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Comparison of water consumption estimates for tropical and winter forages by FDR probes and weighing lysimeters

Consumo de água em forrageiras tropicais e de inverno obtido por sonda FDR e lisímetros de pesagem

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Abstract

Soil moisture determination is essential for a good use of available water resources. In this regard, the use of frequency domain reflectometry (FDR) probes has as advantages mobility and practicality in relation to lysimeters. The experiment was carried out between April and June 2016 at the Luiz de Queiroz College of Agriculture (ESALQ/USP), located in Piracicaba, SP at the geographical coordinates 22°42′14.6″ S and 47°37′24.1″ W and altitude of 546 m. This study aimed to assess these FDR probes to estimate water consumption in comparison to measurements by weighing lysimeters (ETc_{Lys}) and reference evapotranspiration (ETo) in Mombaça and Bermuda grass pastures under single cultivation and overseeded with oat and ryegrass. Soil moisture was assessed daily by FDR probes by estimating crop evapotranspiration ($ETc_{FDR\ probe}$) from soil water balance calculation, which was correlated with ETc_{Lys} and ETo (Penman-Monteith, FAO 56). For all treatments, FDR probes presented the highest water consumptions when compared to the other two evapotranspiration methods, with accumulations of 126.5 and 125.6 mm for single and overseeded Mombaça grass, respectively. For Bermuda grass, water consumption was 123.4 mm in the single cultivation and 128.5 mm when overseeded. The method of estimating evapotranspiration by FDR probes showed good correlations with ETo and ETc_{Lys}.
Key words: Capacitive probe. Evapotranspiration. *Lolium multiflorum*. *Avena strigosa*. Soil moisture.

Resumo

A determinação da umidade do solo é preponderante para o bom uso dos recursos hídricos disponíveis. Neste aspecto, as sondas de Reflectometria no Domínio da Frequência (FDR) tem a vantagem da mobilidade e praticidade em relação aos lisímetros. O experimento foi conduzido entre abril e junho de 2016 na Escola Superior de Agricultura “Luiz de Queiroz” (ESALQ/USP), localizada em Piracicaba, SP nas coordenadas geográficas 22°42′14.6″ S e 47°37′24.1″ O e altitude de 546 m. O objetivo desse

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trabalho foi avaliar o uso de sonda FDR para estimativa do consumo de água em relação a medidas obtidas através de lisímetros de pesagem (ETc_{Lis}) e da evapotranspiração de referência (ETo) em pastagens de capim Mombaça e Cynodon em cultivos exclusivos e sobressemeados com aveia e azevém. A umidade de solo foi diariamente avaliada pela sonda FDR estimando a evapotranspiração de cultura ($ETc_{sonda\ FDR}$), a partir do cálculo de balanço hídrico no solo, que foi correlacionada com a ETc_{Lis} e a ETo (Penman-Monteith - FAO 56). A sonda FDR apresentou para todos os tratamentos os maiores consumos em relação aos outros dois métodos de evapotranspiração, com acúmulos durante o ciclo de 126,5 mm e 125,6 mm, no Mombaça exclusivo e sobressemeado, respectivamente. No *Cynodon* spp., o consumo foi de 123,4 mm no cultivo exclusivo e 128,5 mm no sobressemeado. O método de estimativa de evapotranspiração pela sonda FDR apresentou boas correlações com a ETo e ETc_{Lis}.
Palavras-chave: Sonda capacitiva. Evapotranspiração. *Lolium multiflorum*. *Avena strigosa*. Umidade do solo.

Introduction

Irrigated agriculture aims to maximize production while maintaining quality standards at the lowest possible cost without degrading the environment. The development of better irrigation procedures is necessary to overcome water restrictions resulting from the increased demand and the limited resources available (SILVA et al., 2017). In this context, soil moisture has been recognized as an important factor to understand the hydrological and meteorological processes, separating evapotranspiration from precipitation, runoff, and infiltration (TRAN et al., 2015; SANTOS et al., 2016), with the need to develop techniques for continuous soil moisture measurements (KAPILARATNE; LU, 2017).

