








# Managing runoff in rainfed agriculture under no-till system: potential for improving crop production

Tiago Hörbe<sup>(1)</sup> , Jean Paolo Gomes Minella<sup>(1,2)\*</sup> , Fabio Jose Andres Schneider<sup>(1)</sup> , Ana Lúcia Londero<sup>(1)</sup> , Paulo Ivonir Gubiani<sup>(1,2)</sup> , Gustavo Henrique Merten<sup>(3)</sup>  and Alexandre Schlesner<sup>(1)</sup> 

<sup>(1)</sup> Universidade Federal de Santa Maria, Departamento de Solos, Pós-Graduação em Ciência do Solo, Santa Maria, Rio Grande do Sul, Brasil.

<sup>(2)</sup> Universidade Federal de Santa Maria, Departamento de Solos, Santa Maria, Rio Grande do Sul, Brasil.

<sup>(3)</sup> University of Minnesota-Duluth, Department of Civil Engineering, Duluth, Minnesota, United States.

**ABSTRACT:** Strategies to mitigate degradation and ensure food and water security are among the main challenges in agricultural development. Unconsolidated information about the positive impact of conservationist practices on productivity increase is fundamental for their adoption by farmers. This study evaluated if the saved rainfall excess in catchment with terrace generates higher soybean and corn yield due to greater water availability in the crop rooting zone. Experiments were conducted in southern Brazil during the agricultural years of 2016/17 (soybean) and 2017/18 (corn) in two paired zero-order catchments (~2.4 ha) with similar topography and soil properties. One catchment has no terraces, while the other has five broad-based terraces as a complementary practice to control runoff. Soybean and corn yield was compared between catchments through five paired transects, totaling 47 sampling points. The fraction of available water (FAW – the current in relation to the total available water) was monitored at two points in each catchment, one at the base and the other at the top, considering the elevation. The FAW was monitored with CS616 probes at eight soil layers (from 0.00 up to 1.60 m) at each point during the crop growth cycle. The FAW was higher in the terraced catchment than the non-terraced catchment during the soybean (14 %) and corn (8 %) cycles. The terraced area provided higher soybean (12 %) and corn (10 %) than the non-terraced area. These results highlight the importance of terraces to increase productivity by managing runoff on hillslopes, indicating the potential of terraces to mitigate water deficits.



**Keywords:** broad-based terraces, infiltration, conservationist agriculture, water productivity, catchment.

\* **Corresponding author:**  
E-mail: jean.minella@ufsm.br

**Received:** March 19, 2021

**Approved:** August 19, 2021

**How to cite:** Hörbe T, Minella JPG, Schneider FJA, Londero AL, Gubiani PI, Merten GH, Schlesner A. Managing runoff in rainfed agriculture under no-till system: potential for improving crop production. Rev Bras Cienc Solo. 2021;45:e0210015.  
<https://doi.org/10.36783/18069657rbc20210015>

**Editors:** José Miguel Reichert  and Jackson Adriano Albuquerque 

**Copyright:** This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided that the original author and source are credited.



## INTRODUCTION

Defining strategies of soil and water management are essential to meet diverse demands, such as improving agricultural production and ensuring food security with minimum water consumption (Godfray et al., 2010; Foley et al., 2011; Pfister et al., 2011; Grassini et al., 2015; McNeill et al., 2017). Food production must increase from 60 to 110 % to attend to the global demand for food until 2050 (Alexandratos and Bruinsma, 2012; Tilman et al., 2011). As a result, water consumption by agriculture, which currently stands at  $7100 \text{ km}^3 \text{ yr}^{-1}$ , will have to increase by 30-40 % (de Fraiture et al., 2007). This increment can be as high as 90 % if the water productivity ( $\text{kg mm}^{-1}$ ) is not optimized (Evans and Sadler, 2008; Rockström et al., 2009; Bossio et al., 2010). The increase in water productivity will result in greater water availability for other uses, such as urban and industrial supply.

Water deficits are one of the main limiting factors in agricultural production (Bhatia et al., 2008; Van Ittersum et al., 2013; Aramburu Merlos et al., 2015; Fisher et al., 2015; Battisti et al., 2016; Zhang et al., 2016; Guilpart et al., 2017). Water soil refilling is necessary to create appropriate moisture conditions in crop root zones and relies on rainwater infiltration (Reichert et al., 2009). Therefore, cultivation strategies to maximize infiltration and conserve soil moisture in the crop rooting zone are vital to optimize water availability and increase crop productivity (Rockström et al., 2010).

No-till (NT) is commonly used in Brazil for this purpose and is based on sowing crops without eliminating cultural residues and minimal soil mobilization (Derpsch et al., 2014). No-till is employed in approximately 33 million ha of land (Fuentes-Llanillo et al., 2021), with roughly 86 % of agricultural fields sown with soybean and corn (Conab, 2019). The wide adoption of NT resulted from its ability to conserve and maximize soil environmental functions after a long period with high soil losses, as in the 1970s and 1980s (Lal et al., 2012; Williams et al., 2014). In that period, conventional tillage was responsible for high water erosion rates (Busscher et al., 1996; de Freitas and Landers, 2014).

Nonetheless, water and soil losses caused by runoff have been significant on catchment (Didoné et al., 2014, 2015) and hillslope (Deuschle et al., 2019; Londero et al., 2021) scales in southern Brazil, even after approximately 30 years of no-till consolidation. In a stormwater event, runoff will be conveyed according to the spatial variability of the topography (Berry, 2005), leading to erosion and sediment transfer to water bodies (Morgan, 2005). Furthermore, topography analysis can be useful to spatially soil moisture (Fraisse et al., 2001). The influence of topographic wetness index on the spatial variability of crop productivity and its high correlation with yield was evaluated by Marques and Silva (2008) and Schwalbert et al. (2019).

Complementary conservationist practices (e.g., terracing) are recommended for water management in no-till areas in Brazil (Merten et al., 2015; Deuschle et al., 2019) to reduce soil water losses by runoff. Runoff control structures such as water management methods aim to detain and infiltrate the runoff generated by rainfall that exceeds the soil infiltration capacity, and terraces may reduce runoff remarkably (Al Ali et al., 2008; Londero et al., 2017). These benefits are more noticeable in periods of abundant rainfall, and the infiltrated rainfall excess is turned into noticeable positive increases in available water to plants in the following periods of rainfall shortage (Freitas et al., 2021). However, the benefits of terracing on crop yield in no-tilled soils of Brazil have still not been investigated. Given this scenario, the main objective of this study was to evaluate if the saved rainfall excess in the catchment with terrace generates higher soybean and corn yield due to greater water availability in the crop rooting zone. We also investigated if terracing diminishes the spatial variability in soybean and corn yield, which is crucial to achieving crop yield stability over the years. The assumption is that the soil water availability is higher on terraced hillslopes determining their higher productivity. Although scarce, hydrological monitoring data

in no-tilled soils is relevant to assessing how terracing affects soil available water and influences crop yield.

## MATERIALS AND METHODS

This study was conducted in a region representative of the grain production system under NT to evaluate the influence of the presence and absence of terracing (Figure 1) on water availability and crop productivity. The study is part of a soil conservationist project to improve soil conservation practices, reduce water and soil losses, and maximize water availability.

