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HIGH PRECISION WEIGHING LYSIMETERS FOR EVAPOTRANSPIRATION MEASUREMENTS OF SUGARCANE PRE-SPROUTED PLANTLETS

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KEYWORDS

irrigation, water balance, water requirement.

ABSTRACT

Sugarcane pre-sprouted plantlets (PSP) production system is an innovative method to enhance crop multiplication rate. Determination of crop evapotranspiration (ET_c) is crucial for water requirement identification throughout the plant cycle for irrigation management. ET_c can be satisfactorily measured by weighing lysimeters. The objective of the study was to construct and calibrate three low-cost weighing lysimeters to measure ET_c of PSP. The built lysimeters had 0.6909 m² area (1179 mm x 586 mm), with 400 mm depth supported by 3 load cells. Lysimeters calibration showed excellent precision measurements, due to high linear correlation ($R^2 = 1.0000$) between electric signal and equivalent mass, high accuracy, confirmed by mean absolute error between 0.0272 and 0.0382 mm, mean square error between 0.0011 and 0.0024 mm² and Willmott's index of agreement (d) equal to unit. Maximum hysteresis (0.1951 mm) and hysteresis at full scale (0.4492%) did not compromise the evaluations. Daily ET_c measurements showed variation of 0.27 mm among lysimeters and were coincident with daily course of reference evapotranspiration (ET_o). The cost of the equipment was low, except for the data acquisition system. Therefore, lysimeters presented low cost and were adequate to measure ET_c of PSP in greenhouse-grown.

INTRODUCTION

The system of production of pre-sprouted plantlets (PSP) is an innovative and efficient method for sugarcane planting, as it allows the reduction in the use of buds, providing higher crop's multiplication rates and better control in plants vigor quality. The PSP production consists on growing plantlets originated from buds (species asexual reproductive structure) contained in stalks nodes, named as mini-stalks, planted in tubes filled with substrate (Landell et al., 2012).

PSP is grown in greenhouses, where correct irrigation management is of great importance for a successful production. Pardossi & Incrocci (2011) warn that poor irrigation often causes production losses and reduced quality on final product, while excessive irrigation increases crop susceptibility to diseases, pumping energy costs, water wastage, and environmental pollution due to nutrient leaching. Despite the industry's willingness to provide high technology equipment for irrigated agriculture to producers, in many cases, irrigation

management is carried out empirically (Pardossi & Incrocci, 2011; Repullo et al., 2015).

Adequate replenishment of consumptive water by a crop is of fundamental importance to the success of irrigated agriculture, and its determination depends on numerous edaphoclimatic variables, of management and crop, that must be analyzed prior to the implementation of the hydraulic project. Among various methods available, the FAO-56 (Allen et al., 1998) is considered standard for determining crop water requirements in general. In such a method, crop evapotranspiration (ET_c) is calculated as a function of the product between crop coefficient (K_c), experimentally determined, and reference evapotranspiration (ET_o), calculated with meteorological data obtained at the location where K_c was previously determined.

Among several methods of experimentally determination of ET_c and K_c, the methodology of weighing lysimeters is considered a standard in studies of water consumption of crops (Mariano et al., 2015; Hagenau et al., 2015). This equipment is a small representative plot of a large area, constructed to measure

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water balance components of a vegetated surface or of bare soil. With lysimeter measurements, K_c value can be experimentally determined by the ratio between ET_c and ET_o along the crop cycle.

Lysimeters are composed of a tank filled with soil or substrate, installed with its surface level to the area around the land, and being desirably, undetectable to the naked eye due to the similarity of its cover in relation to external area. They are supported in a weighing mechanism that measures the mass variation of the system and transmits it as an electrical signal to a datalogger that registers the values at defined time intervals (Peñalver et al., 2015; Hagenau et al., 2015). One of the difficulties in using lysimeters is the high cost of construction and installation (Nascimento et al., 2016; Silva et al., 2016).

In the literature, there is no information on ET_c from PSP under protected cultivation to calculate the water requirement of sugarcane, unlike other species traditionally grown in this environment such as tomato (Qiu et al., 2014), strawberry (Gavilán et al., 2015) and gerbera (Carmassia et al., 2013). There are also no suitable lysimeters for the measurement of ET_c of PSP in protected environment.

In this context, the present study was conducted with the objective of exposing details of the construction and calibration of three low cost lysimeters as well as evaluating their capacities to measure ET_c under protected environment conditions for PSP production.

MATERIAL AND METHODS

Place of study

The present study was carried out in a greenhouse using pre-sprouted sugarcane plantlets from the São Martinho Mill (São Martinho S/A), located at the geographic coordinates 21°19'23'' S and 48°06'47'' W and 528 meters of altitude, in the municipality of Pradópolis, SP. According to the classification of Köppen-Geiger (Alvares et al., 2013), the climate of the place is classified as humid subtropical (Aw), with dry and mild winter and hot and rainy summer. The greenhouse of the study was composed of 8 spans with arches of 7 m wide and 24 modules of 4.5 m of length each, totaling 6048 m² (56 m wide and 108 m long). In the cover, a Polysack Ginegar diffuser plastic film was used, with a thickness of

150 µm and ultraviolet treatment with 15% solar radiation filter, while the frontal and lateral ones were made of white net with a thickness of 150 µm and ultraviolet treatment with 30% filter.

