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Water balance for determination of excess water in soybean cultivated in lowland soils

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ABSTRACT

The aim of this study was to derive a methodology for calculating a sequential water balance that accurately estimates the occurrence of excess water in soybeans cultivated in lowlands. We tested four calculation strategies of water balance associated with the simulation of soybean development, which differed on the calculation of rainfall and time of water drainage from the soil macropores. Data of volumetric moisture monitored in three soil layers throughout the soybean cycle in the 2014/15 agricultural year were used as a reference. Microporosity was used as a lower limit for the occurrence of excess water in the area. Excess water was considered to be whenever the daily volumetric soil moisture in the 0-100 mm layer was greater than 0.39 $mm^3 mm^{-3}$. Over the 111 days of measurement, soil moisture indicated the presence of excess water in 38 days. The traditional calculation strategy of water balance underestimated the occurrence of excess water, as well as the other strategies that considered effective precipitation in their formulas. The calculation strategy that considers that all the rainfall infiltrates in the soil and that the water from macropores is removed only by crop evapotranspiration exhibited good performance and indicated 35 days of excess water, being the most appropriate and recommended for determining excess water in lowland soybeans.

Keywords: compute model, effective rainfall, *Glycine max*, hypoxia.

Balanço hídrico para a determinação do excesso hídrico na soja em terras baixas

RESUMO

O objetivo deste trabalho foi obter uma metodologia de cálculo do balanço hídrico sequencial que estime com acurácia a ocorrência de excesso hídrico na soja em terras baixas. Foram testadas quatro estratégias de cálculo do balanço hídrico associadas à simulação do desenvolvimento da soja, as quais se diferenciaram em função da forma de cômputo da chuva e do tempo de drenagem da água dos macroporos do solo. Como referência foram utilizados os dados de umidade volumétrica monitorada em três camadas de solo ao longo do ciclo da soja no ano agrícola 2014/15. A microporosidade foi utilizada como limite inferior da ocorrência de excesso hídrico na área. Assim, o excesso hídrico foi considerado sempre que a umidade volumétrica diária do solo na camada 0-100 mm foi maior que 0,39 $mm^3\ mm^{-3}$. Ao longo dos 111 dias de medição, a umidade do solo indicou a presença de excesso hídrico em 38 dias. A estratégia de cálculo tradicional do balanço hídrico subestimou a ocorrência de excesso hídrico, assim como as demais estratégias que consideraram a precipitação efetiva na sua metodologia. A estratégia de cálculo que considera que toda a chuva infiltra no solo e que a água dos macroporos é removida somente pela evapotranspiração da cultura apresentou bom desempenho e indicou 35 dias de excesso hídrico, sendo a mais adequada e recomendada para a determinação do excesso hídrico na soja em terras baixas.

Palavras-chave: *Glycine max*, hipóxia, modelo de cômputo, precipitação efetiva.

1. INTRODUCTION

High demand for vegetable protein and favorable economic condition enables the expansion of soybean cultivation in areas that were not traditionally cultivated, i.e., the lowland areas in southern Brazil (Rocha *et al.*, 2017; Sartori *et al.*, 2016), entailing 1/3 of the area traditionally sown with irrigated rice (IRGA, 2019). In addition, crop rotation is an alternative to control weed infestations (Scherner *et al.*, 2018; Fraga *et al.*, 2019), break pest and disease cycles, improve soil conditions for plant development and increase the sustainability of the system (Goulart *et al*., 2020)

Imperfectly drained soils (Planosols) predominate in these areas due to the water table being close to the surface (Streck *et al.,* 2008). In areas cultivated with irrigated rice, the superficial layers undergo disruption and compaction due to mechanized operations used for rice cultivation, which usually take place under soaked soil conditions and reduce the water infiltration rate (Sartori *et al.*, 2016).

