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Transpiration Reduction Factor and Soybean Yield in Low Land Soil with Ridge and Chiseling

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ABSTRACT: Water and oxygen deficiencies in the soybean crop cultivated on lowland soils are an important topic of research. The objective of this study was to investigate changes in water and oxygen supply and soybean yield caused by soil management in lowland soils. A soybean crop was grown under four soil conditions: no-tillage (NT), chiseling (CH), ridge tillage on no-tillage (NTR), and ridge tillage on chiseling (CHR). Soil bulk density, total porosity, macro- and microporosity, air permeability, and saturated hydraulic conductivity were measured at 0.05, 0.15, 0.25, and 0.35 m depths. Soil volumetric water content was monitored at the same depths every 30 min during the soybean cycle. The transpiration coefficient was calculated from volumetric water content to express both water and oxygen deficiency. The groundwater level was monitored throughout the soybean cycle. Plant performance was evaluated by measuring plant population, shoot dry matter, yield, and taproot depth. Soil porosity, air permeability, and saturated hydraulic conductivity were most improved in CH and CHR, and less in NTR. Nonetheless, expected improvement in soil aeration in CH, CHR, and NTR was eliminated when the water table raised to near the soil surface. The transpiration coefficient indicated that CH decreased oxygen deficiency, but caused little water deficit. The CH also provided the highest yield (4,610 kg ha^{-1}), which was not surpassed by the addition of ridge tillage on chiseled soil (CHR) (4,001 kg ha^{-1}). The lowest yields were observed in NT (2,842 kg ha^{-1}), and NTR (3,565 kg ha^{-1}), in which oxygen deficiency was more severe. Lower oxygen deficiency for soybean in chiseled lowland soil is regulated by the water table. As the transpiration coefficient is dependent on all the processes determining soil water dynamics, it is more informative than soil structural properties regarding water and oxygen deficiency in soybean in lowland soil.

Keywords: water stress, oxygen deficiency, water table.

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INTRODUCTION

In the vast plains areas of the South of Brazil, soils undergo continuous or periodic water saturation, exhibiting redoximorphic features mainly in flat landscape locations. Both deficient drainage and flat relief make soil suitable for irrigated rice (*Oryza sativa* L.). Around 1.1 million hectares of rice are cultivated annually in Rio Grande do Sul (Conab, 2017). The necessity of crop rotation to reduce pests, diseases, and weeds in rice areas (Gomes et al., 2002) has motivated rice farmers to introduce soybean cultivation in floodplain areas. However, the flood plain condition desirable for rice may not be adequate for soybean cultivation (Sartori et al., 2016b).

In wetland soils, soybean plants are subjected to oxygen deficiency (OD) and to water deficiency (WD). Oxygen deficiency is predominant, as it is common to find the water table close to the soil surface (Fiorin et al., 2003), and the soil floods with abundant rainfall. In addition, the low water permeability of the B horizon in the subsurface (due to the presence of expansive clays) reduces drainage and extends OD over time. When the water table goes down, WD can occur because the amount of water available in the A and E (when present) sandy horizon does not ensure water supply for a long time.

The use of flood-tolerant soybean genotypes (Schöffel et al., 2001; Pires et al., 2002; VanToai et al., 2010) does not prevent yield declines if excessive rainfall occurs (VanToai et al., 1994; Cornelious et al., 2006). The occurrence of OD at several phenological stages reduces soybean yield (Schöffel et al., 2001). Germination is a critical period, as well as crop establishment, as OD reduces the plant population (Wuebker et al., 2001). During this period, WD is also harmful, since it hinders emergence and crop establishment (Tavares et al., 2013). In later stages, WD causes flower abortion and affects grain weight (Mundstock and Thomas, 2005).

The presence of a compact soil layer detected at the 0.07-0.10 m (Munareto et al., 2010) and 0.10-0.20 m (Sartori et al., 2015; Sartori et al., 2016b) is another problem for those intending to rotate crops in lowland areas cultivated with irrigated rice. The presence of this less permeable layer intensifies OD by keeping the soil moist during rainfall periods and intensifies WD by confining the roots in the surface layer of the soil, which increases the risk of water stress during periods of low rainfall. To reduce the risk of soybean yield loss in lowland soils, tolerant cultivars, the seeding period, and soil management strategies must be selected in a combined manner to minimize stress. The effectiveness of these actions, however, depends on rainfall, which controls the water table (Ronen et al., 2000; Gomes et al., 2012), the key factor in the occurrence of OD.

Several studies indicate that chiseling (Sartori et al., 2015; Sartori et al., 2016b) and the use of ridge tillage are effective management strategies in lowland soils for increasing soybean yield (Silva et al., 2007). Chiseling favors internal drainage of the profile (Sartori et al., 2016a), whereas the ridge promotes a more aerated zone, which is also elevated in relation to the groundwater level (Sartori et al., 2015). Studies have not yet evaluated the combination of these two approaches. The expectation is that together they can provide greater aeration in the root zone of plants, though intensify water stress during periods of drought.

