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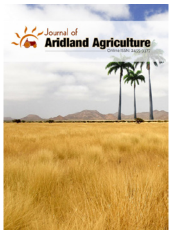
Research Article



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Measured versus calculated net radiation and soil surface heat flux values in an automated weather station in arid lands, and its application in the FAO Penman-Monteith method

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ABSTRACT

For efficient irrigation timing in arid land agriculture, it is essential to know the daily evapotranspiration rate of each crop (ETc) established in a specific location. ETc can be obtained from the reference evapotranspiration rate (ETr) according to the procedure of the FAO-56 method and the crop coefficient development (Kc). However, the daily rates of ETr obtained with calculated values of net radiation (Rn) and soil surface heat flux (G) may differ from those obtained when Rn and G are measured in the same automated weather station. The objective of this study was to evaluate the difference between the daily rate of ETr obtained with the FAO-56 method using calculated and measured data of net radiation and soil surface heat flux in an arid land. On an arid land of northern Mexico, a Campbell-brand automated weather station (Campell Sci., Inc. Logan, Utah, USA) was located at the center of a circular area of 12 m in diameter, with a green grass of full surface coverage 12 cm height with no soil moisture deficit, to measure at a height of 2 m (1 s scan and 30 min averaged values) the air temperature and relative humidity, wind speed and direction, incident solar radiation, barometric pressure, and rainfall. Furthermore, the net radiation over the grass and the soil surface heat flux were also measured. The data generated by the automated weather station was used to calculate the daily rate of ETr (FAO-56 method) using both calculated and measured values of net radiation and soil surface heat flux. The results of this study showed that the ETr (FAO-56 method) obtained with Rn and G measured was 17.63% higher than the ETr (FAO-56 method) determined with Rn and G calculated. The Rn measured (using a net radiometer) was 14.08% larger than the Rn calculated (FAO-56 method). G measured was 36.6% smaller than G calculated as 10% of the Rn (FAO-56 method). The daily ETr rate (FAO-56 method) using Rn and G measured in the automated weather station was higher than the ETr rate (FAO-56 method) obtained with Rn and G calculated, due to a bigger value of Rn and a lower value of G measured in the automated weather station than the values of Rn and G calculated by the FAO-56 method.

KEYWORDS: Crop evapotranspiration, FAO-56 method, Soil surface heat flux, Net radiation, Reference evapotranspiration

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INTRODUCTION

Knowing the daily evapotranspiration rate of different crops (ETc) is essential for efficient water management in arid land agriculture. The daily ETc rate of a given crop can be determined with the reference evapotranspiration rate (ETr) using the FAO Penman-Monteith method (Allen *et al.*, 1998). The technique is adjusted with a crop coefficient (Kc), which depends on the type of crop and its phenological stage of development.

The FAO Penman-Monteith method has been widely used in various regions of the world, with different climatic conditions, to determine the ETr and the current evapotranspiration rate of crops (ETc), as well as its application in adequate irrigation programming. For example, Trezza *et al.* (2008) compared the FAO Penman-Monteith method against the soil water balance method for irrigation scheduling in a sugar cane plantation (*Saccharum officinarum*).

Intrigliolo *et al.* (2009) employed the FAO Penman-Monteith method to calculate the evapotranspiration rate of a grapevine plantation (cv Riesling) for irrigation scheduling purposes. Moratiel and Martínez-Cob (2011) determined the ETr to calculate the ETc of a vine plantation (*V vinifera*, cv. Red Globe) from a semi-arid climate with shade mesh over the plant canopy. Zermeño-González *et al.* (2017) made comparisons of the ETc rate of a vineyard (V. *vinifera)* obtained using eddy covariance measurements with the ETr obtained using the FAO Penman-Monteith method. The efficiency of irrigation scheduling in a pecan orchard was evaluated by comparing the ETr (FAO Penman-Monteith) with the evapotranspiration rate of the orchard trees obtained with eddy covariance measurements (Zermeño-González *et al.*, 2023). Zia *et al.* (2021) used the FAO Penman-Monteith method to schedule irrigation in a lemon tree (*Citrus limon*) orchard.

