






Division - Soil Processes and Properties | Commission - Soil Physics

Terracing increases soil available water to plants in no-tillage

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ABSTRACT: Several management practices can increase soil water storage capacity, but their effectiveness to minimize the adverse effects of drought depends on their potential to increase the soil available water to plants. Terracing is an effective option to increase soil water storage, but its effect on available water to plants in no-tillage system is still a knowledge gap. In this study, we monitored soil water content at eight layers down to 1.6 m in two zero-order paired catchments for 16 months. Presence of five broad-based terraces in one of the catchments was the main difference between the two. Water availability to plants over time was expressed as a fraction of available water capacity (FAW). Positive differences of FAW between the terraced and non-terraced catchments were noticed over periods of rainfall shortage, but they were barely perceptible in periods of abundant rainfall. Over the 16 months, the frequency of FAW higher than 0.75 was between 46 and 50 % in the non-terraced catchment, and between 67 and 75 % in the terraced catchment. This benefit of terracing is more noticeable in thicker upper-section of the soil profile evaluated and with greater number of terraces upstream from the point of observation. We concluded that terracing in no-tillage turn excess rainfall into noticeable positive increases in available water to plants in the following periods of rainfall shortage.

Keywords: paired catchments, conservation agriculture, rainwater harvesting.


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INTRODUCTION

Water deficit is one of the main causes of the yield gap of several grain crops in Brazil, especially in the South, where rainfall tends to be more irregular during the summer crops. The soybean yield gap is on average 29 % in Brazil, and 43 % in the state of Rio Grande do Sul (Sentelhas et al., 2015). However, this gap can be over 80 % in the southern states, including Rio Grande do Sul, Santa Catarina and Paraná, during La Niña years (Sentelhas et al., 2015). The average yield gap for corn is 15 % in Brazil and 35 % in Rio Grande do Sul (Amdrea et al., 2018). These gaps could be reduced with irrigation, but less than 5 % of large-scale grain crops (excluding rice) are irrigated in Brazil (ANA, 2019; CONAB, 2020). This is mainly due to the high installation and operation costs of irrigation systems (ANA, 2017). Thus, in agriculture largely dependent on rainfall, management practices are needed to reduce yield losses caused by water deficit, by increasing soil water availability to plants and improving the use of rainfall water.

Soil management based on minimum soil disturbance, maintaining residues on the soil surface and rotating crops with varied root architecture are pillars of the no-tillage system, widely adopted in Brazil since the 80s and 90s (Landers, 2001; Fuentes-Llanillo et al., 2021), and improving water availability to plants in comparison to soil management with tillage (Dalmago et al., 2009). There may still be an increase in water accessibility by roots in no-tillage when soil layers with high bulk density and mechanical resistance, which restrict root deepening, are chiseled (Calonego et al., 2017; Pott et al., 2019). However, the benefits of chiseling generally last less than two years (Drescher et al., 2016) and do not always promote increased crop yields (Benjamin et al., 2003; Sivarajan et al., 2018).

The diversification and intensification of crops to increase the input of biomass in the soil and to improve soil structure have been widely indicated to improve soil quality related to water infiltration, drainage, aeration, and root penetration (Nunes et al., 2018; Bowles et al., 2020). However, the increase in water available to plants due to improvements in soil structure and increased organic matter content is still a controversial subject (Minasny and McBratney, 2017). Furthermore, water loss due to runoff is commonly reported in well-managed no-tillage crops (Merten et al., 2015; Didoné et al., 2017; Londero et al., 2021). Whether the water lost as runoff would be a share needed to refill available water to plants up to its capacity is still an issue that needs further examination.

Terracing is a strategy to retain water that is unable to infiltrate the soil during a rainfall event and can contribute to increase water availability in no-tillage systems. It emerged as a conservation practice to reduce soil and water loss by erosion in tillage systems (Pruski et al., 1997; Bertol et al., 2007), but its use was discouraged with the introduction of no-tillage system (Levien et al., 2011). However, significant water loss occurs even in crops properly managed under no-tillage (Didoné et al., 2017; Londero et al., 2021). This is drastically reduced with the use of terraces (Londero et al., 2017). Water retained by terraces gradually infiltrates, and can increase soil water storage if the soil is not saturated at the end of a rainfall event. However, we still need to investigate whether the greater amount of water infiltrating in terraced soils results in higher soil water content over time within the limits of available water (difference between field capacity and permanent wilting point). Several studies addressed the effect of different types of terraces on the dynamics of water content in different cultivation systems (Siriri et al., 2013; Zhang et al., 2017; Wei et al., 2018; Mesfin et al., 2019; Chen et al., 2020), but none specifically investigated the effect of terracing on water content available to plants.

This study aimed to analyze data of soil water content in an area with and without terraces to verify whether terracing increases the available water content to plants in soil managed under no-tillage.

