Construction, calibration and evaluation of mini-lysimeters in the management of irrigation in a protected environment

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Abstract. The production of forest seedlings requires controlled environments and specific practices, highlighting the need for rational irrigation management. Historically, excessive irrigation has compromised seedling quality, underscoring the importance of developing technologies and research focused on water use efficiency in nurseries. Thus, technologies that are more financially accessible to producers contribute not only to cultivation but also to the social inclusion of these producers in broader markets. Mini-lysimeters can be effectively used to monitor the water balance in potted and tray-grown plant production, thereby reducing water waste in forest nurseries. In this study, portable electronic weighing mini-lysimeters were constructed for greenhouse evapotranspiration research using load cells (capacity: 20 kg), as sensor elements, and dataloggers for data acquisition. Calibration curves were established by correlationg standard weights and voltage readings, and were analyzed using regression analysis. The coefficient of determination (r^2) and the standard error of estimation (*SEE*) were used to evaluate model accuracy. Under field conditions, the lysimeters' performance was assessed using the correlation coefficient (*r*); Willmott's index (*d*); performance index (*c*) and SEE, with pine and eucalyptus seedlings. The calibration curves were well described by linear models, with r^2 values exceeding 0.994. The highest *SEE* (2.44 g), observedin mini-lysimeter III, remained below the 4 g detection threshold of the load cell. All performance indicators (*r*, *d*, and *c*) were above 0.999, with SEE values ranging from 6.2 to 36.2 g (less than 1 g per tube), demonstrating that the mini-lysimeters are suitable for monitoring daily evapotranspiration.

Key words: Lysimetry, forest seedlings, load cells, evapotranspiration, irrigation management.

INTRODUCTION

For proper irrigation management it is necessary to know the crop's rate of evapotranspiration (ETc), and the daily water demands can be obtained directly and accurately using lysimeters. Different lysimeter models are described in the literature, and the size and mounting design of each are based on the specific requirements of the study and the construction conditions and costs involved.

The main advantages of its use are related to calibration, which can be validated mechanically. The smaller fetch requirement when compared to micrometeorological methods, such as the eddy covariance or Bowen ratio, which facilitates its application in protected environments where large homogeneous areas are not always available. the possibility of complete automation and the ease of inspections, as the system is almost fully visible (Allen et al., 2011).

According to Kirnak et al. (2017), under water deficit conditions, applying irrigation at strategic stages of the crop growth cycle can significantly increase yields, even in semi-arid regions. This management highlights the importance of precise technologies, such as mini-lysimeters, to monitor water needs and optimize available resources.

The costs involved in the construction of lysimeters are considered high (Santos et al., 2008; Allen et al., 2011), but the cost savings from using load cell mechanism for measurements make the construction of weighing lysimeters viable (Faria et al., 2006; Santos et al., 2008; Vilela et al., 2015); and they are considered more modern, as they allows automation when coupled with a data acquisition system, thus providing reliable results on the hourly scale, and therefore standing out from the other types of lysimeters (Carvalho & Oliveira, 2012). However, its use has limitations related to operational difficulties due to the sensitivity of load cells, observed on days of heavy rain, following days with intermittent rain, and also on days with intermittent winds (Carvalho et al., 2007).

Given the limitations of using conventional lysimeters in ET studies in protected environments, due to their dimensions, several authors (Grimmond et al., 1992; Misra et al., 2011, Oliveira, 2012, Vilela et al., 2015) developed lysimeters for weighing with smaller structures, also called 'mini-lysimeters', which aim to measure the ET of plants grown in pots or trays.In the literature, there are uses of mini-lysimeters in plants of the species of the family Heliconiaceae (Gervásio & Melo Júnior, 2014); cultivation of vines (*VitisVinifera* L.) in pots (Canales et al., 2013; Ruiz-Peñalver et al., 2015); French hydrangea (*Hydrangea macrophylla*) (McCauely & Nackley, 2022); lawns (Wherley et al., 2009); tree species seedlings (Carvalho et al., 2024); eucalyptus seedlings (Oliveira, 2012); wheat (*Triticum aestivum* L., cv. Lang.) (Misra et al., 2011), among others. However, volume limitation of root growth containers is considered to be the biggest problem in the use of mini-lysimeters (Grimmond et al., 1992). However, the main advantages of using mini-lysimeters described in the literature are related to the accuracy of measurements (Grimmond et al., 1992; Misra et al., 2011; Gervásio & Melo Júnior, 2014; Ruiz-Peñalver et al., 2015), and low manufacturing costs (Wherley et al., 2009; Misra et al., 2011; Canales et al., 2013), also emphasizing the greater versatility due to the dimensions (Grimmond et al., 1992; Gervásio & Melo Júnior, 2014); possibility of a greater number of field repetitions and greater operator autonomy (Wherley et al., 2009),

besides the possibility of its use in irrigation system automation (Canales et al., 2013). Additionally, Svoboda et al. (2020) emphasized that root system density and its distribution within the soil profile are directly influenced by irrigation, reinforcing the need to adjust the maximum irrigation depth according to the specific demands of the plants. Tools like mini-lysimeters play a crucial role in this detailed monitoring.Load cell robustness is a feature highlighted by Misra et al. (2011) highlighting that variables such as hysteresis, room temperature and signal response time do not significantly influence the performance of the mini-lysimeter, which has a measurement capacity below 100 kg, being commonly used load cells with a capacity of 20 or 30 kg.

Considering the importance of irrigation management in the preservation of water resources and the advantages of using lysimeters in the measurement of ET by crops, enabling irrigation system automation, the objective of this work was to develop a model of a portable electronic weighing mini-lysimeter for operation in greenhouses; to perform calibration; to evaluate the performance under field conditions, in the irrigation management of eucalyptus (*Eucalyptus urograndis*) clone seedlings cultivated in a protected environment, and to compare the ET values obtained by a mini-lysimeter in contrast to the values calculated according to the UN FAO (the Food and Agriculture Organization of the United Nations) methodology.

MATERIALS AND METHODS

Experiment Location

The experiment was conducted at the Forest Garden of the Rio de Janeiro Botanical Garden Research Institute (JBRJ) – Latitude 22°58'05" S, Longitude 43°14'20" W, altitude 92 m – located in Rio de Janeiro, Brazil. The local climate is classified as Köppen Aw, characterized by a rainy season with high precipitation in summer and a dry winter season (Peel et al., 2007). The average annual precipitation is approximately 2,000 mm, and the mean annual air temperature is 23.8 °C, with a maximum of 30.3 °C recorded in February and a minimum of 16 °C in July (INMET, 2014).