In the FAO Penman-Monteith method, the net radiation (Rn) of the reference surface (12 cm of a tall grass that completely covers the surface and has no soil water deficiency) is calculated from radiation data obtained from the information corresponding to the latitude, altitude, barometric pressure of the location, and the day of the year. Furthermore, the soil surface heat flux (G) is calculated as 10% of the net radiation (Rn). Such information may differ from the net radiation and soil surface heat flux obtained with direct measurements at the site of the automated weather station. Therefore, this study aimed to evaluate the difference between the FAO Penman-Monteith ETr rate determined with measured and calculated values of Rn and G.

MATERIALS AND METHODS

The study was conducted at an automated weather station (meteorological observation) located in the Hydraulic Garden of the Irrigation and Drainage Department at the Antonio Narro Autonomous Agrarian University in Saltillo, Coahuila, Mexico. It is situated at 25°22' N, 101°00' W, at 1742 m above sea level. The average yearly temperatures, rainfall, and evaporation are 19 °C, 325 mm, and 1956 mm, respectively. According to the Modified Köppen Classification for Mexico, Saltillo, Coahuila has a climate of the type BWhw (x´) (e) (García, 2004), which corresponds to a desert dry, warm climate with low rainfall in the winter and variable temperatures. The station is 12 m in diameter, with grass of the San Agustín variety (*Stenotaphrum secundatum*) that covers the entire soil surface. The grass is irrigated with four fixed sprinklers at a rate of 1200 LPH per sprinkler (Rain Bird 5000 series) at a frequency of two days to maintain adequate soil moisture, ensuring that the evapotranspiration rate of the grass meets the evaporative demand of the atmosphere. The grass growth was kept at a height of approximately 12 cm by pruning at the required frequency (using a pruning machine). The grass at the weather station was cultivated to match the reference surface conditions specified by the FAO Penman-Monteith method.

A Campbell-brand automated weather station (Campell Sci., Inc. Logan, Utah, USA) (Figure 1) was located at the center of the station to measure at a frequency of 1 s and store average 30 min values of air temperature and relative humidity (HC2S3 temperature and relative humidity probe, Campbell, Sci., Logan, Utah), wind speed, and direction at 2 m above the soil surface (Met One 034B Wind Set, Campbell, Sci., Logan, Utah), incident solar radiation (Silicon Pyranometer; model SP-510, Apogee Inst., Logan, Utah, USA), barometric pressure (CS100 Barometric Pressure Sensor, Campbell, Sci., Logan, Utah), rain sensor (TE 525 Tipping Bucket Rain Gage, Campbell, Sci., Logan, Utah).

Furthermore, to measure the net radiation on the grass (equivalent to the reference surface), a Net Radiometer (LITE Net Radiometer; KEEP and ZONEN, Netherlands) was installed at the weather station site. To measure the soil surface heat flux, a flux transducer (model HFP01, Campbell, Sci., Logan, Utah) and a four-rod thermocouple (chromel–constantan) (Campbell Sci., Inc., Logan, Utah, USA) were also used. The soil surface heat flux was measured by adding the heat flux measured at 8 cm below the soil surface, the change in the energy of the soil layer above the heat flux transducer. All described sensors were connected to a CR1000 datalogger (Campbell, Sci., Inc., Logan, Utah, USA) for continuous measurements (frequency of 1 s) of all the described variables, saving 30-minute averages.

Additionally, six mini-lysimeters of PVC (11 cm in diameter by 15 cm in height) were installed equally spaced in a circumference of 3 m in radius from the center of the station, to measure the daily evapotranspiration rate of the grass (by the difference in the daily weight of the mini lysimeters) to ensure an adequate water supply for optimal grass growth. Also, six micro tensiometers (0 to 40 kPa) of 12 cm length were buried in the soil in the same manner as the mini-lysimeters, to maintain a humidity tension between 10 and 20 kPa.

