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THREE-DIMENSIONAL WATER EXTRACTION IN THE ROOT ZONE OF DRIP-IRRIGATED TOMATO

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1 ABSTRACT

Soil water sensing is a common alternative for irrigation management. Due to the difficulty to determine the spatial-temporal variability of water extraction (WE) in the root zone of a crop it is still arbitrary the definition of number and position of water content sensors to be installed for irrigation management purposes. The main objectives of this work are to use Time Domain Reflectometry (TDR) to detail – in three-dimensions – WE in the root zone of tomato plants cultivated in covered and uncovered soil; and, to evaluate if there are differences in the values of tomato crop evapotranspiration (ET) determined through soil water balance (SWB) with one, two, three and four TDR probe monitoring profiles. The study was carried out under semiarid condition. Tomatoes were grown in the field and two drainage lysimeters were installed in the center of cultivation area. In one lysimeter the soil surface was maintained uncovered, while in the other the soil surface was covered with a black plastic canvas. Eight TDR probes were installed within each lysimeter for the three-dimensional monitoring of soil water content (SWC). WE was estimated with SWC data. It was found that WE in tomato root zone is more intense in regions of greater water availability in the soil, i.e, on wet wet bulb formed inside the soil. There are no differences in the estimation of tomato crop evapotranspiration through soil water balance varying the position of two-dimensional soil water content monitoring. However, when soil water balance is performed in three-dimensions there may be large differences in daily tomato crop evapotranspiration estimation compared to the two-dimensional soil water balance.

Keywords: tomato, sensor placement, irrigation management.

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2 RESUMO

O sensoriamento de água no solo é uma comum alternativa para o manejo da irrigação. Devido à dificuldade em se determinar a variabilidade espaço-temporal da extração de água na zona radicular dos cultivos, ainda é arbitrária a definição do número e posicionamento de sensores de água no solo a serem instalados para fins de manejo de irrigação. Diante disso, objetivou-se com o referido trabalho utilizar a Reflectometria no Domínio do Tempo (TDR) para detalhar, em três dimensões, a extração de água pelo tomateiro em cultivo com solo coberto e descoberto, e verificar se existem diferenças nos valores de evapotranspiração da cultura determinados pelo balanço de água no solo com um, dois, três e quatro perfis de monitoramento. O trabalho foi conduzido em condição semiárida nas fases de floração e frutificação da cultura. Montou-se um sistema de aquisição de dados, composto por uma TDR 100 e um datalogger modelo CR 800 para leitura e armazenamento de dados do conteúdo de água no solo. Dois lisímetros de drenagem foram instalados no centro de uma área de cultivo, sendo um mantido com a superfície do solo coberto com lona plástica. Em cada lisímetro, foram distribuídas oito sondas de TDR de modo a formar quatro perfis de monitoramento na zona radicular do tomateiro. A extração de água da zona radicular do tomateiro é mais intensa na região de maior disponibilidade de água, especificamente, na região do bulbo molhado. Não há diferença nos valores de evapotranspiração do tomateiro estimado variando-se a posição do perfil bi-dimensional. Entratanto, ao se comparar valores diários de evapotranspiração do tomateiro estimado com balanço de água no solo realizado em duas e três-dimensões, verificou-se haver largas diferenças.

Palavras-chave: tomate, extração de água no solo, manejo da irrigação.

