Journal of Agricultural Science; Vol. 8, No. 7; 2016
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Soil Water Storage in Soybean Crop Measured by Polymer Tensiometers and Estimated by Agrometeorological Methods

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Received: April 30, 2016 Accepted: May 31, 2016 Online Published: June 15, 2016

doi:10.5539/jas.v8n7p30 URL: http://dx.doi.org/10.5539/jas.v8n7p30

Abstract

The estimation of soil water status in cropped areas continues to be challenging for soil and climate scientists. This study contributes to this issue estimating soil water storage by the water balance of Thornthwaite and Mather, Rijtema and Aboukhaled, and Dourado and de Jong van Lier, combined with crop potential evapotranspiration estimated by Penman-Monteith, to compare them with soil water storage values calculated from polymer tensiometer data of a soybean crop field experiment. The experiment was conducted in Piracicaba, SP, with tensiometers installed at 0.05, 0.15 and 0.3 m depths. Results show that the tensiometers presented good performance to measure soil water pressure head in the whole range of the available water capacity for the crop. The tensiometer presents the advantage of allowing measurements of soil water storage in layers, in contraposition to climatologic water balance calculations which assume one single layer. Rijtema and Aboukhaled presented the best correlation with the water storage estimated from tensiometer data.

Keywords: soil water pressure head, crop water stress index, evapotranspiration

1. Introduction

The estimation of soil water storage S (mm) is of great importance for the management of agricultural crops. Calculation of soil water storage is commonly based on soil water content θ (m^3m^{-3}) measurements, for which several laboratory and field methods are available. For contiuous monitoring of θ the number of available methodologies is restricted, all of which present some disadvantages. A novel method is the use of polymer tensiometers capable of measuring the soil water pressure head h (m) within the whole range of soil water contents prevailing in agriculturally used soils (Bakker et al., 2007; Van Der Ploeg et al., 2008). Measured values of h can be transformed to θ when the $h(\theta)$ relation (water retention curve) is known. Polymer tensiometer data have been used by Durigon et al. (2011) and Durigon and de Jong van Lier (2013) polymer for laboratory observations; Durigon et al. (2012) reported data from field measured values with this tensiometer.

Besides these soil water based measurements of water storage, S can also be estimated from meteorological measurements through the water balance (WB), which accounts for water inputs and outputs in a defined soil volume. *WB* models have as inputs climatological and soil data and one of their outputs is S and its variation in time. Calculations depend on estimations of the potential evapotranspiration (ET_p) using a variety of models and of the availability of crop coefficients K_c. The most commonly used method is the Penman-Monteith (Allen et al., 1998) formula. Other, less data-requiring models are also frequently used. For low latitudes (< 40°), the monthly average Thornthwaite (1948) method is an alternative sometimes used.

According to Dourado et al. (1999), the *WB* is a very useful tool for the understanding of the use of soil water by crops, helping in decision making in the management of agricultural crops. In the *WB*s, the availability of soil water to plants can be assumed following several models, the most common being those of Thornthwaite and Mather (1955), Rijtema and Aboukhaled (FAO, 1975), and to some extent Dourado and de Jong van Lier (1993).

This last model avoids the discontinuity of the abrupt evapotranspiration decrease at the critical soil water content, as assumed by the FAO method, by using a cosine shaped evapotranspiration decrease.

Within this context, this study aimed to explore the use of the newly developed polymer tensiometer by comparing results of S measured directly in the field (reference method) with data obtained by these three methods of WB modeling.

2. Methods

A soybean (*Glycine max* (L.) Merrill) cultivar BRS 232 crop was established on an Oxisol in Piracicaba, SP, Brazil (22°42′S, 47°38′E) between January and May, 2012. Local climate is classified as humid subtropical, with dry winters and hot summers (CWa climate type according to the Köppen classification). The annual rainfall is approximately 1,200 mm. Meteorological data were obtained from an automatic station located 1.5 km from the experimental site (Figure 1a).