Figure 1: Automated weather station (Campbell Sic., Logan, Utah, USA) to obtain the meteorological variables for determining the FAO Penman-Monteith reference evapotranspiration

The daily reference evapotranspiration rate (ETr) was calculated using the following equation (Allen *et al.*, 1988; Zermeño-González *et al.*, 2017).

$$LE\_ref = \frac{S*(Rn-G)+\rho_a*Cp*\frac{(\Delta e)}{r_a}*(f)}{S+\gamma*(1+\frac{r_s}{r_a})} \qquad (1)$$

Where LE_ref is the reference latent heat flux (MJ m^{-2} d^{-1}), S is the slope of the curve of saturation vapor pressure versus temperature corresponding to the air temperature (kPa K^{-1}), Rn is the net radiation on the reference surface (MJ m^{-2} d^{-1}), that was measured (LITE Net Radiometer; KEEP and ZONEN, Netherlands, and calculated (FAO-56 method), G is the soil surface heat flux (MJ m^{-2} d^{-1}) which was measured (flux transducer model HFP01, Campbell, Sci., Logan, Utah) and calculated as 10% of Rn, ρa is the density of the air (kg m^{-3}), CP is the heat capacity of the air (J kg^{-1} K^{-1}) Δe is the saturation vapor deficit of the air (kPa), γ is the psychrometric constant of the site (kPa K^{-1}), r_a is the aerodynamic resistance of the air to water vapor flux (s m^{-1}), r_s is the canopy resistance to water vapor flux (s m^{-1}) the factor f ($8.64*10^4$) is for the transformation of units from s m^{-1} to s d^{-1}. The soil surface heat flux (G) was calculated as 10 % of the net radiation (FAO-56b method) and measured using the following equations:

$$G = G_8 + \rho_b*Cs*\Delta Z*(\Delta Ts/\Delta t) \qquad (2)$$

Where: G_8 is the soil heat flux measured 8 cm below the soil surface (W m^{-2}), using a flux transducer model HFP01, Campbell, Sci., Logan, Utah, which was factory-calibrated, ρ_b is soil bulk density (kg m^{-3}), Cs is the heat capacity of humid soil (J kg^{-1} K^{-1}), ΔZ is the soil depth (8 cm), ΔTs is the change in the average soil temperature at 2 and 6 cm below the soil surface (measured with a 4-rod chromel-constant soil thermocouple), and Δt is time-lapse (30 min). Cs was calculated with the equation:

$$Cs = Cds + \theta w*Cw \qquad (3)$$

Cds is the heat capacity of the dry soil minerals (840 J kg^{-1} K^{-1}), θw is the soil water content (g/g), and C_W is the heat capacity of water (4184 J kg^{-1}).

According to the FAO Penman-Monteith method (FAO-56 method), at the site of the automated weather stations, the net radiation (Rn) on the reference surface is calculated from measurements of incident solar radiation, extraterrestrial radiation, and longwave radiation emitted by the reference surface, which are a function of the latitude, altitude of the place and day of the year, according to the following relationships:

$$Rn = Rns - Rnl \qquad (4)$$

Rns is the shortwave radiation absorbed by the reference surface (MJ m^{-2}), and Rnl is the longwave radiation emitted by the same surface. Rns is calculated with the following equation:

$$Rns = (1-\alpha_s)*Rsw \qquad (5)$$

Where α_s is the reflectivity index of the reference surface to the incident solar radiation (Rsw), for a green grass that covers the entire surface, α_s has a value of 0.25 (FAO-56 method). Rnl is calculated with the next equation (FAO-56 method):

$$Rnl = \sigma Ta^4(0.34 - 0.14*e_a^{0.50})\ (1.35*(Rsw/Rso) - 0.35) \qquad (6)$$

Where σ is the Stefan-Boltzmann constant (4.903e-9 MJ K^{-4} m^{-2} day^{-1}), Ta is the air temperature (K), e_a is the actual air vapor pressure (kPa), and Rsw is the incoming solar radiation at the surface (MJ m^{-2} day^{-1}). In this study, Rsw was measured by using a Silicon Pyranometer (model SP-510, Apogee Inst., Logan, Utah, USA), and Rso is the clear sky solar radiation (MJ m^{-2} day^{-1}) that was calculated with the next equation:

$$Rso = (0.75 + 2e\text{-}5*z)*Ra \qquad (7)$$

Where z is the weather station elevation n above sea level (m), and Ra is extraterrestrial radiation (calculated with the procedure of the FAO-56 method). In this study, the Rn was also measured using a Net radiometer (LITE Net Radiometer; KEEP and ZONEN, Netherlands).