The tests were carried out in a greenhousealigned in the east-west direction, measuring 12 m in lengrh and 4 m in width, with side walls 1.70 m high, covered with 50% shade cloth. The arched roof was covered with 100-micron plastic film, and the same shade cloth used on the sides was installed above the plastic roof. The greenhouse ends were covered with shade mesh, maintaining the same height as the sides, and the remaining area coated with the same plastic film used for the roof. The maximum ceiling height at the central span the greenhouse was 3 m. The floor, both inside and around the structure, was covered with ground cover mesh (ground raffia).

Determination of *ETc* by FAO method

Based on data obtained from an automated weather station (model 2550, WATCHDOG brand, USA), equipped with indoor sendors for temperature, relative humidity, and photosynthetically active radiation (PAR), and an outdoor wind speed sensor, of air installed outside, reference evapotranspiration (*ETo*) was calculated using the Penman-Monteith equation as parameterized in FAO-56 (Allen et al., 1998), as showm in Eq. 1:

$$ET_o = \frac{0.408 \cdot \Delta \cdot (Rn - G) + \gamma \cdot \dfrac{900}{T_m + 273} \cdot U_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot U_2)} \qquad (1)$$

where ET_o is the reference evapotranspiration (mm d^{-1}); Δ is the slope of the vapor pressure curve at the mean air temperature point (kPa °C^{-1}); Rn is the net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux (MJ m^{-2} d^{-1}), assumed to be zero, for daily times stemps; γ is the psychometric constant, equal to 0.0725 kPa °C^{-1}; U_2 is the wind speed at 2 m hight (m s^{-1}); es is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa), and Tm is the daily mean air temperature (°C).

To determine e_s, e_a; Δ and T_m, the equations described by Allen et al. (1998) were used. Wind speed (U_2) was estimated as 5% of the outdoor values to reflect indoor confitions, following the methodology adopted by Blanco & Folegatti (2004), Farias et al. (1994).

The net radiation (Rn) was estimated from the measured PAR values. For the conversion of PAR (µmol m^{-2} s^{-1}) to radiation in MJ m^{-2} d^{-1}, the factor of 4.57 mol MJ^{-1} was used, proposed by McCree (1972), cited by Steidle Neto et al. (2008) for conditions of both direct and diffuse radiation. A PAR/Rs ratio of 45% was adopted, and albedo (α) was set to 0.23, as proposed by Allen et al. (1998). The radiation balance was then calculated using equations provided in FAO-56. To compare the evapotranspiration values measured by the mini-lysimeter with those estimated using the FAO-56 methodology, the daily crop evapotranspiration (ET_c) values were obtained by the product between the daily ET_o values (Eq. 1) and the value of crop coefficients (Kc), as shown in Eq. 2. A Kc value of 0.82 as suggested by Alves et al. (2013), was used:

$$ET_c = ET_o \cdot KC \qquad (2)$$

Mini-lysimeter Construction

Three mini-lysimeters (I, II, III) were constructed, each with a support base made from a metal container (0.35 m high and 0.24 m in diameter) similar to those commonly used in paint. The containers were filled with concrete up to two-thirds of their volume to increase weight and, consequently, stability, allowing for the central installation of a galvanized steel pole. The pole had a square cross-section of 0.06 m and a height of 1.9 m. A its upper end, a metal support arm (0.4 m in length and with a 0.05 m × 0.03 m rectangular profile), was attached using screws, where the load cell was mounted.

At the end of the support arm, an 'S' type load cell (model BTS-20, Berman Load Cells, Brazil) was installed and powered by a 12 V direct current source. The load cell was made of aluminum, with dimensions of 0.051 m width and 0.076 m height, a maximum capacity of 20 kg, accuracy of 0.02% of full scale (4 g), and sensitivity of 2 ± 0.2 mV/V. According to the manufacturer, the load cell has an IP65 protection rating, offering complete protection against dust and resistance to low-pressure water jets, which was consistent with the environmental conditions observed during the experiment. The nominal temperature operating range is from -10 °C to +40 °C, with a recommended excitation voltage of 10 VDC and a maximum of 15 VDC. The temperature compensation factor (span) is $\pm 0.03\%$ of the full scale per 10 °C. The load cells supported the seedling trays via plastic-coated steel wires (diameter of 0.00165 m), secured with ties (Fig. 1).

The acquisition and storage of data from the mini-lysimeters, collected via load cells, were carried out using an electronic datalogger (Fieldlogger 512K model, NOVUS, Brazil). Each load cell was connected to a analog input port of the datalogger, where built-in a 24-bit A/D (analong-to-digital) converter processed the signal. Using the FieldloggerConfig V 1.6.0 software, each channel has been individually configured. Data logging was programmed to run continuously, recording values every minute throughout the day. A specific feature in the software, known as a 'Virtual Channel', allowed the insertion of mathematical operations (equations) that converted the sensor readings. This enabled a direct relationship to be established between the load cell output voltage (mV) and the recorded mass (g) according to the calibration equations determined after the final calibration of the mini-lysimeters.

A cost analysis was also performed to evaluate the economic feasibility of the system. The approximate costs of the main components were as follows: S-type load cell (20 kg) – R$ 440.00 to R$ 605.00 (US$ 80 to US$ 110); datalogger (Fieldlogger NOVUS) – R$ 3,245.00 to R$ 4,235.00 (US$ 590 to US$ 770); irrigation controller (4 stations) – R$ 451.00 to R$ 660.00 (US$ 82 to US$ 120); solenoid valves (1 inch) – R$ 159.50 to R$ 181.50 (US$ 29 to US$ 33); and electrical materials (wiring and power supplies) – R$ 154.00 to R$ 165.00 (US$ 28 to US$ 30). This total cost is considered low when compared to conventional weighing lysimeters and demonstrates the potential for implementation in small-scale or low-budget agricultural systems.

Figure 1. Illustration with the structural components and mounting form of the mini-lysimeter. The wall thickness of the cultivation tubes (tubetes) was 1 mm (0.001 m). The load cells were installed following the manufacturer's guidelines (BERMAN, model BTS-20), positioned so that the axis of the load cells was perpendicular to the support arms.