Building and installation of the equipments

Three lysimeters (Lysimeter 1, Lysimeter 2 and Lysimeter 3) were installed in the greenhouse, each one made to support a set of three trays composed of 54 tubes of 180 ml each, totaling 162 plants of PSP of sugarcane by lysimeter.

The lysimeter tanks were made in a rectangular format with dimensions of 1179 mm in length, 586 mm in width (0.6909 m²) and 400 mm in height, using 1.58 mm thick carbon steel plates that were painted with gray epoxy paint to prevent oxidation of the materials (Figure 1). In order to facilitate drainage water in the lower part of the tanks, four plates were installed in the diagonal direction between the four vertices, forming a four-direction flow system. In the center of the lower part, was installed a tube and a manual valve, also of carbon steel. In each lysimeter tank, a holder for a load cell junction box was installed on the larger side (1179 mm), which was also made of 12.7 mm thick carbon steel, but with dimensions of 200 mm in length and 150 mm wide. At the side of the junction box, a level indicator was also installed, which the purpose was to monitor the water level and identify the time to drain the excessive water. Under each tank were welded three solid sticks of 150 mm long and 24 mm in diameter, with the presence of external threads throughout its length. For the height adjustment, in these solid sticks were threaded sticks of 250 mm long, 30 mm in diameter and 3 mm thick, with internal threads also throughout its length, allowing a maximum length of the set of threaded sticks up to 400 mm. The bottom of the hollow stick was fitted with a smooth solid stick 80 mm long and 24 mm in diameter, screwed into the upper face of one side of the load cell. On the other side, the top and bottom faces of the load cells were screwed into welded supports on a rectangular support base with the dimensions of 600 mm long, 400 mm wide and 12.7 mm thick. The base was laid on the ground by four pointed sticks 150 mm long and 20 mm in diameter, located at the 4 ends of the lower part for penetration and fixation of the base on the ground.