The precise monitoring of soil water content is an important action for studies on soil water dynamics,thus, measuring or estimating water consumption of crops is a basic point for irrigation management (ALMEIDA et al., 2017), which can be calculated by several direct or indirect methods (PRIMO et al., 2015). The gravimetric method is a direct and simple method, but destructive and unusual. In the last years, the frequency domain reflectometry (FDR) has stood out due to its precision (PRIMO et al., 2015; TRAN et al., 2015; SOUZA et al., 2016; KAPILARATNE; LU, 2017).

An FDR probe works as an electronic capacitor that, when activated, the soil-water-air matrix forms a dielectric medium whose capacitance increases considerably as the number of water molecules increases (SOUZA et al., 2016). This probe can be used in pipes vertically installed in soil profile without altering it (EVETT et al., 2012).

Lysimeters, on the other hand, are expensive equipment composed of a block of land (tank) where the variation of soil water content can be estimated by the difference of inputs and outputs (ALLEN et al., 2011a; BILIBIO et al., 2017). Therefore, an FDR may be an interesting alternative to lysimeters, which have high implantation costs and frequent repairs (HOFFMANN et al., 2016). However, some of the aspects of an FDR can lead to estimation errors. In this sense, the spatial and vertical variability of soil bulk densitycaused by root zone growth, differences in soil wetting profile (precipitation or irrigation efficiency), and steady trampling around the access pipes may lead to overestimation of water consumption (EVETT et al., 2006; ALLEN et al., 2011a).

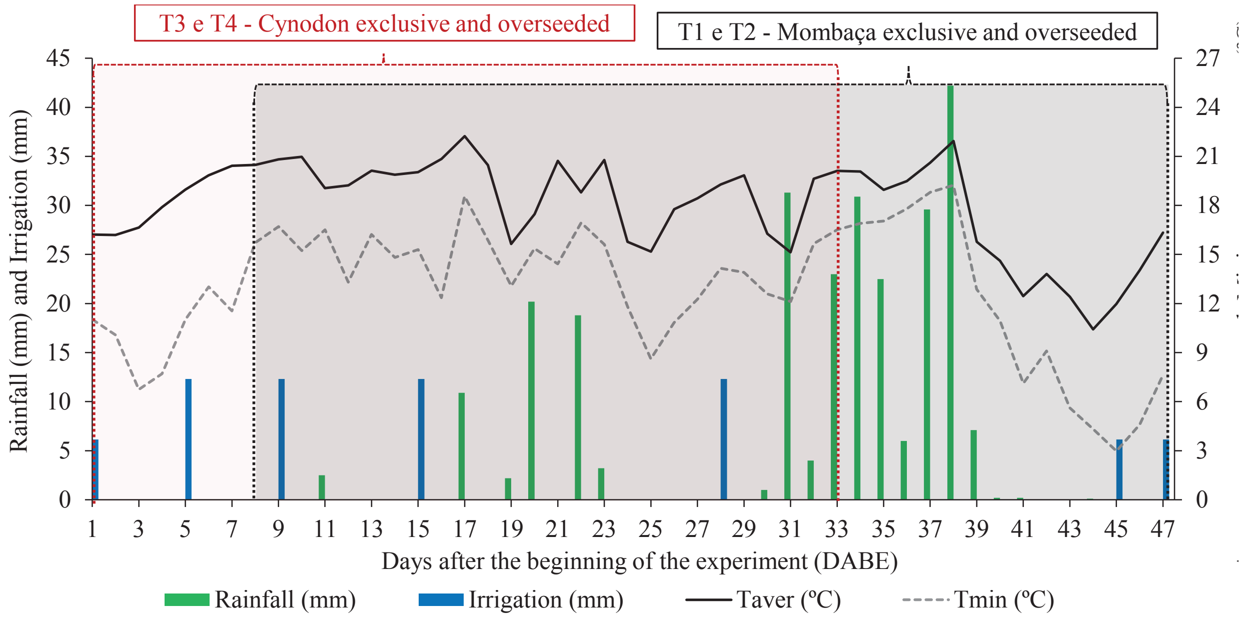
Several studies have assessed water consumption by crops in different soils with FDR type sensors (FERREIRA et al., 2015; NASCIMENTO et al., 2015; SOUZA et al., 2015). For a clay-textured soil of the Northeast of Brazil, the use of an FDR probe showed a great variation in soil water estimate over time as a function of vegetation cover (SANTOS et al., 2011). In an experiment with watermelon conducted in Teresina, PI, an underestimation was observed for water consumption estimated by means of a probe when compared to ETo (Penman-Monteith, FAO 56) in 30% (FERREIRA et al., 2015).