Mini-lysimeter calibration

For the calibration procedure, standard masses were used, plastic bags filled with sand, of 50, 100, 150, 500, 1,000, 2,000, 2,500, 5,000 g. These masses, either individually or in combination were placed on the trays (without seedling tubes), totaling 20 observations per mini-lysimeter. During the loading phase, the standard masses were gradually applied, and the datalogger readings (in mV) were recorded after stabilization, typically occurring within 1 to 2 minutes. Subsequently, the masses were removed in
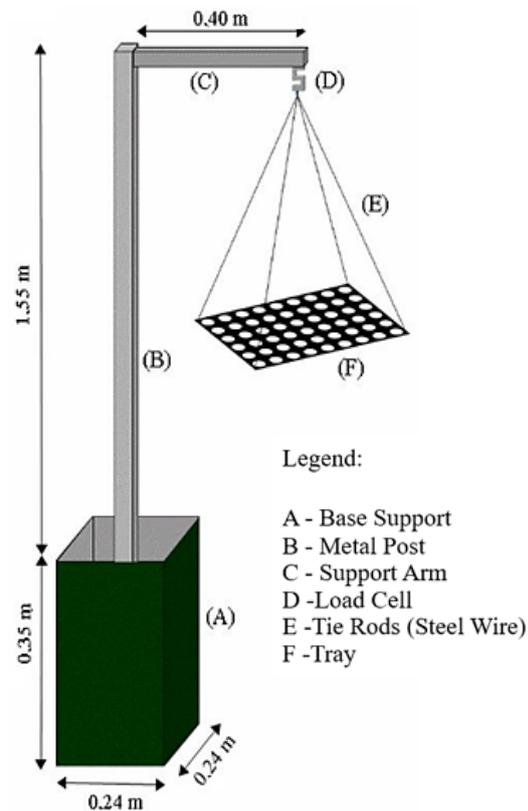
reverse order, following the methodology described by Vilela et al. (2015). For each applied mass (in g), the average of voltage readings (in mV) from both the loading and unloading phases was calculated, establishing the relationship between voltage and mass values. Calibration curves correlating output voltage (mV) with mass (g), along with their respective equations, were generated using a spreadsheet. These equations were later inserted into the datalogger via the 'Virtual Channel' feature of the configuration software, enabling real-time mass readings on each mini-lysimeter.

According to the load cell manufacturer, the temperature compensation factor (span) is approximately 0.03% of full scale per 10 °C. Considering the 20 kg capacity and the average temperature during calibration (~25 °C), a correction of 0.01 mV was applied to the recorded values.

The results of the relationship between masses (applied) and meansured values (readings) were subjected to statistical regression analysis. The coefficients of the regression equations were evaluates using the Student's t-test p at a significance level of $p < 0.01$. The coefficients of determination (r^2), was used to assess to proportion of the total variation in the measured values that could be explained by the variation in the applied standard masses (Eq. 3). In addition, the standard error of estimation (*SEE*), was calculated to verify the influence of other factors on the values recorded by the datalogger (Eq. 4), serving as an indicator of the quality of the fitted models (equations).

$$r^2 = \frac{\sum (V_L - V_{MP})^2}{\sum (V_P - V_{MP})^2} \tag{3}$$

$$SEE = \frac{\sum \sqrt{(V_p - V_l)^2}}{n - 2} \tag{4}$$

where *VL* are the measured values (readings); *PMV* are the means of the default values; *VP* are the default values (real), and n is the number of observations made.

Performance under field conditions

In order to evaluate whether the performance of the mini-lysimeters was influenced by field conditions, including exposure to high temperatures, humidity, and dust, it was verified whether the mass values recorded by the datalogger, derived from the initial calibration models, remained consistent with the actual mass values applied to the mini-lysimeter after two weeks of use. To confirm the consistency of the results across the load cell measurement range (0 to 20 kg), data analysis was carried out using mini-lysimeters I and III, with applied loads near upper limit (20 kg), and in lysimeter II, with loads near the lower limit (0 kg).

For mini-lysimeters I and III, the initial condition included trays containing 54 tubes, and three tubes were removed at a time until only 27 tubes remained, totaling 10 observations. For mini-lysimeter II, the same initial condition (54 tubes), was used, but six tubes removed at a time until none remained, also resulting in 10 observations.

To evaluate whether the mass values estimated by the regression models were correlated with the applied mass values, the following indicators were used: precision, assessed through the correlation coefficient (*r*); accuracy, evaluated using Willmott index (*d*); and the standard error of estimation (*SEE*).

The correlation coefficient (Eq. 5) was used to determine the accuracy of the calibration equation - indicating the repeatability and stability of the measurement, since it indicates the degree of dispersion of the data obtained (estimated by the equation) in relation to the mean, that is, the random error.

$$r = \frac{n\sum_{i=1}^{n}V_P \cdot V_E - \sum_{i=1}^{n}V_P \cdot \sum_{i=1}^{n}V_E}{\sqrt{n\sum_{i=1}^{n}V_P^2 - \left(\sum_{i=1}^{n}V_P\right)^2} \times \sqrt{\sum_{i=1}^{n}V_E^2 - \left(\sum_{i=1}^{n}V_E\right)^2}} \tag{5}$$

where VP is the applied value; VE is the value obtained by the model; and 'n' is the number of observed values (equal to 10).

To determine accuracy, the Willmott index was used, as it reflects the deviation of the mass values estimated by the model from the actual applied mass values. The index ranges from zero, indicating no agreement, to one, indicating perfect agreement. It is calculated using Eq. 6. To assessed reliability, the method proposed by Camargo and Sentelhas (1997) was adopted, which combines the precision index (r) and the accuracy index (d) into a single metric to evaluate overall model performance, as shown in Eq. 7.

$$d = 1 - \frac{\sum_{i=1}^{n}\left(V_E - V_P\right)^2}{\sum_{i=1}^{n}\left[\left(V_E - V_M\right) + \left(V_P - V_M\right)\right]^2} \tag{6}$$

$$c = r \cdot d \tag{7}$$

where VM is the average value applied (default).

Standard error of estimation (SEE) values were also used to evaluate the influence of other factors on the readings obtained by the datalogger (Eq. 4).

Determination of ideal weight

To evaluate the performance of the mini-lysimeter in irrigation management under field conditions, trials were conducted using trays containing 54 tubes with a volumetric capacity of 280 cm³, planeted with eucalyptus (*Eucalyptus urograndis*) seedlings. In order to maintaim optimum conditions regarding water availability in the substrates, an 'ideal weight' was determined, corresponding to substrate moisture near field capacity. The sets (tray + tubes + seedlings), with the bottom of the tubes protected by foam to prevent substrate loss, were partially immersed plastic reservoirs (water tanks) for 12 hours to promote substrate saturation.After the saturation process, the trays were placed in the shaded, and after 30–40 minutes (a period sufficient for water drainage to cease, as verified in tests using the mini-lysimeter), the sets were weighed using a MICHELETTI model MIC P15 digital scale, with a capacity of 15 kg and a resolution of 0.005 kg. After weighing a total of 24 sets, the value of 10,600 g was defined as the ideal mass of the set, i.e., the mass at which sufficient water is available for optimal seedinling growth.