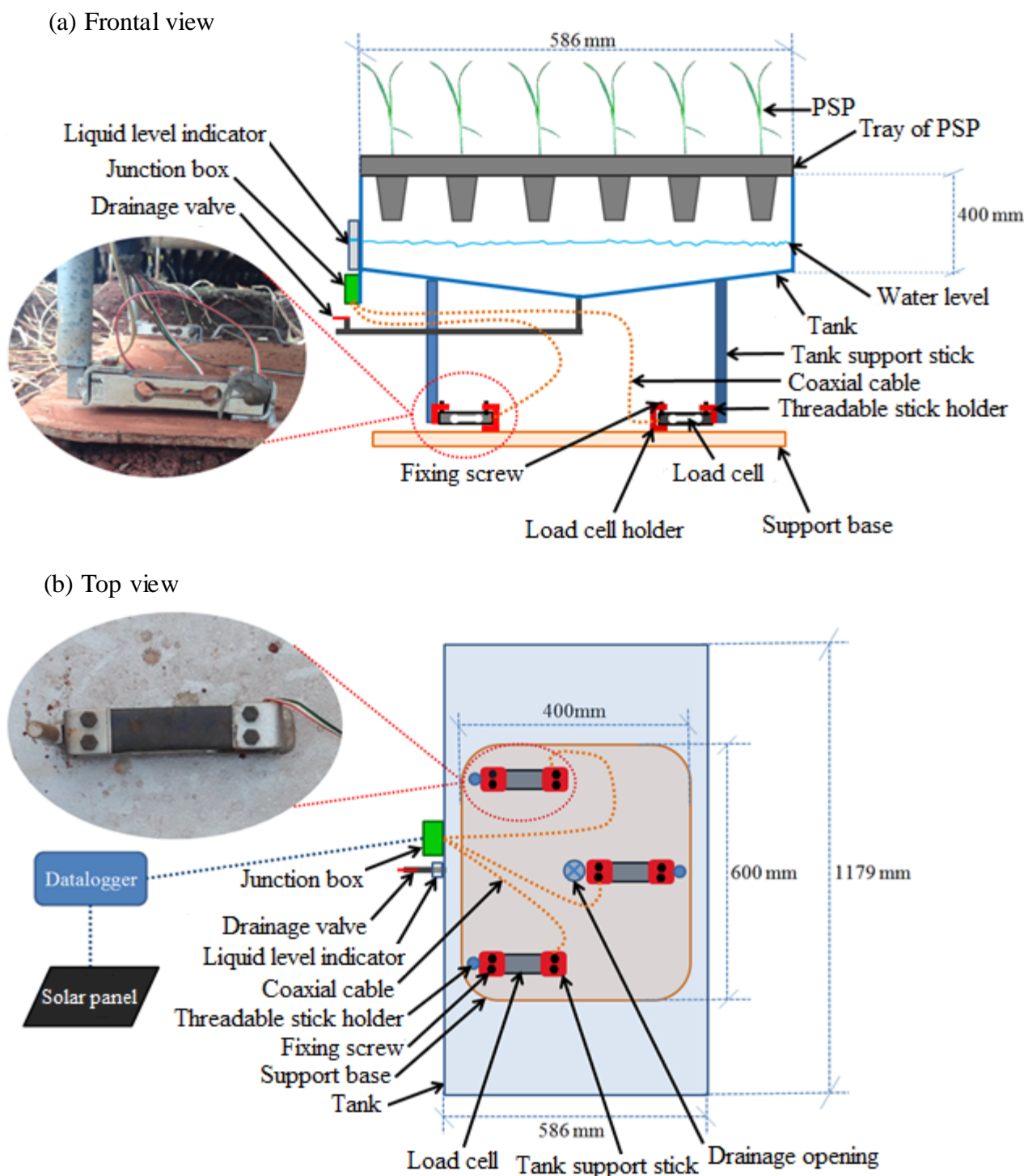


FIGURE 1. Schematic frontal view (a) and top view (b) of the lysimeters.

Previously to lysimeter installation, soil was leveled and a support base was constructed at the installation site. Load cell holders were then installed on main support base, the load cells being subsequently installed in these supports. Two screws were used to attach the load cells to the supports. Then, the lysimeter tank was supported by the triple set of load cells. The lysimeter sticks were attached to the top of the load cells, also using two screws for the correct fixation. The junction box has been properly fixed by four screws on the junction box support. Positioning adjustments were made to ensure the free flotation of the tanks on the load cells so that there was no external interference.

Subsequently, the lysimeter data acquisition system was installed composed of datalogger, multiplexer and solar panel for the supply of electric energy to a battery. The installation was made using prefabricated steel supports and fixed at the support posts of the structure of the greenhouse. After the structural installation, cables were connected between load cells, junction boxes and lysimeter data acquisition system.

The load cells used (GL-30, Alfa Instrumentos Eletrônicos Ltda., São Paulo, SP, Brazil) were manufactured in aluminum with nominal capacity of 30 kg, sensitivity of $2.0000 \pm 10\% \text{ mV V}^{-1}$ and accuracy of 0.03% full scale according to the manufacturer. A junction

box (4134 A, Alfa Instrumentos Eletrônicos Ltda., São Paulo, SP, Brazil) per lysimeter was used. It had the function of combining the electrical signal of the three load cells which was then retransmitted by only one coaxial cable to the datalogger. A data acquisition system for the three lysimeters was used for the collection and storage data from the load cells. This system was composed by multiplexer of differential channel (AM 416 Relay Multiplexer, Campbell Scientific, Logan, Utah, USA) and datalogger (CR10, Campbell Scientific, Logan, Utah, USA). The system power supply was made with a 12V and 7A battery coupled to a solar panel generator (SP20R-PW, Campbell Scientific, Logan, Utah, USA). Stored data transfer was done directly to the microcomputer or indirectly to the memory module that later had the data transferred into a microcomputer through a software (PC200W, Campbell Scientific, Logan, Utah, USA) specific for this purpose. The datalogger was programmed to perform load cell readings every second

and the data storage was published on average every 20 minutes.

A meteorological station was installed with sensors to register temperature and relative humidity of the air in the canopy (HC2SC3-L, Campbell Scientific, Logan, Utah, USA) protected with radiation shield 12 plates, net solar radiation (Campbell Scientific, Logan, Utah, USA) and wind velocity at 2 meters (A100LK, Campbell Scientific, Logan, Utah, USA). The data acquisition system of this weather station is independent of the lysimeter data acquisition system, being configured to perform readings every second and store the average data every 10 minutes by datalogger (CR10X, Campbell Scientific, Logan, Utah, USA), also with differential channel multiplexer (AM 416 Relay Multiplexer, Campbell Scientific, Logan, Utah, USA) and 12V and 7 A battery and solar panel-power (SX10M, Campbell Scientific, Logan, Utah, USA) (Figure 2).

