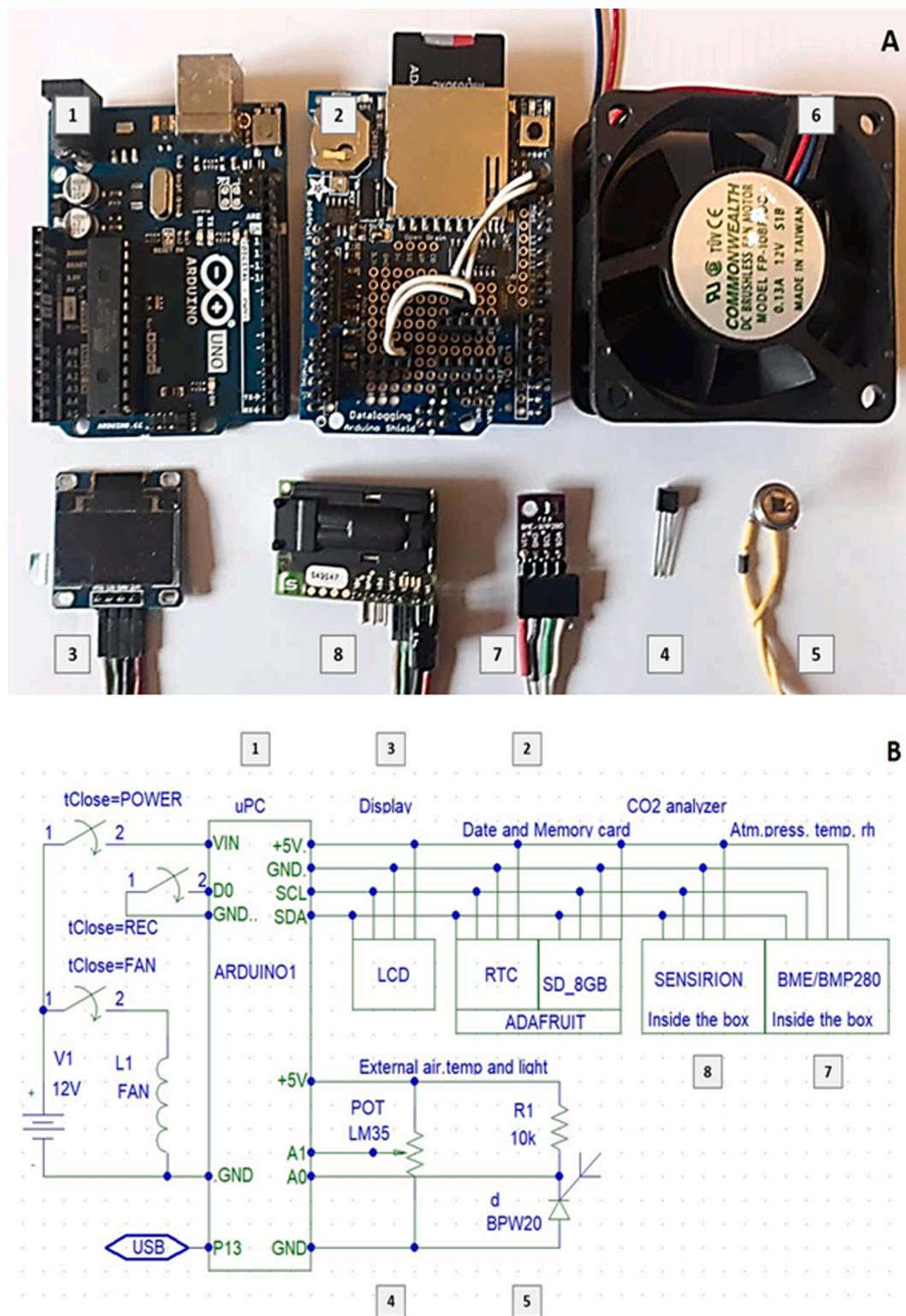


Fig. 2. Actual components (A) and wiring (B) of the chamber electronic system. Components are: 1) Arduino1 Rev3 micro-controller; 2) Adafruit Assembled Data Logging shield for Arduino (Adafruit industries, NY, USA) made of an SD mass memory, a clock and a dater; 3) OLED 96C 0.96" Display (Futura Group s.r.l. divisione elettronica, Gallarate, VA, Italy); 4) an outside-the-chamber temperature sensor LM335 (STMicroelectronics, GE, Switzerland); 5) a Silicon Photodiode BPW20RF (Vishay Intertechnology Inc., PA, USA) and a 12 V 7Ah rechargeable battery (not shown); 6) brushless fan (Commonwealth Industrial Corporation, Taiwan); 7) pressure, temperature and humidity sensor GY BME280 (Bosch Sensortec GmbH, RT, Germany) and 8) CO₂, temperature and humidity sensor Sensirion SCD30 (Sensirion AG, ZH, Switzerland). The holes for inserting the sensor and the fan cable in the chamber were sealed with solvent glue.

Table 1

List of components and relative current costs (USD and Euro) for assessing ET fluxes. Material and equipment quantities are calculated for one single portable closed chamber system.