Irrigation management

The trays containing the eucalyptus seedlings were irrigated with Rain Bird model X360 Mister micro-sprinklers, with an approximate flow rate of 0.65 m^3 h^{-1}, positioned 0.60 m above each tray. Irrigation was started daily at 7:30 a.m. by a Rain Bird STP6L controller (powered at 100V). The control board activated a ¾' solenoid valve (model DVF-75M Rain Bird), allowing water flow to the seedling stands. However, between the controller and the valve, the electrical circuit was connected to the alarm relay terminal of the data acquisition module (datalogger). This relay, which is normally closed (NC), allowed the passage of electric current and the opening of the valve at the preset time.

In the analog terminals of the data acquisition module were connected to the mini-lysimeter load cells, which monitored the mass variation of the trays containing the eucalyptus seedlings. The configuration, performed using the FieldloggerConfig software, defined the alarm triggering parameter, namely, whenever the set weight of one of the mini-lysimeters was equal to or greater than that ideal value for seedling growth (10.600) g), the relay was activated. This caused it to operate in the normally open (NO) mode, interrupting the electric current, closing the valve, and consequently stopping the irrigation.

RESULTS AND DISCUSSION

Calibration

After recording the voltage readings (mV) during the standard mass loading and unloading processes, the mean voltage values (in mV) were calculated. The observed hysteresis effect was considered negligible, consistent with findings reported by Carvalho et al. (2013); Faria et al. (2006); Gervásio & Melo Junior (2014); Oliveira (2012) and Silva et al. (1999) who also worked with weighing lysimeters equipped with load cells.

Fig. 2 presents the calibration equations obtained through linear regression using the mean values from both loading and unloading cycles, which relate the mass variation to the voltage output of the mini-lysimeters load cells. The linear model adequately represented the mass-to-voltage relationship across all treatments, with coefficient of determination (r^2) exceeding 0.994.

According to the results, the voltage values ranged from 0.24 to 22.93 mV in mini-lysimeters I and II. However, mini-lysimeter III exhibited higher voltage values, ranging from 9.86 to 114.25 mV. This difference is associated with the gauge of the wires used. Due to the distance between the mini-lysimeters and the data logger, thicker wires (1.5 mm diameter) were used for mini-lysimeter III, while 1.0 mm diameter wires were used for mini-lysimeters I and II. These variations altered the input and/or output impedance but did not compromise the final results due to proper calibration.

The variation in the wire length also influenced the voltage readings. Because the lysimeters were installed in different locations within the greenhouse, the lengths of the power supply and data transmission wires varied, leading to differences in the voltages recorded by the datalogger, attributed to wire resistance in addition to connection resistance.
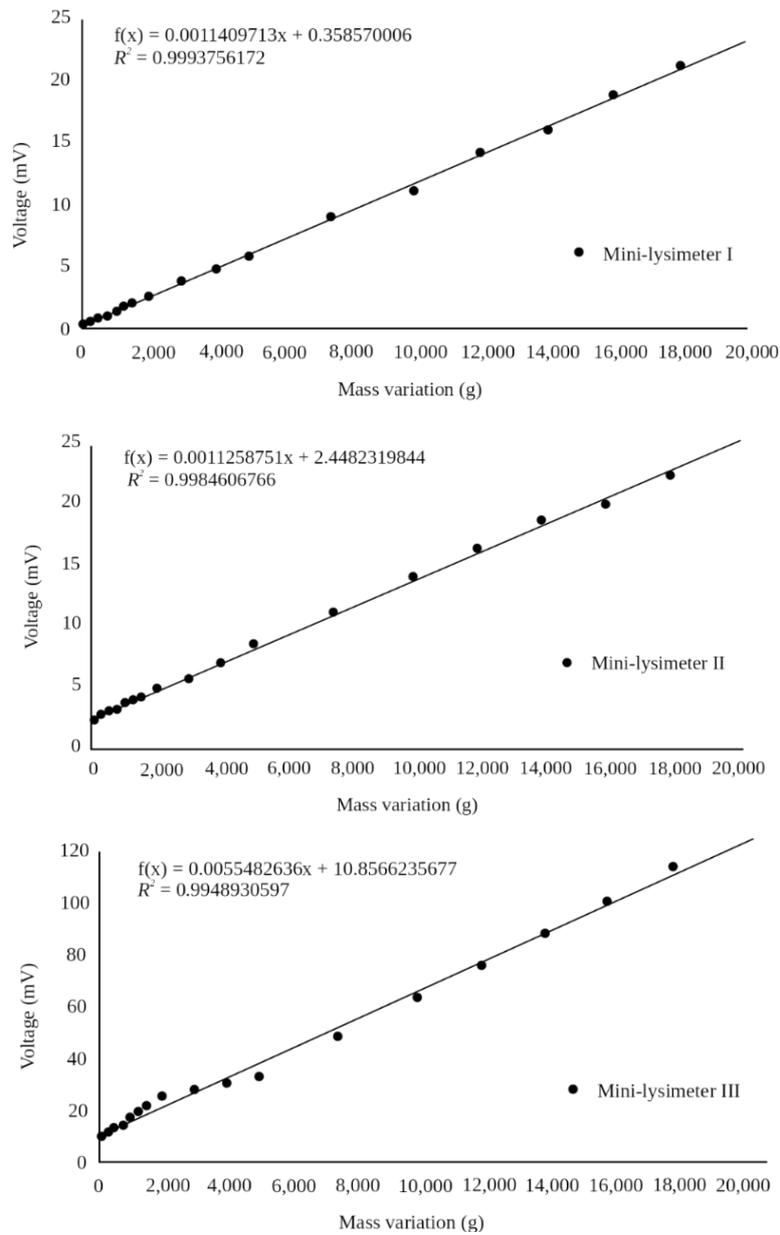
Figure 2. Relationship between mass variation (g) and voltages (mV), with the respective calibration curves of the three mini-lysimeters.

All regression equation coefficients were statistically significant according to the Student's t-test at the 1% probability level (Table 1).