Therefore, knowing the performance of an FDR probe and comparing it with other water balance methods is essential to identify its potential use. Thus, the aim of this study was to assess the performance of an FDR probe for estimating water consumption in relation to weighing lysimeters in pastures of *Panicum maximum* cv. Mombaça and *Cynodon* spp. under single cultivation and overseeded with oat and ryegrass.

Materials and Methods

The experiment was carried out between April and June 2016 at the Luiz de Queiroz College of Agriculture (ESALQ/USP), located in Piracicaba, SP at the geographical coordinates 22°42′14.6″ S and 47°37′24.1″ W and altitude of 546 m. The soil of the experimental area is classified as a Kandiudalfic Eutrudox (SANTOS et al., 2013), with the following particle size characteristics: 32.50% of sand, 18.95% of silt, and 48.55% of clay. According to Köppen's classification, regional climate is defined as Cwa, i.e. a humid subtropical climate (PEREIRA et al., 2016). During the experimental period, the minimum temperature was 3.0 °C (Figure 1).

Figure 1. Rainfall, irrigation, and average (T_{aver}) and minimum (T_{min}) temperatures over the experimental period from April 30 to June 15, 2016. Piracicaba, SP.



Four experimental plots measuring 144 m² each, totaling 576 m² of experimental area, were used. Treatments consisted of two tropical grass species (*Panicum maximum* cv. Mombaça and *Cynodon* spp.) under single cultivation and overseeded with oat (*Avena strigosa* cv. Garoa) and ryegrass (*Lolium multiflorum* cv. São Gabriel).

Area preparation started in August 2015 with soil tillage (plowing and harrowing), correction of pH and soil fertility according to Raij et al. (1997), and subsequent construction of lysimeters. The cultivation of tropical grasses occurred in October 2015 by planting Bermuda grass seedlings and sowing Mombaça grass. Overseeding were performed in April 2016 (the day before the beginning of the experiment).

Treatments consisted of Mombaça grass under single cultivation (T1), Mombaça grass overseeded with black oat and ryegrass (T2), Bermuda grass under single cultivation (T3), and Bermuda grass overseeded with black oat and ryegrass (T4). Data collection was performed from May 7 to June 15, 2016, for T1 and T2 and from April 30 to May 31, 2016, for T3 and T4.

A nitrogen fertilization was performed at the beginning of the crop cycle by using urea at a dose of 50 kg N ha^{-1}. Data collection periods were established according to the forage, being 40 days for Mombaça and 33 days for Bermuda grasses, both under single cultivation and overseeded with oat and ryegrass. Before starting the experiment, a post-cut height (residue) of 30 and 15 cm were adopted for single and overseeded Mombaça grass, respectively, and of 10 cm for Bermuda grass under both cultivation.

Plot irrigation was conducted with a conventional sprinkler irrigation system with a sectoral device (angle of 90° and individualized per plot) with a working pressure of 25 meters water column and flow rate of 0.592 m^3 h^{-1} installed in a spacing of 12 × 12 m, resulting in an application intensity of 12.3 mm h^{-1}. Irrigation time varied according to crop water consumption measured by weighing lysimeters in each plot.