MATERIALS AND METHODS

Soil water content was monitored in two zero-order paired catchments, one of 2.35 ha with terraces (TER) and another of 2.43 ha without terraces (NoTER), in the experimental station of the Fundação Estadual de Pesquisa Agropecuária (FEPAGRO), located in the municipality of Júlio de Castilhos, state of Rio Grande do Sul (RS) (29° 13' 39" S, 53° 40' 38" W, and an altitude of 514 m). The region's climate is humid subtropical (Cfa) according to the Köppen classification system, with an average annual rainfall of 1678 mm regularly distributed during the year, but irregularly distributed within the warmer months (late spring and summer). The average annual Penman-Monteith evapotranspiration is around 1170 mm, according to Sistema Irriga®, a global service for irrigation management. The catchments were delimited in 2014 to study the effect of terracing on reducing runoff, sediment and nutrient loss (Londero et al., 2021). The effect of terracing on the variation of soil water content, which is the focus of this study, was evaluated from November 1, 2016 to February 28, 2018 (729 days).

Description of the area

The soil in both catchments is a clayey, deep, strongly weathered and well drained, classified as a *Nitossolo Vermelho* (Santos et al., 2018) in the Brazilian Soil Classification System and as a Nitisol according to IUSS Working Group WRB (2015). The relief is characterized as a gently rolling landscape, with slopes ranging from 5 to 13 %. The soil has been managed under no-tillage, and the crop rotation system adopted is soybean or corn in summer, and wheat or oats/turnip in winter.

The catchments were delimited by ridges to prevent water from entering or exiting the catchment. Thus, the entry of water into the catchments occurred exclusively through precipitation. Five broad-based terraces were built in the catchment, which had a slightly steep and long hillslope (Figure 1). The terraces were built using a 3-disc plow to raise a ridge with a 6-m-wide base and an average height of 0.50 m. All terraces were closed at the ends to prevent water from leaving the terrace. More details about the catchment's physiography and the terrace building procedure can be found in Londero et al. (2017).

Water content was monitored at two positions in each catchment, one at a high position in the relief (high) and another at approximately 90 m below the other (low). These positions were named TER_high and TER_low for the catchment with terracing, and NoTER_high and NoTER_low for the one without terracing (Figure 1). The TER_high was located between the first and the second terrace and the TER_low between the fourth and the fifth (last) terrace (Figure 1). During the monitoring period of soil water content, the catchments were cultivated with wheat (winter 2016), soybean (summer 2016/17), turnip (winter 2017) and corn (summer 2017/18).

Soil characterization and water content monitoring

At each monitoring position, a 1.60 m deep trench was opened and eight soil layers were defined based on morphological observations. At the center of each layer, water content probes (WCR, model CS616, Campbell Scientific Inc., Logan/UT, USA) were inserted and connected to a datalogger (model CR1000, Campbell Scientific Inc., Logan/UT, USA) which recorded soil water content (θ ; $\text{m}^3 \text{m}^{-3}$) every 30 min. The readings of θ provided by the device calibration function were corrected with equation 1, calibrated by Pereira (2017) based on eight comparisons between θ measured by probes (θ_p) and θ measured in soil samples with varying soil water content collected at different dates (θ_m):

$$\theta_m = -1.5737 \theta_p^2 + 1.6729 \theta_p \quad (R^2 = 0.7182) \quad \text{Eq. 1}$$

Five undisturbed soil samples were collected at each layer with metal rings (0.03 m high and 0.057 m in diameter). Disturbed soil samples were also collected at these

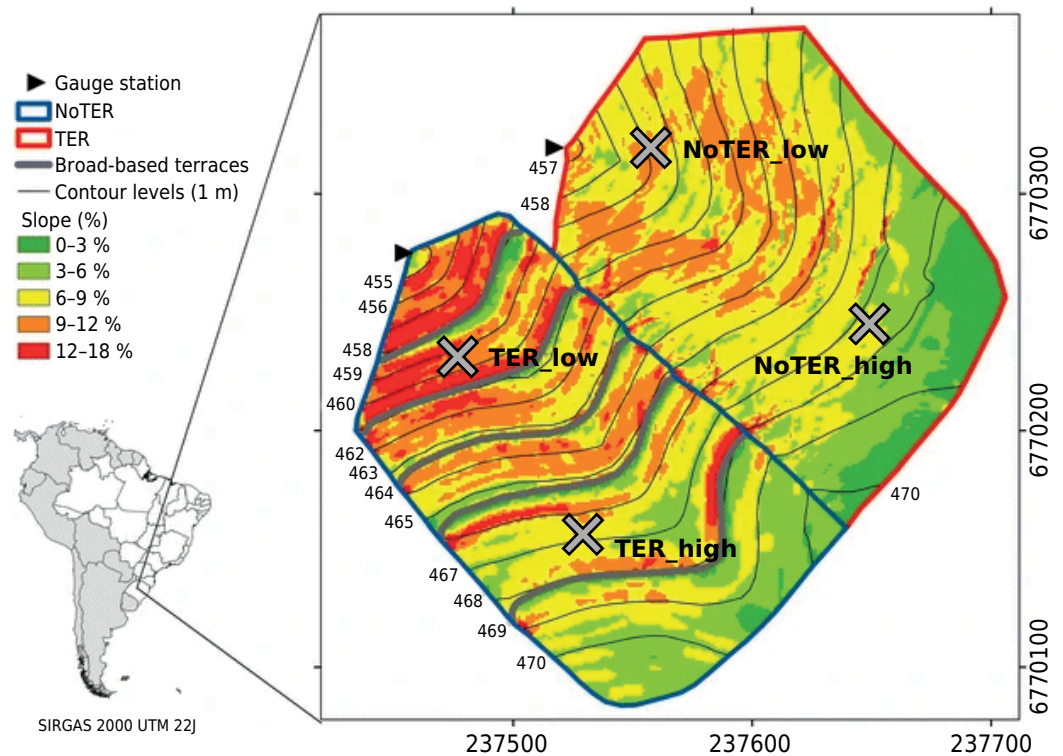


Figure 1. Topographic map of two catchment areas with terrace (TER) and without terrace (NoTER) and landscape positions (high and low) where water content was monitored. Source: adapted from Londero et al. (2021).