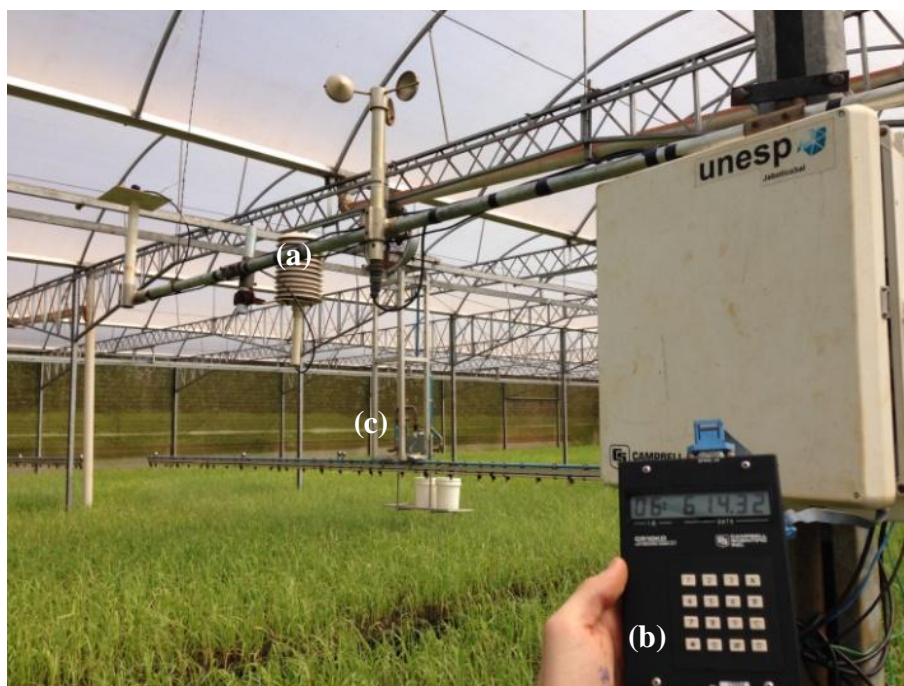


FIGURE 2. Weather station (a), data acquisition display module (b) and irrigation bar (c).

Calibration of lysimeters

After installation, the calibration of the three lysimeters was performed on September 25th, 2016 and lasted 3 hours and 20 minutes (7:00 a.m. to 10:20 p.m.), with approximately 1 hour per lysimeter and 20 minutes for calibration preparations. During the calibration, the canopy air temperature ranged from 15.4 °C to 28.4 °C, the relative humidity of the air from 87.9% to 54.3%, and the wind velocity at 2 m of 0.0 to 0.8 m s⁻¹.

The methodology used in the calibration process of the lysimeters consisted of a correlation between the electric signal (ES), emitted from the load cells, and known masses applied in the system, in order to establish the linearity and hysteresis of these measurements (Faria et al., 2006). Before starting the calibration sequence, a mass of 26.4 kg was inserted on each lysimeter, which was equivalent to three trays with plantlets, in order to represent the dead weight in each lysimeter.

For the calibration, were used hermetically sealed bags filled with sand previously dried in drying oven of hot air circulating at 60 °C for 48 h. For the measurement of known masses, a precision digital scale of 0.01 g was used. The plastic bags totaled 40 units, of which 30 contained a mass of 664.68 g (bag S1), equivalent to 0.962 mm, and 10 units had a mass of 66.47 g (bag S2), equivalent to 0.0962 mm. The equivalent mass (EM) in mm was obtained by the relation between the sand mass by the lysimeter area (0.6909 m²). After establishing the dead weight of the lysimeter, the addition and removal of mass in the lysimeter started. The sequence of addition and removal of the bags was chosen so that the calibration comprised variations of equivalent mass of approximately 3 mm (set of 3 bags S1), 0.3 mm (set of 3 bags S2) and 0.1 mm (1 bag S2) to reach a total equivalent mass of approximately 30 mm. A set of 3 S1 bags (2.8860 mm) was added 5 times, providing an equivalent mass of 14.4349 mm, once a set of 3 S2 bags (0.28886 mm),

totaling 14.7195 mm, 4 times 1 bag S2 (0.0962 mm), totaling 15.1043 mm, once a set of 3 bags S2 (2.886 mm), totaling 15.3930 mm, 5 times a set of 3 bags S1 (0.28886 mm), totaling 29.8238 mm. Finally, in reverse sequence, the same procedure was performed for the discharge of lysimeters. The time between each addition and removal was 30 sec, the load cell voltage reading being performed at 10 and 20 after the addition or removal of the known mass. The 10 seconds of difference were chosen to guarantee that stabilization in the weight of the lysimeter occurred after the addition or removal of the mass.

The data obtained in the calibration were submitted to the coefficient of determination calculated in Microsoft Excel® spreadsheet to determine the precision, the mean absolute error (Equation 1), the mean square error (Equation 2) and the concordance index (Equation 3) proposed by Willmott (1985) to determine the accuracy. The Willmott index varies from 0 to 1, with 1 being the maximum agreement of the values estimated to the observed.

$$MAE = \frac{\sum |Y_{obs} - T_{est}|}{n} \quad (1)$$

$$MSE = \frac{\sum (Y_{obs} - T_{est})^2}{n} \quad (2)$$

$$d = 1 - \frac{\sum (Y_{obs} - Y_{est})^2}{\sum (|Y_{est} - \bar{Y}_{obs}| + |Y_{obs} - \bar{Y}_{obs}|)^2} \quad (3)$$

in which,

MAE - mean absolute error, mm;

MSE - mean square error, mm²;

n - number of observations, dimensionless;

d - Willmott concordance index, dimensionless;

Y_{obs} - standard equivalent masses used for calibration of lysimeters, mm;

Y_{est} - equivalent masses obtained in calibration of lysimeters, mm, and

\bar{Y}_{obs} - mean of standard equivalent masses used for calibration of lysimeters, mm.