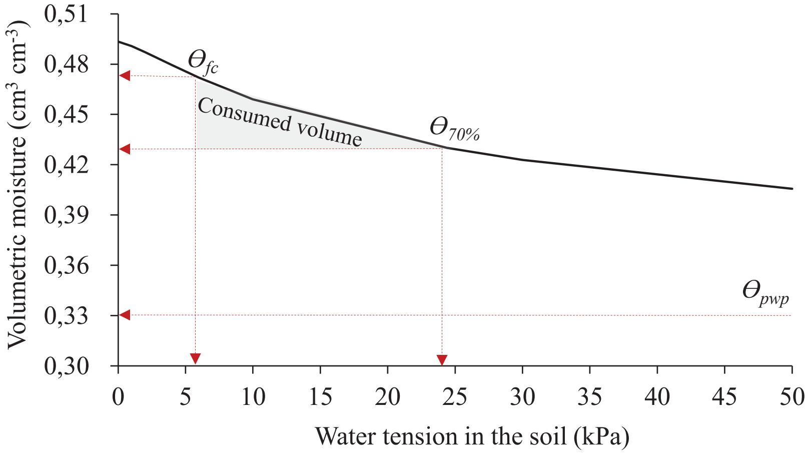
Weighing lysimeters were used for determining crop evapotranspiration (ETc), which consisted of circular rigid PVC boxes of 500 L with upper and lower diameters and height of 1.22, 0.95, and 0.58 m, respectively. Each lysimeter had a weighing system and a water collection and drainage system, as in Sanches et al. (2017).

Irrigation depth (ID) applied was determined from the consumption registered in the lysimeters (ETc, in mm), considering an effective root depth (Z) equal to 0.6 m. The maximum interval between irrigations was previously established based on estimates of ETc and soil water storage capacity in order to maintain a critical moisture corresponding to 70% of the available water capacity (Θ_{70} = moisture at 70% AWC) (Figure 2). Thus, moisture values at field capacity (θ_{fc}) and permanent wilting point (θ_{pwp}) were considered as the matrix potential values Ψ_{m_fc} = 6 kPa and Ψ_{m_pwp} = 1500 kPa, respectively (BENEVENUTE et al., 2016). Current moisture (Θ_c) values were estimated by means of soil water retention curve, obtained by using a tension table and Richards extractor adjusted by the Van Genuchten (1980) equation:

$$\theta_c = 0.2938 + \left[\frac{(0.4934 - 0.2938)}{\left[1+(0.113\Psi_{ma})^{1.3211}\right]^{0.2431}}\right]; (R^2=1.00 \text{ and } P<0.01) \quad (1)$$

where Θ_c is the current volumetric moisture (cm^3 cm^{-3}) and Ψ_{ma} is the current matric potential of soil water (bar).

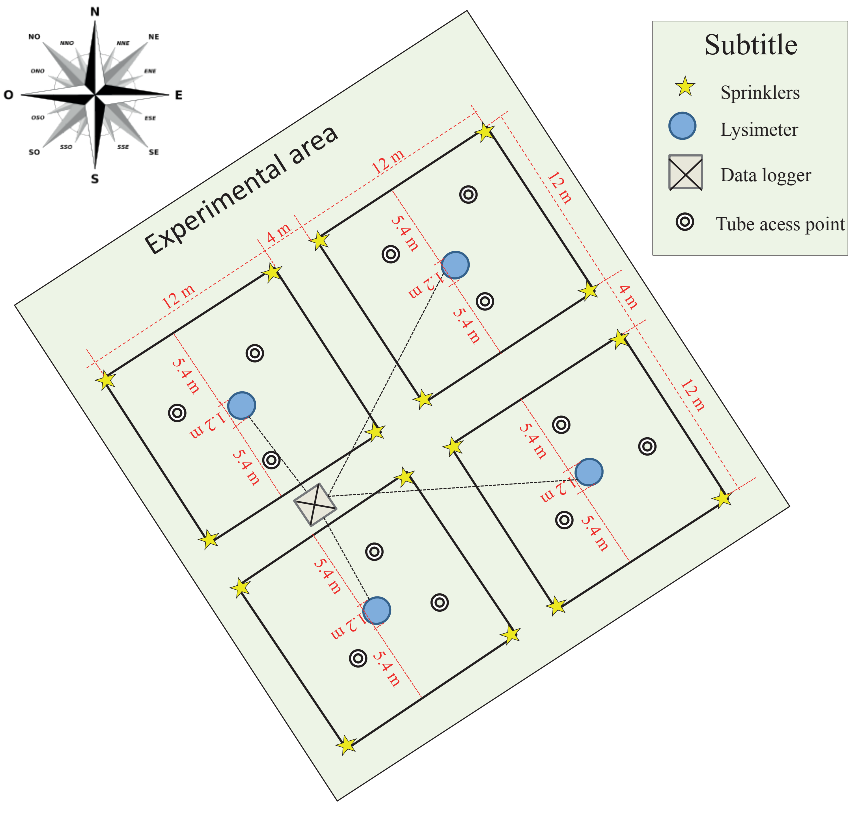
Figure 2. Characteristic soil retention curve of the experimental area. Piracicaba, SP, 2016.