Excess water is one of the main risk factors for soybean grown in lowland areas (Bortoluzzi *et al.*, 2017; Gubiani *et al.*, 2018). The assessment of excess water can be performed by measuring the soil water content or aeration condition. However, prediction of risks due to excess water requires modeling the water balance throughout the crop cycle. Bortoluzzi *et al.* (2017) carried out a risk analysis of excess water for soybean cultivation in lowlands in the central region of Rio Grande do Sul (RS) by adapting the calculation of the daily sequential water balance (SWB) of Thornthwaite and Mather (1955). The authors also considered the effective precipitation (EP) of the U.S. Soil Conservation Service as infiltration as described by Frizzone and Andrade Júnior (2005) and applied the crop development model proposed by Trentin *et al.* (2013). Excess water was considered to be whenever the soil water content was above the field capacity. Another assumption was that after soil saturation two days of drainage were required for water content to decrease to field capacity.

One of the improvements required in the SWB carried out by Bortoluzzi *et al.* (2017) is the adjustment of the effective root depth. The authors considered that the roots explored a 0-400 mm layer, based on the effective depth used in the SWB calculation performed by Fietz and Rangel (2008) for soybeans grown in well-drained soils (Latosol or Rhodic Hapludox). However, lowland studies have shown that soybean roots are concentrated in superficial layers, which requires redefinition of the layer utilized for the soil available water capacity (AWC) calculation. For example, there are reports that the taproot reached a maximum depth of 230 mm (Marchesan *et al.*, 2013) and between 130 mm and 300 mm (Rocha *et al.*, 2017).

The deepening of roots is often restricted in lowland areas because the water table level is often close to the surface. Gubiani *et al.* (2018) found that soil moisture was close to the saturation moisture during practically the entire soybean crop cycle in the 300-400 mm layer. In this case, there is a strong impediment to root penetration, considering that soil saturation can cause the death of the soybean taproot and increase the growth of lateral and adventitious roots (Pires *et al.*, 2002).

Flat relief hinders runoff and favors the accumulation of water on the lowland soil surface (Streck *et al.*, 2008). Moreover, the use of effective precipitation (EP) from the U.S. Soil Conservation Service tends to underestimate infiltration and overestimate the runoff in these areas. Therefore, calculation adjustments for infiltration and runoff in the SWB carried out by Bortoluzzi *et al.* (2017) are also required to improve the model for predicting the risk of water excess for lowland soybeans.

Field capacity (θ_{fc}) also deserves consideration to establish the upper limit of AWC. In soils with drainage limitations such as lowland soils, the concept of field capacity based on negligible drainage criteria is difficult to detect in the field. In addition, the time for soil water content to decrease to θ_{fc} in lowland soils is greater than in well-drained soils (Gubiani *et al.* 2018). This increased time can result in a significant portion of water available to plants while the water content in the soil is above θ_{fc} (de Jong van Lier, 2017). In order to compute this additional available water, a strategy would be to replace θ_{fc} with the θ corresponding to the microporosity in the AWC calculation, since the value of the second (θ at the 0.6 m pressure head) is slightly higher than the estimates of the first (θ at the 1 m pressure head).

For lowland areas with slow drainage, a water balance calculation that immediately removes the water content from the soil between the upper AWC limit and soil saturation can underestimate the soil water content. If deep drainage from the macropores is very slow, the decrease in water content down to the AWC upper limit is predominantly dependent on the daily crop evapotranspiration. Furthermore, this adaptation can be included in SWB calculations to account for deep drainage limitations in lowland areas in determining excess water in soybeans.

Significant parts of the soybean process-based models were developed to estimate growth and productivity in the potential condition, without considering soil restrictions (Setiyono *et al.*, 2010). Likewise, the CROPGRO model (Boote *et al.*, 1998) allows the simulation of SWB and is one of the most used worldwide (Cera *et al.*, 2017), but has weaknesses in the estimates of excess water simulations in lowlands (Fensterseifer *et al.*, 2017).

This study aimed to explore whether the change in the parameterization of the upper limit of the AWC along with the inclusion of the calculation of macropore drainage time allows the SWB to better estimate the occurrence of excess water for lowland soybean cultivation.

2. MATERIALS AND METHODS

The study was carried out by comparing the excess water data obtained from four strategies of calculating the daily sequential water balance (SWB) with water excess data measured in a soybean field. The calculation and parameterization strategies, meteorological data and model calibration are described below.

TM_{1955}: traditional methodology proposed by Thornthwaite and Mather (1955) and described by Pereira *et al.* (1997). In this strategy, the entire precipitation infiltrates in the soil, but only the amount of water held between an upper and a lower limit is considered for computing the AWC. Surplus water from precipitation is immediately drained and excess water is considered to be whenever the soil water storage exceeds the AWC upper limit.