Quantification of OD and WD in soybean cultivation in floodplain areas is a relative unexplored issue but can be evaluated based on an approach involving physical properties that directly affect crop growth and production (Letey, 1985). In the case of OD and WD, the dynamics of oxygen consumption and water uptake rates are the processes of interest (van Lier and Gubiani, 2015). Measuring these processes throughout the plant cycle is not always possible, due to lack of equipment. Modeling them is also a difficult task as it requires a large set of parameters and variables of the soil-plant-atmosphere system. For these reasons, indexes related to these processes are often used (Gubiani et al., 2013a). The transpiration reduction factor (λ), which represents the relationship between actual and potential transpiration (van Lier et al., 2008), has been widely used to assess

OD and WD. The reduction function proposed by Feddes et al. (1978) has often been used for estimating λ in hydrological models, such as HYDRUS-1D (Šimůnek and van Genuchten, 2008), and has also been compared with new approaches of calculating λ using matric flux potential (van Lier et al., 2008; Casaroli et al., 2010). Although estimation of λ using the matric flux potential seems more accurate (van Lier et al., 2008; Casaroli et al., 2010), calculation of λ with the Feddes function remains much simpler. Thus, the Feddes function is a simple and useful proposition for relative evaluation of the effect of soil management on λ dynamics.

In this study, λ dynamics were determined in lowland soil cultivated with soybean under no-tillage, chiseling, ridge tillage on no-tillage, and ridge tillage on chiseling. Our hypothesis is that λ is better than soil physical properties for predicting soybean performance in lowland soil. The objective of this study was to evaluate the effect of soil conditions on soil physical properties and λ; and to relate them with soybean performance.

MATERIALS AND METHODS

The study was carried out in an experimental area of the Federal University of Santa Maria, located in the Central Depression region of Rio Grande do Sul, Brazil (-29.72 S, -53.72 W). The soil was classified as an Albaqualf (Soil Survey Staff, 2014) and as a *Planossolo Háplico Eutrófico típico* according to the Brazilian Soil Classification System (Santos et al., 2013). The soil up to the 0.40 m depth, expressed in g kg^{-1}, is composed of (mean ± standard deviation) 196 ± 32 of sand, 570 ± 17 of silt, and 235 ± 17 of clay. Climate in the region is “Cfa” type according to the Köppen climate classification system (Peel et al., 2007).

In the spring of 2013, the experimental area was cultivated with irrigated rice in a minimum tillage system. In April and May 2014, the remaining crop residue was incorporated with a knife roller. Subsequently, 1 Mg ha^{-1} of dolomitic limestone was incorporated into the 0.00-0.15 m soil layer with a disk harrow. The roughness of the soil surface caused by harrowing was reduced with a leveling blade. During May to August, the area remained in fallow, occupied mainly by Azevém (*Lolium multiflorum*).

In August 2014, vegetation was desiccated with glyphosate herbicide for soybean cultivation in four soil conditions: no-tillage (NT), chiseling (CH), ridge tillage on no-tillage (NTR), and ridge tillage on chiseling (CHR). These soil conditions were randomized into plots (6 × 8 m) distributed in four blocks, covering an area of 768 m^2 under this specific experiment.

For the CH and CHR treatments, the soil was prepared on October 10, 2014, with a chisel plow (five shanks spaced 0.5 m apart), operating at a 0.35 m depth, followed by a disk harrow to break up the mobilized soil blocks. For the NTR and CHR treatments, the ridges were made by the same machine used for sowing the soybean (Hyper Plus KF 6/4, manufactured by Industrial KF). This planter forms a triangular shaped ridge with approximately a 0.85 m base and 0.12 m height.

Soybean was sown on November 14, 2014, with 15 seeds m^{-1} in rows spaced 0.5 m apart. The seed rows were positioned on the faces of the ridge in the ridge treatments. The cultivar Brasmax Tornado RR (6863 RSF) was used, due to its resistance to root rot and stem canker and its good performance in floodplain soils. The seeds received insecticide containing the mixture Piraclostrobin + methyl thiophanate + Fipronile and the micronutrients molybdenum and cobalt. Since the area had not been cultivated with soybean before and because of the low survival rate of rhizobia in the soil in lowland areas due to flooding (Thomas et al., 2005; Bailey-Serres et al., 2012), twice the recommended rate of inoculant was applied to the seeds to introduce a suitable population of rhizobia. Fertilizer containing percentages of 4-27-17 of N, P_2O_5, and K_2O, respectively, was applied at a rate of 330 kg ha^{-1}, in accordance with soil analysis and technical recommendations (CQFS-RS/SC, 2004). Crop treatments and phytosanitary controls followed the technical recommendations for the soybean crop for the state of Rio Grande do Sul (Costamilan et al., 2012).

The plant population was evaluated 30 days after sowing (DAS) by counting the plants growing in a distance of two meters from two randomly chosen rows in each plot. Shoot dry matter was quantified according to Fehr and Caviness (1977) in plants collected over an area of 1 m^2 at the R3 phenological stage. The plants were cut and oven dried at 65 °C and, subsequently, dry matter was determined. Grain yield was determined by harvesting the four central rows of each plot (20 m^2). The plants were harvested manually and their pods were mechanically threshed. To estimate the grain yield (kg ha^{-1}), the weight of the harvested beans was adjusted for grain moisture of 13 %. The depth reached by the taproot was measured with a measuring tape after digging a pit close to soybean plants and exposing the roots in the soil profile at the R3 phenological stage.

Twelve days after soybean sowing (11/26/2014), at the V1 phenological stage, and seventy days after sowing (02/4/2015), at the R2 phenological stage, soil samples were collected between rows using metal rings with a 0.057 m diameter and 0.04 m height. The soil samples were collected in duplicate at the center of the 0.00-0.10, 0.10-0.20, 0.20-0.30, and 0.30-0.40 m layers. The samples were saturated by capillary rise and subjected to tensions (h) of 0.1, 0.6, and 1 m in a sand column (Reinert and Reichert, 2006), and 3.3 and 10 m in Richards chambers (Klute, 1986). At saturation and after drainage ceased at each tension, the samples were weighed for determination of volumetric water content (θ). Soil air permeability (Ka) was determined at tensions of 0.6, 1, 3.3, and 10 m using a constant head permeameter, as described in Mentges et al. (2016). At the end of the 10 m tension, the samples were resaturated for determination of saturated hydraulic conductivity (Ks) using a constant head permeameter as described by Libardi (2005). After determination of Ks, the samples were oven dried at 105 °C for 48 h to determine soil bulk density (Bd). Water retention between the tensions of 50 and 1000 m was obtained by the psychometric technique using a WP4 (Decagon Devices, 2000), as described in Gubiani et al. (2013b).