Legend: Θ_{fc} = moisture at field capacity; Θ_{70} = moisture at 70% of the availability factor, Θ_{pwp} = moisture at permanent wilting point.

The measurements of crop evapotranspiration (ETc), obtained with lysimeters, and reference evapotranspiration (ETo) were compared with the measurements obtained by FDR probes with a Diviner 2000® portable module (Sentek, Stepney, Australia). In order to use it, three access tubes were installed in each plot, as shown in Figure 3.

Figure 3. Scheme of the experimental area with the location of access tubes to FDR probe. Piracicaba, SP, Brazil, 2016.



PVC access tubes were installed with a reading capacity of up to 0.7 m. However, the water variation data in the profile was used up to 0.6 m for consumption calculation, being the last layer used only to determine the underground drainage, thus simulating the effective lysimeter depth (0.6 m), as in Sanches et al. (2017).

Data from FDR probes were collected in the soil profile at intervals of 0.1 m depth. Its principle of operation is in relative frequency (RF), variable according to the water content in the soil. Thus, frequency data were transformed into volumetric moisture (ϴ) by Equation (2):

$$\Theta = 10^{\frac{(log\frac{RF}{A})}{B}} \quad (2)$$

where ϴ is the soil volumetric moisture (mm), RF is the relative frequency, and A and B are the calibration curve coefficients (A = 0.256 and B = 0.3422). The coefficients were obtained by calibrating the probe. Probe readings were performed daily (early in the morning) from the variation of soil water storage by subtracting the previous reading (initial) from the current reading. For soil moisture variation, we adopted multiple intervals of 3 days for single and overseeded Bermuda grass and 4 days for single and overseeded Mombaça grass, according to their cycle. Thus, water storage variation in the soil profile was calculated from the sum of determined depths (0-0.6 m), as in Equation (3):

$$\Delta_{stg} = \sum_{i=1}^{n}(\Theta_{initial} - \Theta_{current}) \times NID \quad (3)$$

where Δ_{stg} is the storage variation (mm), $\Theta_{initial}$ is the previous moisture reading (mm), $\Theta_{current}$ is the current moisture reading (mm), and NID is the number of intervals of days (3 or 4 days).

For calculating the crop evapotranspiration (ETc) obtained by FDR probes, surface runoff was disregarded since the terrain is flat (smooth wavy terrain with a slope ≤ 0.06). Thus, drainage (D) was the storage variation in the layer of 0.6 to 0.7 m. According to EVETT et al. (2012), when there is water increase in a layer without new entrances (rain and irrigation), flow is considered as drainage and presents a negative value in the equation. Therefore, ETc was calculated as Equation (4):

$$ETc\ (FDR\ probe) = \Delta_{stg} + I + P - D \quad (4)$$

where ETc (FDR probe) is the crop evapotranspiration measured by the Diviner FDR probe (mm), Δ_{stg} is the storage variation (mm), I is the irrigation in the period (mm), P is the precipitation in the period (mm), and D is the underground drainage (mm).

The results were processed using an Excel® worksheet with a quantitative descriptive data analysis by using the average water consumption data in a 3-day scale for single and overseeded Bermuda grass and a 4-day scale for single and overseeded Mombaça grass. The cycles had a duration of 33 days (single and overseeded Bermuda grass) and 40 days (single and overseeded Mombaça grass). A linear regression analysis was performed between the water consumption estimation data obtained by the capacitive probe and the ETc measured by lysimeters, as well as ETo estimated through the data from the ESALQ Meteorological Station by the Penman-Monteith model (ALLEN et al., 1998).