The AWC calculation was performed by Equation 1:

$$AWC_1 = (\theta_{mic} - \theta_{pwp})Z_1 \quad (1)$$

Where AWC_1 is the available water capacity (mm), θ_{mic} is the volumetric water content corresponding to the microporosity ($mm^3\ mm^{-3}$), which was set as the upper limit; θ_{pwp} is the volumetric water content at the permanent wilting point ($mm^3\ mm^{-3}$); and Z1 is the root system depth over the crop cycle (mm).

Up to the first trifoliate leaf (V2), we considered Z_1 = 100 mm, which resulted in an AWC_1 of 22 mm. For the subperiod between V2 and the beginning of flowering (R1), the AWC_1 ranged from 22 mm at Z_1 = 100 mm to 66 mm at Z_1 = 300 mm. The deepening of the roots was simulated with a sigmoidal growth curve of the root system (Dourado Neto *et al.*, 1999) as a function of the development rate (DR) calculated by a non-linear model of response to air temperature and photoperiod (Sinclair *et al.*, 1991), according to Equation 2. The maximum depth of 300 mm was defined considering the root depth verified by Gubiani *et al.* (2018) in the study area. After R1, AWC_1 was maintained at 66 mm. The θ_{mic} and θ_{pwp} values were, respectively, 0.39 $mm^3\ mm^{-3}$ and 0.17 $mm^3\ mm^{-3}$ (Gubiani *et al.*, 2018).

$$AWC_n = AWC_{V2} + \frac{(AWC_{R1} - AWC_{V2})}{2} \times [1 - cos\ cos\ (\pi \times DR)\ ] \quad (2)$$

Where AWC_n is the AWC stored in the day "n" (mm), AWC_{V2} is the AWC stored up to V2 stage (mm), AWC_{R1} is the AWC stored after R1 stage (mm); and DR is the development rate, variable from 0 to 1. MAC_{PM}: new methodology proposed in this study, where the total AWC was composed of a portion of the AWC stored in the micropores and another in the macropores (Figure 1). The AWC stored in the micropores is the AWC_1 calculated in the TM_{1995} strategy.

The AWC stored in the macropores was calculated using Equation 3:

$$AWC_2 = (\theta_{sat} - \theta_{mic})Z_2 \quad (3)$$

Where AWC_2 is the AWC stored in the macropores (mm), θ_{sat} is the volumetric water content at saturation ($mm^3\ mm^{-3}$); and Z_2 is the root system depth up to which the effect of the water table level in the absence of flooding can be considered of little importance throughout the cycle (mm). AWC_2 is computed only in a surficial layer (Figure 1) where the macropores will be occupied with water only in periods of complete saturation of the soil profile, generally coinciding with the flooding event. Based on the monitoring of θ by Gubiani *et al.* (2018) in the study area, Z_2 was considered 100 mm (Figure 1), and the θ_{sat} value was 0.45 $mm^3\ mm^{-3}$.

The total AWC (AWC_{tot}, mm) was calculated using Equation (4):

$$AWC_{tot} = AWC_1 + AWC_2 \quad (4)$$

We also considered that all measured rainfall infiltrates the soil and that the maximum soil water storage is equal to AWC_{tot}. Excess water is considered to be whenever $AWC > AWC_1$, a condition that can occur due to excess precipitation and also due to the drainage time of the AWC portion occupying AWC_2 after the end of the precipitation event. In situations where $AWC_1 \leq AWC \leq AWC_{tot}$ after the end of precipitation, the portion of AWC occupying AWC_2 (AWC_{tot} - AWC_1) is daily reduced by crop evapotranspiration. Consequently, there is a gradual reduction of water storage in the soil until reaching the upper limit of AWC_1. The duration of this period depends on the condition of atmosphere evaporative demand and the crop development stage. During this period, the fraction of air-filled/water-filled macropores gradually increases and water excess due oxygen restriction gradually reduces. Usually, a value of 0.10 $mm^3\ mm^{-3}$ of air-filled porosity is considered an empirical non-limiting threshold for aeration (Gubiani *et al.*, 2018). We considered that the plants were subjected to oxygen deficiency while the soil macropores were not totally drained, because their capacity of store air (θ_{sat} - θ_{mic} = 0.06 $mm^{-3}\ mm^{-3}$) is less than the non-limiting threshold for aeration (0.10 $mm^3\ mm^{-3}$).