The equation 1, proposed by van Genuchten (1980), was fitted to the h and θ data:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m} \qquad \text{Eq. 1}$$

in which θ, θ_s, and θ_r are the estimated, saturated, and residual volumetric water contents (m^3 m^{-3}), respectively; h is the tension applied during drainage of the samples (m); α (m^{-1}), m, and n are fitting coefficients of the equation, where m = 1 - (1/n). Equation 1 was fitted using the Solver Add-In available on Microsoft Office Excel.

Total porosity (Tp) was considered as the θ at saturation; microporosity (Mi) was considered as the θ at a tension of 0.6 m; and macroporosity (Ma) was calculated by the difference between Tp and Mi.

Time Domain Reflectometry (TDR) probes (two 0.19 m metal strips) were inserted in the center of each soil layer described above to monitor θ every 30 min. The probes were connected to a TDR100 controlled by a CR1000 datalogger (both from Campbell Scientific, Inc.). The dielectric constant (ε) measured by TDR100 was converted to θ by the calibration equation suggested by Topp et al. (1980). From various samples collected at different soil moisture conditions, it was verified that no specific calibration was necessary, because the θ estimated was very close to the measured θ (maximum 0.05 m^3 m^{-3} for the absolute difference). Growth and crop production were compared to the class frequency (described below) of the transpiration reduction factor λ. The λ was estimated using the empirical function of Feddes et al. (1978), which considers λ as a function of water stress in the soil or its corresponding θ. In this study, θ was used to estimate λ, according to equation 2:

$$\lambda(\theta) = \begin{cases} \lambda_{OD} = \dfrac{\theta_1 - \theta_i}{\theta_1 - \theta_2} & \theta_2 < \theta_i \leq \theta_1 \\ \lambda = 1 & \theta_3 \leq \theta_i \leq \theta_2 \\ \lambda_{WD} = \dfrac{\theta_i - \theta_4}{\theta_3 - \theta_4} & \theta_4 \leq \theta_i < \theta_3 \end{cases} \qquad \text{Eq. 2}$$

in which λ_{OD} and λ_{WD} quantify the OD and WD stress, respectively; and θ_i is the soil water content at each instant of measurement, $\theta_1 = \theta_s$ (θ at saturation), $\theta_2 = \theta_s - 0.1$ (θ for 10 % aeration porosity), $\theta_3 = \theta_c$ (θ critical for water stress, assumed as the θ at a tension of 30 m), and $\theta_4 = \theta_{pmp}$ (θ at permanent wilting point). The values of θ_c and θ_{pmp} were calculated using equation 1 adjusted to the experimental data of each treatment, layer, and period of soil sampling. All these parameters were specific from both treatment and soil layer. The parameters λ_{OD} and λ_{WD} vary linearly from zero (maximum stress, growth stopped) to one (1) (no stress). The θ_2 and θ_3 indicate the water conditions that start the stress induced by OD and WD, respectively. For each treatment and soil layer, the frequency of the $\lambda_{OD} \leq 0.5$, $0.5 < \lambda_{OD} < 1$, $\lambda = 1$, $\lambda_{WD} \leq 0.5$, and $0.5 < \lambda_{WD} < 1$ classes was calculated considering all measures of θ done with the TDR.

Water table depth (Z) was monitored in six vertical holes drilled one meter away from the TDR probes, similar to those described by Cruciani (1987). After drilling the soil with an auger, a 50 mm diameter PVC pipe that was laterally perforated and coated with a Bidim drainage filter was inserted and fixed laterally in the soil with sand to prevent soil obstruction. The pipes were covered with a removable PVC cap to prevent external water input. The groundwater depth was measured on the days of rainfall and on the first and fourth days after rainfall. When no new rainfalls occurred, weekly measurements were taken. To measure Z, a thin floating graduated metal rod (3 mm diameter) with a Styrofoam base on the bottom end was inserted in the PVC pipe at each measurement time.

For statistical analyses, normal distribution analysis of data was preformatted using the Shapiro-Wilk test. When normal distribution was rejected, the data were subjected to logarithmic transformation. For each layer, the effect of soil treatments on soil and plant variables was evaluated by analysis of variance. When the F test was significant, the Tukey test was applied to detect mean differences.

RESULTS AND DICUSSION

At 12 days after sowing (11/26/2014), Bd (0.00-0.10 m) was lower, Tp (0.00-0.10 m) and Ma (0.00-0.10 and 0.20-0.30 m) were higher for the CHR, which did not differ for the CH (Table 1). At 70 days after sowing (02/04/2015), Bd was lower and Ma was higher in CHR, but only in the 0.10-0.20 m layer, also with no difference for CH. The absence of differences in the first layer 70 days after sowing indicates that rainfall (Figure 1) caused soil reconsolidation, which commonly occurs in a period of less than a year, even in highland clayey soils (Drescher et al., 2016). Although reduction in the initial degree of compaction from chiseling remained for a short period, its effect on the transpiration reduction factor was more noticeable, as will be discussed later. It is also important to note how little the chisel plow changed the soil structure below 0.20 m. Increased Bd and Mi and reduction in Tp and Ma were detected in the 0.30-0.40 m layer (Table 1). Compaction next to the lower limit of the chisel plow shank is still a controversial issue (Mentges et al., 2010; Rosa et al., 2011). In soil with high plasticity, the chisel plow shank compresses aggregates and may increase soil bulk density (Rosa et al., 2008). As the moisture was high in the 0.30-0.40 m layer (typical in lowland soils with some flooding occurrence), the chisel plow shank only created a slit, compacting the area beside it, as the soil behaved like a plastic material.