Item	Item	Cost	
	(No.)	(Euro)	(USD)
PVC sheet	1	2.33	2.82
Plastic conical frame	1	1.2	1.45
Plastic conical lid	1	0.99	1.20
Rubber gasket	1	2.5	3.03
Steel frame	1	6.9	8.35
Battery	1	16	19.36
Brushless fan	1	6.77	8.19
Arduino1 Rev3 micro-controller	1	22.5	27.23
Sensirion SCD30	1	58.56	70.86
GYBMEP BME/BMP280	1	8.5	10.29
Display OLED96C 0.96"	1	11	13.31
Adafruit Assembled Data Logging shield for Arduino	1	17.02	20.59
Temperature sensor LM335	1	0.51	0.62
Silicon Photodiode BPW20RF	1	6.5	7.87
Other electronic material	14	12.8	15.49
Total cost		174.08	210.64
Workload cost¹		24.00	29.04

¹ Workload cost for 1 ha sampling where 40 readings are assumed to be needed.

$$n_w = \frac{n^* p_w}{p} \quad (4)$$

where p_w (Pa) is the actual water vapour pressure, p (Pa) is the total pressure of the gas mixtures present in the chamber measured at 15 s intervals by the sensor and n (mol) is the number of moles that can be held inside the chamber volume V (l).

From the ideal gas equation where:

$$V_m = \frac{R*T}{p} = \frac{V}{n} \quad (5)$$

n (mol) can be obtained as:

$$n = \frac{V}{V_m} \quad (6)$$

Then, V_m can be calculated from Eq. (5) using sensor measured T (°C) and p (Pa) and the gas constant R (8.324 L Pa K⁻¹ mol⁻¹). V_m is then expressed as L mol⁻¹.

Once n_w (mol) is calculated from Eq. (4), the amount of water "lost" (g), i.e. evaporated, every 15 s from the ground surface covered by the chamber can be estimated as

$$H_2O = n_w * 18.015 \quad (7)$$

where 18.015 g mol⁻¹ is the water molecular weight. The amount of water evaporated every 15 s is then expressed as mm m⁻².

Then, a quadratic regression (QR) model was applied (Wagner and Reicosky, 1992)

$$y = at^2 + bt + c \quad (8)$$

where y is the water evapotranspiration flux; a , b and c are fitted parameters and t is the sampling time. The use of QR is appropriate since the water vapour concentration inside the chamber increases with time, leading to a decreasing water vapour deficit which reduces the measured ET.

In order to determine the instantaneous ET, the calculation time window (TW) disregards the very first record and "time zero" is considered to be the reading taken at 15 s after chamber positioning. Therefore, the time window comprised between time zero and 60 s afterwards is the one used for inferring ET calculation.

Of these 60 s curve, the slope is calculated through the first derivative

of the QR according to the following equation:

$$\frac{dy(0)}{dt} = b \quad (9)$$

The instantaneous ET (i.e. b) is then expressed as mm h⁻¹ and when needed, converted into mm d⁻¹.

2.3. Chamber calibration

A mass balance method was used in a laboratory test to determine the accuracy and stability of the chamber measurements. Calibration was initially performed comparing evaporation (E) from a water-soaked cloth measured using the canopy chamber against its gravimetric water loss measured with a precision balance. The weighing system consisted of an electronic scale (model PS 2100.R2.M, Radwag, Radom, MZ, Poland) with a resolution of 0.01 g. The calibration consisted of 25 chamber runs each lasting 120 s. For each run, the water lost from the cloth was calculated using the equations previously described, whereas the gravimetric loss was determined by weighing the cloth before and right after the chamber measurements. The data were expressed as hourly rate of evaporation (mm h⁻¹).

A second round of calibration testing was made outdoors on 22 July 2020 at the Università Cattolica del Sacro Cuore (Piacenza, Italy, 45°2'N; 09°42'E) on eight pots (0.27 m deep with an internal diameter of 0.26 m). Pots were filled with clay-loam soil having 35% sand, 36% silt and 29% clay. After Saxton et al. (1986), the total available water was calculated at 0.14 cm cm⁻¹, whilst field capacity and wilting point were 32.8 and 18.7 % vol, respectively.

Four different pot management practices were tested with two replicates each. The four treatments were: i) wet soil tillage (WST); ii) surface-dry soil tillage (ST); iii) *Lotus corniculatus* (LC) and iv) *Festuca arundinacea* (FA) grassed soils (Fig. 3). Both *L. corniculatus* and *F. arundinacea* were pot seeded in April 2020 and by the time calibration readings were taken both cover crops had 100% soil coverage and no weed species growth was recorded (Fig. 3).

To facilitate grass establishment and avoid any water deficit, a single dripper was fitted in each pot delivering 350 mL of water 3 times a day. Automated irrigation was stopped one day before the calibration test and, the day before, 1L of water was given to each pot. In order to include in the comparison a tilled treatment having a dry surface, in ST irrigation was interrupted 8 days before measurements.

Pot soil management consisted of one mowing event and one soil tillage. On the 6 July 2020, the cover crop in the four pots assigned to LC and FA treatments was hand-trimmed to 4 cm. On the same day, soil tillage was implemented in the WST and ST treatments. Surface soil was lightly cultivated using a three-tooth rake.

Calibration consisted of one full day experiment. Each pot was weighed in the morning at the beginning of the calibration run and then the chamber measurements were conducted every 2 h (from 9:00 to 19:00). Daily water loss was estimated as the area underneath the regression curve that represented best fit to each pot diurnal evapotranspiration (ET) pattern. Whereas, the gravimetric loss was determined by weighing the pot at the beginning and end of the day. Data were then expressed as daily rate of evapotranspiration (mm d⁻¹).