same positions. In the undisturbed samples, the saturated water content (θ_s ; $\text{m}^3 \text{m}^{-3}$) was determined after 24 h of saturation in a tray, and bulk density (BD ; Mg m^{-3}) was calculated by dividing the mass of the oven-dried soil (105 °C for 24 h) by its volume (ring volume). In the disturbed samples, the water content at the permanent wilting point (θ_{pwp} ; $\text{m}^3 \text{m}^{-3}$) and particle-size fractions (sand, silt and clay) were measured. The θ_{pwp} (θ at -1500 kPa) was determined using a dew-point psychrometer (Dew point Potentiometer, Model WP4) (Gubiani et al., 2012), and the particle-size fractions were determined by the pipette method according to Suzuki et al. (2015).

Soil water content at field capacity (θ_{fc} ; $\text{m}^3 \text{m}^{-3}$) at each layer was estimated by observing the decrease in water content (measured every 30 min by the WCR) after all the times the soil water content reached or was close to saturation. The θ_{fc} was visually defined as the intersection point of the segment of sharp decrease and slow decrease of θ . By this criterion, the intersection point corresponded approximately to the point of maximum curvature of the θ curve. Although it may be partially subjective, this strategy estimates θ_{fc} by observing the drainage of the soil profile, which is the most suitable criterion for defining field capacity. The average of all θ_{fc} estimated at each layer was considered its θ_{fc} .

Fraction of available water

The fraction of available water (FAW, dimensionless) was used to evaluate water availability to plants. In each soil layer, the FAW was calculated based on θ , θ_{fc} and θ_{pwp} by equation 2.

$$\text{FAW} = \begin{cases} 1 & \text{if } \theta \geq \theta_{\text{fc}} \\ \frac{\text{AWa}}{\text{AWC}} & \text{if } \theta_{\text{fc}} > \theta > \theta_{\text{pwp}} \\ 0 & \text{if } \theta \leq \theta_{\text{pwp}} \end{cases} \quad \text{Eq. 2}$$

in which AWa is actual available water ($\text{m}^3 \text{m}^{-3}$) and AWC is available water capacity ($\text{m}^3 \text{m}^{-3}$):

$$\text{AWa} = \theta - \theta_{\text{pwp}} \quad \text{Eq. 3}$$

$$\text{AWC} = \theta_{\text{fc}} - \theta_{\text{pwp}} \quad \text{Eq. 4}$$

Rainfall and runoff

The rainfall rate was recorded at 2-min intervals with an automatic rain gauge and the cumulative rainfall in 24 h was measured with two rain gauges installed next to the discharge points in each catchment (Figure 1). Rainfall and runoff were measured by the Grupo Interdisciplinar de Pesquisa em Erosão e Hidrologia de Superfície (GIPEHS) at the Universidade Federal de Santa Maria, and methodological details are described in Londero et al. (2017).

Data analysis

The variation of water content over time at all the layers of the four soil profiles was analyzed graphically. In each soil profile, the FAW of each layer was analyzed using a box plot graph. Ideally, the data in each layer should be compared statistically. However, the soil layers had the same thickness only in the TER_high and NoTER_high locations. Then, the different position in the soil profile of both layers been compared could add bias in the statistical result. Additionally, in each soil profile, the FAW of layers above 0.75 m (for the profiles at low) and layers above 0.8 m (for the profiles at high) were grouped every month, analyzed in a box-plot graph, and then related to monthly rainfall.

RESULTS

Sand, silt and clay contents, and BD were similar between TER_high and NoTER_high (Figure 2). Therefore, θ_{fc} and θ_{pwp} (which determine AWC) were also similar between these two positions (Figure 3). However, sand and silt contents were higher and clay was lower at all layers at TER_low compared to NoTER_low (Figure 2). Consequently, θ_{fc} and θ_{pwp} were slightly closer to each other at NoTER_low in comparison to TER_low (Figure 3). Bulk density (Figure 2c) and θ_{s} (Figure 3) along the profile were similar among all the monitoring points. There was an increase in BD and a decrease in θ_{s} only at the layers 0.1-0.3 and 0.3-0.5 m at TER_low.