Regarding the *SEE* values presented in Table 1, the highest value observed for mini-lysimeter III was 2.44 g; which is below the maximum permissible error of the load cell, specified as 4 g accuracy. Considering the surface area of the tray (0.2204 m^2), a mass variation of 2.44 g corresponded to an equivalent water depth of approximately 0.011 mm (or 0.015 mm when considering only the area of the tubes). This value is substantially lower than those reported by other authors during the calibration of 'conventional' lysimeters, such as Carvalho et al. (2011) (0.2 mm); Carvalho et al. (2007)

(0.278 mm), Carvalho et al. (2013) (0.66 mm). These differences are attributed to the capacity and full-scale range of the load cells used in each respective study.

Performance under field conditions

According to the results of the field condition tests, graphs were generated to represent the relationship between the applied masses and the masses recorded by mini-lysimeters I, II and III (Fig. 3); the mean relative error percentages observed were 0.73, 2.67 and 3.84%, respectively.

Table 1. Coefficients of the regression equation (angular coefficient x_1 and intercept - constant) and estimated standard error values, obtained for mini-lysimeters, L_I, L_{II} e L_{III}

Coefficients	Mini-lysimeters		
	L_I	L_{II}	L_{III}
Constant	0.35850*	2.44820*	10.85660*
x_1	0.00114*	0.00113*	0.00555*
SEE	0.175160	0.271508	2.44142
N	19	19	19

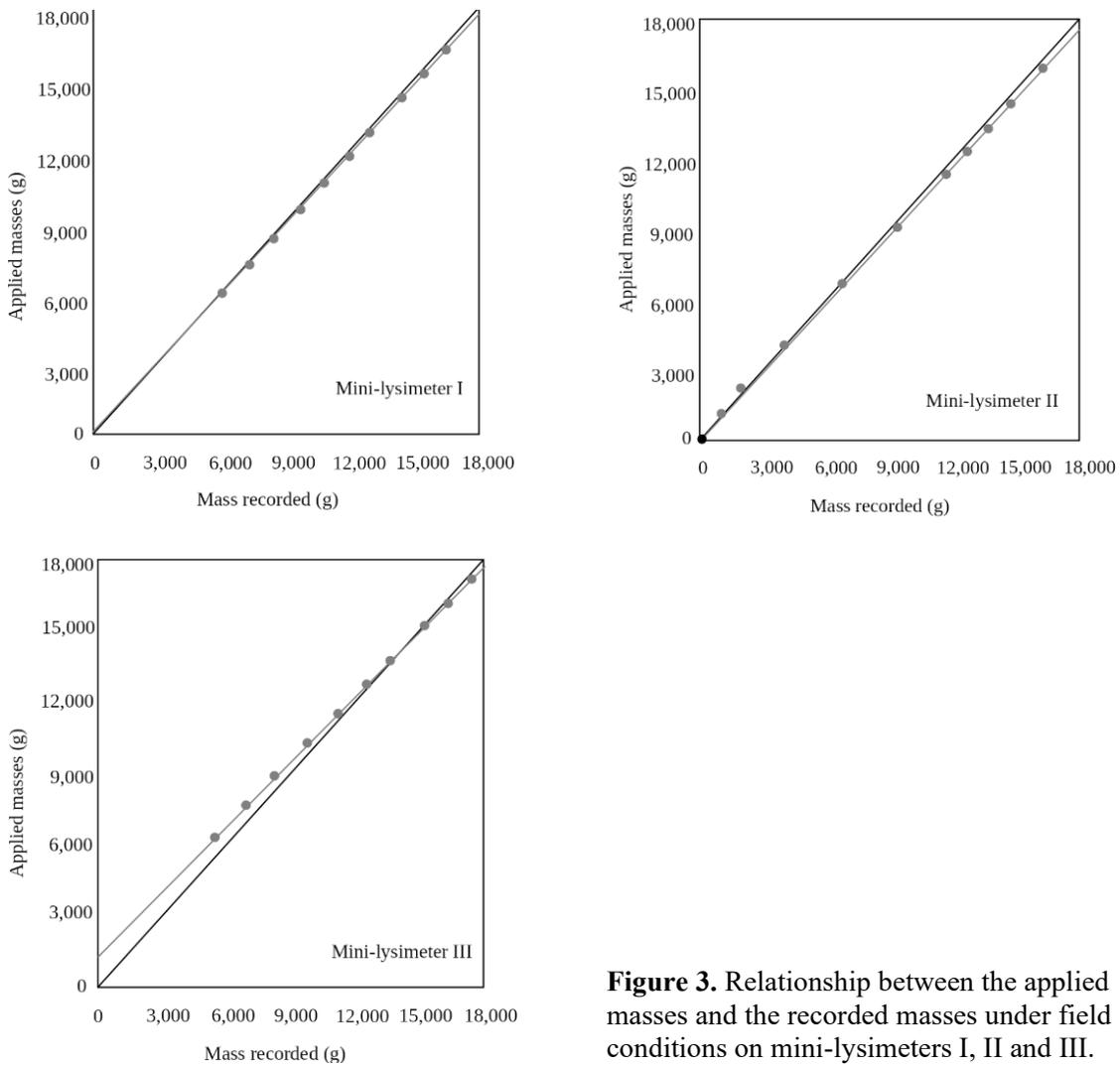*Significance at $p < 0.01$; x_1 – angular coefficient; N – number of samples.

Figure 3. Relationship between the applied masses and the recorded masses under field conditions on mini-lysimeters I, II and III.

The standard errors of estimation (*SEE*) observed between the applied and registered (modeled) masses were 8.49 g, 31.91 g and 6.20 g, for mini-lysimeter I, II and

III, respectively. The higher *SEE* value observed in mini-lysimeter II highlights the challenge of calibrating under low-load conditions, where system instability may lead to inaccuracies at the time of measurement. In contrast, mini-lysimeters I and III, which were calibrated under more stable (higher load) conditions, exhibited significantly lower errors. It is important to note that each mini-lysimeter unit contained 54 tubes, meaning the observed errors correspond to less than 1 g per tube, thereby supporting the conclusion that the regression equations provided a good fit to the sample data.

The highest value of EPE (2.44 g) was obtained for the calibration curve for the Eucalyptus 400% treatment, which is below the detectable limit of the cell, which is 4 g. In the field condition evaluation, all treatments had values of correlation coefficient, Willmott index and performance index above 0.999, with EPE ranging from 6.2 to 36.2 g (less than 1 g per tube).