The steel frame was omitted in this pot calibration and the chamber was directly laid on the pot surface having a diameter allowing a perfect fit without gas leak risks.

During each measurement, the air temperature and relative humidity outside and inside the chamber was measured at 15 s intervals with the air VPD calculated accordingly. For each pot ET assessment, PAR was recorded through the silicon photodiode positioned on the upper lid facing the outside of the chamber.

Data were recorded on the SD card and simultaneously visualized in the small display set on the lid or directly on the tablet connected through a USB-cable. All data were collected only under clear sky conditions.



Fig. 3. View of the treatments tested as: A) *F. arundinacea*; B) *L. corniculatus* and C) bare soil.

2.4. Pot experiment

To demonstrate ability of the new sensor to detect even small differences in water use by different cover crops as compared to two control treatments in a different condition (i.e. wet and dry bare soil) a further experiment was conducted on 23 July 2020 on twelve pots as previously described in the outdoor calibration test. The same four different soil management treatments were tested, this time with three replicates each.

Before mowing (6 July 2020), the above-ground biomass of 15 plants from each cover crop treatment (i.e. five plants per pot per treatment) was collected. Grass height was measured and, once scanned, green leaf area was estimated using the image-analysis Image J software (National Institutes of Health, Bethesda, MD, USA). Leaf area index (LAI) was then calculated as m^2 of green leaf area per m^2 of ground area. Cover crop LAI on the experiment day was estimated using the linear relationship between cover crop height and LAI obtained for both *F. arundinacea* ($y = 0.1358x + 0.6749$, $R^2 = 0.94$) and *L. corniculatus* ($y = 0.1389x + 0.8867$, $R^2 = 0.91$). The portable chamber operating as a closed system was used, as already illustrated, to assess the difference in terms of water loss. No further gravimetric confirmation was conducted in this experiment based on the quite encouraging outcome from the pot calibration itself.

Data were expressed as hourly rate of evaporation ($mm\ h^{-1}$) and converted in daily rate ($mm\ d^{-1}$) for further evaluations.

2.5. Statistical analysis

The degree of variation around means was given as a standard error (SE). Both linear (LR) and quadratic (QR) regression analysis were used

when appropriate. One-way analysis of variance (ANOVA) was applied to the pot experiment data to evaluate treatment differences within each sampling time using the SigmaStat software package (Systat Software, Inc.). In case of significance of Fisher's test, mean separation was performed through the Student Newman Keuls (SNK) test at 5% probability.

3. Results and discussion

3.1. Laboratory and pot calibration of the chamber system

The plot of the gravimetric evaporation data versus the corresponding values obtained using the chamber system yielded a highly significant linear relationship ($R^2 > 0.96$) for both the laboratory and the pot system calibration test (Fig. 4 A,B). However, plotting chamber derived E ($mm\ h^{-1}$) vs gravimetric evaporation from the water filled cloth, showed that with increasing cloth drying the chamber measure tended to increasingly underestimate E data, especially above the $0.4\ mm\ h^{-1}$ threshold.

This is not surprising as due to the quite small chamber volume (28L) progressive RH build up within the chamber is expected to decrease evaporative demand around the wet cloth. Sticking to closed chamber systems, the nearest comparison in literature is the one reported by Luo et al. (2018) who worked on different field crops using chambers of different sizes. Although, their smallest chamber was 1395 L in volume, therefore much bigger than the one we used. Using the same calibration methodology and plotting data over the same range of E values (i.e. $0-0.85\ mm\ h^{-1}$) they found no chamber underestimation at relatively high values. Yet, at the same time, they also confirmed that the closest relationship was held from 0 to $0.4\ mm\ h^{-1}$ E rates. Despite the huge