3 INTRODUCTION

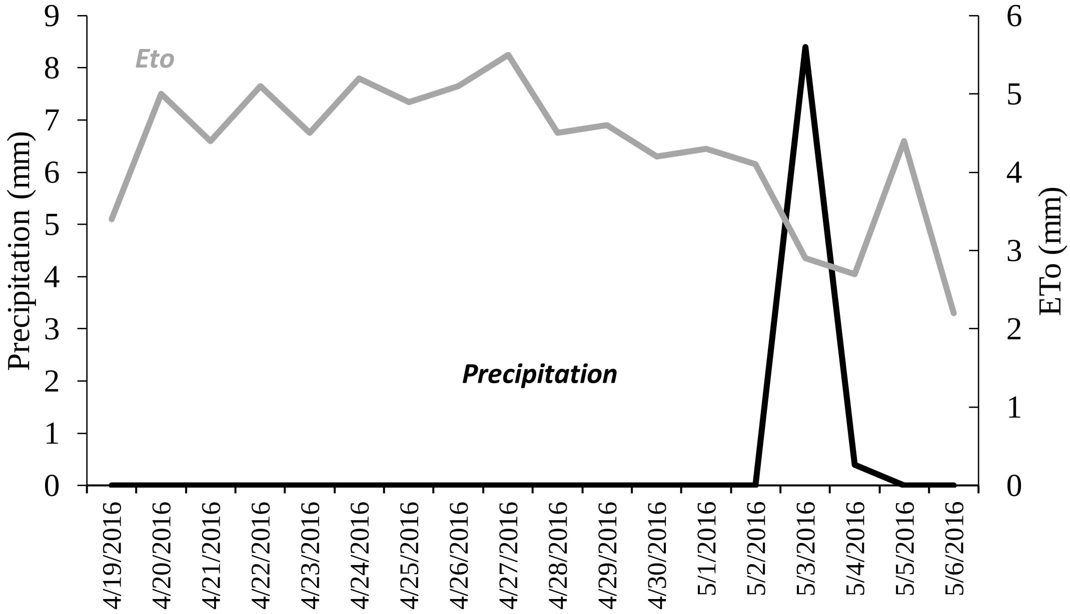
Soil water sensing is a common alternative for irrigation management and soil water balance (SWB). Nonetheless, the definition of the number and location of water content sensors (WCS) installation is still arbitrary. Studies have shown the existence of variability of water extraction in the root zone of various crops (JAVAUX et al., 2008; SILVA; COELHO; COELHO FILHO, 2009; SRAYEDDIN; DOUSSAN, 2009; DABACH; SHANI; LAZAROVITCH, 2016). In a study with the banana crop Silva, Coelho and Coelho Filho (2015) observed that spatial variability of water extraction (WE) affects the crop evapotranspiration (ET) estimate through SWB. However, in the case of short-cycle crops it is still a hypothesis the claim that the WE variability can affect the precision and accuracy of the ET estimates by SWB.

The difficulty to attribute optimal sensor placement for irrigation management and SWB is due the difficulty of spatial-temporal monitoring of WE in the root zone. Given the above, this study aimed to use Time Domain Reflectometry (TDR) to detail in three dimensions the extraction of water by the tomato crop cultivated in covered and uncovered soil, and verify the existence of differences in crop evapotranspiration values determined through SWB with one, two, three and four monitoring profiles.

4 MATERIAL AND METHODS

The study was carried out in Senhor do Bonfim-BA (latitude 10º 26’ 44" S; longitude 40° 08' 55" W and altitude of 532 m), semi-arid climate, with mean annual rainfall of 768 mm. The temporal distribution of the daily mean values of reference evapotranspiration (ETo) and rainfall recorded during the experimental period is presented in Figure 1. Rainfall occurred only in two days, totaling 8.8 mm, while the mean ETo in the period was 5.5 mm ± 2.2 mm.

Figure 1. Temporal distribution of Rainfall (mm) and ETo (mm) along the experimental period.