Table 2 presents the correlation coefficients (*r*) and Willmott indices (*d*), obtained for the mini-lysimeters equipped with trays cultivated with eucalyptus seedlings.

Based of the correlation coefficients (*r*), it can be inferred that all mini-lysimeters exhibited a very strong correlation (*r* > 0.9), indicating that the calibration equations presented in Table 2 demonstrated satisfactory accuracy.

Table 2. Statistical indicators of correlation coefficient (*r*) and Willmott index (*d*) for the relationships established between the models and the patterns observed in mini-lysimeters (L_I, L_{II} e L_{III})

Mini-lysimeters	Parameters			
	r	*d*	*C*	*SEE*
L_I	0.99999	0.99974	0.99974	8.64
L_{II}	0.99998	0.99985	0.99984	31.91
L_{III})	0.99999	0.99972	0.99972	6.21

Furthermore, according to the Willmott index (*d*) values (*d* > 0.9), there was a strong agreement between the reference (observed) values and those estimated by the regression models.

Irrigation monitoring

Considering the superior performance of mini-lysimeter I, this was selected and configured to monitor the irrigation system in the eucalyptus seedling cultivation. The goal was to replace 100% of the evapotranspiration that occurred over a 24-hour period (Eucalyptus 100), restoring the system daily to the predefined reference weight (= 10.600 g) throughout the experiment. Fig. 4 displays the graph generated by the FieldloggerConfig software using the 'Records graph' feature, which shows the mass variation recorded at one-minute intervals between July 7, 2015, and July 17, 2015.

The graph llustrates the water replacement through irrigation ('a'), which increasing the system's weight up to the predefined reference value of 10,600 g; the rapid drainage of applied water ('b') immediately following irrigation, attributed to the combined effects of factors such as the intensity of application from the micro-sprinklers, the water-holding capacity of the substrate, the ease of water drainage from the containers (tubes), evaporation of water retained in tray surfaces, and losses due to evapotranspiration ('c').

The most pronounced fluctuations observed in the graphs are associated with operational activities carried out in the cultivation environment, including: movement of personnel near the trays; removal of weeds from the tubes; cleaning of fallen leaves from

the trays; temporary removal of tubes for monitoring seedling morphophysiological traits; and replacement of tubes containing dead plants. These actions caused disturbances that were recorded by the datalogger.
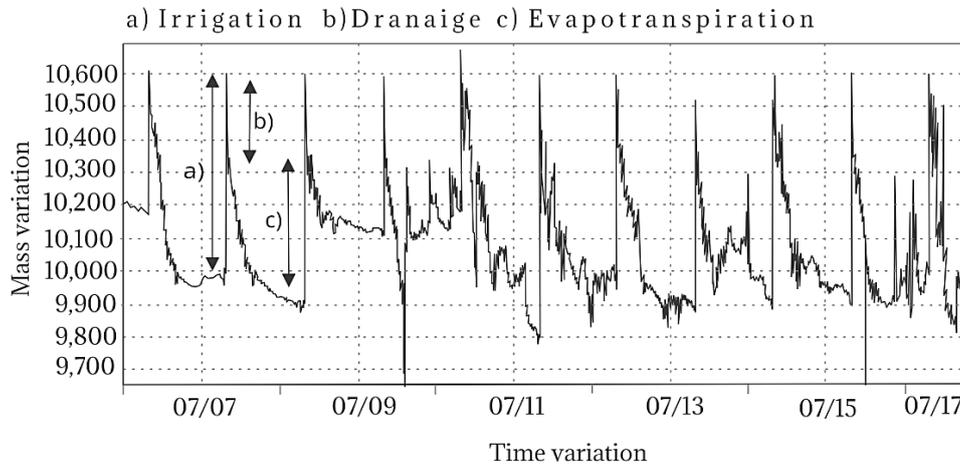

Figure 4. Mass variation recorded at one-minute intervals between 07/07/2015 and 17/07/2015, as generated by the FieldloggerConfig software.

Considering the masses measurements taken at three different times during the experiment, i.e., prior to the start of irrigation (7:30 h), immediately after the end of irrigation (approximately 10–20 minutes after initiation), and at the end of the day (18:00 h) the graph in Fig. 5 was generated, illustrating the mass variations recorded throughout July. During the first three days, improper configuration of hysteresis parameters in the datalogger resulted in multiple activations of the irrigation system. This led to the system mass exceeding the predefined target value due to oscillations around the set point (10,600 g), a problem that was corrected from the third day onward.
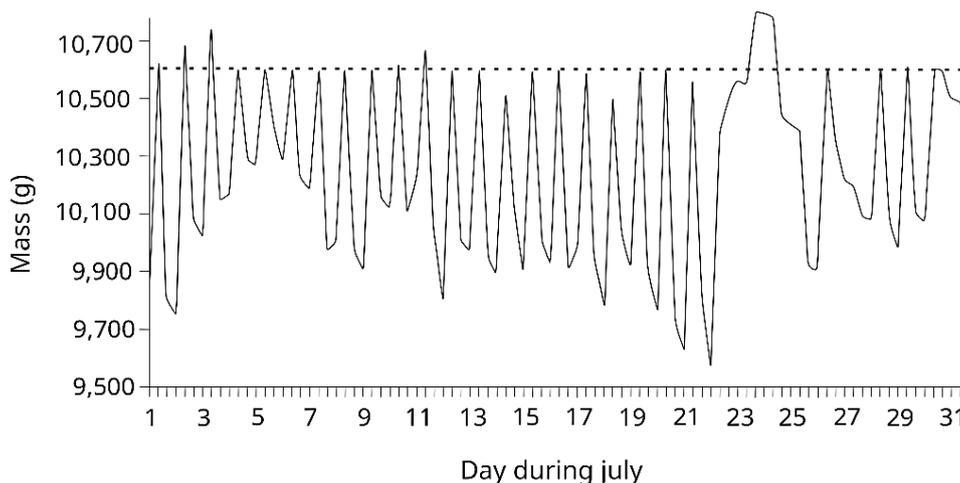

Figure 5. Mass variation recorded before irrigation, immediately after irrigation, and at the end of the day throughout the month of July.

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Values exceeding the predefined threshold were also observed on July 11 and 24. On the 11th, a more detailed analysis of the 'Record Chart' suggests that some management activity may have occurred simultaneously with irrigation, as indicated by the strong oscillations recorded at that time. On the 24th, the excess water applied manually using watering cans, intended to compensate for the lack of water in the irrigation reservoirs, resulted in values above the predefined limit. Water supply issues also affected irrigation on the 14th and 18th, during which the applied volumes did not reach the target value due to the limited availability of water in the reservoirs. Between July 21 and 25, the lack water required manual application using watering cans, a procedure that was repeated on the 27th.