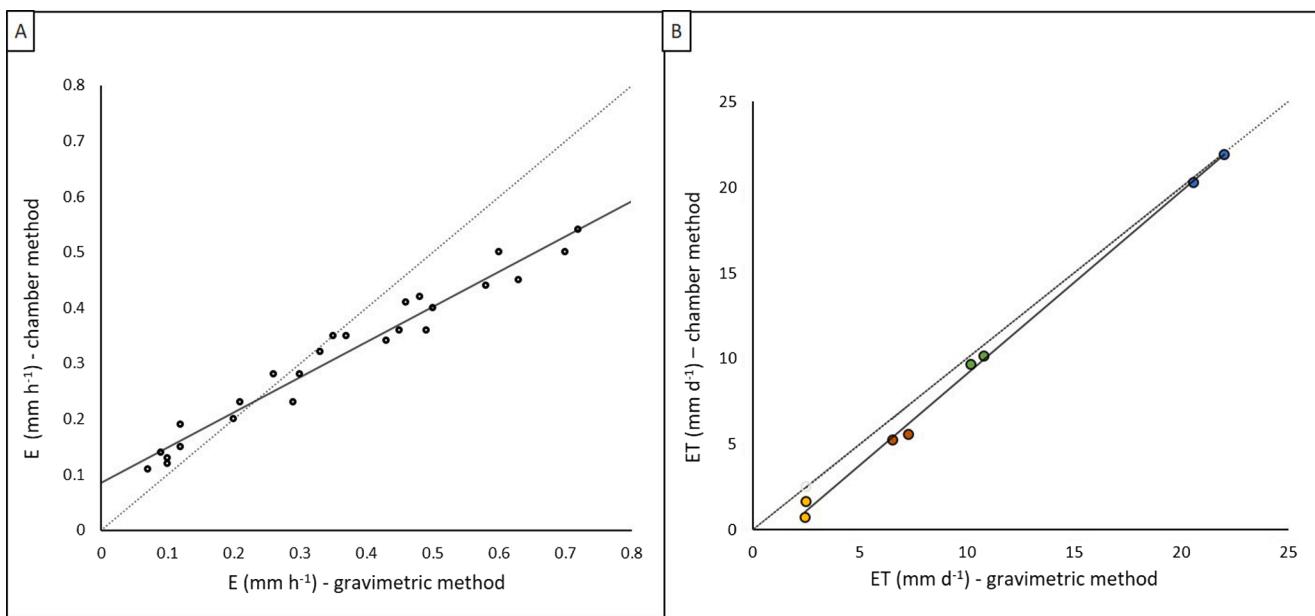


Fig. 4. Linear regression analyses between (A) the cloth water loss (hourly averages of evaporation) measured gravimetrically and estimated by the chamber and (B) cumulated pot daily water loss measured gravimetrically and determined as the area under the daily ET curves estimated by the chamber. Four different treatments are represented in (B): *L. corniculatus* (blue circles), *F. arundinacea* (green circles); wet soil (orange circles) and surface-dry soil (yellow circles). Linear regression equations are (A) $y = 0.6325x + 0.0856$, $R^2 = 0.9611$ and (B) $y = 1.0649x - 1.5513$, $R^2 = 0.9979$. Dotting indicates the 1:1 line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

difference in chamber size, this is in close agreement with our data and it suggests that, regardless of chamber volume within the above specified limits, reliable instantaneous E measures up to about 0.4 mm h^{-1} can be granted by a closed chamber system. Taken on a daily basis and assuming an average of 10 h of not limited transpiration, the calculated amount of about 4 mm d^{-1} would be able to accommodate even the transpiration rates of the most luxurious grass (Lopes et al., 2004). When the same water cloth calibration was carried out, again for a very similar range of water loss rates ($0\text{--}0.6 \text{ mm h}^{-1}$) and at two different air flow rates (9.2 and 21.6 L s^{-1}), using an open chamber system with a volume of 196 L (Centinari et al., 2009) the underestimation found in our study vanished. This confirms that, when using a closed chamber system with a limited chamber volume, it is critical to define the maximum time recording window beyond which RH build up inside the chamber would render E estimation less accurate.

Fig. 4B presents the daytime cumulative chamber and gravimetric evapotranspiration (ET) values performed outside in small pots sown with two different cover crops and two bare soil controls (one wet and the other one with dry surface) whereas Fig. 5 shows an example, for the 4 treatments, of ET (A), relative humidity (B), temperature (C) and VPD (D) variation over the 120 s readings taken at 16:00, having time zero set at 15 s after chamber positioning.

Despite slight underestimations of the actual gravimetric daily water loss when below 5 mm d^{-1} , the chamber measurements showed a very close linear fit ($R^2 = 0.99$) and the regression line was not significantly different from the 1:1 line (Fig. 4B). These results are quite encouraging since, in agreement with Lou et al. (2018), it is confirmed that increasing the time scale of measurements (in our case from instantaneous to daily ET values) is quite helpful to smooth out the error inherent to instantaneous readings. When examining the dynamic of ET of the 4 treatments within the 120 s time window (Fig. 5A), it is apparent that maximum ET gain occurred over the first 60 s (+88%, +88%, +84% and +83%) as compared to time zero for LC, FA, WST and ST, respectively with a tendency to become linear during the second 60 s half. Clearly, low evaporation rates recorded in the surface dry soil treatment were not able to quickly saturate the chamber volume and maintained a more linear trend over the recording time window. Not surprisingly, similar

patterns were also found for RH increase (Fig. 5B), however it is worth noticing that LC, FA and WST tended to overlap over similar RHs as a likely result of fast chamber humidification. Correctness of our time window length is confirmed by the air heating pattern inside the chamber (Fig. 5C) showing that it never exceeded 2°C as compared to time zero and saturated in all treatments after the 60 s time window. This shows that the wet bulb temperature is reached after 60 s of chamber closure as it coincides with the adiabatic saturation temperature (Stull, 2011).

3.2. Cover crop and soil water loss in the pot experiment

Data collection performed on 23 July at five times during the day from 9:00 to 19:00 occurred at an ambient relative humidity (RH) varying between 32 and 53% (Fig. 6A) while air temperature changed from 31.1°C recorded at 9:00 to the peak of 38.6°C registered at 13:00 (Fig. 6B). As a result, daily VPD varied from a minimum of 1.8 kPa to a maximum of 3.3 kPa recorded at 16:00 (Fig. 6C).

As expected, upon chamber placement, the RH increase was faster and higher in grassed pots and lower in the surface-dry soil tillage (Fig. 6A). After 60 s of chamber closure, FA and LC RH ranged between 80 and 90%, whilst ST relative humidity never exceeded 70%. RH increase in ST was higher in the first part of the day (i.e. 9:00 and 11:00) while in the afternoon ST relative humidity recordings were very close to the outside values. That is probably due to some dew accumulation during the night on the soil surface that is progressively lost during the day. Conversely, inside the chamber RH increase in WST closely paralleled that of grassed pots albeit recording slightly lower rates.