The psychrometric constant of the site is obtained with the following equation:

$$\gamma = \frac{Pb*Cp}{L*\varepsilon} \qquad (8)$$

Where Pb is site barometric pressure (kPa), L is the heat of vaporization of water (MJ kg^{-1}), and ε is the ratio between the molecular weight of water vapor and dry air (0.622).

The air density was determined using the following equation:

$$\rho_a = \frac{3.848*(Pb-e_a)}{Ta} \qquad (9)$$

Where Pb is site barometric pressure (kPa) e_a is the actual vapor pressure (kPa), and Ta is the air temperature (K).

For the reference surface that corresponds to an extensive area of vegetation with a height of 12 cm of total surface coverage without water deficit in the soil, the aerodynamic resistance of the air to water vapor flux (r_a) is obtained with the following equation:

$$r_a = \frac{208}{u_2} \qquad (10)$$

where u_2 is the wind speed (m/s) measured at 2 m above the surface.

The canopy resistance (r_s) to water vapor flux has a value of 70 s/m for the reference surface (FAO-56 method).

To compare the daily ETr along the months of the years obtained with calculated data of net radiation (Rn) and soil heat flux (G), according to the FAO-56 method, against the ETr determined with measured data of Rn and G, the Welch test ($\alpha \leq 0.05$) for time series with normal distribution or the Wilcoxon test ($\alpha \leq 0.05$) for conditions of non-normality of the time series was applied. Comparisons were made between the ETr and the grass evapotranspiration rate (ETc) measured with the mini lysimeters.

RESULTS AND DISCUSSION

Measured and Estimated Net Radiation and Soil Surface Heat Flux

The average net radiation (Rn) of each month that was measured (LITE Net Radiometer; KEEP and ZONEN, Netherlands) was higher than the Rn calculated (FAO-56 method) for all the months evaluated except for August 2022 and September 2023, which are the months with the greatest rainfall in the region where the study was conducted. In both evaluation years, October had a more significant difference between the measured and estimated Rn. In October 2022, it was 21.25% higher; in October 2023, it was 42.05% higher (Table 1). The average daily Rn measured for all months evaluated over the two years was 15.76% higher than the calculated Rn. This result indicates that the Rn is underestimated when calculated using the FAO-56 method, and the ETr could be higher when Rn is measured (by a net radiometer) above the grass of the automated weather station than when obtained with the calculated Rn (FAO-56 method).

To estimate the value of the measured Rn based on the calculated Rn, a linear regression was performed using the daily integrated values from the evaluated months of 2022 and 2023 (Figure 2). The regression fit was performed with the y-intercept set to zero. The high value of the determination coefficient ($R^2=0.9483$) indicates that, with the regression coefficient of the adjusted linear equation, it is possible to make reasonable determinations of the measured Rn based on the calculated Rn (FAO-56 method). The value of the regression coefficient of the equation (slope) (1.1408) reveals that, on average, the measured (daily) Rn was 14.08% greater than the calculated (daily) Rn. Therefore, to obtain the measured (daily) Rn, the calculated Rn (FAO-56 method) must be multiplied by factor 1.408.