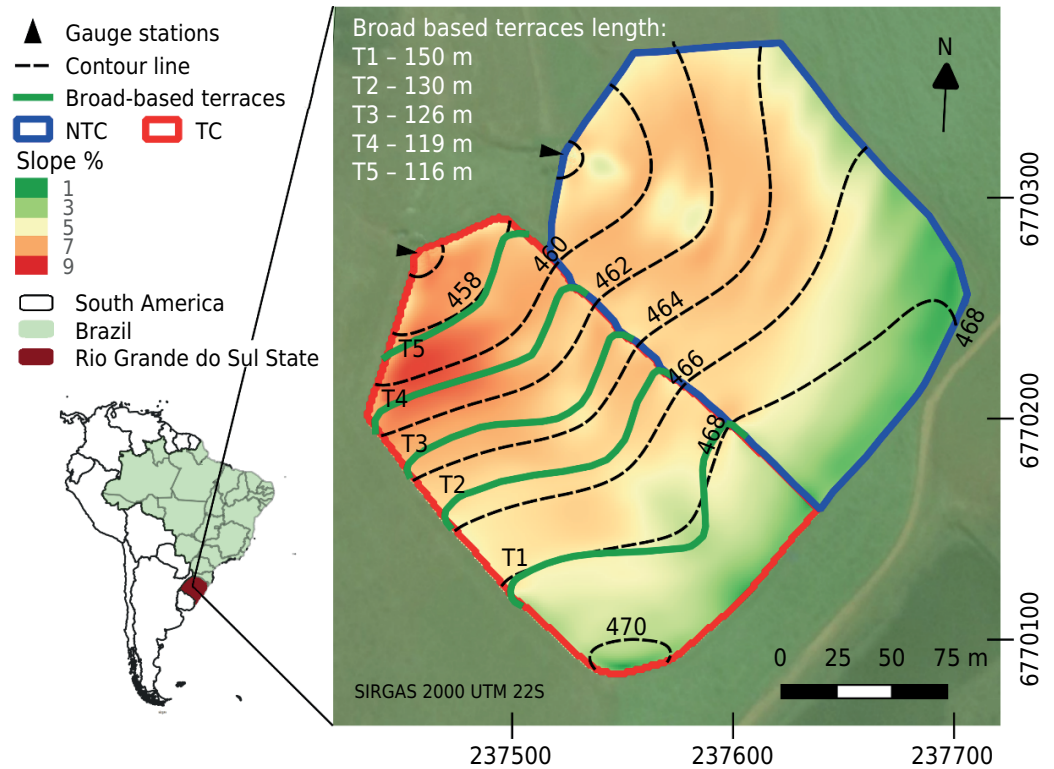
### Site description

The experiment was performed in two paired zero-order catchments, one without terracing (non-terraced catchment - NTC; 2.43 ha) and the other with terracing (terraced catchment - TC; 2.35 ha), located in Rio Grande do Sul State, which is the southernmost state of Brazil (29° 13' 39" S and 53° 40' 38" E) in the southern basaltic plateau at an elevation of 514 m a.s.l. (Figure 2). The relief is undulated with slopes varying between 5-13 %. The catchment contributing areas have similar soil and topography characteristics. The soil in both catchments is well-drained, deep, and has low natural fertility. The soil is classified as Rhodic Dystric Nitisol (WRB, 2014), and in the Brazilian System of Soil Classification, as *Nitossolo Vermelho Distrófico típico* (Santos et al., 2018). The climate is humid subtropical (Cfa) according to the Köppen classification system, with rainfall regularly distributed throughout the four seasons and an annual average of 1678 mm. The minimum and maximum precipitation over the period 1997 to 2018 were 1.161 and 2.541 mm, respectively. The annual average of the minimum and maximum air temperatures are 8.8 and 28.4 °C, respectively, with the maximum solar radiation being 21.0 MJ m<sup>-2</sup> day<sup>-1</sup> (Wrege et al., 2018).

No-tillage system without terrace has been the main soil tillage system in this region and the experimental area for the last 20 years. The main summer crops were soybean



**Figure 1.** Terraced catchment and effect of the terraces in controlling runoff after a stormwater event (07/20/2015) with rainfall volume of 65 mm and maximum 30-min intensity of 18 mm h<sup>-1</sup>.



**Figure 2.** Location and slope characterization of the non-terraced catchment (NTC) and terraced catchment (TC) in Rio Grande do Sul State, southern Brazil.

[*Glycine max* (L.) Merr.] and corn (*Zea mays* L.), while winter crops were wheat (*Triticum aestivum* L.) intercropped with black oat (*Avena strigosa* L.), throughout this period. The historical (1976 to 2016) average rainfall for the months when soybean (November to March) and corn (September to February) were grown is 670 and 920 mm, respectively. The total potential evapotranspiration in the soybean and corn cycles are approximately 837 and 570 mm, respectively (Matzenauer et al., 2002). The broad-based terrace was chosen because it is well accepted among farmers in southern Brazil and allows operations with agricultural machinery and cultivation on the soil. Terrace allocation was based on equation 1 of Lombardi Neto et al. (1994) to estimate vertical spacing between the terraces. Calculations were performed using Terraco for Windows 4.1<sup>®</sup> software (Griebeler et al., 2005).

$$VE = 0.4518 K S^{0.58} (u+m)/2 \quad \text{Eq. 1}$$

in which VE is the vertical spacing,  $K$  is the erodibility factor,  $S$  is the slope (%),  $u$  is the land-use factor, and  $m$  is the soil management factor.

A digital elevation model (DEM) was obtained from a field campaign with a high definition GPS-RTK (Java D model Triumph 1). A high-quality DEM was created with Qis 3.10 software using the IDW interpolation algorithm with a final spatial resolution of 1 m. The terraces were distributed and dimensioned according to the estimated runoff volume for a design rainfall of 110 mm based on a ten-year return period for 6 h of duration. The basic infiltration rate is measured in concentric rings in the order of 20 mm h<sup>-1</sup>. The terraces have ~2 m<sup>2</sup> cross-sectional areas that are ~0.50 m high. The terraces were built in level using a 3-disc plow. A 6 m wide strip of soil was mobilized to build five broad-based terraces. The vertical spacing between terraces was 2.7 m and horizontal spacing ranges between 30 and 40 m. The non-terraced catchment (NTC) and terraced catchment (TC) had similar organic matter and chemical soil properties, while soil physical properties were slightly different at the 0.00-0.10 m soil layer (Table 1).

## Crop implementation and yield measurement

Soybean cycle was monitored from November 2016 to March 2017, and the corn cycle from September 2017 to February 2018. During the 2016/17 agricultural year, soybean was sown on 11/7/2016 after black oat cultivation. The cultivar used was Nidera 5909RR, with a final population of 250,000 plants ha<sup>-1</sup>. In the 2017/18 agricultural year, corn sowing was carried out on 09/13/2017 after cultivating black oats intercropped with radish (*Raphanus sativus* L.). The corn plant population used was 70,000 plants ha<sup>-1</sup>. Both soybean cultivar and corn hybrid are the most commonly cultivated in southern Brazil. Other crop management techniques, including herbicide, insecticide, and fungicide application, followed the technical recommendations for each crop (Oliveira and Rosa, 2014).