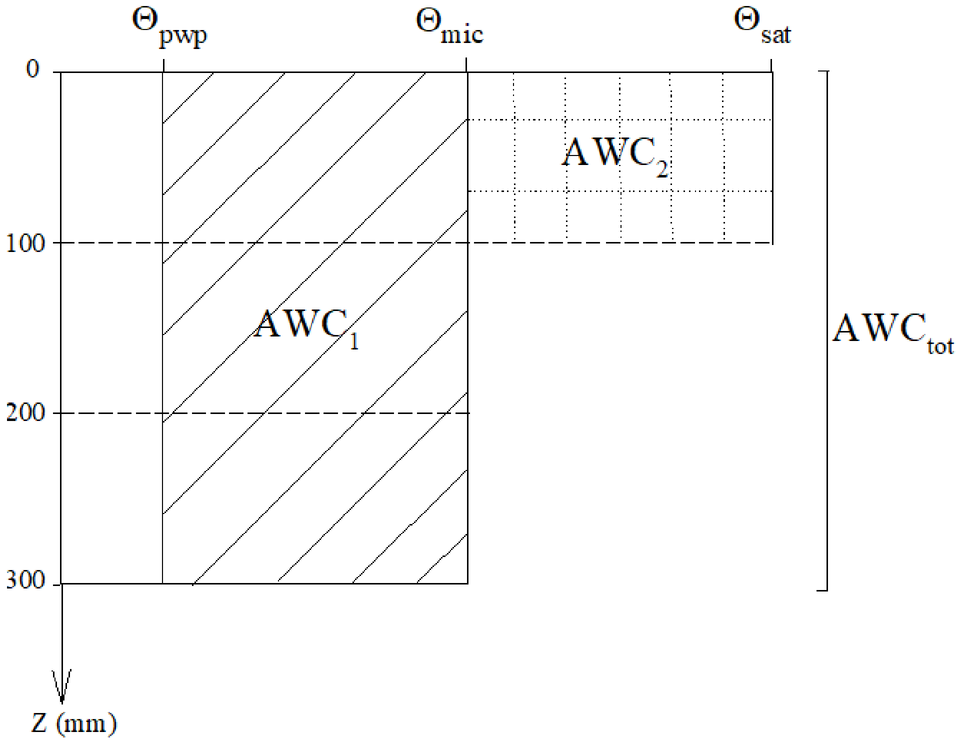

Figure 1. Scheme representation of the limits of soil water content referring to the methodologies that consider the drainage time of the macropores (MAC_{PM} and MAC_{PE}). They are represented by the soil water content between saturation (θ_{sat}) and microporosity (θ_{mic}) (AWC_2) until 100 mm depth; AWC_1 is the water content between θ_{mic} and permanent wilting point (θ_{pwp}) up to 300 mm depth (Z) and AWC_{tot} is the sum of AWC_2 e AWC_1.

MAC_{PE}: this strategy is similar to MAC_{PM}, with the only difference being the consideration of the effective precipitation (EP) of the U.S. Soil Conservation Service as the water infiltrated into the soil, as described by Frizzone and Andrade Júnior (2005). The value of the curve number (CN) used was 91 as the soil in the field area has more than half of the granulometric composition of silt and clay (Gubiani *et al.*, 2018), and a loss of 25% of initial precipitation was assumed due to interception. Therefore, we were able to assess whether there is an important difference in the estimate of excess water due to the method of rain computation.

$BORT_{2017}$: this strategy is the same used by Bortoluzzi *et al.* (2017) with a slight change in the AWC upper limit, replacing the volumetric water content in the field capacity (θ_{fc}, $mm^3\ mm^{-3}$) by θ_{mic}, which establishes the maximum water storage in the soil. Infiltration is considered to be EP (Frizzone and Andrade Júnior, 2005) and in the event of excess water from precipitation, a drainage time of two days is required for the soil to reach θ_{mic}. Excess water is defined when water storage in the soil exceeds the AWC upper limit.