Soil water pressure head was measured using polymer tensiometers, which allow automated measurements of soil water tension and are especially interesting for measurements under drier soil conditions. The polymer tensiometer consists of a porous coup sensible element with a polymer inside a chamber. The polymer expands or contracts as water enters or leaves the chamber, so that the pressure inside is proportional to h. With the aid of calibrated pressure transducers a signal is recorded. The installation of the polymer porous cups in the field is very similar to that of classical porous cup tensiometers. The main and important difference is the possibility of linking them to dataloggers and have continuous readings. Their operational range extends from the saturation water content (θ_s m^3m^{-3}) down to pressure heads around -15 atm, close to the permanent wilting point (*PWP* = -150 m), far beyond the range covered by conventional water-filled tensiometers (Durigon & de Jong van Lier, 2013). Due to their recent development, the polymer tensiometers are still very costly and not easily available in the market. This study also aims to widen their use and so decreasing costs. Therefore, only two sets of polymer tensiometers were installed at three depths: 0.05, 0.15 and 0.30 m, to represent three soil layers: 1. 0-0.1 m, 2. 0.1-0.2 m and 3. 0.2-0.4 m, and at two locations, with measurements recorded by built-in data-loggers every 15 min. We understand that this low number of replicates is a restriction of our study due to soil spatial variability, but the very good data obtained and the very few published reports on the use of polymer tensiometers are points we considered to carry out this project.

Soil water content θ (m^3 m^{-3}) was estimated from daily time averages of h, using the van Genuchten model (Van Genuchten, 1980; Dourado et al., 2011) for each layer of soil,

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha h)^n]^m} \quad (1)$$

Where, θ_r is the residual soil water content; h is the daily average matric potential head (m); α (m^{-1}), m and n are empirical parameters.

Daily values of S (mm) for the 0-0.4 m soil layer were then calculated using the classical concept of available water (AW). This concept assumes that the available water to plants lies between a maximum value called field capacity θ_{FC}, here assumed corresponding to h = -1 m, a commonly used value for Brazilian Oxisols (Reichardt, 1988; Reichardt & Timm, 2012) and a minimum called permanent wilting point θ_{PWP} (assumed to correspond to h = -150 m). The water between saturation θ_s and θ_{FC} is considered to be subject to rapid gravitational drainage, thus not available to plants. The water below θ_{PWP} is considered to be unavailable to plants due to soil hydraulic restrictions. With these assumptions, the available water (*AW*) is defined as [θ_{FC} - θ_{PWP}], and the available soil water storage (S_{AV} or *AWC*, mm) was calculated as,

$$S_{AV} = (\theta_1 - \theta_{PWP}) \times 100 + (\theta_2 - \theta_{PWP}) \times 100 + (\theta_3 - \theta_{PWP}) \times 200 \quad (2)$$

Where, θ_1, θ_2 and θ_3 are soil water contents in layers 1, 2 and 3.

Since only one soil water retention curve was available for the three layers, one single value of θ_{PWP} was used. This value was also assumed to correspond to all values of h lower than -150 m when measured by the polymer tensiometers. For values of h above -1 m, θ was considered equal to θ_{FC}. During the cropping cycle plants received water from rainfall P (mm) or irrigation I (mm), and during *WB* calculations, for each time the calculated S was greater than *AWC* it was set equal to *AWC*. Within the *AWC* range, water is either evaporated at the soil surface or transpired by plants, resulting in the actual evapotranspiration ET_a (mm). Water is not equally available in the whole range of the *AWC*, its extraction from the soil by plants is reduced when approaching the *PWP*. This is due to drastic decreases in soil hydraulic conductivity as the soil dries out. There are several models to describe the process of water extraction from the soil by plants, and we use here three models: Thornthwaite and Mather (*M*); Rijtema and Aboukhaled (*R*); and Dourado and de Jong van Lier (*C*), using the potential evapotranspiration ET_p estimated by Penman-Monteith (Allen et al., 1998), corrected by the crop coefficient K_c, with initial values of 0.4, varying to 0.8, 1.1, 0.8 and 0.5 along the development of the soybean crop.