Table 1: Measured and calculated net radiation (Rn) and soil surface heat flux (G) (average integrated daily value of each month), and the differences (Diff) between the measured and the calculated values of Rn and G (%)

Year, month	Rn measured (MJ $m^{-2)}$	Rn calculated (MJ m^{-2})	Dif (%)	G measured (MJ m^{-2})	G calculated (Mj m^{-2})	Diff (%)
2022, June	13.34	13.06	2.10	1.06	1.31	-23.58
2022, July	13.26	12.67	4.44	0.94	1.27	-35.11
2022, August	11.40	11.54	-1.23	0.80	1.15	-43.75
2022, September	10.51	10.13	3.62	0.50	1.01	-102
2022, October	9.60	7.56	21.25	0.43	0.76	-76.74
2022, November	7.59	6.08	19.90	0.33	0.61	-84.85
2022, December	6.09	4.95	18.72	0.35	0.50	-42.86
2023, January	6.19	5.15	16.82	0.51	0.52	-1.33
2023, February	7.57	6.94	8.34	0.66	0.69	-5.89
2023, March	9.82	8.62	12.20	0.67	0.86	-28.68
2023, April	12.81	10.89	15.02	0.73	1.09	-48.26
2023, May	13.61	11.26	17.23	0.64	1.13	-75.97
2023, june	16.83	13.09	22.23	0.63	1.31	-107.32
2023, July	17.02	12.71	25.33	0.56	1.27	-125.63
2023, August	13.01	11.76	9.62	0.43	1.18	-174.17
2023, September	9.36	10.71	-14.43	0.60	1.07	-77.44
2023, October	11.77	6.82	42.05	0.44	0.68	-53.50

Similar results were reported by Carmona *et al.* (2017), who found a slope of 1.15 in the relationship between the measured and calculated Rn, with a determination coefficient of 0.920. The relationship between the measured Rn (REBS Q7.1 Net Radiometer) and the calculated Rn (FAO-56 method) was 1.07, with a determination coefficient of 0.93 (Irmak *et al.*, 2010).

Measurements of Rn in five locations in South Africa (LITE Net Radiometer; KEEP and ZONEN) and its comparison with Rn (FAO-56 method) resulted in regression coefficients between 1.04 and 1.22 with a determination coefficient between 0.89 and 0.96 (Myeni *et al.*, 2020). In summary, the value of the regression coefficient (slope) between the measured and calculated Rn (FAO-56 method) obtained in this study (1.1408) is in the range of the values reported by previous studies.

A linear regression was also performed between the measured and calculated (daily) soil surface heat flux (G) of the evaluated months of 2022 and 2023 (Figure 3). The regression fit was performed with the y-intercept set to zero. The value of the determination coefficient ($R^2=0.8736$) indicates that using the regression coefficient of the fitted linear equation (0.634), the measured daily G can be determined with reasonable precision from the G calculated using the FAO-56 method. This result also shows that G, calculated as 10% of Rn, overestimates by 57.7% the values of G measured (by a heat flux transducer and a 4-rod chromel-constantan soil thermocouple). The lower value of the measured G can result in a higher ETr than that obtained with the G calculated (because in the Penman-Monteith equation, the value of Rn is subtracted from the G value).

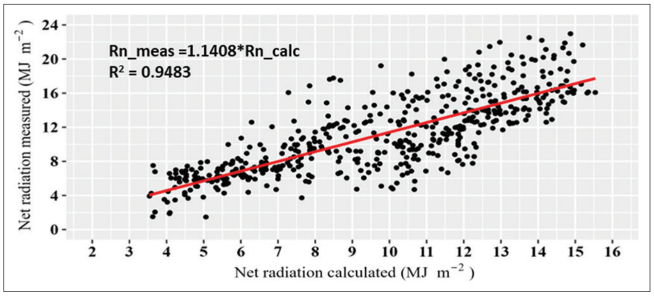

Figure 2: Linear regression fit of daily data from June 2022 to October 2023 of calculated net radiation (FAO-56) and measured net radiation (LITE Net Radiometer; KEEP and ZONEN, Netherlands)