The four SWB calculation strategies use crop evapotranspiration (ETc) calculated as the product of reference evapotranspiration (ET_o) by the crop coefficient (Kc). ET_o was estimated by means of the Penman-Monteith method (Allen *et al.*, 1998). The FAO-recommended Kc values of 0.40, 1.15 and 0.50 for soybeans were considered constant respectively for the subperiods between sowing (S) and first trifoliolate leaf (V2); beginning of flowering (R1) to beginning of seed filling (R5) and from the beginning of maturation (R7) to full maturation (R8) (Allen *et al.*, 1998). In the V2-R1 subperiod, the daily Kc was calculated respectively as a function of the variation in the relative development rate (SD) (Sinclair *et al.*, 1991) and in the R5-R7 subperiod as a function of the thermal sum (Martorano *et al.*, 2012), according to Equations 5 and 6:

$$Kc = 1.087 \cdot SD + 0.063 \quad (5)$$

$$Kc = -0.0012 \cdot TS_{R5-R7} + 1.1512 \quad (6)$$

Where Kc is the crop coefficient, SD is the relative development rate and $TS_{R5\text{-}R7}$ is the accumulated thermal sum between the R5- R7 subperiod.

All the daily meteorological data required to operationalize the four SWB calculation strategies were collected at the Main Weather Station of Santa Maria, RS, Brazil. The simulation period was from November 14, 2014 to March 26, 2015, which coincides with the period between soybean sowing and physiological maturity (Gubiani *et al.*, 2018) in a lowland area at 800 m from the weather station. The daily water excess determined during the soybean cycle was used to evaluate the efficiency of the SWB calculation strategies.

The soybean was grown after a fallow season of a field previously cultivated with irrigated rice, with straw turnover after harvest. The field was leveled with a 'remaplan' blade and kept fallow during the winter season, with pre-emergent weed control. During the soybean crop, the volumetric water content in the soil (θ) was monitored with TDR100 sensors at 30 minute intervals in three soil layers from December 6, 2014 until the end of the cycle (111 days of monitoring). The calculation of excess water was performed through the θ daily mean measured at four monitoring points in the 0-100 mm depth layer, where most of the soybean roots were concentrated. Condition of excess water was considered whenever θ was greater than the volumetric water content corresponding to the microporosity (θ_{mic}) for this soil layer (0.39 mm^3 mm^{-3}).

Details of soybean cultivation, θ monitoring and microporosity determination are described in Gubiani *et al.* (2018). Lastly, the TM_{1955}, MAC_{PE}, MAC_{PM} and $BORT_{2017}$ strategies were compared with each other and with the excess water measured in field conditions.

3. RESULTS AND DISCUSSION

The soil water content recorded by the TDR sensors in the 0-100 mm layer was greater than the microporosity (θ_{mic} = 0.39 mm^3 mm^{-3}) in 38 days of the 111 days of measurement period (Table 1). These 38 days of excess water (EXC) were due to the total rainfall of 551 mm, distributed during the period from December 6, 2014 until March 26, 2015. The SWB modeling strategy that estimated the number of EXC days closest to the number of EXC days observed in the field (38 days) was MAC_{PM}, with 35 days of EXC (Table 1). Additional strategies were not very efficient, indicating respectively 17, 16 and 13 days of EXC with MAC_{PE}, $BORT_{2017}$ and TM_{1955} (Table 1).

The MAC_{PE} and $BORT_{2017}$ strategies presented similar EXC days to field-observed values only until the beginning of January (Table 1). After that period, the strategies that used effective precipitation (EP) calculated by the U.S. Soil Conservation Service methodology as an estimate of soil water infiltration underestimated the number of days with EXC. However, Lucas *et al.* (2015) deployed a similar strategy to $BORT_{2017}$, with satisfactory performance for sunflower cultivation in different types of highland soils, where the use of PE is more appropriate.

Table 1. Measured daily volumetric soil moisture (Mv), measured precipitation (MP) and days with excess water (EXC) estimated by different water balance calculation strategies (*), over the soybean cycle in a Haplic Planosol during the 2014/15 agricultural year in Santa Maria, RS.