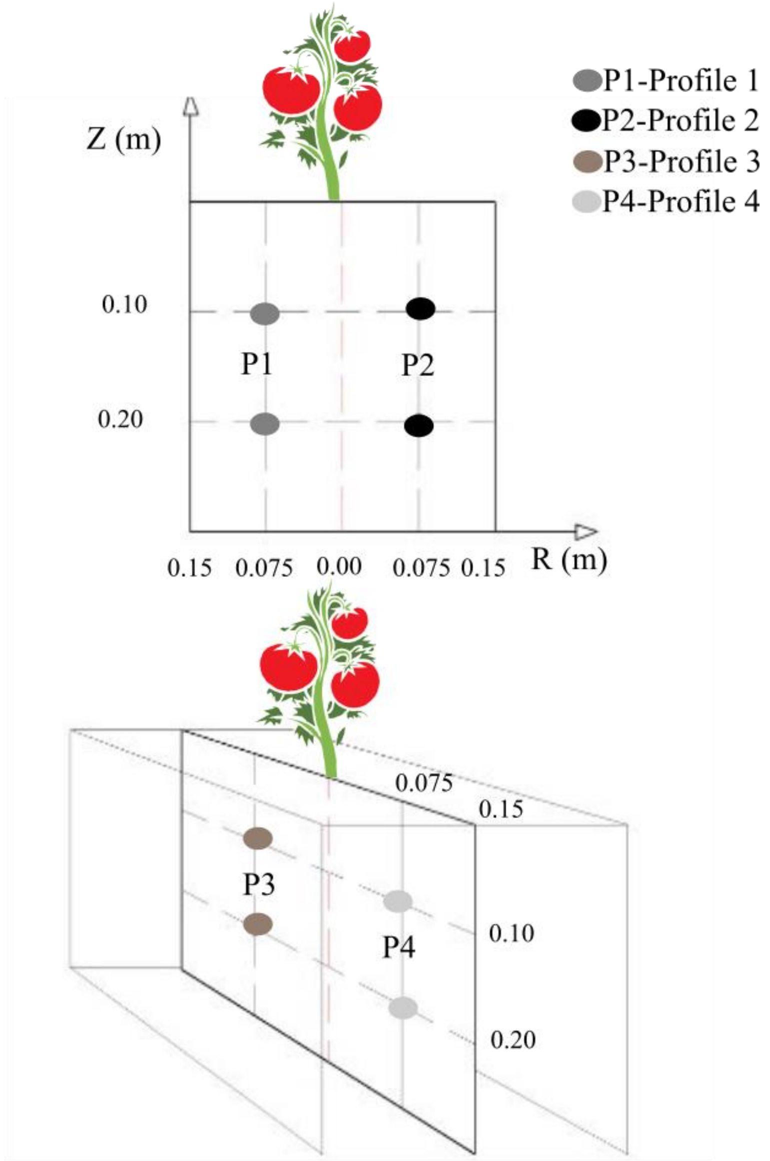
In order to detail WE in the tomato root zone, two drainage lysimeters were installed in the center of a cultivation area of 3,000 m^2. The lysimeters were cylindrical with diameter of 0.88 m, depth of 0.53 m and capacity for 322 L. In one lysimeter, the soil surface was maintained uncovered, while in the other the soil surface was covered with a black plastic canvas. To induce a free drainage system in the lysimeters, the 0.2 m bottom was divided into two layers: (i) 0.1 m composed of washed sand; (ii) 0.1 m composed of crushed stone. The lysimeters were filled with soil from the cultivation area and some Physical-hydraulics properties are presented in Table 1. TDR probes were installed into each lysimeter in four profiles, forming a three-dimensional arrangement to SWC monitoring. In each profile, two probes were installed, spaced by 0.10 m and located at 0.05 m and 0.2 m from the soil surface, according to Figure 2.

Table1. Physical-hydraulic characterization of the soil used in the experiment.

Depth (m)	**Textural Class**	**θ_{fc} (%)**	**Saturated soil (%)**	**θ_{pwp} (%)**	**A(%)**	**AW(%)**
0.20	Sandy loam	19.11	41.5	11.06	22.39	8.05

θ_{fc} = water content at field capacity (-1 m H_2O)
θ_{pwp} = permanent wilting point (- 150 m H_2O)
A= Aeration at θ_{fc}
AW = available water.

Figure 2. Scheme of installation of TDR probes.



The TDR probes were calibrated to relate the SWC and apparent dielectric constant (Ka) of the soil. For that, soil samples were collected in the cultivation area. The soil was air-dried, sieved through a 2-mm mesh and accommodated in three PVC pipe with diameter of 100 mm. Screens were placed at the bottom part of the pipe to allow only the outlet of water. Then, the soil was saturated inside the tubes for 24 hours, in which TDR probes were introduced until the sensor rods were completely covered. After that, readings of the weight of the 'tube + probe + soil + screen' set were taken simultaneously the measuring of the "Ka". Initially, the measurements were taken every five minutes. As percolation reduced, the measurements were taken in longer time intervals. The SWC of each weighing was determined by Equation 1:

$$\theta = \left(\frac{w_1 - w_2}{w_2 - w_3}\right)\frac{ds}{dw} \tag{1}$$

Where:
θ is the soil water content ($m^3.m^{-3}$)
w_1 is the weight of the PVC pipe – water – soil – TDR probe - screen (kg)
w_2 is the weight of the PVC pipe – soil – TDR probe -screen (kg)
w_3 is the weight of the PVC pipe –TDR probe -screen (kg)
ds is soil density (1.700 kg m^{-3})
dw is water density (1.000 kg m^{-3})

As a result of the calibration, equation 2 was obtained:

$$\theta = 6\times10^{-5} ka^3 - 3.4\times10^{-3} ka^2 + 7.63\times10^{-2} ka \ - 0\times4234 \qquad (2)$$

Where:
θ is the soil water content (m^3 m^{-3})
Ka is the dielectric constant measured by the TDR

In the field, SWC were automatically obtained using a data acquisition system composed of TDR 100 and data logger model CR 800.