Furthermore, at 12 days after sowing, the values of Ks were higher in CHR and CH in the 0.00-0.10 m layer (Table 2), and Ka was also higher in CH and CHR in the 0.00-0.10 m layer (Table 3). However, at 70 days after sowing, the statistical differences practically faded away. In general, the differences noted for Ks and Ka are properly associated with changes in porosity (Table 1), i.e., the higher the Tp and the Ma, the higher the Ks (Mesquita and Moraes, 2004; Prevedello et al., 2013) and the Ka (Rodrigues et al., 2011; Prevedello et al., 2013).

The positive relation of Ka with water tension at 12 days after sowing was stronger in CHR and CH than in NTR and NT (Table 3). A greater number of large pores present in CHR and CH (Table 1) allowed tension to drain a considerable volume of the total porosity, favoring the flux of gases. These results are in agreement with the positive relationship between Ka and the pores with an apparent diameter greater than 300 micrometers (Prevedello et al., 2013) and porosity free of water (Rodrigues et al., 2011). The Ka and Ks indicate that CHR and CH may have decreased the frequency and the duration of the flooding and of the oxygen deficiency for soybean cultivation in the first two layers. However, excess rainfall, and the consequent rise in groundwater levels can override these potential benefits of chisel plowing, which can not be known by measuring only Ka and Ks.

Table 1. Soil bulk density and porosity in different layers of each soil condition

Sampling date	**Layer**	**Soil condition**				**CV**
		CHR	**CH**	**NTR**	**NT**	
	m					%
		Bd (Mg m^{-3})				
11/26/2014	0.00-0.10	1.27 a	1.40 ab	1.48 b	1.52 b	6
	0.10-0.20	1.42 a	1.34 a	1.57 b	1.61 b	4
	0.20-0.30	1.49 a	1.58 a	1.50 a	1.53 a	4
	0.30-0.40	1.61 ab	1.69 b	1.46 a	1.50 a	6
02/04/2015	0.00-0.10	1.31 a	1.30 a	1.24 a	1.39 a	6
	0.10-0.20	1.46 a	1.52 ab	1.55 ab	1.60 b	4
	0.20-0.30	1.58 a	1.45 a	1.50 a	1.49 a	4
	0.30-0.40	1.62 ab	1.67 b	1.50 ab	1.48 a	6
		Tp (m^3 m^{-3})				
11/26/2014	0.00-0.10	0.53 a	0.49 ab	0.45 b	0.44 b	7
	0.10-0.20	0.43 a	0.44 a	0.41 a	0.41 a	6
	0.20-0.30	0.44 a	0.42 a	0.45 a	0.43 a	5
	0.30-0.40	0.42 ab	0.39 b	0.46 a	0.44 a	6
02/04/2015	0.00-0.10	0.47 a	0.48 a	0.50 a	0.46 a	7
	0.10-0.20	0.44 a	0.43 a	0.41 a	0.39 a	6
	0.20-0.30	0.41 a	0.41 a	0.42 a	0.42 a	5
	0.30-0.40	0.39 a	0.39 a	0.43 a	0.44 a	6
		Ma (m^3 m^{-3})				
11/26/2014	0.00-0.10	0.15 a	0.11 ab	0.07 b	0.05 b	40
	0.10-0.20	0.06 a	0.07 a	0.03 a	0.04 a	55
	0.20-0.30	0.06 a	0.04 ab	0.04 ab	0.03 b	34
	0.30-0.40	0.04 a	0.03 a	0.03 a	0.03 a	24
02/04/2015	0.00-0.10	0.09 a	0.10 a	0.09 a	0.08 a	40
	0.10-0.20	0.08 a	0.08 a	0.02 b	0.02 b	55
	0.20-0.30	0.04 b	0.08 a	0.02 b	0.02 b	34
	0.30-0.40	0.03 a	0.03 a	0.02 a	0.03 a	24
		Mi (m^3 m^{-3})				
11/26/2014	0.00-0.10	0.37 a	0.39 a	0.38 a	0.40 a	6
	0.10-0.20	0.38 a	0.37 a	0.38 a	0.37 a	4
	0.20-0.30	0.38 a	0.38 a	0.41 a	0.40 a	5
	0.30-0.40	0.38 ab	0.35 a	0.43 b	0.41 b	7
02/04/2015	0.00-0.10	0.38 a	0.38 a	0.40 a	0.38 a	6
	0.10-0.20	0.36 a	0.37 a	0.38 a	0.38 a	4
	0.20-0.30	0.37 ab	0.34 a	0.40 b	0.40 b	5
	0.30-0.40	0.35 a	0.36 ab	0.41 b	0.41 b	7

Means followed by the same letter in a row do not differ statistically from each other by the Tukey test at 5 % probability of error. CV = coefficient of variation; NT = no-tillage; CH = chiseling; NTR = ridge on no-tillage; CHR = ridge on chiseling.