In order to verify the variability in mass determination by the load cell between addition and mass removal, the hysteresis error (H) was calculated by the maximum difference between addition readings and the removal of the same mass values (Equation 4). In order to compare the errors of the two weighing systems, the hysteresis is expressed as a percentage of the full scale (HFS), according to [eq. (5)].

$$H = |Y_{ad_i} - Y_{rem_i}| \quad (4)$$

$$HFS = \frac{|Y_{ad_i} - Y_{rem_i}|}{C} \times 100 \quad (5)$$

in which,

H - hysteresis, mm;

Y_{ad_i} - equivalent mass obtained during calibration during the addition of mass "i" in lysimeters, kg;

Y_{rem_i} - equivalent mass obtained during calibration during removal of mass "i" in lysimeters, kg;

HFS - hysteresis at full scale, %, and

C - load cell capacity, 43.4 mm.

Lysimeters test

After the calibration, it was performed a mass variation check test in the lysimeters (M) for determination of ET_c, by the [eq. (6)].

$$ET_{c_i} = M_{i+1} - M_i + \sum_{i=1}^n B_i - \sum_{i=1}^n D_i \quad (6)$$

in which,

ET_{c_i} - crop evapotranspiration on the lysimeter at day "i", mm;

M_{i+1} - mass equivalent at 0h on the day following the "i", mm;

M_i - mass equivalent at 0h on "i", mm;

B_i - irrigation depths on the day "i", mm, and

D_i - drainage on the day "i", mm.

The values of ET_c obtained in each lysimeter were compared to ET_o, calculated by the Penman-Monteith equation (Equation 7), parameterized by the FAO-56 method (Allen et al., 1998) using the meteorological variables records obtained by the weather station.

$$ET_o = \frac{0.408 s (R_n - G) + \frac{\gamma 900 U_2 (e_s - e_a)}{T + 273}}{s + \gamma (1 + 0.34 U_2)} \quad (7)$$

in which,

ET_o - reference evapotranspiration, mm d⁻¹;

S - slope of saturation vapor pressure curve, kPa °C⁻¹;

R_n - net solar radiation, MJ m⁻² d⁻¹;

G - soil heat flux, MJ m⁻² d⁻¹ (negligible for daily values);

γ - psychrometric constant, 0.063 kPa °C⁻¹;

U₂ - wind speed at 2 m, m s⁻¹;

e_s - saturation vapor pressure, kPa;

e_a - actual vapor pressure, kPa, e

T - mean air temperature, °C.

PSP trays of the cultivar SP801816 were used 32 days after planting (DAP), previously selected and produced according to standard methodology of the nursery where the study was installed. This methodology was based on the following steps: (1) cutting and selection of mini-stalks; (2) planting mini-stalks in 180 ml tubes containing previously aged sugarcane bagasse; (3) mini-stalks coverage with vermiculite and; (4) sprouting of the

mini-stalks in an acclimatized greenhouse (7 days at 30 °C and 90% relative humidity). Three trays containing the plantlets were allocated to each lysimeter on September 30th, 2016. The measurements were held on October 1st and 2nd, 2016.

The irrigation was performed by spraying, applied by a 14 m wide irrigation bar, composed of 33 nozzles (TT TEEJET 11008VS, TeeJet, Springfield, Illinois, USA), spaced at 0.43 m (Figure 2). The regulation of the applied water level was adjusted by the speed of the bar, in which the flow was fixed in 2.6 l min⁻¹ nozzle⁻¹ and speed was limited in 8 m min⁻¹, with the possibility of applying depths greater than 0.67 mm with each pass.

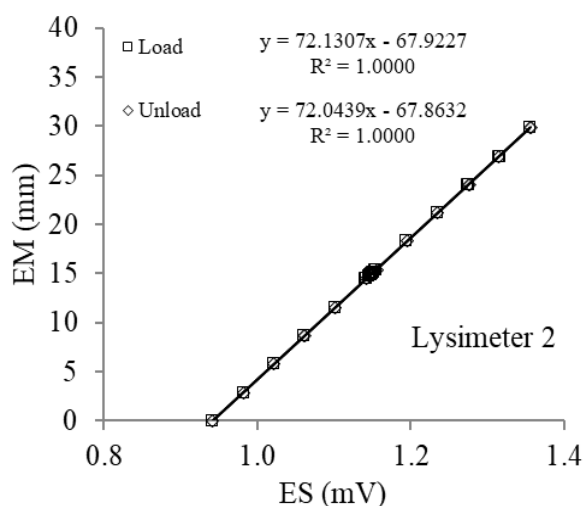
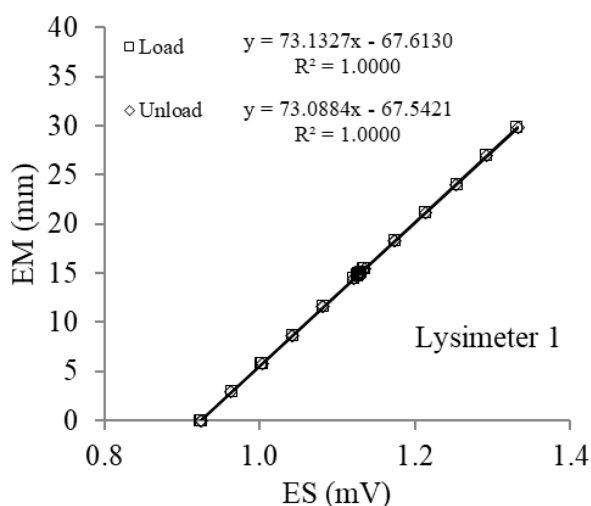
RESULTS AND DISCUSSION