Tomato was sown in a greenhouse covered with a black 50% shading screen on January 7, 2016. On February 9, 2016, the seedlings were transplanted to the field. The detailed monitoring of SWC to determine the WE was performed in the stages of crop flowering and fruiting, when plants exhibited the characteristics presented in Table 2.

Table 2. Biometric characterization of the tomato crop in the stages of flowering and fruiting.

Cultivation condition	Main branch length (m)	Stem diameter (cm)	Number of leaves	Number of flowers	Number of fruits
Flowering					
Without cover	0.37	1.05	27	6	0
With cover	0.35	1.01	16	5	0
Fruiting					
Without cover	0.78	1.89	91	87	38
With cover	0.62	1.53	67	51	19

Irrigation management was performed based on SWC data obtained through the TDR probes. Daily, the volume of water required to return the soil profile to the θ_{fc} (see Table1) was applied. A drip irrigation system was used, with two pressure-compensating emitters of 2.3 L/h per plant.

WE was daily determined using data set of SWC. The SWC measurements times were: t_1, immediately before irrigation (θ_{t1}); t_2, 30 minutes after irrigation (θ_{t2}); t_3, late afternoon (θ_{t3}); and t_4, immediately before the subsequent irrigation (θ_{t4});. WE and the variation in soil water storage (Δh) were calculated in each monitoring point (R_i Z_i) and in each profile (P_i), based on Equations 3 and 4:

$$WE = \frac{\sum_{i=1}^{n}\left(\int_0^L \theta_{t2}dz - \int_0^L \theta_{t3}dz\right)}{n} \quad (3)$$

$$\Delta h_{Rn} = \frac{\sum_{R=i}^{n}\int_0^L \theta(z_i)_{t2}\,dz}{n} - \frac{\sum_{R=i}^{n}\int_0^L \theta(z_i)_{t1}\,dz}{n} \quad (4)$$

Where:
"WE" is the water extraction in the soil in one region of interest in the profile ($cm^3\ cm^{-3}$)
Δh is the variation in soil water storage (mm)
Ri and Zi represent the monitoring points in distance and depth
L is the length of the profile.

For each monitoring point (R_iZ_i), the percentages of available water in the soil were determined based on the moisture values referring to field capacity and permanent wilting point, using Equation 5.

$$AW_{(Ri,Zi)} = \left(\frac{\theta_{(Ri,Zi)} - \theta_{pwp}}{\theta_{fc} - \theta_{pwp}}\right) \quad (5)$$

Where:
$AW_{(Ri,Zi)}$ is the percentage of available water in one point "R_i Z_i" of the soil profile
$\theta_{(Ri,Zi)}$ is the soil water content in one point "R_i Z_i" of the soil profile ($m^3\ m^{-3}$)
θ_{pwp} is the water content at permanent wilting point
θfc is the water content at field capacity

ET was estimated in the lysimeter without soil cover, through the water balance, represented by Equation 6:

$$ET = P + I - \Delta h - D \quad (6)$$

Where:
ET is the tomato crop evapotranspiration (mm)
P is the rainfall (mm), I is the irrigation (mm)
Δh is the variation in soil water storage (mm)
D is the drainage (mm)

The ET values calculated with SWC data obtained in one, two, three and four monitoring profiles (SP_1, SP_2, SP_3 and SP_4) were compared, where SP4 is the sum of P1 + P2 + P3 + P4, SP 3 is the sum of P1 + P2 + P3, and so on. The statistics used are recommended by Tedeschi (2006), fitting a simple linear regression model with the ET values obtained in the four profiles in the Y-axis over the other conditions in the X-axis, through equations like y = ax+b, subject to the joint null hypothesis of the estimated parameters a and b: H0: a=1 and H0: b= 0, proving or rejecting these hypotheses through the F test suggested by (MAYER; STUART; SWAIN, 1994), with a 95%

confidence level. For this, we use the Model Evaluation Software (MES), version 3.1.17 (TEDESCHI, 2006).