Date	Mv* (mm^3 mm^{-3})	MP (mm)	MAC_{PM}	MAC_{PE}	$BORT_{2017}$	TM_{1995}
09/12/2014	-	12.6	EXC	-		
10/12/2014	0.427	22.6	EXC	EXC	EXC	EXC
11/12/2014	0.409	0	EXC	EXC	EXC	-
12/12/2014	0.395	0	EXC	EXC	EXC	-
13/12/2014	-	0	EXC	EXC	-	-
16/12/2014	0.401	0.5	-	-	-	-
17/12/2014	0.437	29.1	EXC	EXC	EXC	EXC
18/12/2014	0.429	0	EXC	EXC	EXC	-
19/12/2014	0.397	0	-	-	EXC	-
21/12/2014	0.438	71.6	EXC	EXC	EXC	EXC
22/12/2014	0.428	21.2	EXC	EXC	EXC	EXC
23/12/2014	0.403	0	EXC	EXC	EXC	-
24/12/2014	-	0	-	-	EXC	-
27/12/2014	0.433	101.1	EXC	EXC	EXC	EXC
28/12/2014	0.427	0.7	EXC	EXC	EXC	-
29/12/2014	0.430	3.5	EXC	EXC	EXC	-
30/12/2014	0.418	0	EXC	-	-	-
31/12/2014	0.405	0	-	-	-	-
01/01/2015	0.406	0	-	-	-	-
02/01/2015	0.444	23.8	EXC	EXC	EXC	EXC
03/01/2015	0.427	0	EXC	EXC	EXC	-
04/01/2015	0.403	0	-	-	EXC	-
09/01/2015	0.421	18.6	-	-	-	-
10/01/2015	0.432	14.7	EXC	-	-	EXC
11/01/2015	0.432	13	EXC	EXC	-	EXC
12/01/2015	0.429	0.1	-	-	-	-
14/01/2015	0.417	19.8	EXC	EXC	-	EXC
15/01/2015	0.441	8.8	EXC	-	-	EXC
16/01/2015	0.430	0	EXC	-	-	-
17/01/2015	0.436	10.5	EXC	EXC	-	EXC
18/01/2015	0.428	0	EXC	-	-	-
29/01/2015	0.448	33.8	EXC	-	-	EXC
30/01/2015	0.433	3.4	EXC	-	-	-
31/01/2015	0.394	0	-	-	-	-
11/02/2015	0.405	31.4	-	-		-
20/02/2015	0.425	29.4	-	-	-	-
21/02/2015	0.395	0.1	-	-	-	-
26/02/2015	0.427	16.8	EXC	-	-	-
27/02/2015	0.416	4.6	EXC	-	-	-
02/03/2015	0.397	15.8	EXC	-	-	EXC
03/03/2015	-	0	EXC	-	-	-
04/03/2015	-	0	EXC	-	-	-
05/03/2015	0.398	5.9	EXC	-	-	-
06/03/2015	-	0	EXC	-	-	-
07/03/2015	-	0	EXC	-	-	-
11/03/2015	-	9	EXC	-	-	-
12/03/2015	-	0	EXC	-	-	-

(*) Soil moisture determined from data measured by Gubiani *et al.* (2018) in the 0-100 mm layer; (-) days without occurrence of water excess. AWC_{PM} and MAC_{PE} are strategies that respectively consider the measured precipitation (MP) and the effective precipitation (EP) as the time required to drain the macropores and use as infiltration; $BORT_{2017}$ is the methodology proposed by Bortoluzzi *et al.* (2017); TM_{1955} is the Thornthwaite and Mather (1955) methodology.

In contrast, the MAC_{PM} strategy was efficient throughout the entire period because it considered that all precipitation infiltrates into the soil and that the water in the macropores is temporarily stored. The TM_{1955} strategy differs from MAC_{PM} by not considering that water in the macropores is temporarily stored. Poor performance of TM_{1955} showed that water retention in the macropores is an important conditioning factor for EXC and should be included in WB models for accurate prediction of EXC.