Mineral fertilizer rates were adjusted to the expected production of 4 and 10 Mg ha<sup>-1</sup> for soybean and corn, respectively. For soybean, 40 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub> and 60 kg ha<sup>-1</sup> of K<sub>2</sub>O were applied to the sowing line. For corn, 21 kg ha<sup>-1</sup> of N, 105 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub>, and 70 kg ha<sup>-1</sup> of K<sub>2</sub>O were applied to the sowing line. Additionally, in the four- and eight-leaf collar stages (V4 and V8, respectively) of corn, broadcast N was split into two equal applications of 70 kg ha<sup>-1</sup> of N.

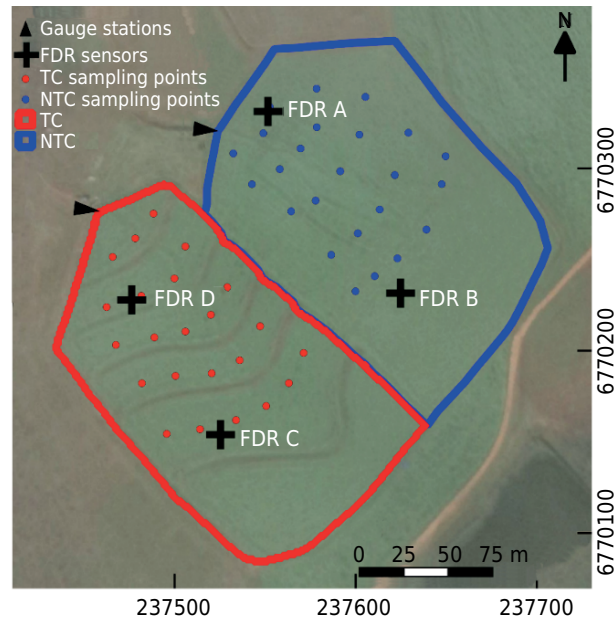
Crop grain yields were estimated by manually harvesting soybean and corn plants at 47 sampling points georeferenced and distributed in five lines at different elevations in the catchments (Figure 3). A 3-m<sup>2</sup> area was delimited for crop harvesting in each sampled location. The weight of the grains was adjusted to 13 % moisture. The water productivity was calculated from the crop production data and accumulated rainfall during the crop cycle in the experimental units by converting kg of grain per millimeters of rain. The method used to analyze water use efficiency is based on Rockström et al. (2009).

A productivity map was generated for the experimental units to evaluate the spatial variability of crop performance in both study units by the inverse square distance interpolation method. Minimum, maximum, standard deviation, mean, and median of

**Table 1.** Chemical and physical soil properties at 0.00-0.10 m soil layer in the agricultural year 2016/2017, for the non-terraced catchment (NTC) and terraced catchment (TC), in the Rio Grande do Sul state, south Brazil

Property	Catchment		p value
	NTC	TC	
pH(H <sub>2</sub> O)	5.7	5.7	0.04
P (mg dm <sup>-3</sup> )	25.7	21.7	0.03
K (mg dm <sup>-3</sup> )	138.5	147.4	0.02
CEC (cmol <sub>c</sub> kg <sup>-1</sup> )	11.3	11.6	0.06
Organic matter (g kg <sup>-1</sup> )	27	27	0.15
Coarse sand (g kg <sup>-1</sup> )	154	147	0.29
Fine sand (g kg <sup>-1</sup> )	228	205	0.03
Silt (g kg <sup>-1</sup> )	273	267	0.37
Clay (g kg <sup>-1</sup> )	348	380	0.04
Total porosity (m <sup>3</sup> m <sup>-3</sup> )	0.405	0.431	0.01
Macroporosity (m <sup>3</sup> m <sup>-3</sup> )	0.354	0.390	0.01
Microporosity (m <sup>3</sup> m <sup>-3</sup> )	0.073	0.061	0.01
Bulk density (Mg m <sup>-3</sup> )	1.6	1.5	0.10
K <sub>sat</sub> (mm h <sup>-1</sup> )	143	71	0.12

pH is the hydrogenic potential (at a soil:solution ratio of 1:1); P is the phosphorus content; K is the potassium content; CEC is the cation-exchange capacity; K<sub>sat</sub> is the saturated hydraulic conductivity; p-value is the result of the statistical analysis based on T-test distribution.



**Figure 3.** Sampling for crop grain yields and moisture monitoring points in the non-terraced catchment (NTC) and terraced catchment (TC) in Rio Grande do Sul State, southern Brazil.

the fraction of available water (FAW) were calculated with the R software (R Development Core Team, 2018) for each catchment. The Bayesian inference method (Kruschke, 2013) was used to analyze the differences in grain yield between both crops. The analysis considers the known yield thresholds for each crop and assesses the probability of a difference in each yield class.

### Soil moisture measurements

Soil moisture ( $\theta$ ;  $\text{cm}^3 \text{cm}^{-3}$ ) was measured every 24 h by frequency domain reflectometry sensors (CS616-L, Campbell Scientific, Logan, Utah, USA) in eight homogeneous layers from 0 to 1.50 m in four monitoring points (Figure 4) during the agricultural years 2016/17 (soybean) and 2017/18 (corn). A data logger (CR1000, Campbell Scientific, Logan, Utah) connected to the CS616 sensors recorded the  $\theta$  for 143 and 191 days (soybean and maize, respectively). The readings of  $\theta$  provided by the device were corrected with a calibration function ( $R^2 = 0.72$ ) generated with direct moisture measurements under different soil moisture conditions (Pereira, 2017). The  $\theta$  was used to calculate the FAW of plants (dimensionless) for each soil layer to evaluate the relationship between water availability dynamics and terrace and crop productivity.

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

in which  $AW_a$  is the actual available water ( $\text{cm}^3 \text{cm}^{-3}$ ) and  $AWC$  is the available water capacity ( $\text{cm}^3 \text{cm}^{-3}$ ) of a soil layer:

$$AW_a = (\theta - \theta_{pwp}) \quad \text{Eq. 3}$$

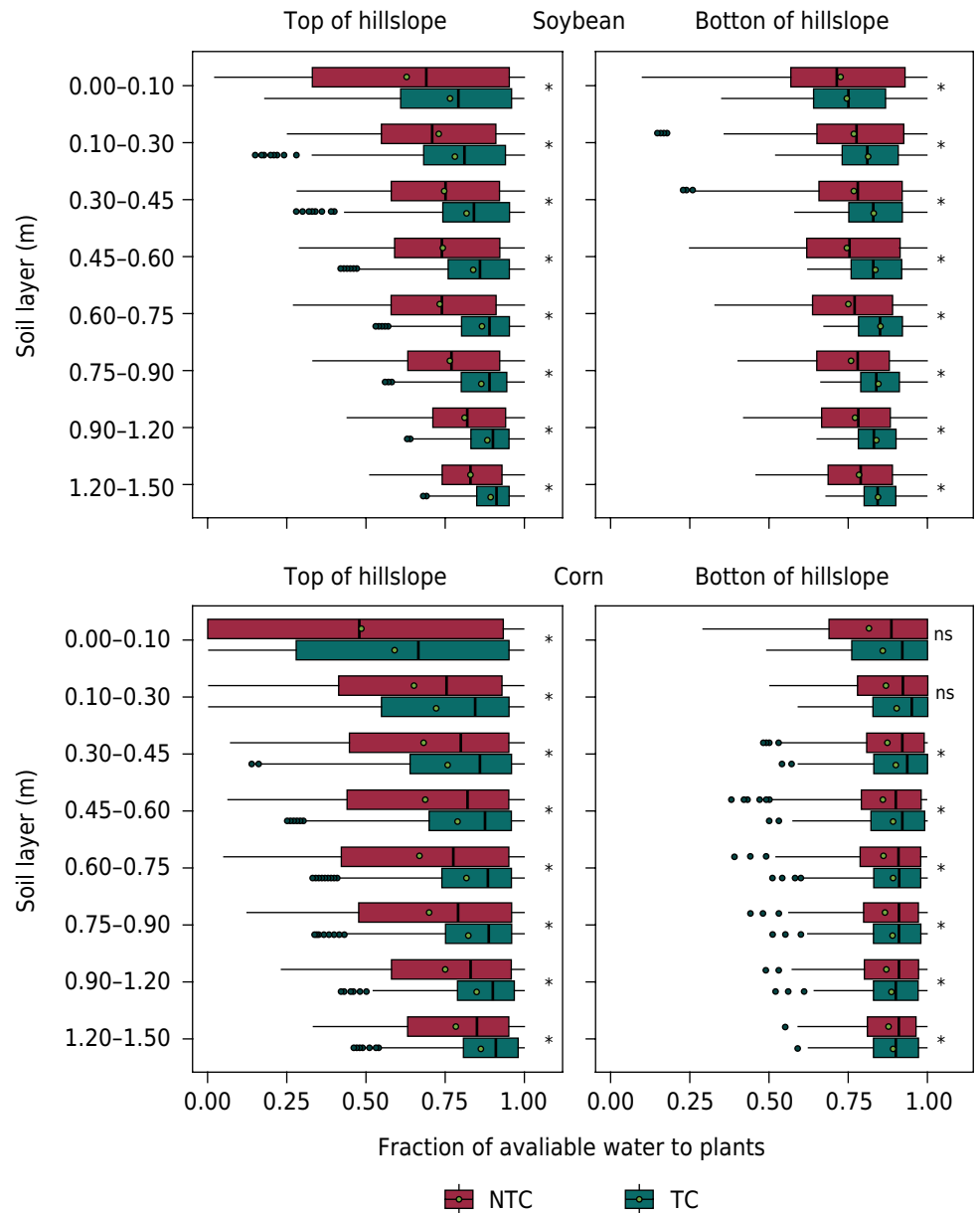
$$AWC = (\theta_{fc} - \theta_{pwp}) \quad \text{Eq. 4}$$

in which  $\theta$  is the current volumetric moisture ( $\text{cm}^3 \text{cm}^{-3}$ ),  $\theta_{pwp}$  is the permanent wilting point ( $\text{cm}^3 \text{cm}^{-3}$ ), and  $\theta_{fc}$  is the field capacity ( $\text{cm}^3 \text{cm}^{-3}$ ) of a soil layer. The  $\theta_{pwp}$  and  $\theta_{fc}$

were acquired from Pereira (2017), who determined  $\theta_{pwp}$  as the volumetric moisture at a matric potential of -15000 cm and  $\theta_{fc}$  as the volumetric moisture at a matric potential of -100 cm.

## RESULTS

The amplitude of FAW was greater towards the surface and higher on the NTC than on the TC (Figure 4). The range containing the second and third quartiles of FAW (horizontal bars) moved further away from the maximum FAW (FAW = 1) and extended further towards lower FAW at NTC points in corn and soybean cultivation. Conversely, the range containing the second and third FAW quartiles was closer to the maximum FAW (FAW = 1) and extended less towards lower FAW at the TC points. Using a FAW = 0.75 as a reference for comparison purposes, one notices a large proportion of FAW < 0.75 at NTC points and a large proportion of FAW > 0.75 at TC points. The water availability throughout the



**Figure 4.** The fraction of available water for plants (FAW) during the corn and soybean cycles in eight layers of the soil profile at the top and bottom position in the non-terraced catchment (NTC) and terraced catchment (TC) in Rio Grande do Sul State, southern Brazil.

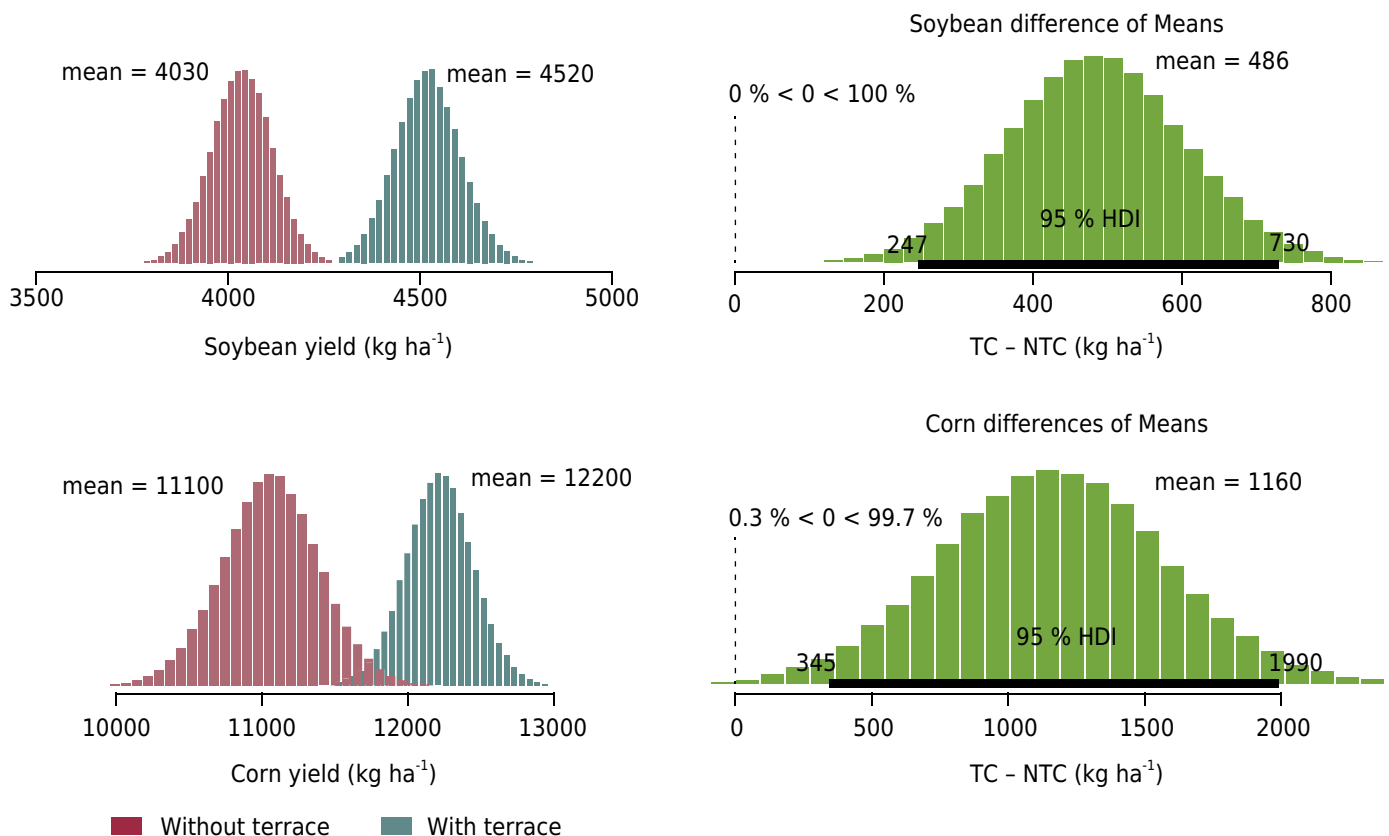
soybean and corn cycles was higher in the TC than in the NTC when comparing the FAW interquartile variability.