The calibration of the three lysimeters presented a high correlation ($R^2 = 1.0000$) between equivalent mass in mm and electrical signal, evidencing a high precision in the measurement of the equipments. The analysis of the results indicated high homogeneity in the weighing characteristics between lysimeters, with values of angular coefficient (a) of linear regression varying from 72.0868 mm mV⁻¹ to 73.1104 mm mV⁻¹, that is, variation of 1.0236 mm mV⁻¹. In the same way, the variation of this coefficient between load and discharge was 0.0443 mm mV⁻¹ for Lysimeter 1, 0.0868 mm mV⁻¹ for Lysimeter 2 and 0.4109 mm mV⁻¹ for Lysimeter 3 (Figure 3). These variations

were lower than those found by Mariano et al. (2015), due to the smaller capacity of the load cells used by the authors. The linear regression coefficient (b) varied from -66.5319 mm to -67.8924 mm, that is, a difference of 1.3605 mm, which can be attributed to the differences in dead weights of each lysimeter. The mean absolute error varied from 0.0272 mm to 0.0382 mm, lower than those found by Mariano et al. (2015), Nascimento et al. (2011), Howell et al. (1995), Allen & Fischer (1991) and Faria et al. (2006) and similar to Campeche (2002). The mean square error varied from 0.0011 mm² to 0.0024 mm², it can be concluded that lysimeters are highly accurate. In addition, to the accuracy of the equivalent mass measurement in mm was also demonstrated by Willmott's index of agreement (d) (Willmott et al., 1985) which presented values of 1.0000 for the three lysimeters (Table 1), a result similar to observed by Mariano et al. (2015). The maximum hysteresis value of 0.1951 mm and hysteresis at the full scale of 0.4492% observed in Lysimeter 3 did not compromise the equivalent mass ratings in mm in the three lysimeters of the study. Therefore, the equipments are suitable for ETc of PSP evaluations with precision and accuracy around 0.1 mm, which is suitable for applications in protected cultivation.

TABLE 1. Coefficients of linear regression of the line $y = ax + b$ between equivalent mass (y, in mm) and electrical signal (x, in mV), coefficient of determination (R^2), mean absolute error (MAE), mean square error (MSE), Willmott index (d), hysteresis (H) and full scale hysteresis (HFE) of the calibration of the three lysimeters.

Lysimeter	a	b	R^2	MAE (mm)	MSE (mm ²)	d	H (mm)	HFS (%)
1	73.1104	-67.5774	1.0000	0.0272	0.0011	1.0000	0.1260	0.2901
2	72.0868	-67.8924	1.0000	0.0330	0.0017	1.0000	0.1649	0.3798
3	73.0558	-66.5319	1.0000	0.0382	0.0024	1.0000	0.1951	0.4492



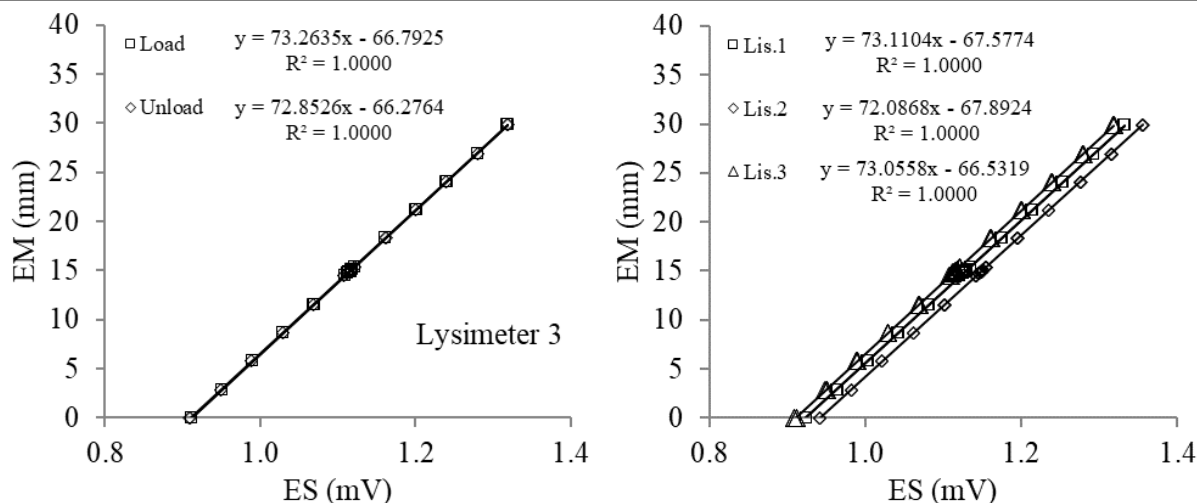


FIGURE 3. Relationship between equivalent- mass (EM) and electric signal (ES) for load and unload of lysimeter 1 (a), lysimeter 2 (b), lysimeter 3 (c) and for load and unload together values on the different lysimeters (d).