The variability of θ was consistent with that of rainfall, i.e., θ increased at each rainfall event and gradually decreased until the following event (Figure 4). This relationship is more evident with greater cumulative rainfall and at shallower layers, due to the greater extraction of water by crops and evaporation. In most cases, it is also clear that θ was lower the closer the layer was to the surface. This was consistently associated with the decrease in θ_{fc} towards the soil surface (Figure 3). The greatest variability of θ occurred from September to January (spring and summer) due to the higher atmospheric demand and water uptake by soybean and corn. During the evaluation period (March 1, 2016 to February 28, 2018), there was 3310 mm of rainfall, regularly distributed (Figure 4), except for June 2016 and July 2017, in which it was less than 10 mm. It is also possible to notice greater θ at TER_high in comparison to NoTer_high (Figure 4). The difference is sharper in favor of the terrace when comparing θ at TER_low with NoTer_low, especially the uppermost layers (Figure 4).

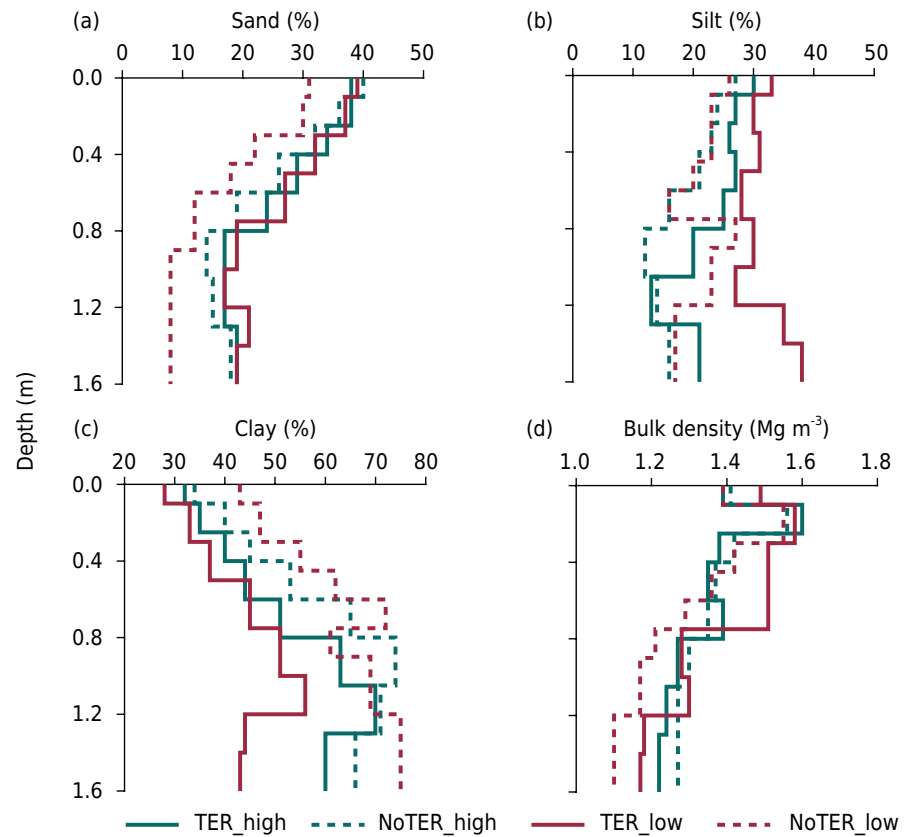


Figure 2. Particle-size distribution (sand, silt and clay) and bulk density in soil profiles of an area with terrace (TER) and without terrace (NoTER) at low and high landscape positions.

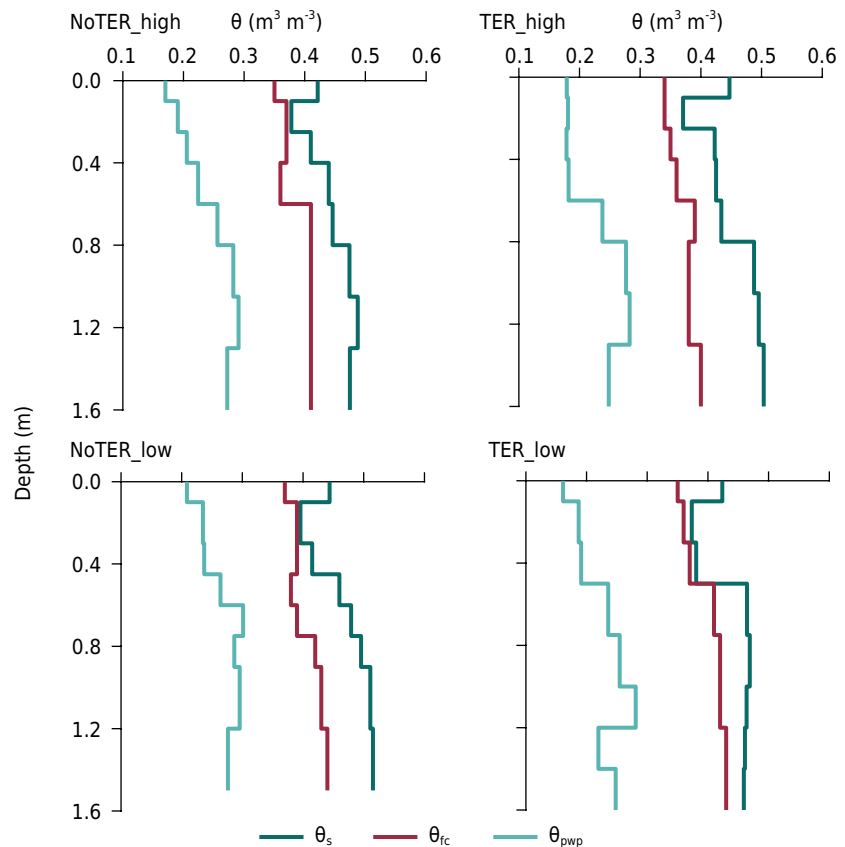


Figure 3. Water content at the limits of saturation (θ_s), field capacity (θ_{fc}) and permanent wilting point (θ_{pwp}) at each soil profile depth of an area with terrace (TER) and without terrace (NoTER) at low and high landscape positions.