The temperature increase (ΔT) inside the chamber never exceeded 2°C more than the one outside (Fig. 6B) therefore falling within a range of acceptable alteration as compared to the surrounding environment (Garcia et al., 1990). The recorded ΔT was similar to the one reported in other studies using closed chambers (Grau, 1995; Guidolotti et al., 2017). However, it is quite relevant that, in our study, reasonable chamber heating was obtained under conditions of high radiation load and VPD; conversely Grau (1995) worked in an environment where ambient temperature never exceeded 22°C therefore making the issue of

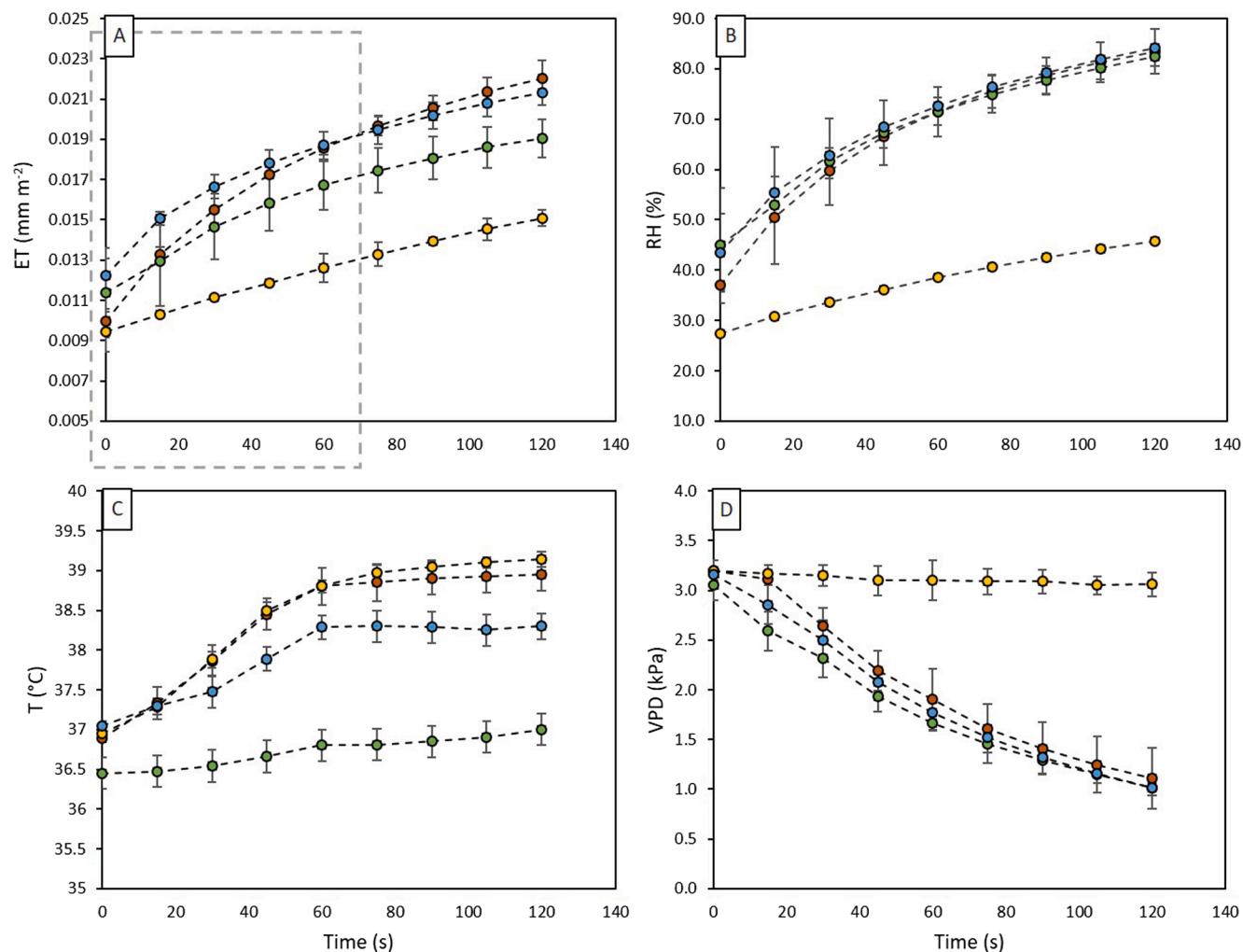


Fig. 5. (A) Representative ET trends (mm m^{-2}) for *L. corniculatus* (LC, blue circles) and *F. arundinacea* (FA, green circles) cultivated soil, wet soil tillage (WST, orange circles) and surface-dry soil tillage (ST, yellow circles). The calculation time window (TW) is referred to the first 60 s of the water loss curve as described by the following quadratic equation: (LC) $y = -1E-06x^2 + 0.0002x + 0.0123$, $R^2 = 0.99$; (FA) $y = -6E-07x^2 + 0.0001x + 0.0113$, $R^2 = 0.99$; (WST) $y = -1E-06x^2 + 0.0002x + 0.01$, $R^2 = 0.99$; (ST) $y = -1E-07x^2 + 6E-05x + 0.0094$, $R^2 = 0.99$. ET values are mean \pm SE ($n = 2$). Inside the chamber trends for relative humidity (B), air temperature (C) and VPD (D) measured for the four treatments during the 120 s of chamber closure are also shown. Relative humidity, Temperature and VPD values are mean values \pm SE ($n = 2$). Data refer to reading taken at 16:00 on 22 July. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

chamber heating less significant. Indeed, our results point out that, even in a small closed chamber, a good control of chamber heating can be achieved also in very warm days provided that rapid measurements for brief periods (1–2 min) are used.