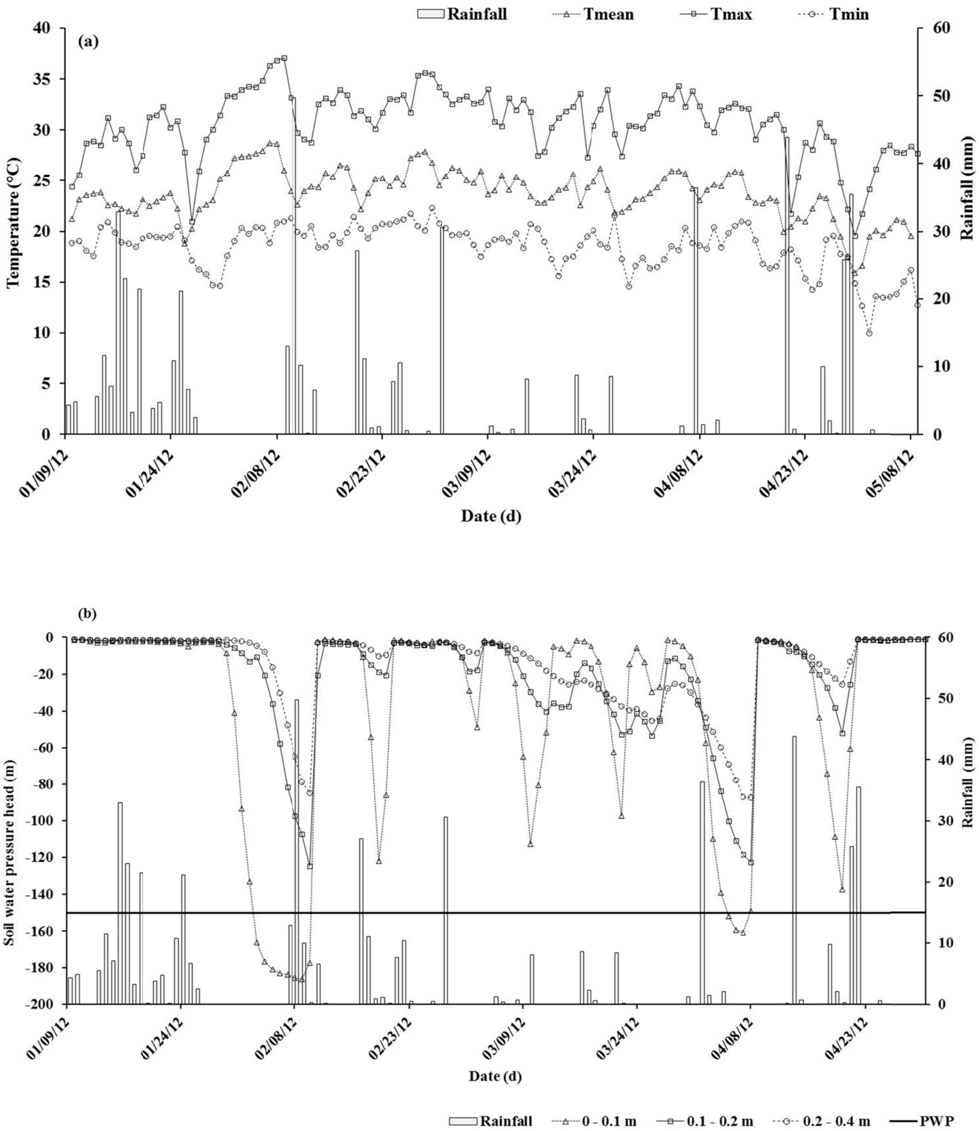

Figure 1. Rainfall and temperature (mean, maximum and minimum) measured on a meteorological observatory, from January, 5th to May, 10th, 2012 (a); Distributions of matric potential head and of rainfall during the experimental period, showing two periods (02/12 and 04/12) with *h* below permanent wilting point (PWP) (b)

For the first *WB* (*M*) model (Thornthwaite & Mather, 1955), the decrease in *S* follows an exponential model,

$$S = AWCe^{-\frac{\theta}{(\theta_{FC} - \theta_{PWP})}} \quad (3)$$

which is a result of assuming that ET_p decreases linearly from *FC* to the *PWP*.