Results and Discussion

Considering the average data, all treatments presented linear regressions with high coefficients of determination between the evapotranspiration obtained by FDR probes ($ETc_{FDR\ probe}$) and reference evapotranspiration (ETo) and crop evapotranspiration (ETc_{Lys}) (Table 1). These high values of coefficients of determination showed that all treatments had a good linear trend of increasing water consumption when compared to the other two methods (ETo and ETc_{Lys}). According to Allen et al. (2011b), combined approaches of soil water observations and simulation modeling provide an adequate precision for evapotranspiration estimates.

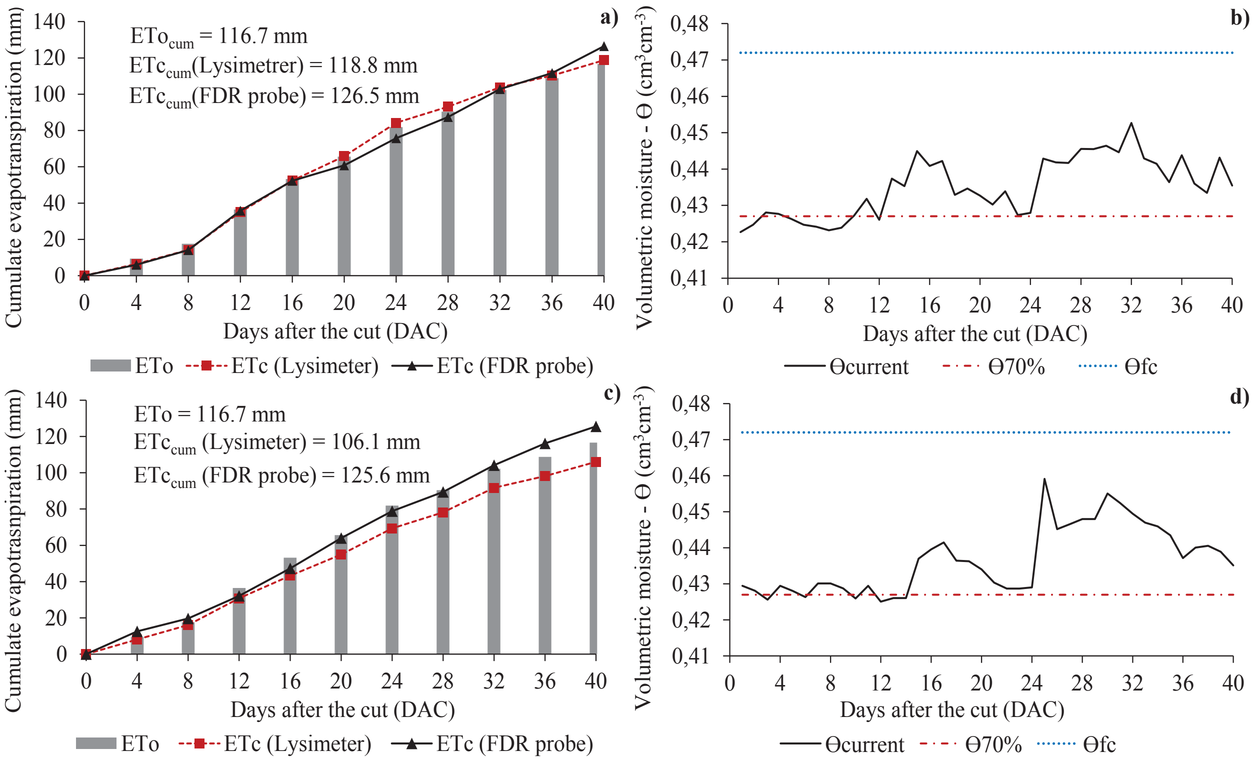
According to the linear regressions, the accumulated water consumption (evapotranspiration) had a direct and increasing relation, what demonstrates the lack of reading errors by the sensor when estimating evapotranspiration. Allen et al. (2011a, b) emphasized the importance of a proper functioning of sensors and their correct calibration in order to allow a good assessment and integrity of the measured data.