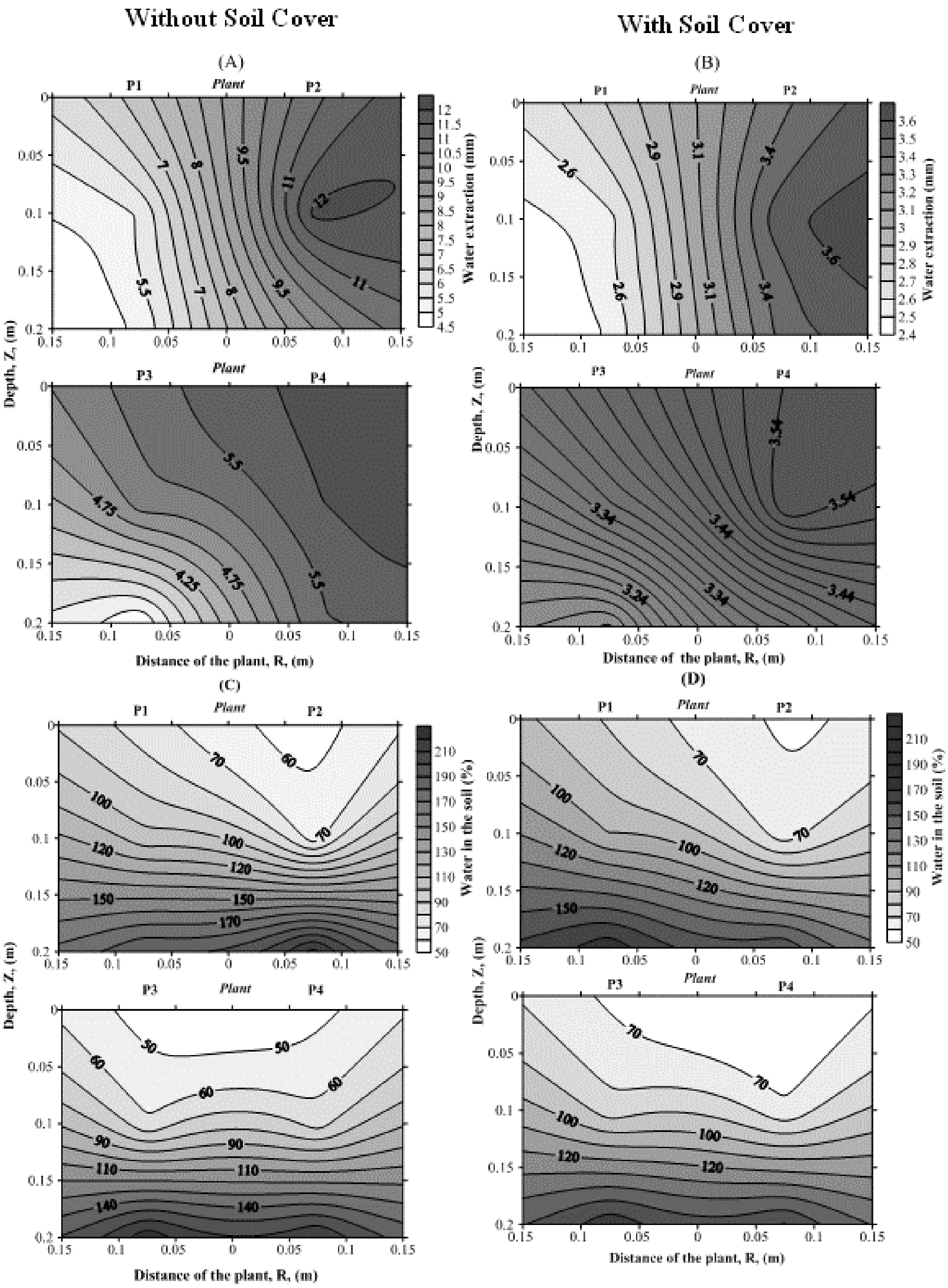
5 RESULTS AND DISCUSSION

The three-dimensional pattern of WE by the tomato crop cultivated with and without cover on soil surface can be seen in Figures 2A and 2B. The figures represent the means of WE calculated in the flowering and fruiting phases of the tomato. In both cultivation conditions WE was more intense on one side of the plant, coinciding with the position of the lateral irrigation line and with the region of higher percent values of available water (Figures 2C and 2D). For a same depth WE is more intense in regions of greater water availability as observed by Green and Clothier (1995) investigating the root water uptake by kiwifruit. Indeed, soil water availability is one of the main determinants of the water uptake pattern (GARDNER, 1964). However, other factors are attributed as intervenient in the water uptake pattern in the root zone of a crop, such as: (i) root density (SHARP; DA VIES, 1985), (ii) number of radicles (ATKINSON, 1980), (iii) xylem maturation, number and diameter of xylem vessels, as well as differences in the formation of endodermis and exodermis with the development of the roots (STEUDLE; FRENSCH, 1996; BARROWCLOUGH; PETERSON; STEUDLE, 2000; WATT; MAGEE; MCCULLY, 2008; DRAYE et al., 2010).