The *WB* (*R*) of Rijtema and Aboukhaled (1975) takes into consideration a water availability factor p for the estimation of *S*, which decreases as,

$$S = (1 - p)AWCe^{\frac{p - \frac{\theta}{\theta_{FC} - \theta_{PWP}}}{(1-p)}} \quad (4)$$

which is a consequence of assuming that the actual evapotranspiration $ET_a = ET_p$ from *FC* to a critical point *p*, thereafter decreasing linearly to zero at the *PWP*.

Dourado and de Jong van Lier (1993) *WB* (*C*) assume a sigmoidal (using part of the cosine function) rate of *ET* decrease, starting smoothly from the critical point and ending also smoothly at the *PWP*. With this model, *S* decreases as

$$S = (1-p)AWC\left\{1-\frac{2}{\pi}arctg\left[\frac{\pi}{2}\left(\frac{\frac{\theta}{\theta_{FC}-\theta_{PWP}}-p}{1-p}\right)\right]\right\} \quad (5)$$

Statistical coefficients (correlation coefficient of performance, reliability index, standard error of estimate) were used to compare the estimated and observed data.

3. Results and Discussion

3.1 Soil Matric Potential h Measured with Polymer Tensiometers

The time course of daily averages of the matric potential head *h* measured by the polymer tensiometer for the whole soybean crop period at the three depths (Figure 1b) shows that the lowest values of *h*, of -186.2 m and -160.8 m were observed on February 9 and April 7, respectively, both below the *PWP*, which is a novelty in field measurements of *h*. It can clearly be seen that the whole root system (0-0.4 m) is exposed to very different values of *h*, showing the limitations of assuming the *AWC* for the whole root zone, as made in most *WB* studies, stressing the importance of observig such systems in a detailed way. Important to mention is that at these moments of water stress mentioned above, even with the top 0.0-0.1 m layer presenting *h* values beyond *PWP*, plants were visually not showing water stress. For soybeans, this surface layer contains an appreciable part of the root system, which reaches extremely low values of *h* apparently recovers from the water stress as soon as there is an input of water by rainfall or irrigation.

To analyze the time course of soil water content θ obtained from corresponding values of *h*, Figure 2a includes the *FC* assumed as the value of θ for h = -1 m (FC_1), as recommended for this soil by REICHARDT (1988), and for h = -3.33 m ($FC_{3.33}$), as taken conventionally in most soil water studies. Considering FC_1, it can be seen that most of the time the soil profile was in the range of available water. On the other hand, considering $FC_{3.33}$ the soil profile would for several periods be out of the available water range, which is unrealistic. This shows again that h = -3.33 m is a too low value for the *FC* of these tropical soils.

3.2 Comparison of Field Soil Water Storages Obtained by the Different Methods

Data of S calculated from tensiometer readings were ploted side by side to those for the methods Thornthwaite and Mather (*M*), Rijtema and Aboukhaled (*R*) and Dourado and de Jong van Lier (*C*) in Figure 2b. As it can be observed, the values of *S* estimated by the different agrometeorologic methods present very similar temporal distribution trends in relation to the polymer tensiometer data, although with a tendency of overestimating the measured tensiometer data. In rainy periods tensiometer data do not reach the *AWC* as the climatologic methods do. This fact and the consistent overestimation can be attributed to the form by which *S* is calculated, using tensiometer data it is calculated layer by layer, while the climatologic methods calculate *S* for the total soil depth.