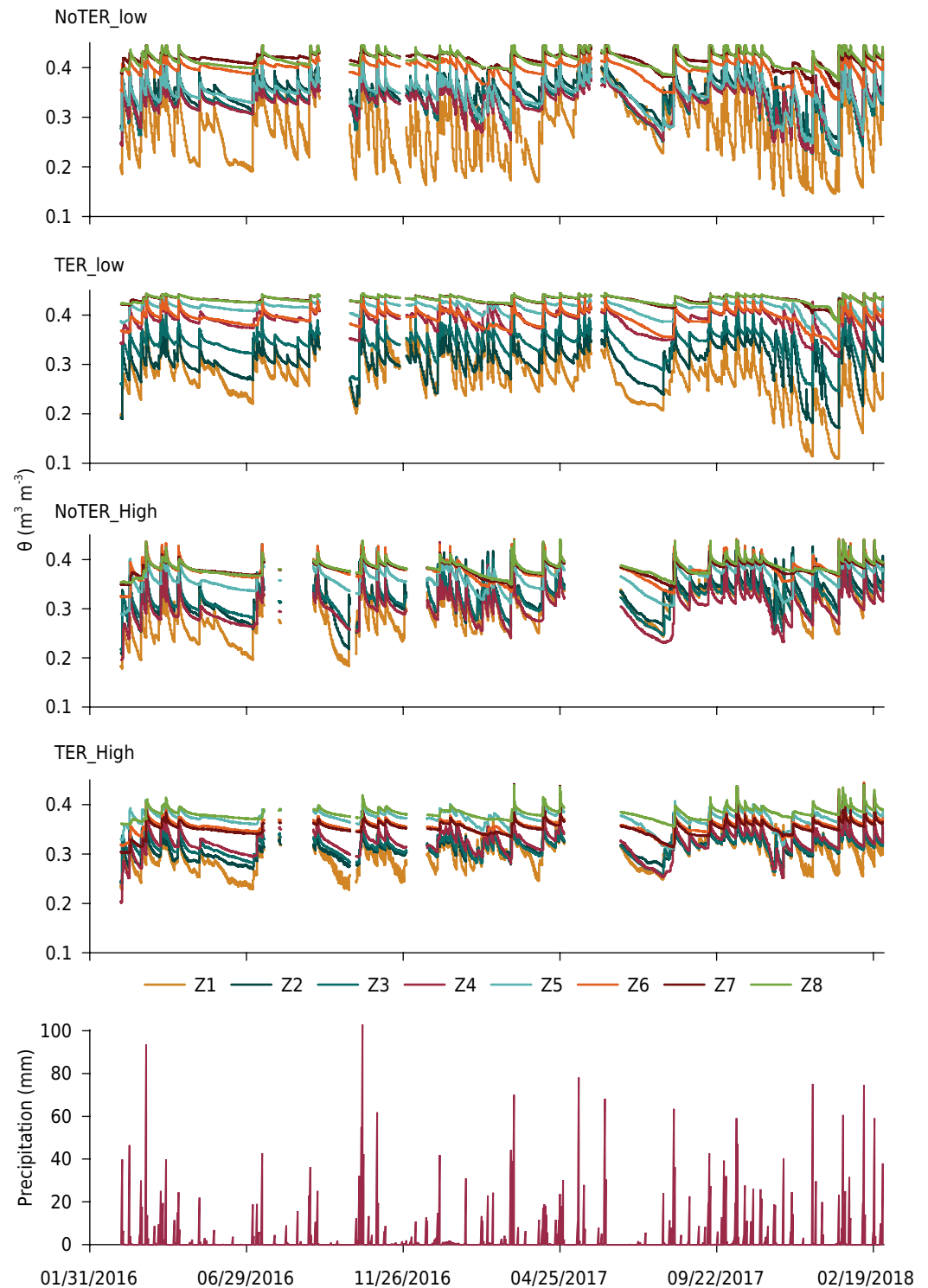


Figure 4. Water content (θ) at eight soil depths of an area with terrace (TER) and without terrace (NoTER) at low and high landscape positions and precipitation during the evaluation period (March 1, 2016 to February 28, 2018). The depths of Z1, Z2, ..., Z8 were 0.05, 0.18, 0.33, 0.50, 0.70, 0.93, 1.18 and 1.45 m for both TER high and NoTER high, 0.05, 0.20, 0.40, 0.63, 0.88, 1.10, 1.30 and 1.50 for TER low, and 0.05, 0.20, 0.38, 0.53, 0.68, 0.83, 1.05 and 1.35 m for NoTER_low. The intervals without data are due to a datalogger failure.