It was verified in tomato cultivation with uncovered soil that the highest mean values of WE occurred at 0.10 m soil depth. WE varied over time between 5 and 12 mm at 0.10 m soil depth. Already at 0.20 m soil depth WE varied between 3 and 9 mm. On the other hand, in the tomato cultivation with covered soil the values of WE at 0.10 m soil depth were very close to those at 0.20 m soil depth. The maximum and minimum values of WE at theses depths were 3.4 and 2.5 mm, respectively.

Therefore, there is a difference in the intensity of WE under the conditions of covered and uncovered soil. As this results indicates, there is strong influence of the evaporation process on the evapotranspiration of the tomato crop cultivated under semiarid conditions irrigated on a daily frequency through a drip system. This results agrees with those found by other authors (DIAZ; JIMENEZ; TEJEDOR, 2005; YUAN et al., 2009; BU et al., 2013) and allows to recommend the use of plastic covers on soil surface as a way to increase water use efficiency in cultivation areas of the semi-arid region that use frequent irrigations.

Figure 3. Distribution of water extraction (A and B) and percentages of available water in the soil (C and D) after drip-irrigation of the tomato crop. * Figures were built with the software SURFER, version 7.0. Golden Software, 1999.



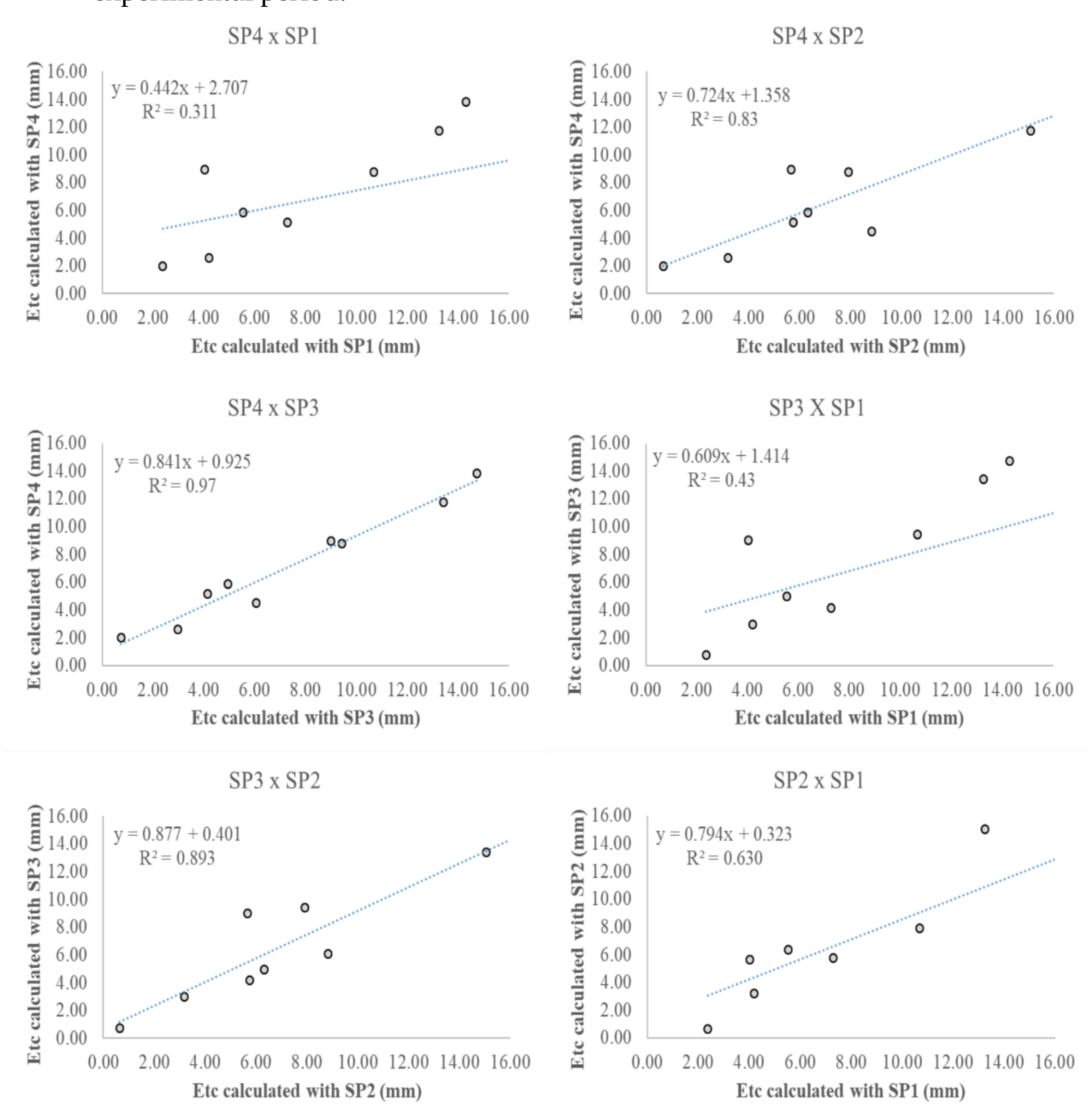
The relationship between the values of ET of the tomato crop cultivated in uncovered soil and estimated based on the SWB with SWC obtained in SP_4, SP_3, P_2