We now explore the relations among the climatologic methods for the estimation of *S* using evapotranspiration data calculated by different methods. Data of Figures 3a, 3b, and 3c are all for *S* calculated using Penmann-Monteith's ET_{CPM}. The correlation between *S* from Rijtema and Aboukhaled (*R*) and from Thornthwaite and Matter (*M*) was 0.987 (Figure 3a), with an intercept of -18.5 mm. Although highly correlated, these two methods show a constant average difference of 18.5 mm (48.3% of the *AWC*), with an overestimation of R with respect to M, due to the intercept. The slope of 1.4535 mm mm^{-1} also indicates a greater increase of R in relation to *M*. For Dourado and de Jong van Lier (*C*) and (*M*) the adjustment was slightly lower, with R^2 of 0.982, an intercept of -15.3 mm and a slope of 1.4144 mm mm^{-1} with a very similar relation as that of *R* and *M* (Figure 3b). For the last case (Figure 3c), the correlation between *C* and *R* was also high (R^2 = 0.969), with an intercept of 3.1 mm (8.1% of the *AWC*) and a slope of 0.9602 mm mm^{-1}. With the intercept approachin zero and the slope very close to 1, *R* and *C* can be considered as equivalent, but deviating from *M*. Since all three methods of *WB* calculation are based on the same P and ET_c data, we chose *C* as the most suitable for the estimation of *S* from climatological data, also because *C* does not present discontinuities of ET_c at the critical point and at the permanent wilting point.

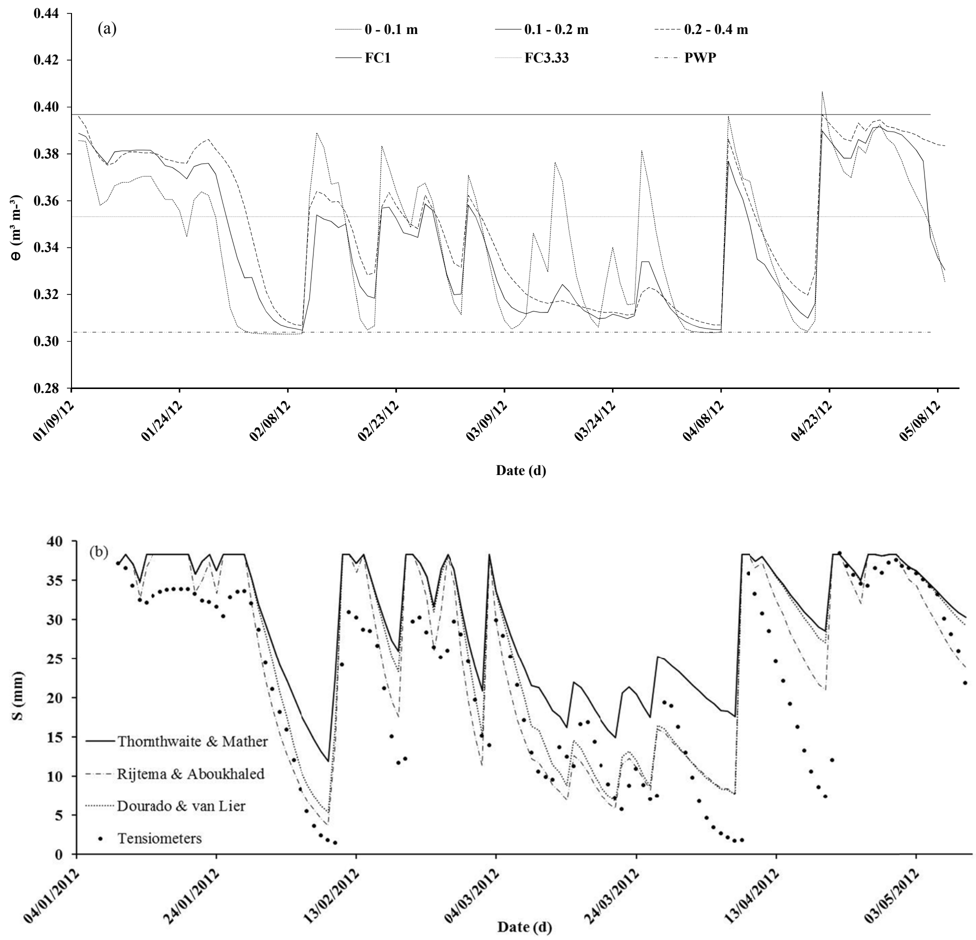

Figure 2. Distribution of soil water content (θ) during the experimental period, showing the ranges of available water for field capacity at h = 1 m (FC_1) and h = 3.33m ($FC_{3.33}$) (a); Distributions of soil water storage S measured by polymer tensiometers and by the three climatologic water balances (b)