In general, the variability in FAW (variation between the minimum and maximum limits) was higher towards the soil surface (Figure 5), following the same trend between θ variability and soil depth (Figure 4). The interval containing the second and third quartiles of FAW (horizontal bars in Figure 5) was located over a range of smaller values of FAW at NoTER_high and NoTER_low. On the other hand, the same interval was located over

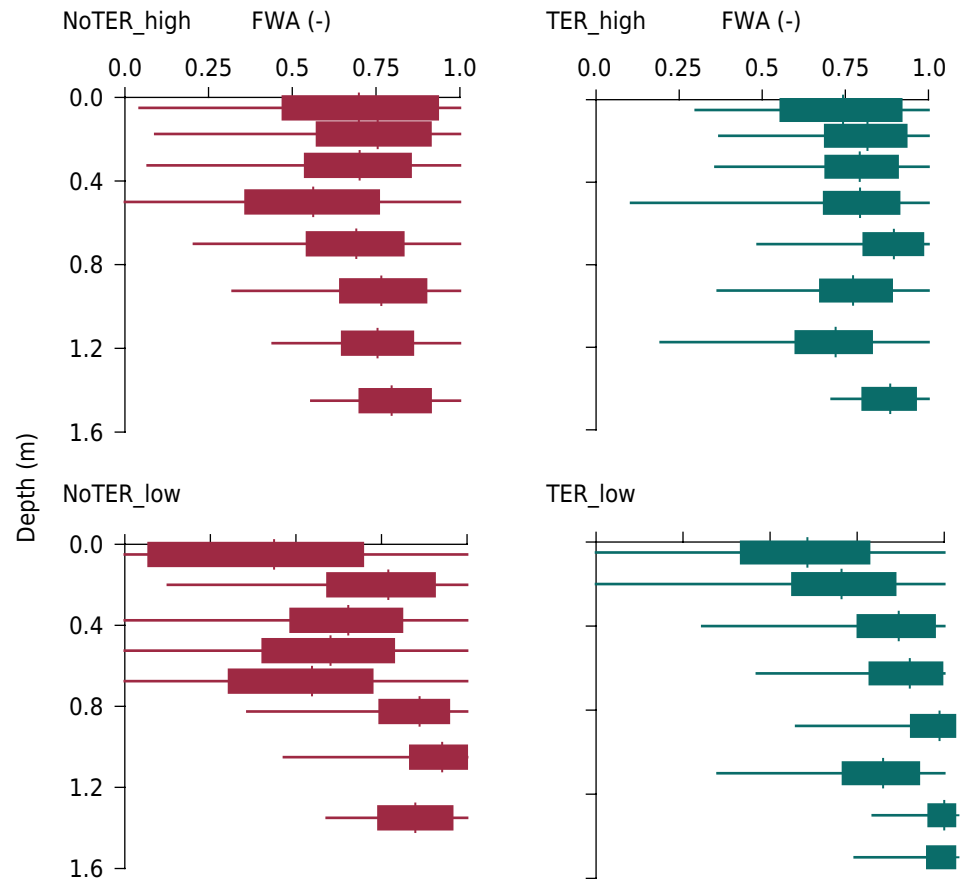


Figure 5. Daily fraction of available water (FAW) in soil depths of an area with terrace (TER) and without terrace (NoTER) at low and high landscape positions.

a range of high values of FAW at TER_high and TER_low, closer to the maximum value of FAW (FAW = 1). The layer two (near soil surface) was the only where FAW was slightly lower at TER_low compared to NoTER_low (Figure 5). Using a quantitative reference, FAW ≥ 0.75 occurred in 46 and 50 % of the measurements at NoTER_high and NoTER_low, respectively, and 67 and 75 % at TER_high and TER_low, respectively.

There were marked differences of FAW in favor of the terrace in months with less cumulative rainfall. However, in months with higher cumulative rainfall, the differences of FAW between areas with and without terraces were barely noticeable (Figure 6). For instance, the difference in the average FAW in favor of the terrace was between 0.1 and 0.24 (dimensionless) when the lowest monthly cumulative rainfall occurred (May, June and September of 2016, and January and July of 2017) (Figure 6). Furthermore, the difference in averages of FAW between areas with and without terrace was between 0.05 and 0.21 when there were rainfall events that caused runoff (March, April and October of 2016, May, June, August and October of 2017, and January and February of 2018) (Figure 6).

DISCUSSION

To properly evaluate the terrace effect on FAW, the value of the parameters θ_{fc} and θ_{pwp} along the profile would ideally be the same at the pairs of monitoring points being compared (NoTER_low vs. TER_low and NoTER_high vs. TER_high). Due to differences in soil texture and bulk density (Figure 2), variability in θ_{fc} and θ_{pwp} is unavoidable in soil profiles in the field (Figure 3). Differences of θ_{fc} and θ_{pwp} between the two points being compared (NoTER_low vs. TER_low and NoTER_high vs. TER_high) propagates towards FAW (Equation 2) of these points via AWa (Equation 3) and AWC (Equation 4), which depends