Within each single measurement session, significant differences between the wet soil tillage (WST) and the dry soil tillage (ST) treatments were found (Fig. 7). For data pooled over the five periods of measurements ET in ST was curtailed by around 30% as compared to WST. The maximum gap between these two treatments was reached during the hottest time periods (i.e. 13:00 and 16:00).

Although in our study we did not measure the daily evaporation rates of a wet soil that is left to dry out, our maximum WST water loss rate is similar to what was reported by Wythers et al. (1999) where recently irrigated bare soil daily evaporation rates were assessed to be as high as 7.5 to 9 mm d^{-1} and to remain around 4.5 to 7.5 mm d^{-1} for the first 6 days of the experiment. This was assessed for a clay-loam type soil that is also the same soil type used in our study. In our experiment, daily averaged ET values of WST were 5.43 mm while ST, which was monitored 9 days after the last irrigation event, registered 1.2 mm d^{-1} of water loss. Evaporation rates measured in the field on bare soil with an open chamber system after two rain events (a condition that approximates to

our WST treatment) were around 3.3 mm d^{-1} (Centinari et al., 2013) a value that is a good match with the daily average amount of 0.54 mm h^{-1} measured in our study.

Indeed, variability in such comparisons should take into account: i) the changes in resistance to evaporation due to differences in soil texture; ii) the amount of energy available able to drive the evaporative process (e.g. soil light interception depending upon time of the day and interaction with the grapevine canopy) and iii) the amount of water available to evaporate (Wythers et al., 1999). It is agronomically relevant from our WST recorded hourly values that a wet soil can have evaporation rates as high as those of *L. corniculatus* cover crop (LC) and even more than *F. arundinacea* (FA). For example, in the warmest hours of the day, WST and LC registered values as high as 0.58 and 0.78 mm h^{-1} , respectively at 11:00 and 13:00, while FA mean hourly ET never exceeded 0.45 and 0.70 mm h^{-1} in the same time period (Fig. 7). It has been shown that water loss trend from a wet soil has a typical exponential dynamic showing that 8–10 days after a wetting event the water loss becomes negligible (Wythers et al., 1999).

Daily evaporation rates measured in ST ranged from 0.18 to 0.30 mm h^{-1} showing a statistical difference with any other treatments at any timing of measurement. The daily evaporation under ST observed in the