3.3 Comparative Analysis among Climatologic Water Balance Methods and Measured S by Polymer Tensiometers

Although differences between pairs of methods *M*, *R* and *C* were detected in the above discussion, we now present regressions between each of them with S measured directly in the field with the polymer tensiometers (Figures 3d, 3e, and 3f). As mentioned in the discussion of Figures 2b and 3a, 3b, and 3c, soil water storage measured by the polymer tensiometers was over-estimated by the three methods *M*, *R* and *C*. This is confirmed by Figures 3a, 3b, and 3c where all intercepts a are positive, the lowest being 5.6 mm for *R*. The slopes b also play an important role in the over-estimation. The closer b is to 1, the better is the relation between pairs. Again, the closest value of b to 1 is that for *R* vs *S*, with a value of 0.8763 mm mm^{-1}. The coefficients of the tree regressions are very similar (and significant), and although for *C* it is slightly higher, we indicate *R* as the best for soil water estimations due to the lowest a and highest b.

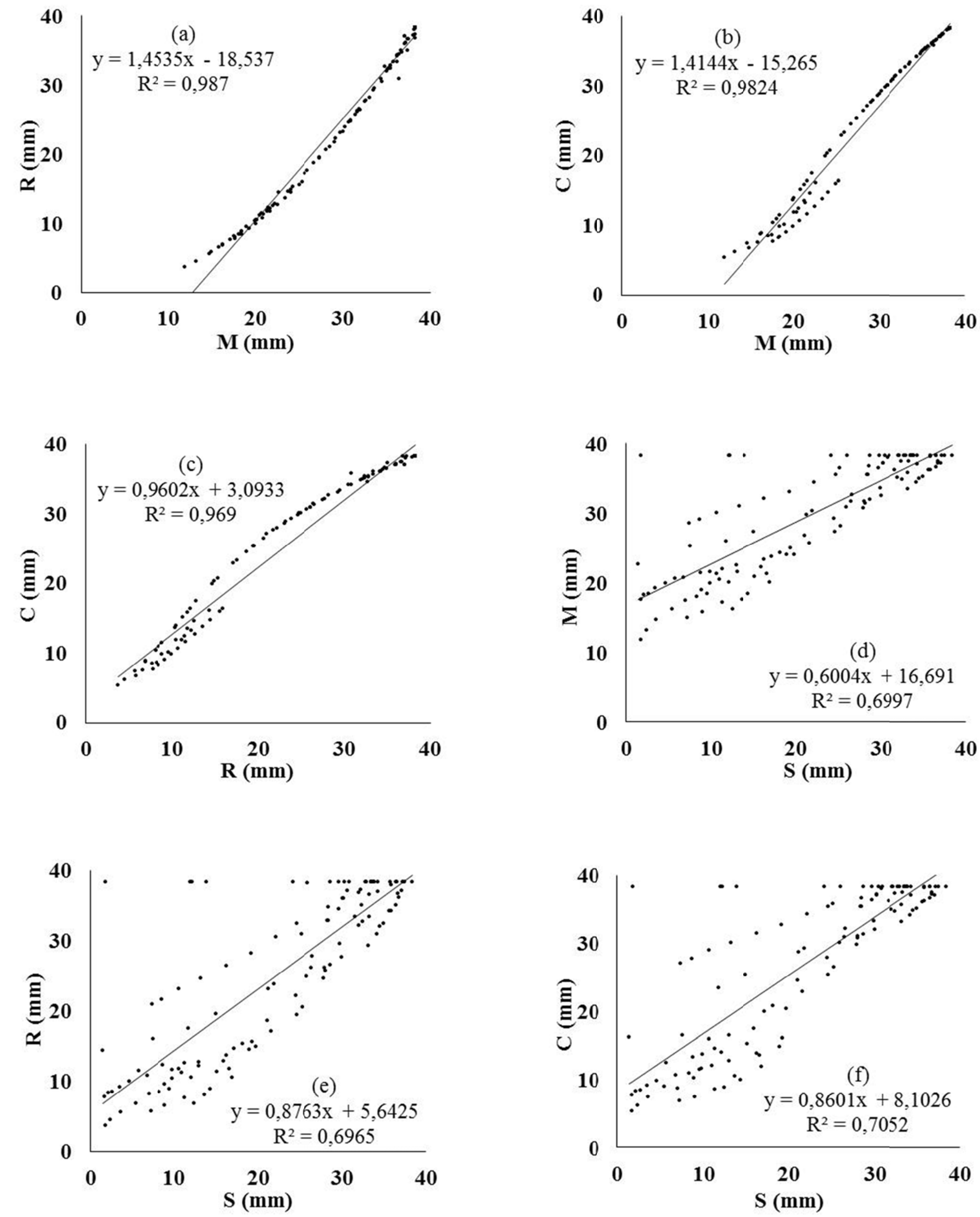

Figure 3. Regressions among soil water storages *S* calculated by the methods of Thornthwaite and Mather (*M*), Rijtema and Aboukhaled (*R*), and Dourado and De Jong van Lier (*C*): (a) *R* vs *M*; (b) *C* vs *M*; and (c) *C* vs *M*; Correlations between soil water storages (*S*) calculated by the methods of Thornthwaite and Mather (*M*), Rijtema and Aboukhaled (*R*), and Dourado and De Jong van Lier (*C*) with field measured soil water storage *S* with polymer tensiometers, considering *FC* corresponding to *h* = 1.0 m and *AWC* = 38.3 mm: (d) *M* vs *S*; (e) *R* vs *S*; and (f) *C* vs *S*

3.4 Comparison of the Rijtema and Aboukhaled (R) Method for AWC Using θ_{FC} for h Values of 0.6, 1.0 and 3.33 m with Field Measured Values

The choice of *h* to *FC* and *AWC* is critical in such calculations, and therefore we tried to use different values of *h*. All previous data here presented and discussed refer to *AWC* = 38.3 mm, with θ_{FC} for *h* = 1.0 m, as recommended by Reichardt (1988). As mentioned above, it is also common also to use θ_{FC} for *h* = 0.6 m (*AWC* = 