The total rainfall of 747 mm from December 2014 to early April 2015 was well distributed throughout the period (Figure 1e), even though the monthly accumulation of 324 mm in December and 190 mm in January was 99 and 49 % higher, respectively, than the standard mean value for the region (Inmet, 2009). In these months, the water table ranged from 0.1 to 0.5 m below the soil surface most of the time, sometimes oscillating within the 0.00-0.10 and 0.10-0.20 m layers. During the month of February and most of March, decreased rainfall resulted in lowering of the water table to depths between 0.75 and 1.1 m.

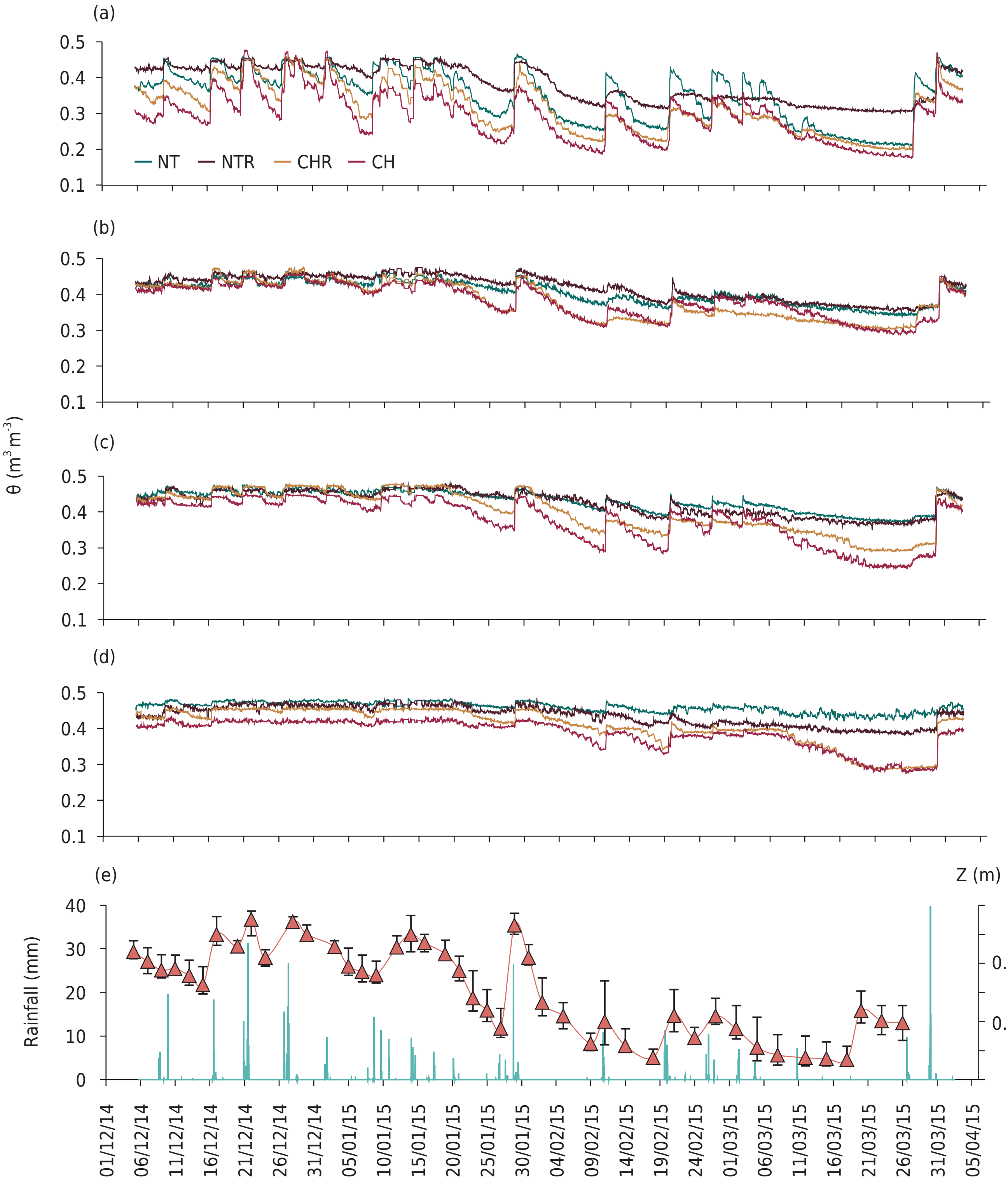

Figure 1. Volumetric water content (θ) in the different treatments for the 0.00-0.10 m (a), 0.10-0.20 m (b), 0.20-0.30 m (c), and 0.30-0.40 m (d) layers and rainfall (columns) and groundwater level - Z - (e) from December to early April. NT = no-tillage; CH = chiseling; NTR = ridge on no-tillage; and CHR = ridge on chiseling.

In the NTR and NT treatments, θ declined slower after the end of each rainfall (Figures 1a, 1b, 1c, and 1d). Therefore, in these treatments, the soil remained, most of the time, with θ close to that of saturation (0.49, 0.46, 0.44, and 0.47 m^3 m^{-3} for NTR, and 0.48, 0.45, 0.45, and 0.45 m^3 m^{-3} for NT, from the first to the fourth layer, respectively), especially in the 0.20-0.30 and 0.30-0.40 m layers. Maintaining high θ in these subsurface layers is associated with their low Ks (Table 2).