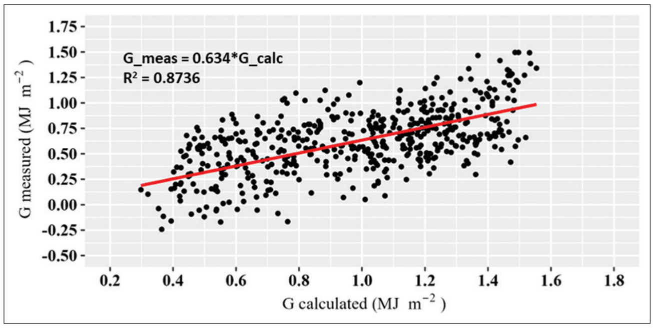

Figure 3: Linear regression fit of daily data from June 2022 to October 2023 of calculated soil surface heat flux (10 % of Rn) and measured soil surface heat flux (heat flux transducer and four-rod thermocouple)

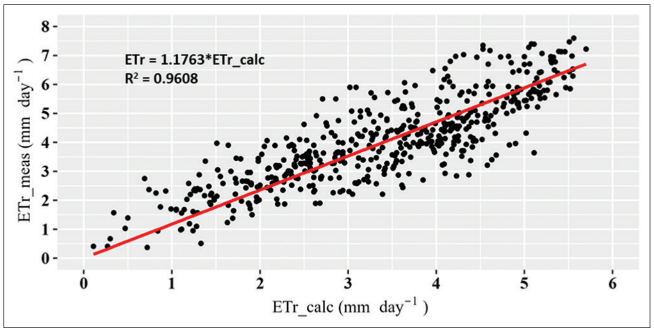

Figure 4: Linear regression fit between the daily rate of evapotranspiration determined with Rn and G measured (ETr_meas) and the one obtained with Rn and G calculated (ETr_calc) from June 2022 to October 2023

Other studies have reported lower values of the determination coefficient between G measured and G calculated. For instance, the study of Irmak *et al.* (2005) reported a determination coefficient of 0.275 between G measured and G calculated. In a similar study, the determination coefficient ranged from 0.75 to 0.53, where G calculated systematically overestimated G measured when the values of G were less than 40 W m^{-2} and underestimated when G was greater than 40 W m^{-2} (Gavilan *et al.*, 2007). The study by Payero *et al.* (2005) demonstrated that the relationship between G measures and G calculated varies throughout the day due to hysteresis caused by changes in soil surface humidity and the impact of variations in plant canopy height.

Measured and Calculated Reference Evapotranspiration

The reference evapotranspiration (ETr) (FAO-56 method) determined with measurements of net radiation (Rn) and soil surface heat flux (G) was higher than the ETr (FAO-56 method) obtained with Rn and G calculated (Table 2). For all evaluated months in 2022 and 2023, only in September 2023, the measured ETr was lower than the calculated ETr due to lower Rn in those months. The highest values of measured and calculated ETr were observed in June and July of 2022 and 2023, where the average measured ETr was 30.45 mm greater than the calculated ETr (Table 2). For an average daily evapotranspiration rate of 5 mm, this difference corresponds to the evapotranspiration of six days of a crop where the foliage covers the entire soil surface. A delay of six days in applying irrigation will occur when scheduling irrigation based on the ETr obtained using the FAO-56 method.

On average, for all months evaluated, the ETr determined with Rn and G measured was 24.5% higher than the ETr obtained with Rn and G calculated (Table 2). The most significant difference was observed in October 2023 due to a greater difference between the Rn measured and the Rn calculated (Table 1). Studies conducted in a Mediterranean climate area of Turkey revealed that the measured ETr was 10% higher than the calculated ETr (Kuzucu & Taş, 2024). This result was lower than the value observed in this study (24.51%). The study by Gavilán and Castillo-Llanque (2009) in Córdoba, Spain, indicated that the measured ETr was 9% higher than the calculated ETr (FAO-56 method), also lower than the one observed in this study. However, measurements conducted by Chen and Robinson (2009) at 19 points in five regions of North Carolina, USA, showed that the measured ETr was 21% greater than the calculated ETr, a result similar to that obtained in this study.