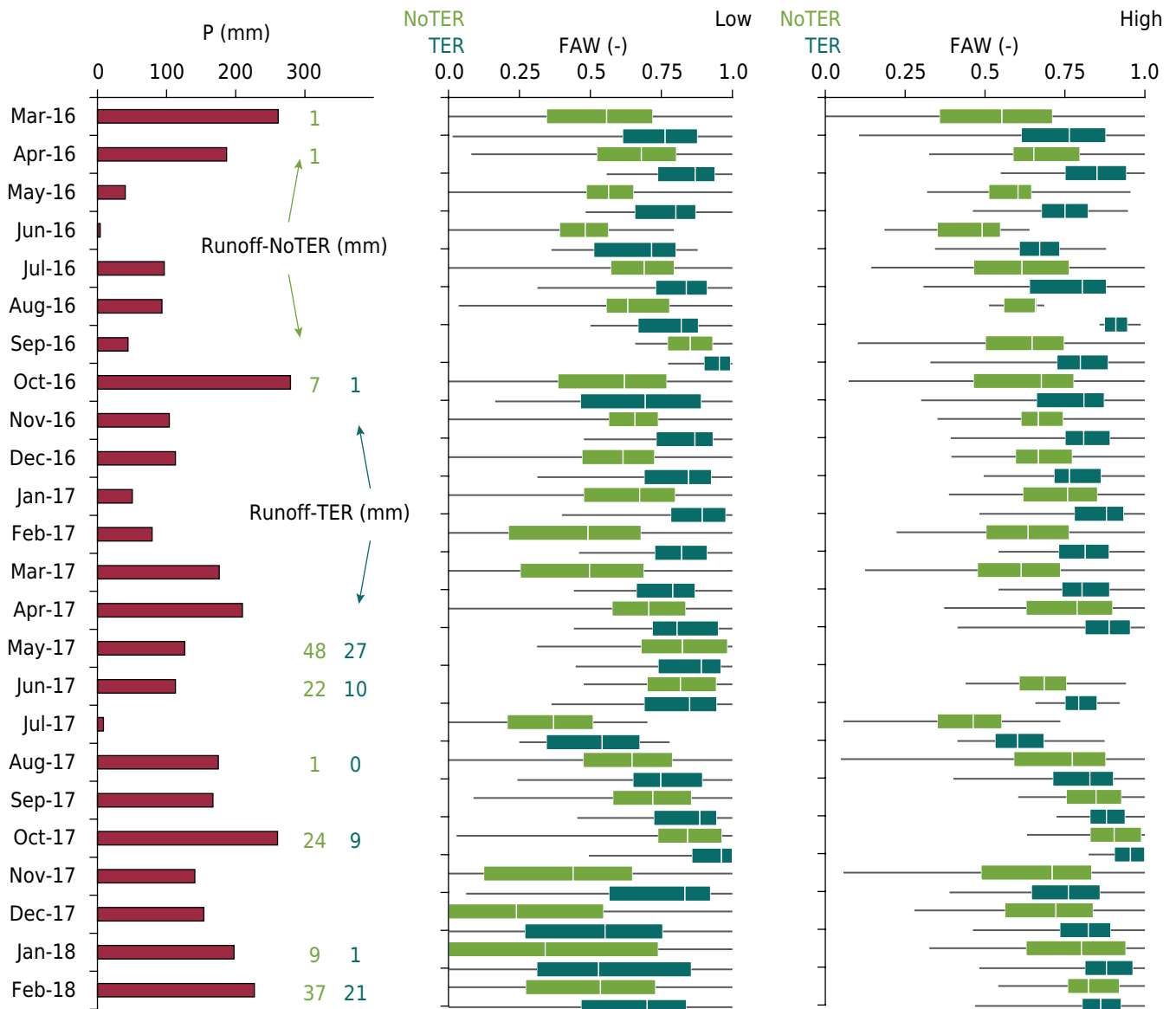


Figure 6. Monthly precipitation (P) in the horizontal bars graph at the left, which also shows the monthly runoff (numbers) in areas with terrace (Runoff-TER) and without terrace (Runoff-NoTER), and the monthly fraction of available water (FAW) in the upper half part of soil profiles of an area with terrace (TER) and without terrace (NoTER) at low and high landscape positions (boxplot graphs). All soil depths above 0.75 and 0.8 m were considered at low and high landscape positions, respectively.

on both θ_{fc} and θ_{pwp} (AWC) or only θ_{pwp} (AWa). However, the ratio of AWC_{TER}/AWC_{NoTER} was in the range 0.8 to 1.2 in 13 of the 16 layers. Thus, in these layers, differences in AWC between points with and without terrace slightly conceal the observed differences in FAW between them. Only in layers below 0.45 m, and in NoTER_low vs TER_low, the ratio AWC_{TER}/AWC_{NoTER} was 1.5, 1.6 and 1.9, respectively for the layers of 0.45-0.60, 0.60-0.75 and 0.90-1.20 m. Thus, the same θ within the available water range of these layers implies smaller FAW at NoTER_low in comparison to TER_low. However, this confounding effect in layers below 0.45 m is less relevant because the soil profile below 0.45 m is little explored by wheat, soybean, turnip and corn roots in no-tillage soils of the south of Brazil (Nunes et al., 2015; Moraes et al., 2019; Moraes et al., 2020). Water stored below the rooted layer is, in large part, not available to the plants, because only a small portion of it can flow upward by capillarity. According to the definition of field capacity (negligible downward flow), available water stored below the rooted layer also barely contributes with flows toward aquifers. Thus, this less mobile water fraction below the rooted layer is also less sensitive to terracing.