On the two days of the evaluation of the lysimeters, two irrigation events occurred on 10/01/2016 (7:40 a.m. and 2:40 p.m.), as well as on 10/02/2016 (10:40 a.m. and 12:00 p.m.). These irrigation events promoted increase in the EM of the lysimeters, while ETc caused a decrease in EM of the lysimeters, especially at the moment of higher atmospheric demand of the day (11:00 a.m. to 01:00 p.m.) (Figure 4).

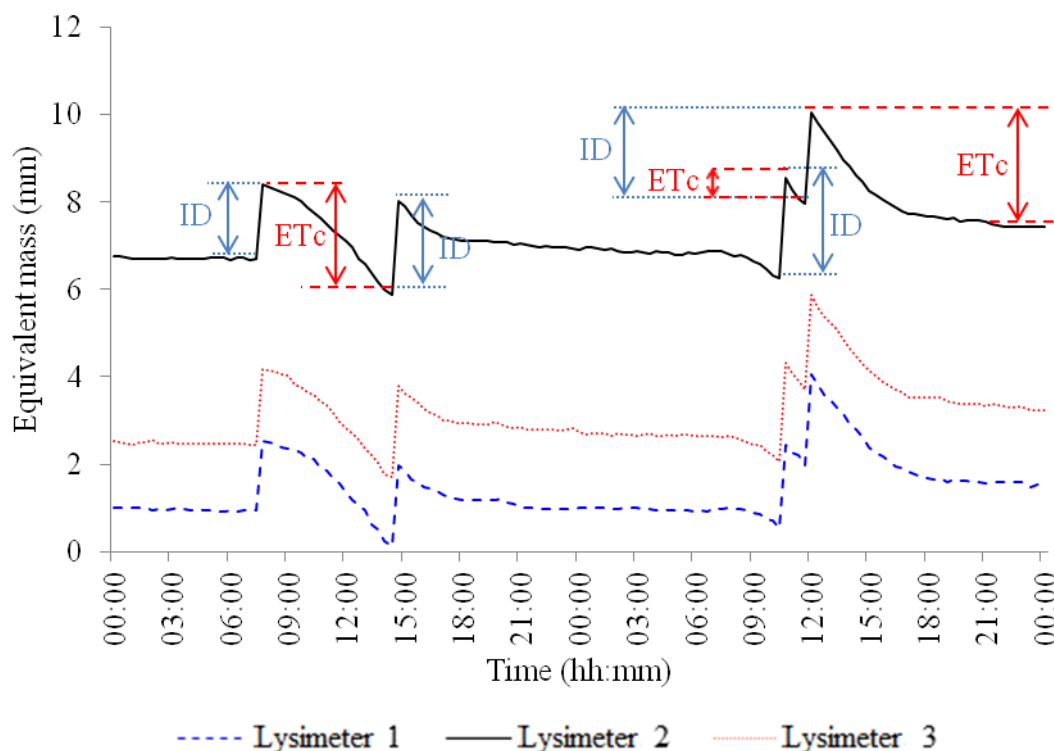


FIGURE 4. Equivalent-mass (mm) registered by the three lysimeters during the test period, highlighting irrigation depths (ID) and crop evapotranspiration (ETc).

The ETc of the first day of test (10/01/2016) totaled 3.56 mm for Lysimeter 1, 3.72 mm for Lysimeter 2 and 3.70 mm for Lysimeter 3, presenting a variation of 0.16 mm between lysimeters. The ETo on this day, calculated by the Penman-Monteith method (Allen et al., 1998), generated a value of 3.47 mm. As for the second day of the test (10/02/2016), the ETc totaled a value of 3.71 mm for lysimeter 1, 3.98 mm for lysimeter 2 and 3.91 mm for lysimeter 3, generating a variation of 0.27 mm between lysimeters, while the ETo on this day generated a value of 3.72 mm (Figure 5).