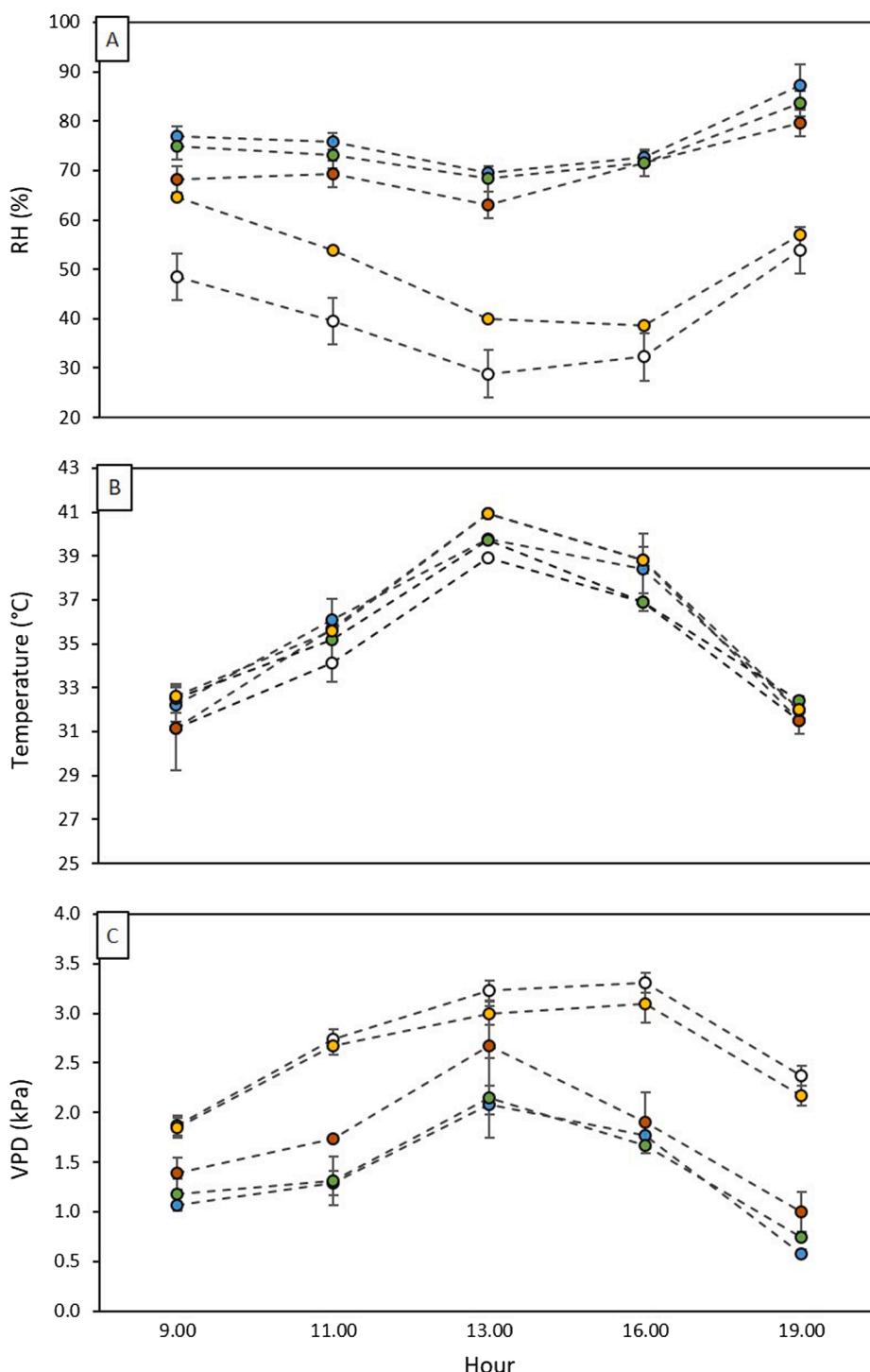


Fig. 6. Diurnal trends for relative humidity (A), air temperature (B) and VPD (C) measured on 23 July outside the chamber (open circles) and inside the chamber for wet bare soil (WST, orange circles), surface-dry soil tillage (ST, yellow circles) and grassed soil with *L. corniculatus* (LC, blue circles) and *F. arundinacea* (FA, green circles) after 60 s of chamber closure. Relative humidity, Temperature and VPD values are mean values \pm SE ($n = 3$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

current study and estimated as the area underneath the regression curve that represented best fit to the diurnal ET pattern was of 1.2 mm d^{-1} . This value is lower than the one found in a vineyard trial as reported in Centinari et al. (2013) where tilled soil registered a water loss of 1.97 mm d^{-1} . Moreover, water loss from ST was fairly constant during the day and did not follow, for instance, air VPD which was maximum at 16:00 (Fig. 6D) when ET was lower than the rate measured at 11:00 (Fig. 7). This behaviour is helpful when trying to estimate how evaporation from dry soil can contribute to whole-vineyard water balance where tillage is still the most frequent practice (Wythers et al., 1999).

FA hourly rates of ET ranged from 0.3 to 0.7 mm h^{-1} showing higher values than ST (ranging from 0.2 to 0.3 mm h^{-1}) yet lower than those of

LC and WST as daily VPD increased. For instance, in the warmest hours of the day (i.e. from 11:00 to 16:00) FA mean hourly ET was of 0.56 mm while LC and WST registered 0.71 and 0.69 mm h^{-1} , respectively. Indeed, when comparing cover crop water use across different experiments, differences in LAI should be taken into account. Similar differences between FA and LC are also presented in Grau (1995) where FA during the day registered values that were 20 to 30% less than those recorded on the legume grass. It is quite encouraging that FA water use estimated by Grau (1995) refers to a grass height (16–18 cm) and a LAI (2.8–3.6) quite similar to the conditions of our study where the same parameters set at 13.5 cm and 2.5, respectively. Our measured daily FA water consumption is also in close agreement with data reported by