The TM_{1955} strategy was able to indicate only one third of the days when there was water excess, evidencing considerable underestimation of EXC in lowlands. The low accuracy occurred because the TM_{1955} strategy does not consider that longer drainage time is necessary in lowlands (Mundstock *et al.*, 2017). Mainly, whenever there was enough rain to saturate the soil, TM_{1955} was able to indicate the presence of excess water. However, when the rain stopped or if there was less rain than the crop evapotranspiration after the day of EXC, the model removed water from the soil, making the current AWC less than AWC_1 (Equation 1), which represents a condition without EXC. For instance, there was an accumulated rainfall of 111 mm on December 27, 2014, but the TM_{1955} strategy did not indicate EXC in the following day (Table 1). On the contrary, the MAC_{PM} model indicated EXC in the following three days, precisely because it considers the delay in draining macropores (Table 1).

The MAC_{PM} strategy indicated eight days of EXC without them having been detected by measurements of volumetric soil moisture (Table 1). However, this inconsistency occurred mainly at the end of the crop cycle, when this condition was verified six times. Until the end of February, the MAC_{PM} strategy indicated precisely the days when the water content measured by the TDR probe in the 0-100 mm layer was above the θ_{mic} (0.39 $mm^3\ mm^{-3}$) of that layer (Figure 2A). The lower accuracy of the MAC_{PM} strategy at the end of the soybean cycle is due to the small crop evapotranspiration (mean of 2 mm day^{-1}), being insufficient to reduce AWC_{tot} up to the upper limit of AWC_1. For example, the crop evapotranspiration of 2 mm day^{-1} was insufficient for the total drainage of the macropores ($AWC_2 = 0$) from the 5th to the 7th of March, indicating the presence of EXC. Nevertheless, the volumetric water content of the 0-100 mm layer decreased from 0.39 to 0.32 $mm^3\ mm^{-3}$ (7 mm of storage difference) in the same period (Figure 2A), characterizing the absence of EXC.

Measurements made with TDR showed that the water content in the 100-200 mm (Figure 2B) and 200-300 mm (Figure 2C) layers was also slightly less than the θ_{mic} of each layer at the end of the crop cycle. This indicates that there was participation of deep and/or lateral drainage in the extraction of water from the evaluated soil, but it was only relevant to affect the EXC estimates of the MAC_{PM} strategy when there was low crop evapotranspiration.

Analyzing the concept of the MAC_{PM} strategy, the likelihood of overestimating the EXC decreases with the increase in the ratio (crop evapotranspiration)/(deep and/or lateral drainage). Soybean crop evapotranspiration is lower in the initial and final growth stages, increasing the likelihood that deep and/or lateral drainage is not negligible for calculating EXC with the MAC_{PM} strategy. However, these stages growth have less relative importance in reducing the productivity in comparison to the soybean vegetative and reproductive phases (Beutler *et al.*, 2014; Rhine *et al.*, 2010; Scott *et al.*, 1989). For this reason, the use of the MAC_{PM} strategy is appropriate for soils where deep and/or lateral drainage can be considered negligible in relation to crop evapotranspiration.

The MAC_{PM} strategy was more efficient and accurate than the other strategies for predicting EXC in almost the entire soybean development cycle. The EXC indication was mostly consistent with the high volumetric water content in the soil measured in the field (Figure 2). In just 16 days in the 100-200 mm layer (Figure 2B) and 10 days in the 200-300 mm layer (Figure 2C) the water content in the soil was below θ_{mic}. In this area, the water table was close to the surface for a considerable period due to the occurrence of high rainfall (Gubiani *et al.*, 2018). This demonstrates that the field scenario was of water excess and that the MAC_{PM}

strategy was efficient in indicating the EXC on most days of its actual occurrence. Overall, the improvement of the excess water estimate through the SWB calculation contributes to the performance of risk analysis using historical series of meteorological data and future inclusion in soybean process-based models. Moreover, accurate estimates assist in the decision-making of management practices and in the reduction of the yield gap.