Reduction in rainfall from February to March sharply lowered θ in the CHR and CH, compared to NTR and NT. This reduction is associated with the high Ks in the 0.00-0.10 and 0.10-0.20 m layers (Table 2). Even though the water table lowered to a depth of 1 m in this period, the permanence of high θ in layers located above the water table has been attributed to what is known as the capillary fringe phenomenon, more noticeable where the proportion of micropores is greater (Ronen et al., 2000). The micropores filled with water at the tension of 0.6 m did not differ among the treatments (Table 1). Therefore, maintenance of greater θ in the NTR and NT must be due to the combined effects of capillary fringe and slow drainage conditioned by the low Ks in these treatments.

In addition, the maintenance of high θ in the CHR and CH in December and January indicates that the benefits of chiseling for drainage and aeration, i.e., an increase in Ks and Ka (Tables 2 and 3), may be temporally eliminated by the rise of water table. Except in the 0.00-0.10 m layer, θ remained close to θs in the CHR and CH in December and January. It is also noteworthy that the passage of the shank of the chisel plow in depth in the CH and CHR may have facilitated water drainage, reducing the θ in the 0.30-0.40 m layer (Figure 1d).

Soil structural changes caused large differences in the empirical transpiration reduction factor (λ). The frequency of λ_{WD} did not exceed 10 % in CH, 7 % in CHR, and 2 % in NT (only in the 0.00-0.10 m layer), and was absent in the NTR (Figure 2). The OD stress in the λ_{OD} ≤0.5 range was the most frequent and increased with depth, and it was always higher in NT and NTR (from 48 to 90 %) and lower in CH and CHR (4 to 66 %). In the CH and CHR, the λ_{OD} ≤0.5 frequency was not higher than the 0.5< λ_{OD} <1 frequency in the first layer. In the four layers, the no stress condition (λ = 1) occurred from 1 to 77 % of the time, higher in the 0.00-0.10 m layer, with a decrease in depth. Regardless of the layer, the frequency of λ = 1 was always higher in CH and CHR (11 to 77 %) and lower in NT and NTR (1 to 43 %).

The CH and CHR soil conditions favor the occurrence of WD, but decreased the appearance of OD, whereas NT and NTR had the opposite effect. The reduction in frequency of λ_{OD} by chiseling was more significant in the 0.00-0.10 m layer, but there was also a decrease in the 0.10-0.20 and 0.20-0.30 m layers compared to the same layers in NT and NTR. Comparison of tillage with and without ridging specifically in the 0.00-0.10 m

Table 2. Saturated hydraulic conductivity in different layers of each soil condition

Sampling date	Layer	CHR	CH	NTR	NT	CV
		Saturated hydraulic conductivity				
	m	mm h^{-1}				%
11/26/2014	0.00-0.10	300.6 a	383.8 a	38.9 b	1.8 c	23
	0.10-0.20	113.1 a	23.5 a	2.5 b	1.6 b	41
	0.20-0.30	147.7 a	1.8 b	9.4 b	13.1 b	52
	0.30-0.40	2.2 ab	2.3 ab	1.9 b	12.1 a	56
02/04/2015	0.00-0.10	220.2 a	53.2 ab	15.4 b	6.3 c	23
	0.10-0.20	50.1 a	16.3 a	0.0 a	0.0 a	41
	0.20-0.30	13.2 a	1.0 a	2.6 a	3.5 a	52
	0.30-0.40	0.1 a	1.8 a	2.1 a	1.9 a	56

Means followed by the same letter in the row do not differ statistically from each other by the Tukey test at 5 % probability of error. CV = coefficient of variation; NT = no-tillage; CH = chiseling; NTR = ridge on no-tillage; CHR = ridge on chiseling.

Table 3. Air permeability at fourth water tension in different layers of each soil condition

Sampling date	Layer	CHR	CH	NTR	NT	CV
	m					%
			Water tension of 0.6 m			
11/26/2014	0.00-0.10	6.63 a	3.84 a	0.39 b	0.15 b	51
	0.10-0.20	1.66 a	0.93 a	0.00 a	0.18 a	100
	0.20-0.30	1.19 a	0.14 a	0.05 a	0.04 a	102
	0.30-0.40	0.25 a	0.00 a	0.05 a	0.06 a	127
02/04/2015	0.00-0.10	3.27 a	1.93 a	2.23 a	1.34 a	51
	0.10-0.20	2.62 a	4.99 a	0.12 a	0.07 a	100
	0.20-0.30	0.43 ab	6.50 a	0.21 b	0.02 b	102
	0.30-0.40	0.33 a	0.45 a	0.01 a	0.06 a	127
			Water tension of 1 m			
11/26/2014	0.00-0.10	7.67 a	5.42 a	0.47 b	0.21 b	50
	0.10-0.20	2.81 a	1.60 a	0.00 a	0.38 a	83
	0.20-0.30	2.15 a	0.36 a	0.08 a	0.14 a	73
	0.30-0.40	0.61 a	0.17 a	0.12 a	0.21 a	90
02/04/2015	0.00-0.10	3.31 a	2.70 a	2.59 a	2.10 a	50
	0.10-0.20	2.93 ab	5.60 a	0.09 ab	0.07 b	83
	0.20-0.30	1.09 ab	7.08 a	0.27 ab	0.02 b	73
	0.30-0.40	0.72 a	0.53 a	0.15 a	0.06 a	90
			Water tension of 3.3 m			
11/26/2014	0.00-0.10	8.38 a	5.77 a	0.53 b	0.26 b	48
	0.10-0.20	2.24 a	3.06 a	0.00 b	0.53 ab	64
	0.20-0.30	2.04 a	0.51 a	0.08 a	0.15 a	58
	0.30-0.40	0.95 a	0.19 a	0.14 a	0.25 a	64
02/04/2015	0.00-0.10	3.50 a	4.22 a	2.47 a	2.19 a	48
	0.10-0.20	3.49 a	7.06 a	0.12 b	0.07 b	64
	0.20-0.30	0.98 ab	8.11 a	0.27 b	0.09 b	58
	0.30-0.40	0.81 a	0.83 a	0.27 a	0.42 a	64
			Water tension of 10 m			
11/26/2014	0.00-0.10	7.91 a	8.87 a	0.73 b	0.73 b	43
	0.10-0.20	7.62 a	9.14 a	0.12 b	1.79 ab	49
	0.20-0.30	5.98 a	1.52 a	0.61 a	0.77 a	34
	0.30-0.40	1.88 a	1.08 a	0.70 a	0.60 a	53
02/04/2015	0.00-0.10	3.94 a	5.72 a	3.71 a	2.48 a	43
	0.10-0.20	4.46 ab	9.16 a	0.32 b	0.08 b	49
	0.20-0.30	2.32 ab	16.08 a	0.36 ab	0.14 b	34
	0.30-0.40	1.31 a	1.81 a	0.32 a	0.77 a	53