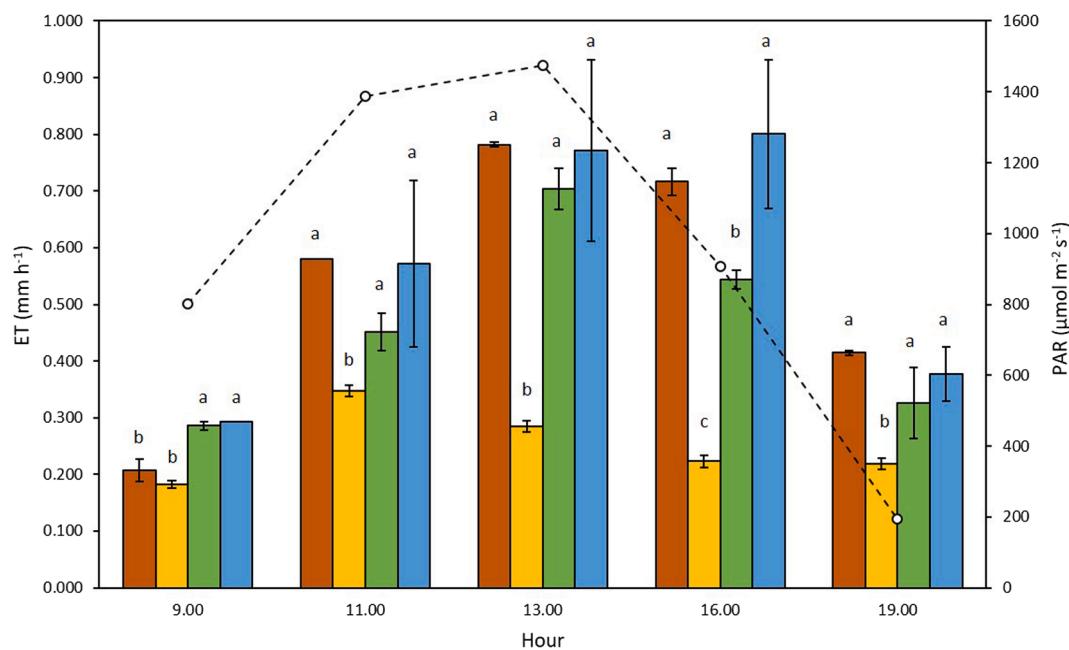


Fig. 7. Diurnal trends of evapotranspiration (ET, mm h⁻¹) for the wet bare soil (■), surface-dry soil tillage (□), *F. arundinacea* (▨) and *L. corniculatus* (▨). Open circles indicate hourly PAR (μmol m⁻² s⁻¹). Data were collected on 23 July. ET are means ± SE (n = 3). For a given hour different letters indicate significant differences among treatments (SNK test, p < 0.05).

Litvak and Pataki (2016) while being higher than the ones recorded in Centinari et al. (2009). That is probably due to different water availability: while in Litvak and Pataki (2016) ET of irrigated turf grass reached a maximum of 10.4 mm d⁻¹, in Centinari et al. (2009), daily water consumption of *F. arundinacea* sown in mid rows of a non-irrigated mature vineyard was estimated at 3 to 4 mm d⁻¹. Our FA recorded ET values of 9 mm d⁻¹ are therefore higher than the ones recorded in Centinari et al. (2009) but very close to what assessed by Litvak and Pataki (2016). Moreover, Centinari et al. (2009) worked under field conditions which were conducive to a slower grass regrowth after cutting: they had 10 cm regrowth upon 21 days after slashing, while we reached 13.5 cm after 17 days. This would confirm likely sub-optimal water supply condition in Centinari's experiment. Our FA daily water loss rates also match quite closely data reported by Uliarte et al. (2013) for the same species. ET rates they reported for a hot summer day (T = 38.1 °C and PAR = 1582 μmol m⁻² s⁻¹) within the time window between noon and 15:00 are around 320 gH₂O m⁻²h⁻¹ against about 250 gH₂O m⁻²h⁻¹ estimated in the current experiment from 13:00 to 16:00. Others have estimated up to 6.8 mm d⁻¹ of water used for tall fescue (*F. arundinacea*) under continuously well-watered conditions using a simulation model (Qian et al., 1996).

L. corniculatus cover (LC) registered, together with the WST, the highest values of water loss. LC ET values ranged between 0.29 (i.e. at 9:00) and 0.8 mm h⁻¹ (i.e. at 16:00). This is in agreement with what found by Grau (1995) where *L. corniculatus* registered over the day values as low as around 3 mmol H₂O m⁻² s⁻¹ in the early morning (i.e. 9:00) reaching a peak value of about 11 mmol H₂O m⁻² s⁻¹ at 14:00. Notably, Grau's work refers to readings taken at the beginning of flowering on a 16–18 cm tall LC cover with a LAI of 4.6–5.0, whereas we were at the same phenological stage yet with grass height of 29.6 cm and a LAI of 5. Shorter grass height in Grau's experiment might explain why their ET increase during the morning was slower than the rate recorded in our experiment.

In terms of a more general discussion on the type of data that the chamber can deliver, as well as modalities and accuracy of sampling, it is inherent the usefulness of this kind of equipment that bursts from the following items: i) vineyard management is rapidly evolving towards sustainable soil management where tillage or native grass are

increasingly replaced by sown cover crops (Diti et al., 2020); ii) proper selection of these implies that their water use, before and after slashing, is known in order to limit water competition towards the associated grapevines and iii) in several instances, presence of grass cover (either native or sown) in a vineyard is a largely neglected factor in terms of contribution to the whole vineyard seasonal water budget and need to be precisely determined and incorporated into this budget. It has been shown that a fraction of water use accounted for/by grass covers in a vineyard ecosystem can represent up to 30–40% of the total water use (Uliarte et al., 2013).

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4. Conclusions

In this study a low-cost, custom-made closed portable chamber was tested under controlled and semi-controlled conditions (i.e. laboratory and an outdoor pot-lot). The plot of the gravimetric evaporation data versus the corresponding values obtained using the chamber system yielded a highly significant linear relationship for both the laboratory and the pot system calibration test (R^2 equal to 0.96 and 0.99, respectively). We infer that running calibration under ambient conditions (as opposed to controlled) greatly reduce chamber biases and provide best accuracy.

The chamber proved to be a reliable, efficient and accurate way to

measure ET for a range of time scales (i.e. instantaneous and cumulated daily) under bare soil conditions and sown crops of *L. corniculatus* and *F. arundinacea*. Moreover, the chamber is low cost, easy to set up and can be transported rapidly across experimental plots. Therefore, the newly proposed system enables, for example, fast multipoint evaluations of ET fluxes at a very reasonable budget. Future studies will include validation of the chamber method over a range of cover crop varieties and orchard field conditions.

CRediT authorship contribution statement

Caterina Capri: Conceptualization, Methodology, Data curation, Visualization, Writing – original draft. **Matteo Gatti:** Conceptualization, Supervision. **Paolo Guadagna:** Investigation, Data curation. **Filippo Del Zozzo:** Investigation, Data curation. **Eugenio Magnanini:** Conceptualization, Investigation, Resources, Software, Validation. **Stefano Poni:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.compag.2021.106361>.

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