In addition to more significant interquartile variability, FAW minimums were lower in almost all soil layers in the NTC in the soybean and corn cycles, both showing lower water availability at the NTC. The FAW decreased with soil depth. However, considering the four monitoring points, this value is higher in the presence of terraces.

During the soybean cycle and considering the two measurement positions (top and bottom), the average FAW in the TC was 14 % higher than the NTC (Figure 4). Particularly for the two monitoring points located at the slope base, FAW in the TC was 20 % higher than the NTC. Nevertheless, FAW in the TC was 8 % higher than the NTC at the top of the slopes. During the corn crop cycle, the average FAW (considering both monitoring positions) of the TC was 7.8 % higher than the NTC FAW. When comparing the TC and NTC in both measurement sites, a 15 % difference in FAW for the TC and a 4 % difference in FAW for the TC were observed for sites at the bottom of the slope. The coefficient of variation (CV) of the FAW for the top and bottom was 1.5 and 1.4 times higher in the NTC and TC, respectively. In addition, this was even higher for corn, being the CV for NTC 1.4 and 1.7 times higher for the top and bottom, respectively, compared to the TC.

Terraces in no-till provided above-average soybean and corn yields (12 and 10 %, respectively; Figure 5). Soybean yields varied between 3.133 and 4.543 kg ha<sup>-1</sup> (CV = 9 %) in the NTC and between 3.920 and 5.739 kg ha<sup>-1</sup> (CV = 9 %) in the TC (Figure 5). Corn yields varied between 7.170 and 13.015 kg ha<sup>-1</sup> (CV = 14 %) in the NTC and between 10.665 and 14.345 kg ha<sup>-1</sup> (CV = 8 %) in the TC.

The water productivity for corn production was 9 and 10 kg ha<sup>-1</sup> mm<sup>-1</sup> in the NTC and TC, representing 11 % of difference in corn productivity. Even without rainfall restrictions,



**Figure 5.** Histogram of grain yield for soybean and corn in the non-terraced catchment (NTC) and terraced catchment (TC) in Rio Grande do Sul State, southern Brazil.

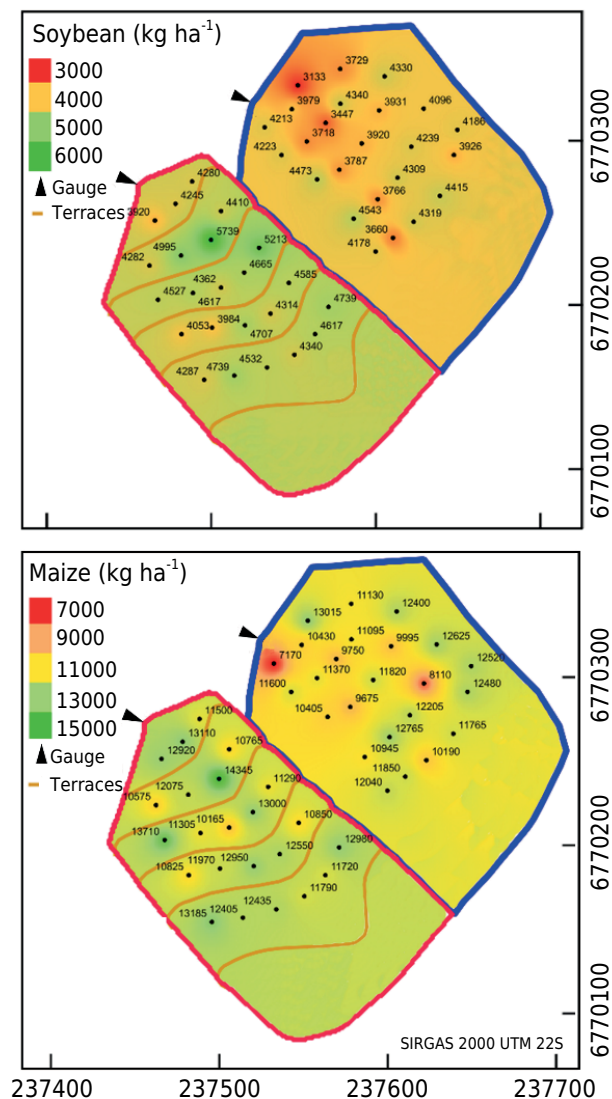


the improvement was substantial. The amount of rainfall recorded for the corn cycle from September to February (1222 mm) was higher than the total crop demand defined by Bergamaschi et al. (2006) (600 mm). The water productivity for soybean production was 7 and 8 kg ha<sup>-1</sup> mm<sup>-1</sup> for the NTC and TC, respectively, being 12 % higher. Different from the previous monitoring cycle, the amount of rainfall recorded (590 mm) from November to March was lower than the optimum limit for the total soybean demand (800 mm) defined by Matzenauer et al. (2003) and Zanon et al. (2016) in southern Brazil.

In the NTC, yield decreased from the top towards the bottom of the hillslope and with higher variation compared with TC (Figure 6). The yield map indicates that the positive effect of the terraces on increasing infiltration leads to higher crop yields. The terraces improved the water redistribution on the hillslope, thus increasing productivity (Figure 7).