Comparison between *ETc* values

Fig. 6 shows the graph containing the *ETc* values obtained by the mini-lysimeter (*ETc* Mini-lysimeter) and calculated by the Penman-Monteith method (Calculated *ETc*), during 31 days of the experiment (July).

According to the Fig. 6, the evapotranspiration (*ETc*) measured by the mini-lysimeter exhibited greater amplitude, ranging from 0.38 to 2.71 mm day^{-1}, whereas the calculated values ranged from 1.23 to 1.88 mm day^{-1}. Although the measured values showed greater variability - likely influenced by specific cultivation conditions that go beyond purely climatic variables – the average *ETc* obtained by the mini-lysimeter was consistent with the calculated value.

The mean *ETc* recorded by the mini-lysimeter during the experimental period was 1.59 ± 0.63 mm day^{-1}, which was only 1.3% higher than the mean *ETc* estimated by the Penman-Monteith method (1.57 ± 0.17 mm day^{-1}). This result demonstrates good agreement, particularly regarding the crop coefficient (*Kc*) used, and resulted in a correlation considered high ($r = 0.59$), according to the classification proposed by Hopkins (2008), between the measured and estimated values.
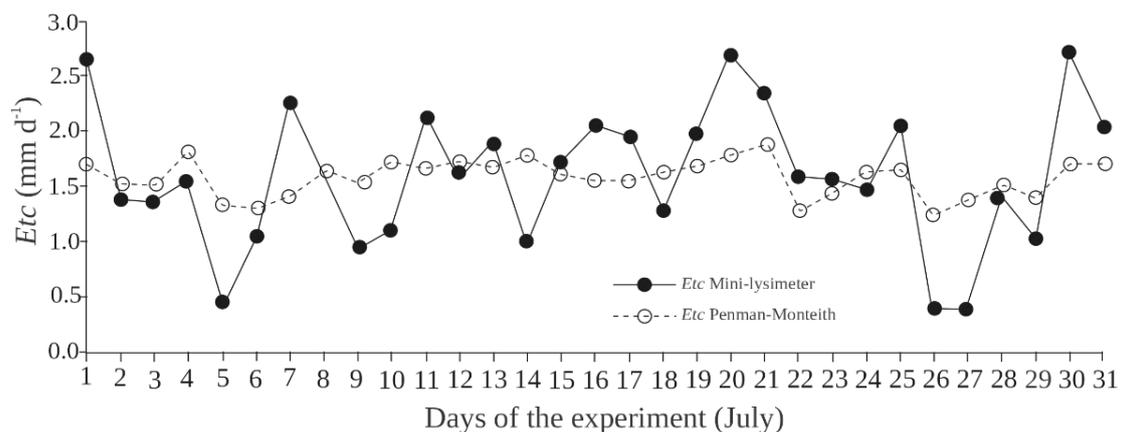

Figure 6. *ETc* values obtained by the mini-lysimeter (*ETc* Mini-lysimeter) and calculated by the Penman-Monteith method (Calculated *ETc*), during period experiment.

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CONCLUSIONS

Considering the high accuracy of mini-lysimeters in monitoring the water balance of crops grown in pots or trays, as well as their benefits for irrigation control, it can be concluded that the developed mini-lysimeter model is viable for use in greenhouse environments. Its compact dimensions allow for easy relocation within the growing area. The calibration process yielded equations that were well fitted to the sample data. The performance of the mini-lysimeters was satisfactory for determining evapotranspiration at sub-daily scales, with errors lower than 1 g per tube, confirming their effectiveness as a tool for monitoring water application through irrigation systems.

The performance of the mini-lysimeters proved to be satisfactory for determining evapotranspiration at sub-daily scales, with the calibration of the mini-lysimeter yielding equations that were well adjusted to the sample data. The evapotranspiration of eucalyptus seedlings, obtained through the mini-lysimeters, showed an average of 1.66 mm d^{-1}. The crop coefficient (Kc) values calculated for eucalyptus cultivation averaged 1.48. The use of the mini-lysimeter was found to be viable in greenhouse vegetation, as its reduced dimensions allow for free movement within the growing environment.

The growth variables studied indicated that different irrigation levels (equivalent to 100%, 200%, 300%, and 400% of evapotranspiration) did not influence the growth of eucalyptus seedlings. However, the results of water use efficiency (WUE) showed that excess water applied in treatments above 100% of evapotranspiration did not result in effective benefits (biomass gain) for the eucalyptus seedlings, representing water waste and reinforcing the importance of proper irrigation management.

The mini-lysimeter model developed proved to be an excellent tool for monitoring water application through irrigation systems, as it enables effective and efficient water use. This contributes to increasingly crucial decision-making in crop water supply, allowing irrigation scheduling to deliver the right amount of water at the right time for a specific crop. Therefore, further testing on different crops is necessary, as well as efforts to expand such technologies for commercial use.

REFERENCES

Allen, R.G., Pereira, L.S., Howell, T.A. & Jensen, M.E. 2011. Evapotranspiration information reporting: I. Factors governing measurement accuracy. *Agricultural Water Management* **98**, 899–920. https://doi.org/10.1016/j.agwat.2010.12.015

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. In: United Nations Food and Agriculture Organization FAO-Irrigation and Drainage Paper 56. FAO, Rome, Italy.

Alves, M.E.B., Mantovani, E.C., Sediyama, G.C & Neves, J.C.L. 2013. Estimate of the crop coefficient for Eucalyptus cultivated under irrigation during initial growth. *Revista Cerne* **19**(2), 247–253. https://doi.org/10.1590/S0104-77602013000200008

Blanco, F.F. & Folegatti, M.V. 2004. Evaluation of evaporation-measuring equipment of estimating evapotranspiration within a greenhouse. *Revista Brasileira de Engenharia Agrícola e Ambiental* **8**(2–3), 184–188. doi: 10.1590/S1415-43662004000200004

Camargo, A.P. & Sentelhas, P.C. 1997. Performance evaluation of different methods for estimating potential evapotranspiration in the state of São Paulo, Brazil. *Revista Brasileira de Agrometeorologia* **5**(1), 89–97 (in Portuguese).