The average volumetric moisture of soil profiles (Θ_{avg}) for single and overseeded Mombaça grass presented values close to 70% (Θ_{70}) of the available water capacity (Figure 4). Water consumption in the cycle by means of FDR probes (Diviner) was higher when compared to the other evapotranspiration methods. However, it presented distinct behaviors: the single Mombaça grass presented values very close to ETc_{Lys} for almost all the experimental period, while the overseeded Mombaça grass presented values higher than those observed for ETc_{Lys} from 12 days after cutting, with an ascending behavior. The data obtained in our study showed a trend different from those obtained by Ferreira et al. (2015) for watermelon, which presented an ETc estimated by the same FDR probe lower than the ETo estimated by the Penman-Monteith (71% of the ETo in the period).

Table 1. Linear regression equations and coefficients of determination between water consumption by Diviner (FDR probe) and reference evapotranspiration (ETo) and water consumption obtained by weighing lysimeters. Piracicaba, SP, 2016.

Treatment (Plot)	$ETc_{(FDR\ probe)}$ & ETo		$ETc_{(FDR\ probe)}$ & $ETc_{(Lys)}$	
	Equation	R^2	Equation	R^2
Single Mombaça grass	$ETc_{Diviner} = 1.05 \times ETo - 3.83$	0.99	$ETc_{Diviner} = 1.01 \times ETc_{Lys} - 1.32$	0.98
Single Bermuda grass	$ETc_{Diviner} = 1.06 \times ETo - 0.35$	0.99	$ETc_{Diviner} = 1.18 \times ETc_{Lys} + 1.4$	0.99
Overseeded Mombaça grass	$ETc_{Diviner} = 1.04 \times ETo - 1.91$	0.99	$ETc_{Diviner} = 1.16 \times ETc_{Lys} - 0.34$	0.99
Overseeded Bermuda grass	$ETc_{Diviner} = 1.16 \times ETo - 5.99$	0.99	$ETc_{Diviner} = 1.18 \times ETc_{Lys} - 1.63$	0.98

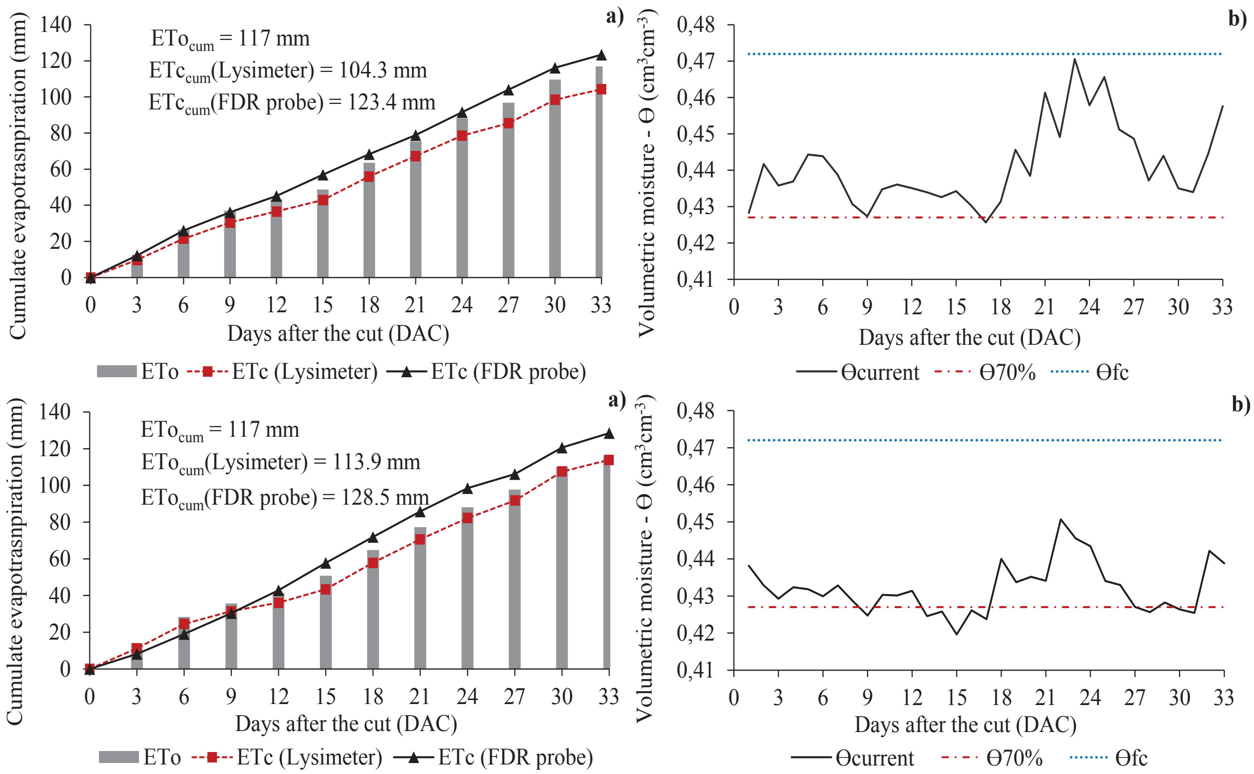
Figure 4. Accumulated evapotranspiration for single Mombaça grass (a), Θ_{avg} of 0-60 cm profiles as a function of FDR probes in single Mombaça grass (b), accumulated evapotranspiration for overseeded Mombaça grass (c), and Θ_{avg} of 0-60 cm profiles as a function of FDR probes in overseeded Mombaça grass. Piracicaba, SP, 2016.