Means followed by the same letter in the row do not differ statistically from each other by the Tukey test at 5 % probability of error. CV = coefficient of variation; NT = no-tillage; CH = chiseling; NTR = ridge on no-tillage; CHR = ridge on chiseling.

layer (where soil mobilization occurred by the ridge formation) indicates that the ridge neither provided an efficient environment to reduce the λ_{OD} frequency nor to increase the frequency of $\lambda = 1$ (Figure 2a).

Shoot dry matter and soybean yields were higher in CH, followed by CHR, NTR, and NT (Table 4). Under OD conditions, it is natural for shoot dry matter (Correa et al., 2006; Fante et al., 2010) and grain yield (Silva et al., 2007) to decrease, and to observe an increase in grain yield due to the ridge in comparison to no-till (Cassol, 2017).

Low grain yield in NT is not just associated with high frequency of λ_{OD}, but also with reduction in plant population (Table 4) due to flooding after sowing. Strong OD at this stage reduces seed vigor and emergence and causes seedling death (Wuebker et al., 2001; Githiri et al., 2006). In the CHR and CH with high Ks (Table 3), all water rapidly

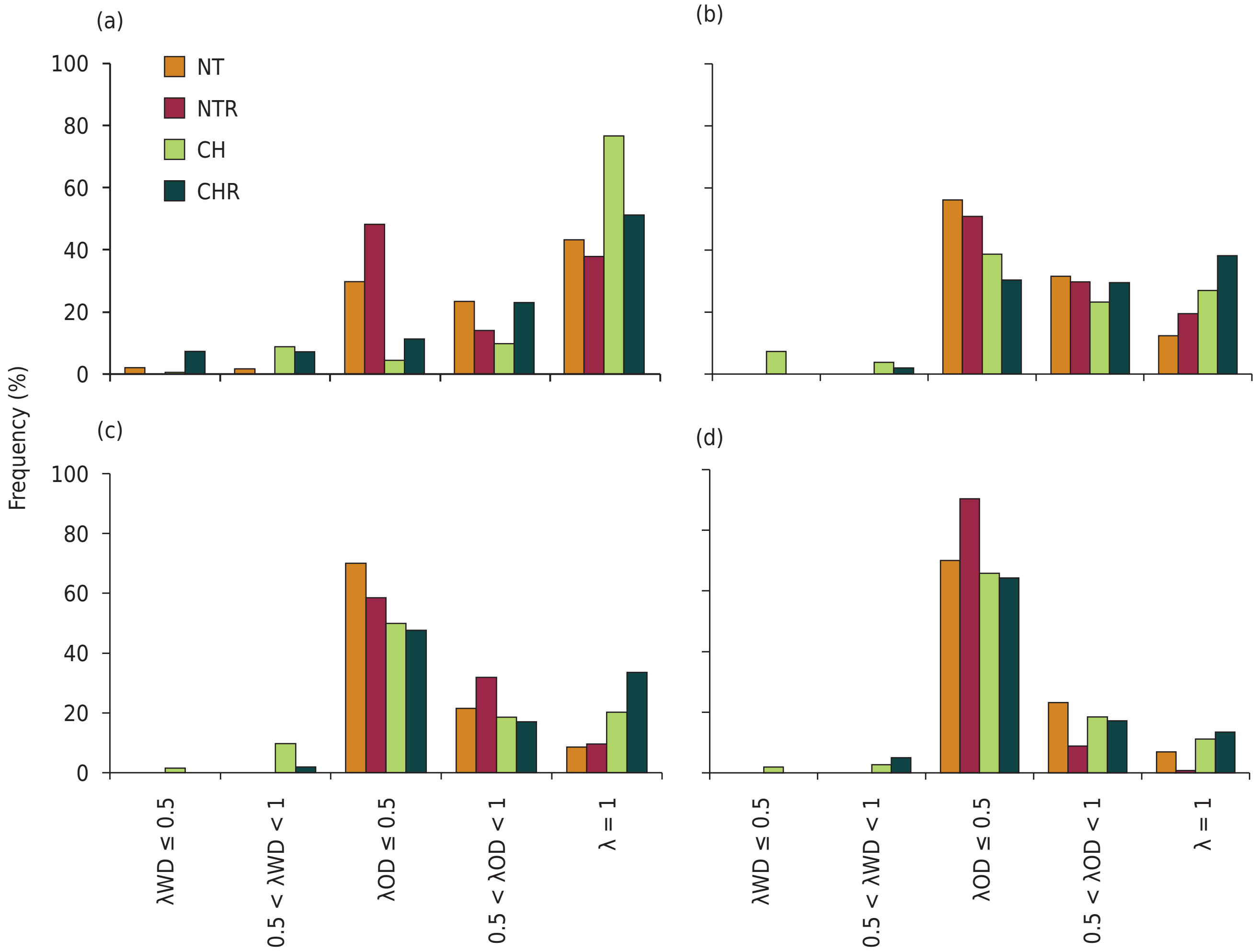

Figure 2. Frequency of λ_{WD}, λ_{OD}, and optimal conditions (λ =1) in the 0.00-0.10 m (a), 0.10-0.20 m (b), 0.20-0.30 m (c), and 0.30-0.40 m (d) layers. NT = no-tillage; CH = chiseling; NTR = ridge on no-tillage; CHR = ridge on chiseling.

Table 4. Plant population, shoot dry matter, and grain yield under different soil tillage systems

Soil condition	Plant population	Shoot dry matter	Yield	Taproot depth
	plants m^{-2}	kg ha^{-1}		m
CH	21 a	4648 a	4610 a	0.13 a
CHR	22 a	4276 b	4001 b	0.16 a
NTR	21 a	2892 c	3565 c	0.09 b
NT	16 b	1426 d	2842 d	0.08 b
CV (%)	9.37	7.36	4.90	5.8

Means followed by the same letter in the column do not differ statistically from each other by the Tukey test at 5 % probability of error. CV = coefficient of variation; NT = no-tillage; CH = chiseling; NTR = ridge on no-tillage; CHR = ridge on chiseling.

infiltrated into the soil right after the rain ceased. In the NTR, water was concentrated in the furrow between the ridges and slowly drained. Thus, CHR, CH, and NTR promoted drainage sufficient to avoid reduction in plant population (Table 4).

Grain yield was 600 kg ha^{-1} less in CHR than in CH (Table 4). Consequently, the addition of a ridge on chiseled soil was not effective in increasing grain yield. This agrees with the fact that the ridge neither provided an efficient environment to reduce the frequency of λ_{OD} nor increased the frequency of λ = 1 (Figure 2a). In this study, chiseling without formation of a ridge (CH) was sufficient to improve drainage, reduce the frequency of OD stress, and ensure greater grain yields.

Even if chiseling was performed up to 0.35 m deep, the roots did not go beyond 0.16 m deep in the chiseled soil (Table 4). Root scarcity in the 0.20-0.30 and 0.30-0.40 m layers is in agreement with the high permanence of λ_{OD} in these layers (Figures 2c and 2d) due to high water contents (Figures 1c and 1d) resulting from the level of the water table and from capillary fringe (Figure 1e). In periods with high rainfall, the water table rises (Gomes et al., 2012), moving the capillary fringe toward the ground surface (Ronen et al., 2000). In this study, the water table level was within the 0.20-0.30 m layer at various times, especially in the initial period, during intense root growth (Figure 1e). Consequently, root growth may have been limited to the 0.16 m depth in the CH by interference of the capillary fringe. The success of the chiseling as a option to deepen soybean roots in lowland areas is obviously conditioned by the level of the water table and the extension of the capillary fringe.