and SP_1 monitoring profiles is presented in Figure 4. The result of the test of joint null hypothesis (MAYER; STUART; SWAIN, 1994) is shown in Table 3. The evaluations of the intercept "a" and the slope "b" point to the non-rejection of the joint null hypothesis (P>0.05) for all evaluated regressions. Hence, although there is spatial variability of water extraction in the root zone of the tomato crop - with higher extraction intensity on the side of the plant with greater water availability - such variability did not alter the mean ET estimate through different numbers of profiles according Mayer; Stuart and Swain, (1994). Nonetheless, in the comparison between ET values obtained with three-dimensional monitoring (SP4) and two-dimensional monitoring (SP1) the force of the relationships decreased as the difference between the number of probes increased. In this case (Figure 4 - SP4 x SP1), the differences in ET calculation can reach up to 10 mm. The differences decrease when comparing the different results obtained in bi-dimensional plans and the regressions between the values of ET show that there are no implications of the different positions of two-dimensional monitoring in the SWB applied to drip irrigated tomato crop.

Table 3. Statistics for regression between the values of tomato evapotranspiration estimated through soil water balance using 1, 2, 3 and 4 moisture monitoring profiles (SP1, SP2, SP3 and SP4) for the uncovered lysimeter.

Item (y= a+bx)	SP_4xSP_1	SP_4xSP_2	SP_4xSP_3	SP_3xSP_1	SP_3xSP_2	SP_2xSP_1
Intercept (a)	2.707	1.358	0.925	1.414	0.401	0.323
Slope (b)	0.442	0.724	0.841	0.609	0.877	0.794
R^2	0.311	0.83	0.97	0.43	0.893	0.63
P value (H_0: a= 0 and b=1)	0.054	0.117	0.09	0.155	0.431	0.343

Figure 4. Relationship between the values of tomato evapotranspiration in the uncovered lysimeter, estimated through soil water balance with variations in water storage calculation using moisture data from four monitoring profiles during the experimental period.



6 CONCLUSIONS

In this work the water extraction in the root zone of the drip irrigated tomato was detailed in three-dmensions. Water extraction in tomato root zone is more intense in regions of greater water availability in the soil, i.e, on wet wet bulb formed inside the soil.

There are no differences in the estimation of tomato crop evapotranspiration through soil water balance varying the position of two-dimensional soil water content monitoring. However, when soil water balance is performed in three-dimensions there may be large differences in daily tomato crop evapotranspiration estimation compared to the two-dimensional soil water balance.

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