## DISCUSSION

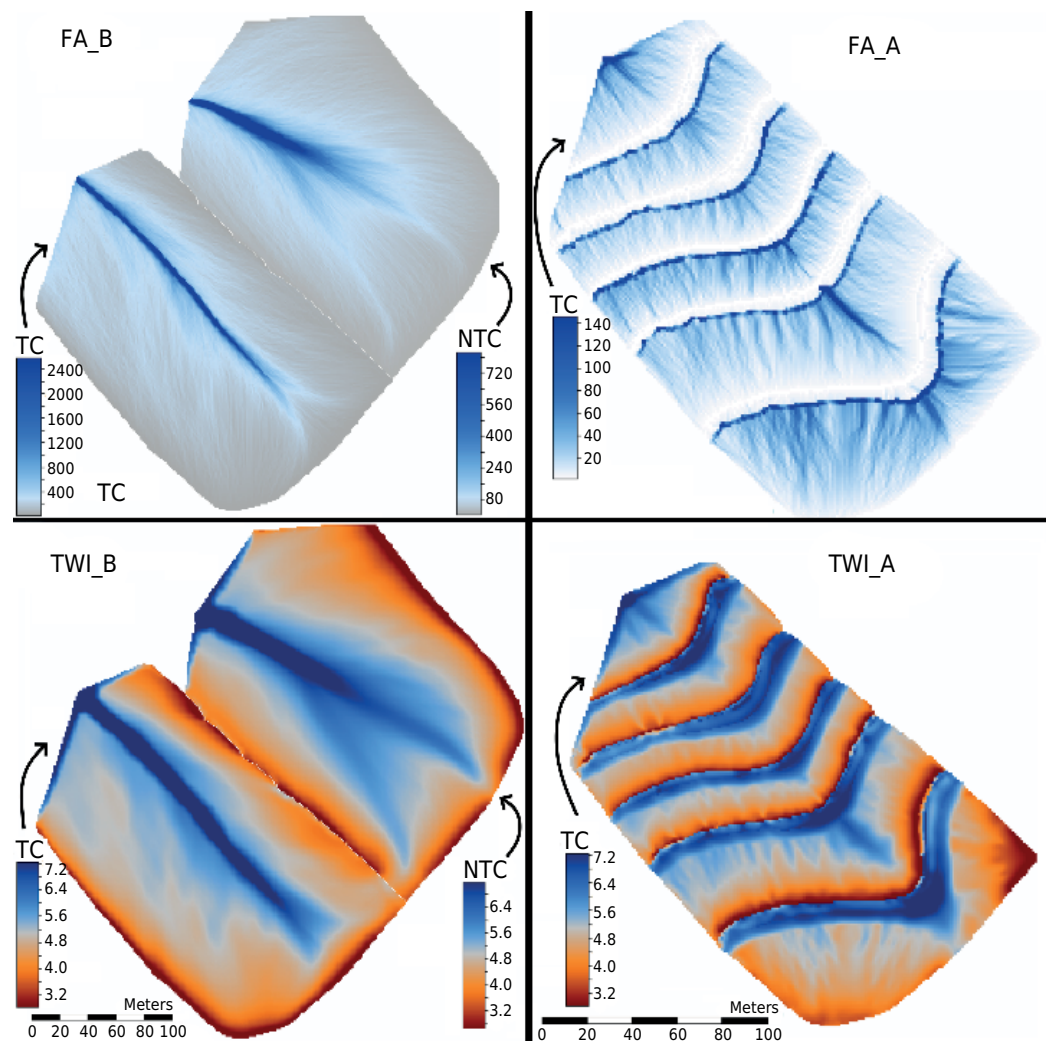
The higher crop yields in TC demonstrate the efficiency of the terraces as a strategy to mitigate water deficits and enhance their positive impacts on crop yield since their presence was associated with higher water availability and soybean and corn



**Figure 6.** Yield map of soybean and corn in the non-terraced catchment (NTC) and terraced catchment (TC) in Rio Grande do Sul State, southern Brazil.

productivity (Figures 4 and 6). There was only a rainfall deficit for soybean, which allowed us to observe a more significant water use efficiency in the terraced areas, as detailed below. Notably, the water deficit was indicated as one of the main factors responsible for productivity gaps in soybean in the order of  $800 \text{ kg ha}^{-1}$  in India (Bhatia et al., 2008),  $900 \text{ kg ha}^{-1}$  in the United States (Zhang et al., 2016),  $1260 \text{ kg ha}^{-1}$  in Argentina (Aramburu Merlos et al., 2015), and up to  $2500 \text{ kg ha}^{-1}$  in southern Brazil (Sentelhas et al., 2015). Regarding corn, there is evidence that water deficit caused productivity gaps of approximately  $4500 \text{ kg ha}^{-1}$  in Argentina (Aramburu Merlos et al., 2015) and  $3500 \text{ kg ha}^{-1}$  in Brazil (Affholder et al., 2013) and China (Liu et al., 2017). Furthermore, this study demonstrates that these productivity gaps can be significantly reduced using terraces, given that soybean and corn productivity increased by 490 and  $1100 \text{ kg ha}^{-1}$  in the TC, respectively (Figure 6). In addition, the yield gains in soybean and corn described herein are similar to the 20 % yield increase of wheat crops in terraced fields in Pakistan, where there was a 16 % increase in soil moisture (Rashid et al., 2016).

Changing soil management significantly affects the hydrological regime. Among the most critical processes, we can emphasize soil-water replenishment and runoff control (Rushton et al., 2006; Seyfried and Wilcox, 2006; Harman et al., 2011). However, the effects of rainwater management in highlands are poorly understood. Although terraces

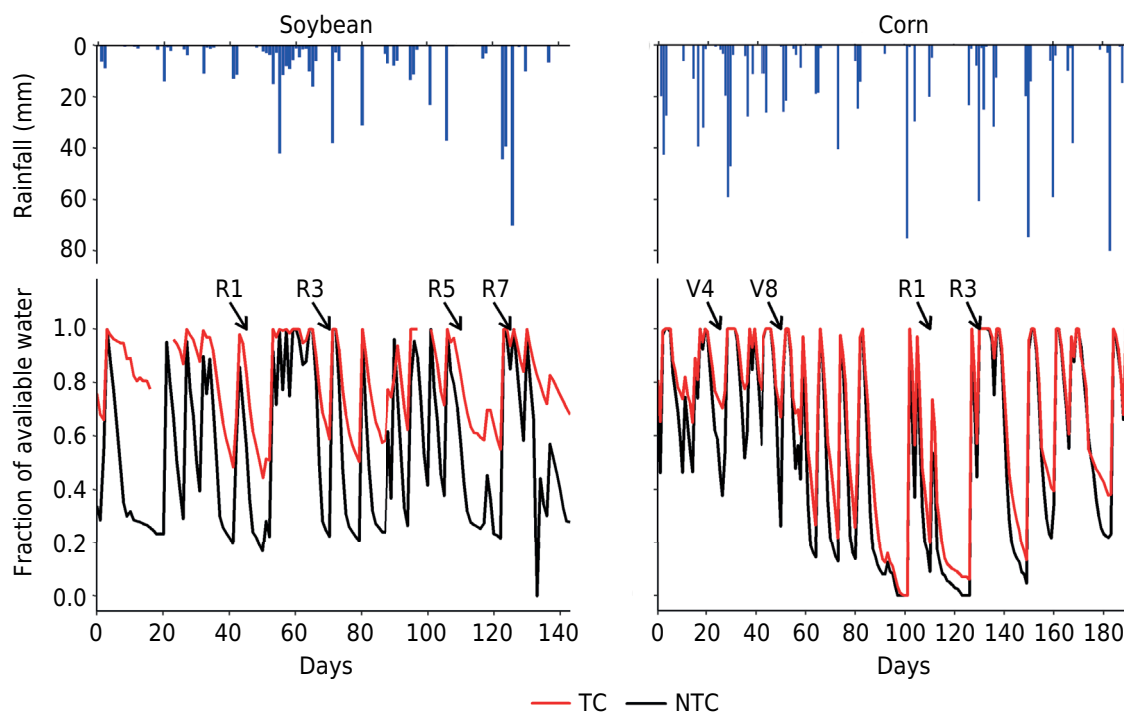


**Figure 7.** Flow accumulation area (FA) and topographic wetness index (TWI) for the non-terraced catchment (NTC) and terraced catchment (TC) before (B) and after (A) the construction of the terraces in the Rio Grande do Sul State, southern Brazil.

are a recognized method of reducing erosion problems by controlling runoff (Posthumus and De Graaff, 2005; Maetens et al., 2012; Miranda et al., 2012; Londero et al., 2021), there is still little research on the economic benefits of terracing. The combined effects of maximizing production with better use of rainwater and controlling soil degradation by erosion are essential to regulate runoff and significantly alter the hydrological dynamics of hillslopes in favor of farmers and society. Water productivity for corn in different regions of the world is on average of  $13 \text{ kg ha}^{-1} \text{ mm}^{-1}$ , whereas this yield can be increased by improving soil management (Rattalino Edreira et al., 2018) and can reach a value of  $28 \text{ kg ha}^{-1} \text{ mm}^{-1}$  (Grassini et al., 2009).