Table 2: Monthly reference evapotranspiration (ETr) determined with measurements of net radiation (Rn) and soil surface heat flux (G), and ETr obtained with calculated values of Rn and G, and the difference between them

Year, month	ETr measured (mm)	ETr calculated (mm)	Difference (%)
2022, June	148.59	135.90	9.34
2022, July	149.36	140.38	6.39
2022, August	122.37	119.53	2.37
2022, September	98.64	83.26	18.48
2022, October	93.83	76.60	22.48
2022, November	81.08	52.70	53.84
2022. December	75.12	48.79	53.98
2023, January	83.77	69.40	20.70
2023, February	89.37	71.89	24.31
2023, March	121.13	113.75	6.49
2023, April	134.34	100.72	33.39
2023, May	144.45	137.20	5.28
2023, June	196.64	149.46	31.57
2023, July	182.03	129.02	41.09
2023, August	148.64	128.48	15.69
2023, September	113.58	120.46	-5.71
2023, October	110.68	62.53	77.01

The daily ETr obtained with Rn and G measured (ETr_meas) was also higher than the daily ETr determined with Rn and G calculated (ETr_calc) for the evaluated months of 2022 and 2023 (Figure 4). The linear regression coefficient (slope) was 1.1763 with a determination coefficient (R^2) of 0.9608 (Figure 4). Therefore, to obtain the value of the ETr_meas, the value of the ETr_calc must be multiplied by 1.1763. This result also indicates that the daily average ETr_meas was 17.73% higher than the daily average ETr_calc. This result implies that when programming the irrigation of a crop based on the ETr_calc, the value must be multiplied by 1.1763 to obtain the irrigation depth to be applied. Otherwise, there would be an irrigation deficit of 17.63%.

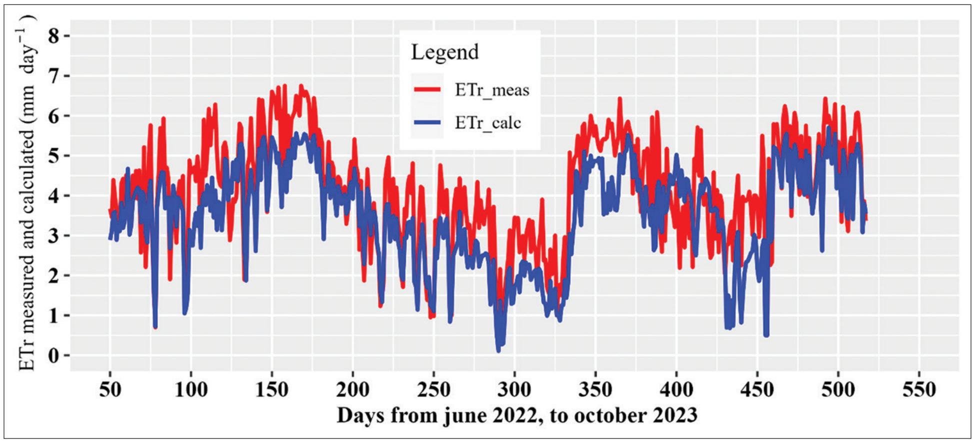

Figure 5: Daily reference evapotranspiration rate determined with Rn and G measured (ETr_meas) and obtained with Rn and G calculated (ETr_calc), with data from an automated weather station from June 2022 to October 2023

Other studies have also reported ETr_meas values higher than the ETr_calc. For example, da Cunha *et al.* (2014) reported that ETr_meas (measuring Rn with a LITE KEEP and ZONEN Net Radiometer) was 24.4% greater than the ETr_calc. Similarly, other studies have observed values of 6% to 29% of ETr_meas (measured with net radiometers) that are superior to those obtained with Rn calculated (Oliveira *et al.*, 2001; Turco *et al.*, 2005; Tagliaferre *et al.*, 2010). To obtain the ETr_meas and its comparison with the ETr_calc, Tagliaferre *et al.* (2010) recommend that Rn be measured with a LITE KEEP and ZONEN Net Radiometer, while Cunha *et al.* (2008) recommend the use of the Q-7.1 REBS net radiometer or the LITE KEEP and ZONEN Net Radiometer.