Nevertheless, yields above 3,500 kg ha^{-1} obtained in CH, CHR, and NTR (Table 4) indicate that high yields of soybean in floodplain areas can be obtained in years with no water deficiency if the surface layer up to 0.10 m is maintained with low OD. These results corroborate those observed by Sartori et al. (2016b) in 2013/14 and 2014/15 soybean cultivation, likewise in lowland soils and without the occurrence of water deficiency. In their study, soybean yield was 3,754 kg ha^{-1} where sowing was performed after tillage with a double offset disk, reaching 4,564 kg ha^{-1} where the soil was chiseled. However, the low grain yield (2,842 kg ha^{-1}) in NT of this study (Table 4) indicates that lack of ridge or chiseling means high risk of loss in grain yield by flooding.

The order of soil conditions by descending grain yield is very similar to the order by ascending frequency of λ_{OD} or descending frequency of $\lambda = 1$. This finding validates the hypothesis of our study, indicating that the λ transpiration reduction factor well represented the differences in the water and anoxic stress dynamics faced by the plants in the different treatments. Therefore, quantification of λ is very informative of water and anoxic stress conditions, since it is conditioned by all the processes determining the soil water dynamics. As a strong relationship between λ and grain yield is widely used in ecophysiological models (van Lier et al., 2008; Casaroli et al., 2010), this study suggests that these models can predict well soybean yield in lowland soils in different climatic and soil conditions. The quantification of soil structural properties (Table 1) or water (Table 2) and gas (Table 3) transport properties do not indicate the water and anoxic stress to which the plants are subjected throughout their cycle. As a result, the magnitude of these properties was much less associated with grain yield than λ. Therefore, the modeling of λ is more helpful for assessing the OD and WD effect on soybean yield in lowland soils. In addition, modeling can predict changes in soybean performance in lowland soils subjected to changes in climate and soil scenarios.

CONCLUSION

Quantification of the transpiration reduction factor (λ) is much more informative of water and anoxic stress conditions than quantification of the soil structural properties related to transport of water and gas. Chiseling decreases the frequency of oxygen deficiency, but increases the frequency of water deficiency; moreover, both are conditioned by the depth of the water table. Furthermore, chiseling increases soybean yield in lowland soils. The use of ridge tillage combined with chiseling is not a profitable alternative, but ridge tillage in untilled soil increases soybean yield.

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