Water productivity results emphasize the importance of terraces to maintain plant productivity in years of low rainfall and severe droughts. Therefore, under reduced rainfall conditions (e.g., summer droughts), productivity differences are expected to be even more significant; or even under conditions of greater fragility in relation to water loss (e.g., greater slopes). At the top of the hillslope, where the slope is less steep, the direction of flow is predominantly vertical, favoring infiltration and greater water availability. At the base of the hillslope, the greater slope favors lateral flow direction with the formation of runoff. A similar pattern for corn as a function of the steeper hillslope was described by Leuthold et al. (2021). The influence of climate and management factors on the yield potential of soybean crops in a subtropical region was evaluated, and the results evidenced that the attainable water productivity was  $9.1 \text{ kg grain ha}^{-1} \text{ mm}^{-1}$ , which is close to the  $9.9 \text{ kg ha}^{-1} \text{ mm}^{-1}$  obtained by Grassini et al. (2015) in the USA (Zanon et al., 2016).

Terraces in no-till provided more efficient rainwater use by plants, which is positively related to FAW during the crop growth cycle (Figure 5). In this way, differences in efficiency in using rainwater were in the order of 135 mm for corn and 76 mm for soybean. The terraces reduced the CV of the FAW, as it conditions a more constant flow of water to the lower layers and decreases their fluctuation in the different soil layers to be lower in the terraced area. Figure 8 illustrates the variation of FAW at the 0.00-0.30 m soil layer in response to the rainfall regime. The highest FAW in the TC study unit occurs at important phenological stages, affecting the production components of the crops and increasing crop productivity in the TC.



**Figure 8.** Rainfall and fraction of available water in the rooting zone (0.00-0.30 m) during the corn and soybean cycles.

Until now, the leading management strategies to reduce the soybean yield gap in Brazil are related to improvements in chemical and physical quality to form a deeper soil profile (Battisti et al., 2018). Liang et al. (2019) highlight that terracing increases water availability in the soil to improve productivity during dry periods. The drought effects in South America, which are primarily a result of the La Niña phenomenon (ENSO), has a substantial economic impact on a society that is highly dependent on the production of summer grains, including soybean and corn (Aramburu Merlos et al., 2015; Sentelhas et al., 2015). Droughts in southern Brazil generally occur between December and February and strongly affect agricultural production (Matzenauer et al., 2003). The period of more frequent droughts is from October to December in southwestern Brazil, coinciding with the growth period of the main crops in the region (Pereira et al., 2018).

Crops yield is related to a complex combination of factors (Shemdoe et al., 2009). The water productivity can also be influenced by the proportion of water lost through runoff if this fraction would be necessary to allow plenty of plant growth and production. During the two-season period, Londero et al. (2017) determined runoff in both catchments. There was an accumulated rainfall of 550 mm and no runoff formation during the soybean cycle in both TC and NTC. It is important to emphasize that during this period there were no rainfall events of high magnitude and intensity with the capacity to generate runoff, even at NTC. In this case, it is assumed that the terraces provided a larger crop yield due to the better redistribution of moisture over time and space. There was an accumulated rainfall of 1222 mm for corn, although 70 mm were lost by runoff in the NTC and only 27 mm in the TC (a difference of 43 mm). Although rainfall was abundant, corn yield was even higher in the TC (Figure 6), where terraces controlled runoff. This indicates that even in a year without rainfall deficits, the crop productivity was higher in the catchment with terrace. Furthermore, as the roughness promoted by the higher phytomass accumulation in no-till is not enough to control runoff, especially in stormwater events (Deuschle et al., 2018), terraces are essential to maximize infiltration and prevent runoff from causing erosion and water resource contamination. The water availability controlled by the management system adopted is essential to improve conservationist agriculture and its adoption by farmers. As demonstrated in figure 6, terracing in no-till can act as a key strategy for water redistribution and reduce the spatial variability of yield imposed by the hillslope.

## CONCLUSIONS

Soil water availability and crop yields were higher in the catchment with terrace. Terracing in no-till provided higher corn and soybean productivity by 10 and 12 %, respectively, thus demonstrating the efficiency of the terraces as a strategy to mitigate crop water deficits by managing runoff.




## ACKNOWLEDGMENTS


Projeto FINEP nº 2165/09 “Sistemas Agrícolas Produtivos Visando ao Aumento da Disponibilidade e à Melhoria da Qualidade da Água” and CNPq (National Council of Scientific and Technologic Development). Finance codes: 437523/2018-7 (PQ) and 420617/2017-5 (PDJ).







## AUTHOR CONTRIBUTIONS




**Conceptualization:**  Jean Paolo Gomes Minella (lead).


**Data curation:**  Jean Paolo Gomes Minella (lead).


**Formal analysis:**  Alexandre Schlesner (equal),  Paulo Ivonir Gubiani (equal) and  Tiago Hörbe (equal).


**Funding acquisition:**  Jean Paolo Gomes Minella (equal).



**Investigation:**  Ana Lúcia Londero (equal),  Fabio Jose Andres Schneider (equal),  Gustavo Henrique Merten (equal),  Jean Paolo Gomes Minella (equal),  Paulo Ivonir Gubiani (equal) and  Tiago Hörbe (equal).




**Methodology:**  Jean Paolo Gomes Minella (equal),  Paulo Ivonir Gubiani (equal) and  Tiago Hörbe (equal).






**Project administration:**  Jean Paolo Gomes Minella (equal).

**Software:**  Alexandre Schlesner (lead).

**Supervision:**  Jean Paolo Gomes Minella (equal).

**Visualization:**  Gustavo Henrique Merten (equal) and  Paulo Ivonir Gubiani (equal).

**Writing - original draft:**  Fabio Jose Andres Schneider (equal),  Jean Paolo Gomes Minella (equal) and  Tiago Hörbe (equal).

**Writing - review & editing:**  Alexandre Schlesner (equal),  Ana Lúcia Londero (equal),  Gustavo Henrique Merten (equal),  Jean Paolo Gomes Minella (equal) and  Paulo Ivonir Gubiani (equal).