Canales, A.R., Ruiz-Peñalver, L., Casado, G.C., Ruiz, A.J., Molina, H.P., Molina, D.I. & Martinez, J.M.M. 2013. Drip irrigation monitoring in potted grapevine (*Vitis vinifera L. cv. Bobal*) using a weighing lysimeter. Some experimental data. An. VII Congresso Ibérico de Agroingenieria y ciências hortícolas, Madrid, pp. 26–29 (in Spanish).

Carvalho, D.F., Costa, G.R. Conforto, B.A.F., Pinto, M.F. & Silva, M.R. 2024. Automated irrigation management system for tree species seedlings using weighing mini-lysimeters. *iForest - Biogeosciences and Forestry* **17**(4), 222–228. doi: 10.3832/ifor4409-017

Carvalho, D.F. & Oliveira, L.F.C. 2012. *Planning and management of water in irrigated agriculture*. Viçosa, MG. Editora UFV, 240 pp. (in Portuguese).

Carvalho, L.G., Rios, G.F.A., Miranda, W.L. & Neto, P.C. 2011. Reference evapotranspiration: current analysis of different estimating methods. *Revista Pesquisa Agropecuária Tropical* **41**(3), 456–465. https://doi.org/10.5216/pat.v41i3.12760 (in Portuguese).

Carvalho, H.P., Melo, B., Atarassi, R.T., Camargo, R., Silva, C.R. & Moraes, M.R.B. 2013. Development weighing lysimeters for coffee culture. *Bioscience Journal* **29**(6), 1750–1760 (in Portuguese).

Carvalho, D.F., Silva, L.D.B., Guerra, J.G.M., Cruz, F.A. & Souza, A.P. 2007. Instalation, calibration and operation of a weighing lysimeter. *Rev. Engenharia Agrícola* **27**(2), 363–372. https://doi.org/10.1590/S0100-69162007000300005 (in Portuguese).

Faria, R.T., Campeche, F.S.M. & Chibana, E.Y. 2006. Construction and calibration of high precision lysimeters. *Revista Brasileira de Engenharia Agrícola e Ambiental* **10**(1), 237–242. https://doi.org/10.1590/S1415-43662006000100035 (in Portuguese).

Farias, J.R.B., Bergamaschi, H. & Martins, S.B. 1994. Evapotranspiration inside plastic greenhouses. *Revista Brasileira de Agrometeorologia* **2**, 17–22 (in Portuguese).

Gervásio, E.S. & Melo Junior, J.C.F. 2014. Use of weighing lysimeter technique for automation of a trickle irrigation system for irrigation of crops in containers. *Revista Irriga* **19**(4), 626–640. https://doi.org/10.15809/irriga.2014v19n4p626 (in Portuguese).

Grimmond, C.S.B., Isard, S.A. & Belding, M.J. 1992. Development and evaluation of continuously weighing mini-lysimeters. *Agricultural and Forest Meteorology* **62**(2–3), 205–218. https://doi.org/10.1016/0168-1923(92)90015-V

Hopkins, W.G. 2008. *Introduction to Plant Physiology*. 4th ed. John Wiley & Sons, 528 pp.

INMET: Instituto Nacional de Meteorologia. 2014. Climatological Normals 1961–1990. https://portal.inmet.gov.br/normais (in Portuguese).

Kirnak, H., Varol, I.S., Irik, H.A. & Ozaktan, H. 2017. Effects of irrigation applied at different growth stages on chickpea yield. *Agronomy Research* **15**(5), 1928–1933 https://doi.org/10.15159/AR.17.046

McCauely, D.M. & Nackley, L.L. 2022. Development of mini-lysimeter system for use in irrigation automation of container-grown crops. *HardwareX* **11**, e00298. doi: 10.1016/j.ohx.2022.e00298

Misra, R.K., Padhi, J. & Payero, J.O. 2011. A calibration procedure for load cells to improve accuracy of mini-lysimeters in monitoring evapotranspiration. *Journal of Hydrology* **406**(1–2), 113–118. https://doi.org/10.1016/j.jhydrol.2011.06.009

Oliveira, A.S. 2012. *Optimization of water use in the production of clonal Eucalyptus seedlings* [Master's thesis, Federal University of Viçosa]. Federal University of Viçosa, Viçosa, MG, 84 pp. (in Portuguese).

Peel, M.C., Finlayson, B.L. & McMahon, T.A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Science* **11**(5), 1633–1644. https://doi.org/10.5194/hess-11-1633-2007

Ruiz-Peñalver, L., Vera-Repullo, J.A., Jimenez-Buendia, M., Guzmán, I. & Molina-Martinez, J.M. 2015. Development of an innovative low-cost weighing lysimeter for potted plants: Application in lysimetric stations. *Agricultural Water Management* **151**(103), 103–113. https://doi.org/10.1016/j.agwat.2014.09.020

Santos, F.X., Rodrigues, J.J.V., Montenegro, A.A.A. & Moura, R.F. 2008. Low cost hydraulic weighing lysimeter performance in the semi arid northeast, Brazil. *Revista Engenharia Agrícola* **28**(1), 115–124. doi: 10.1590/S0100-69162008000100012 (in Portuguese).

Silva, F.C., Folegatti, M.V., Pereira, A.R. & Villa Nova, N.A. 1999. Usage of lysimeter devices for evapotranspiration reference determination. *Revista Brasileira de Agrometeorologia* **6**(1), 19–23 (in Portuguese).

Steidle Neto, A.J., Zolnier, S., Marouelli, W.A. & Carrijo, O.A. 2008. Ratio between photosynthetically active radiation and global radiation during tomato growth inside greenhouse. *Revista Brasileira de Engenharia Agrícola e Ambiental* **12**(6), 626–631. https://doi.org/10.1590/S1415-43662008000600009 (in Portuguese).

Svoboda, S., Raimanová, I., Duffková, R., Fučík, P., Kurešová, G. & Haberle, J. 2020. The effects of irrigation on root density profiles of potato, celery, and wheat. *Agronomy Research* **18**(2), 567–578. https://doi.org/10.15159/AR.20.035

Vilela, M.S., Cabral Filho, F.R., Teixeira, M.B., Amaral, A.M., Vellame, L.M. & Soares, F.A.L. 2015. Accuracy of a mini-weighing lysimeter electronic low cost. *Revista Irriga* **1**, 158–167. 10.15809/irriga.2015v1n2p158 (in Portuguese).

Wherley, B., Sinclair, T., Dukes, M. & Miller, G. 2009. Design, construction, and field evaluation of a lysimeter system for determining turfgrass water use. *Proceedings of the Florida State Horticultural Society* **122**, 373–377.