There is enough consistency in the variation of θ measured by the probes in relation to rainfall variation (Figure 4) as well as in relation to θ_{fc} . As mentioned earlier, at each layer, the highest θ values over time are consistently associated with the occurrence of rainfall, and the higher θ values with increasing depth in a given time are consistently associated with θ_{fc} of the profiles (Figure 3). Thus, the FAW was calculated for a reliable set of 32,523 values of θ for the comparison NoTER_low vs TER_low and 29,033 values of θ for the comparison NoTER_high vs TER_high. The differences in the amount of data are due to datalogger failure (intervals without data in Figure 4).

The greater frequency of higher FAW values (FAW >0.75) in the layers up to 0.8 m in the catchment with terrace (Figure 5) means that θ remained closer to field capacity. These results corroborate previous studies that found higher water content in soil with different types of terraces (Adgo et al., 2013; Rashid et al., 2016; Zhang et al., 2017; Wei et al., 2018; Lü et al., 2019). We noticed that the decrease in θ over time in the catchment with terrace was slower (Figure 4), prolonging more favorable conditions (higher FAW; Figure 5) for the absorption of water by the plants and mitigating the occurrence of water deficit.

When water accumulates in the terrace channel, the duration of infiltration is longer in the catchment without terrace. Thus, the decrease in water content by drainage begins immediately after the end of rainfall in the catchment without terrace, but it takes more time in the catchment with terrace. Consequently, the decrease of θ is delayed in terraced areas in comparison to ones without terraces. This time lag can be noticed at various times when comparing θ of the monitoring points with and without terrace (Figure 4).

Another benefit of maintaining higher FAW in the soil is the reduction of the times that water needs to be applied by supplementary irrigation. Many studies suggest a critical FAW value of between 0.5 and 0.7 to indicate the onset of irrigation in crops such as soybean and corn (Franke and Dorfman, 2000; Andrade et al., 2006; Flumignan et al., 2015; Silva et al., 2020). Therefore, the interval between irrigations and the amount of water applied would be shorter in the catchment with terrace because the FAW would be lower than the critical FAW less frequently throughout the crop cycle.

In relation to the deeper soil layers, the highest values of FAW in the catchment with terrace, especially at the low position (Figure 5), represent a greater amount of available water. Although it is little used by most agricultural crops such as wheat, soybean, corn and oats, as few roots of these plants deepen more than 0.8 m, the increase of θ in depth is necessary to supply the deep drainage flow for recharging groundwater reservoirs and subsurface flow toward small streams and rivers. The terrace also makes the catchment more efficient in these aspects.

Benefits arising from the use of the terrace, such as increased infiltration (Barros et al., 2014), less runoff (Menezes et al., 2020; Londero et al., 2021) and sediment and contaminant transport (Barros et al., 2020; Didoné et al., 2021), and extending river baseflow (Didoné et al., 2017; Minella et al., 2017) are well-known effects and indicators that the availability of water in the soil also should increase in terraced areas. However, this benefit had not yet been evaluated and shown with the details and robustness of the data of our study.

The results of this study also reveal that a greater available water in the terraced area is more noticeable in the periods when the terrace acts less to contain runoff due to abundant rainfall. There were noticeable differences in FAW in favor of the terrace when the lowest monthly cumulative rainfall occurred in May, June and September of 2016, and January and July of 2017 (Figure 6). However, this almost disappeared when rainfall events causing runoff took place in October of 2016, May, June, August and October of 2017, and January and February of 2018 (Figure 6). The great availability of rainfall means there is no deficit of infiltration to fulfill the available water capacity also in the areas without terraces. Thus, the greater retention of runoff water with the use of a

terrace does not reflect an immediate gain in available water when rainfall is abundant and frequent. However, the gain in retaining runoff water in the areas with terraces and the ensuing increase in available water will take effect in subsequent periods of rainfall shortage. In view of the forecasts of increasing periods of rainfall shortage caused by the increased irregularity of rainfall in the coming decades (FAO, 2015; Jia et al., 2019), terracing could be a very useful technology to bring the productivity of agricultural crops closer to their great genetic potential of modern cultivars and to reduce the large yield gaps caused by water scarcity pointed out in several studies (Bhatia et al., 2008; Van Ittersum et al., 2013; Aramburu Merlos et al., 2015; Zhang et al., 2016; Zanon et al., 2016; Guilpart et al., 2017).

CONCLUSION

The increase in available water to plants in favor of terraced areas in no-tillage was noticeable over periods of rainfall shortage, but it was barely perceptible in periods of abundant rainfall. Terracing in no-tillage turn retained water in periods of excessive rainfall into noticeable positive increases in available water to plants in the following periods of rainfall shortage. This benefit of terracing is higher in thicker upper-section of the soil profile and with greater number of terraces upstream from the point of observation. Therefore, terracing is not only an effective option to reduce runoff but also to increase available water to plants in a no-tillage system.

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