42.6 mm) and 3.33 m (*AWC* = 26.8 mm). Regressions made between *R* and *S* for these other *AWC*s are very similar to those presented in Figures 3d, 3e, and 3f, and therefore not shown here. Table 1 presents the summary of these regressions. The regression for *FC* with *h* = 0.6 m, although presenting the largest intercept, has a slope very close to 1 and the highest R^2. This regression we take as the best to be used to simulate soil storage data evaluated by polymer tensiometer measurements. This choice also leads to the conclusion that the *FC* of this soil, based on $h = 0.6$ is a better choice to estimate the *AWC*.

Table 1. Summary of regressions of the Rijtema and Aboukhaled (*R*) method with field measured value of *S* for different *AWC*s

h (m)	*AWC* (mm)	Equation	R^2
0.6	42.6	y = 0.9507x + 7.3041	0.6992
1.0	38.3	y = 0.8763x + 5.6425	0.6965
3.33	26.8	y = 6449x + 2.0296	0.6515

4. Conclusions

1) Polimer tensiometers showed a good performance in field measurements of soil water matric potential in the whole range of soil water availability.

2) The evolution of soil water storage profiles calculated with water balances based on the evapotranspiration models of Thornthwaite and Mather (*M*), Rijtema and Aboukhaled (*R*) and Dourado and de Jong van Lier (*C*), and those measured with polymer tensiometers were very similar, but with *S* overestimating all three climatologic methods *M*, *R* and *C*.

3) Soil water storage *S* estimated by *R* and *C* were best correlated indicating that these methods are equivalent. The coefficients of these regressions are very similar (and significant), and although for *C* it is slightly higher, we indicate *R* as the best for soil water estimations due to the lowest intersept a and the closest slope b to one.

4) Method comparisons are dependent on the choice of *h* for the *FC*, and for the soil of the experimental site the most suitable was $h = 0.6$ m.

Acknowledgements

The authors are grateful for financial support from National Counsel of Technological and Scientific Development (CNPq - Brazil) and to Felipe Brendler Oliveira for providing language help.

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