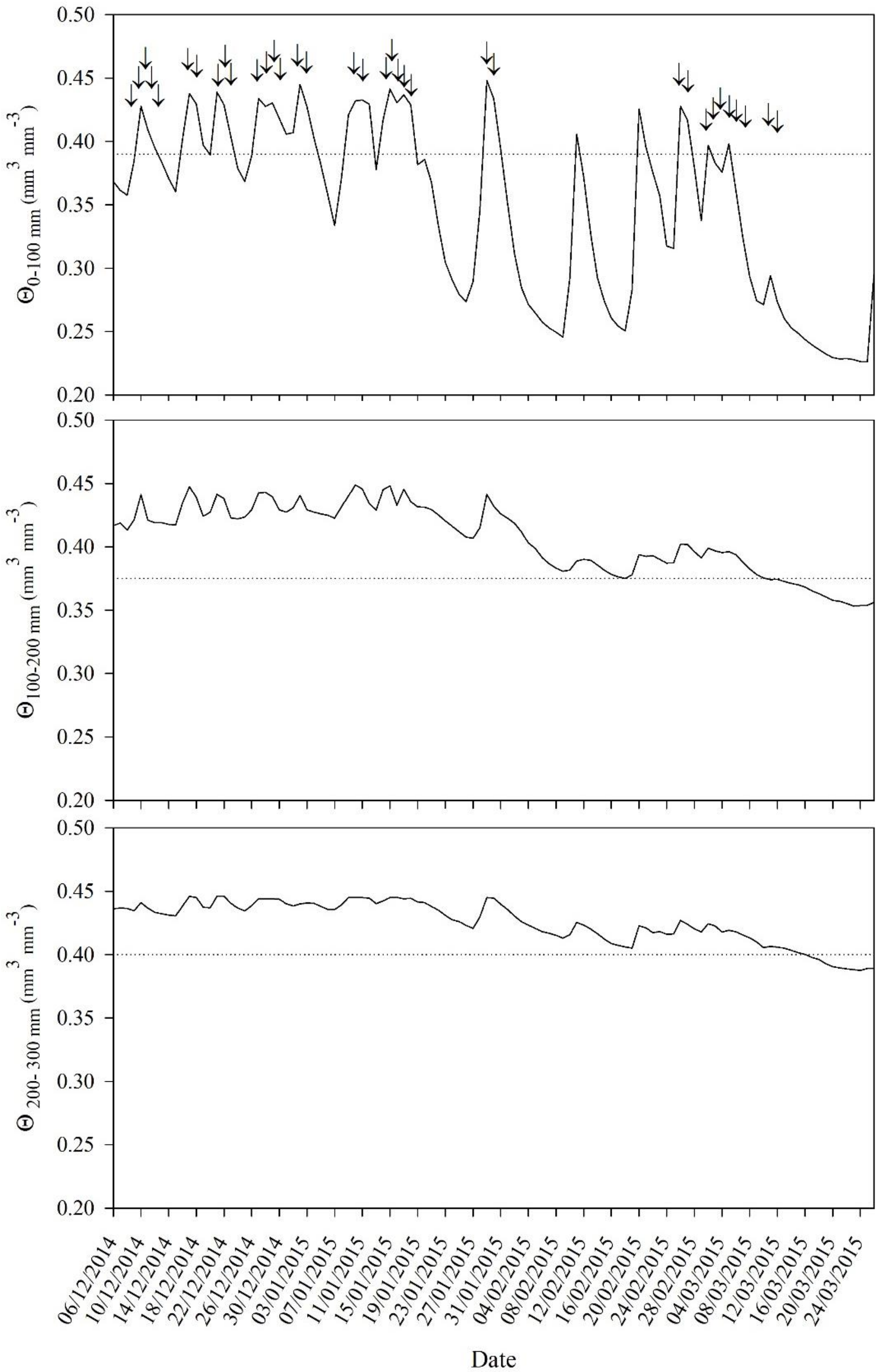

Figure 2. Volumetric water content in the soil (θ) throughout the soybean cycle in Planosol Haplic in the 0-100 mm (A), 100-200 mm (B) and 200-300 mm (C) layers. The horizontal dashed line represents the microporosity (θ_{mic}) and the arrows indicate the days of water excess obtained by the MAC_{PM} methodology for calculating the sequential water balance.

4. CONCLUSIONS

The traditional calculation strategy of water balance TM_{1955} underestimates the occurrence of water excess for lowland soybean cultivation.

The use of effective precipitation in water balance calculations also underestimates the occurrence of excess water in lowland field conditions.

The MAC_{PM} calculation strategy considers that all precipitation infiltrates into the soil and delays the drainage time of the macropores; it is efficient and can be recommended for predicting excess water in soybeans cultivated in lowlands.

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