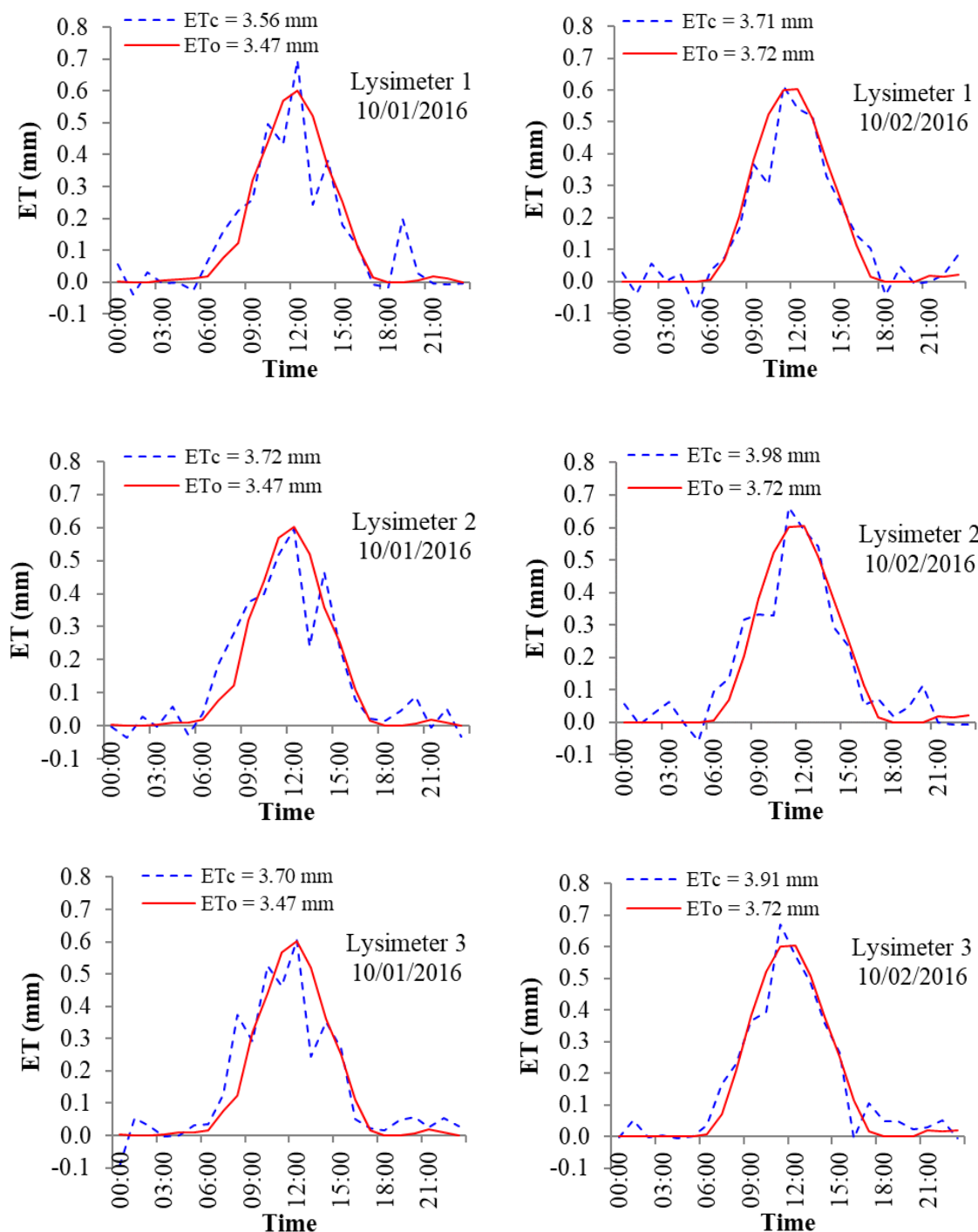


FIGURE 5. Hourly values of crop evapotranspiration (ETc) compared to reference evapotranspiration (ETo – Penman-Monteith) for the three lysimeters during test.

With the exception of the data acquisition system, the cost of lysimeter manufacturing materials can be considered low, totaling R\$ 1,685.80. Data acquisition system used in the survey was budgeted at R\$ 10,938.00, corresponding to 86.6% of the total cost (Table 2). The cost of this component can be attenuated by the use of alternative equipment available on the market.

TABLE 2. Costs of construction and installation of each weighing lysimeter.

Material	Amount	Unitary value (R\$)	Total value (R\$)
Labor	1	204.60	204.60
Carbon Steel Structure	1	165.00	165.00
Carbon Steel Ball Valve 1/2 "	1	21.00	21.00
Liquid Level Indicators	1	32.00	32.00
Load cell (GL-30)	3	266.20	798.60
Junction box (413 A)	1	464.60	464.60
Data Acquisition System	1	10,938.00	10,938.00
Total	-	-	12,623.8

CONCLUSIONS

The constructed and calibrated lysimeters presented excellent accuracy and precision detection of EM variations around 0.1 mm and hysteresis magnitude that did not compromise the equivalent mass evaluations. Conclusions verified by the high linear correlation ($R^2 = 1.0000$) between ES (mV) and EM (mm), as well as coefficients of MAE between 0.0272 and 0.0382 mm, MSE between 0.0011 and 0.0024 mm², $d = 1.0000$, maximum value of H of 0.1951 mm and of HFS of 0.4492%, tolerable values for measures of water consumption in greenhouse-grown.

The tests performed indicated an extremely similar performance in measurement of ET_c among lysimeters, showing a variation of 0.27 mm, and ET_c daily courses coincided with ET_o.

The construction cost of the lysimeters (R\$ 1,685.80) was low, except for the data acquisition system.

Therefore, the equipment presented low cost and its measurements were perfectly satisfactory for the study of ET_c for irrigation management of PSP in greenhouse-grown.

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