Both single and overseeded cultivation started and ended their cycle in the same period (May 7 to June 15, 2016 - 40 days), being possible to observe a similarity in final water consumption, with values of 126.5 and 125.6 mm of water, respectively (Figure 4). When comparing the increased water consumption as a function of the days accumulated in the cycle, $ETc_{FDR\ probe}$ in the single and overseeded Mombaça grass presented similar linear regression equations (Table 1). This behavior may be related to the high soil clay (48.55%), which are more stable in pasture soils and moisture variation has an increasing or decreasing linear behavior according to water consumption (WANG et al., 2016).

For single and overseeded Bermuda grass, ETc by FDR probes also presented a higher water consumption when compared to the other two methods (Figure 5). Water consumption in relation to ETo was approximately 5.5 and 10% with the use of FDR probes in the single and overseeded Bermuda grass, respectively. In comparison, the reproductive phase of cowpea cultivation in Teresina, PI showed a water consumption 13% higher when compared to FDR probes (Diviner 2000®) (OLIVEIRA et al., 2013). Moreover, the flowering phase of corn cultivation showed a water consumption of 75.5 mm (22% higher than ETo) when using FDR probes (SOUZA et al., 2015).

Figure 5. Accumulated evapotranspiration for single Bermuda grass (a), Θ_{avg} of 0-60 cm profiles cm as a function of FDR probes the single Bermuda grass (b), accumulated evapotranspiration for overseeded Bermuda grass (c), and Θ_{avg} of 0-60 cm profiles as a function of FDR probes in overseeded Bermuda grass. Piracicaba, SP, 2016.



Water consumption behavior presented by FDR probes after the ninth day of crop cycle was always higher than ETo in both Bermuda grass cultivation (Figure 5). After plot cutting at the beginning of the cycles, all treatments of both pastures (Mombaça and Bermuda grasses) showed ETo and ETc_{Lys} with values of water consumption very close or higher than those indicated by FDR probes. This result may be due to the low water consumption soon after cutting the plants or even due to the difficulty of operating each system, which led to obtaining ambiguous data, making the comparison of them difficult when using different systems of evapotranspiration measures (ALLEN et al., 2011a, b; EVETT et al., 2012).

Conclusion

The method of water use estimation by FDR probe for Mombaça and Bermuda grasses under single cultivation or overseeded with oat and ryegrass presented higher water consumptions when compared to methods of reference evapotranspiration and crop evapotranspiration by lysimeter.

The method of evapotranspiration estimation by FDR probes presented good correlations with the other methods (ETo Penman-Monteith and ETc Lysimeter). The average volumetric moisture content in the soil profile (Θ_{avg}) measured by FDR probes was within the expected moisture range, according to the performed managements.

Acknowledgments

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