A comparison between the daily ETr_meas and the ETr_calc of the data from June 2022 to October 2023 shows that ETr_meas fluctuates over the ETr_calc. (Figure 5). The Wilcoxon test ($p=2.2*10^{-16}$) showed that the mean of the time series corresponding to the ETr_meas (3.96 mm) was statistically higher than the ETr_calc (3.25 mm).

Rate of Grass and Reference Evapotranspiration

In locations without an automated weather station, the reference evapotranspiration (FAO-56 method) can be estimated based on measurements of evapotranspiration from a grass or other vegetated surface with full soil coverage and a short height, provided there is no soil moisture deficit. Figure 6 shows the relationship between the daily evapotranspiration rate of the grass (ETc) in the automated weather station (average of six weighing micro lysimeters) and the reference evapotranspiration (ETr) (FAO-56 method) for the same days. The regression fit shows that the reference ETr can be estimated by multiplying the ETc by the factor 0.8219. This result also means that the crop coefficient (Kc) of the grass in the weather station was 1.216. or that the grass evapotranspiration rate is 21.6% higher than ETr. This relation can be used for crop irrigation scheduling based on the reference evapotranspiration rate in regions with no automated weather station by implementing evapotranspiration measurements of a grass with complete soil surface coverage and no soil moisture deficit.

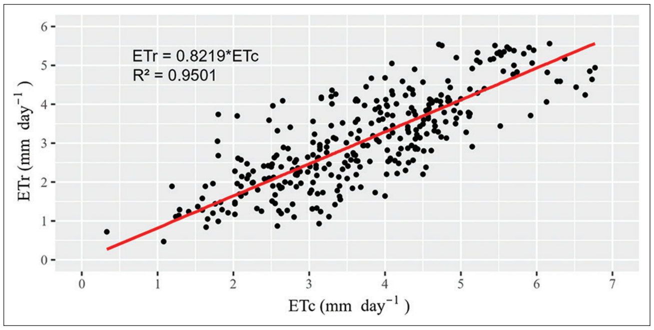

Figure 6: Regression fit between the daily grass evapotranspiration rate (ETc) of the automated weather station (average of six micro lysimeters) and the reference evapotranspiration rate (ETr)

Previous studies have also shown that the evapotranspiration rate of vegetated surfaces (used as reference surfaces) measured by weighing lysimeters is higher than the ETr (FAO-56 method). Diop *et al.* (2015) showed that the alfalfa (*Medicago sativa* L.) evapotranspiration rate obtained by weighing lysimeters was 12.5 to 21% higher than the ETr. Liu *et al.* (2017) observed that the ETr was up to 0.79 mm/day lower than that observed with lysimeter measurements on grass (*Festuca arundinacea* Schreb). The regression coefficient (slope) between the evapotranspiration rate of an alfalfa crop (as a reference surface) and the reference evapotranspiration (FAO-56 method) was 0.910, a value slightly higher than the observed in this study (0.8219) (Kiraga *et al.*, 2024).

In semi-arid climate zones with high wind speeds, the higher values of the transpiration rate observed in lysimeters (with reference crops) over the reference evapotranspiration rate (FAO-56 method) can be attributed to the advection transport of high vapor pressure deficit of air masses from the surroundings towards the area of the lysimeters (Tolk *et al.*, 2006; Evett *et al.*, 2012).

CONCLUSIONS

The FAO-56 daily reference evapotranspiration rate (ETr) obtained with measurements of net radiation (Rn) and soil surface heat flux (G) was 17.63% higher than that obtained with Rn and G calculated (FAO-56 method). Rn measured (with a Net Radiometer) was 14.08% superior to Rn calculated (FAO-56 method). Additionally, the G obtained through measurements (using a soil heat flux transducer and soil thermocouples) was 57.7% smaller than that obtained as 10% of Rn (FAO-56 Method). For locations of arid lands with no disposition of an automated weather station, the ETr (FAO-56 method) can be obtained by multiplying the evapotranspiration measurements of a grass or any short-vegetated surface with full soil coverage and no soil humidity deficit by the factor 0.8219.

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