## REFERENCES

- Affholder F, Poeydebat C, Corbeels M, Scopel E, Tittonell P. The yield gap of major food crops in family agriculture in the tropics: Assessment and analysis through field surveys and modelling. *Field Crop Res.* 2013;143:106-18. <https://doi.org/10.1016/j.fcr.2012.10.021>
- Al Ali Y, Touma J, Zante P, Nasri S, Albergel J. Water and sediment balances of a contour bench terracing system in a semi-arid cultivated zone (El Gouazine, central Tunisia). *Hydrolog Sci J.* 2008;53:883-92. <https://doi.org/10.1623/hysj.53.4.883>
- Alexandratos N, Bruinsma J. World agriculture towards 2030/2050: the 2012 revision. Rome: Food and Agriculture Organization of the United Nations (FAO); 2012. <https://doi.org/10.22004/ag.econ.288998>
- Aramburu Merlos F, Monzon JP, Mercau JL, Taboada M, Andrade FH, Hall AJ, Jobbagy E, Cassman KG, Grassini P. Potential for crop production increase in Argentina through closure of existing yield gaps. *Field Crop Res.* 2015;184:145-54. <https://doi.org/10.1016/j.fcr.2015.10.001>
- Battisti R, Sentelhas PC, Sako H, Shiozaki EA. Incremento de produtividade da soja: Redução do déficit hídrico associado à melhor distribuição e profundidade do sistema radicular. Sorocaba: Comitê Estratégico Soja Brasil (CESB); 2016. (Circular técnica, 1).
- Battisti R, Pascoalino JAL, Sako H. Soybean yield gap in the areas of yield contest in Brazil. *Int J Plant Prod.* 2018;12:159-68. <https://doi.org/10.1007/s42106-018-0016-0>
- Bergamaschi H, Dalmago GA, Comiran F, Bergonci JI, Müller AG, França S, Santos AO, Radin B, Bianchi CAM, Pereira PG. Deficit hídrico e produtividade na cultura do milho. *Pesq Agropec Bras.* 2006;41:243-9. <https://doi.org/10.1590/s0100-204x2006000200008>
- Berry JW. Acculturation: Living successfully in two cultures. *Int J Intercult Rel.* 2005;29:697-712. <https://doi.org/10.1016/j.ijintrel.2005.07.013>
- Bhatia VS, Singh P, Wani SP, Chauhan GS, Rao AVRK, Mishra AK, Srinivas K. Analysis of potential yields and yield gaps of rainfed soybean in India using CROPGRO-Soybean model. *Agr Forest Meteorol.* 2008;148:1252-65. <https://doi.org/10.1016/j.agrformet.2008.03.004>

- Bossio D, Geheb K, Critchley W. Managing water by managing land: Addressing land degradation to improve water productivity and rural livelihoods. *Agr Water Manage.* 2010;97:536-42. <https://doi.org/10.1016/j.agwat.2008.12.001>
- Busscher WJ, Reeves DW, Kochhann RA, Bauer PJ, Mullins GL, Clapham WM, Kemper WD, Galerani PR. Conservation farming in southern Brazil: using cover crops to decrease erosion and increase infiltration. *J Soil Water Conserv.* 1996;51:188-92.
- Companhia Nacional de Abastecimento - Conab. Acompanhamento da safra brasileira 2019/2020 - Segundo Levantamento. Brasília: Conab; 2009. (Boletim grãos novembro 2019 - resumo).
- de Fraiture C, Wichelns D, Rockström J, Kemp-Benedict E, Eriyagama N, Gordon LJ, Hanjra MA, Hoogeveen J, Huber-Lee A, Karlberg L. Looking ahead to 2050: Scenarios of alternative investment approaches. In: Molden D, editor. *Water for food water for life: A comprehensive assessment of water management in agriculture.* London: Earthscan; 2007. p. 91-145. <https://doi.org/10.4324/9781849773799>
- de Freitas PL, Landers JN. The Transformation of agriculture in Brazil through development and adoption of zero tillage conservation agriculture. *Int Soil Water Conserv Res.* 2014;2:35-46. [https://doi.org/10.1016/S2095-6339\(15\)30012-5](https://doi.org/10.1016/S2095-6339(15)30012-5)
- Derpsch R, Franzluebbbers AJ, Duiker SW, Reicosky DC, Koeller K, Friedrich T, Sturny WG, Weiss K. Why do we need to standardize no-tillage research? *Soil Till Res.* 2014;137:16-22. <https://doi.org/10.1016/j.still.2013.10.002>
- Deuschle D, Minella JPG, Hörbe T, Londero AL, Schneider FJA. Erosion and hydrological response in no-tillage subjected to crop rotation intensification in southern Brazil. *Geoderma.* 2019;340:157-63. <https://doi.org/10.1016/j.geoderma.2019.01.010>
- Didoné EJ, Minella JPG, Merten GH. Quantifying soil erosion and sediment yield in a catchment in southern Brazil and implications for land conservation. *J Soils Sediments.* 2015;15:2334-46. <https://doi.org/10.1007/s11368-015-1160-0>
- Didoné EJ, Minella JPG, Reichert JM, Merten GH, Dalbianco L, de Barros CAP, Ramon R. Impact of no-tillage agricultural systems on sediment yield in two large catchments in Southern Brazil. *J Soil Sediment.* 2014;14:1287-97. <https://doi.org/10.1007/s11368-013-0844-6>
- Evans RG, Sadler EJ. Methods and technologies to improve efficiency of water use. *Water Resour Res.* 2008;44:W00E04. <https://doi.org/10.1029/2007WR006200>
- Fisher M, Abate T, Lunduka RW, Asnake W, Alemayehu Y, Madulu RB. Drought tolerant maize for farmer adaptation to drought in sub-Saharan Africa: Determinants of adoption in eastern and southern Africa. *Climatic Change.* 2015;133:283-99. <https://doi.org/10.1007/s10584-015-1459-2>
- Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockström J, Sheehan J, Siebert S, Tilman D, Zaks DPM. Solutions for a cultivated planet. *Nature.* 2011;478:337-42. <https://doi.org/10.1038/nature10452>
- Fraisse CW, Sudduth KA, Kitchen NR. Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity. *T ASAE.* 2001;44:155-66. <https://doi.org/10.13031/2013.2296>
- Freitas LR, Gubiani PI, Mulazzani RP, Minella JPG, Londero AL. Terracing increases soil available water to plants in no-tillage. *Rev Bras Cienc Solo.* 2021;45:e0210046. <https://doi.org/10.36783/18069657rbcs20210046>
- Fuentes-Llanillo R, Telles TS, Soares Junior D, Melo TD, Friedrich T, Kassam A. Expansion of no-tillage practice in conservation agriculture in Brazil. *Soil Till Res.* 2021;208:e104877. <https://doi.org/10.1016/j.still.2020.104877>
- Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C. Food Security: The challenge of feeding 9 billion people. *Science.* 2010;327:812-8. <https://doi.org/10.1126/science.1185383>

- Grassini P, Hall AJ, Mercuro JL. Benchmarking sunflower water productivity in semiarid environments. *Field Crop Res.* 2009;110:251-62. <https://doi.org/10.1016/j.fcr.2008.09.006>
- Grassini P, Torrion JA, Yang HS, Rees J, Andersen D, Cassman KG, Specht JE. Soybean yield gaps and water productivity in the western U.S. Corn Belt. *Field Crop Res.* 2015;179:150-63. <https://doi.org/10.1016/j.fcr.2015.04.015>
- Griebeler NP, Pruski FF, Teixeira AF, Oliveira LFC. Software para o planejamento e a racionalização do uso e sistemas de terraceamento em nível. *Engen Agric.* 2005;25:841-51. <https://doi.org/10.1590/S0100-69162005000300031>
- Guilpart N, Grassini P, Sadras VO, Timsina J, Cassman KG. Estimating yield gaps at the cropping system level. *Field Crop Res.* 2017;206:21-32. <https://doi.org/10.1016/j.fcr.2017.02.008>
- Harman CJ, Rao PSC, Basu NB, McGrath GS, Kumar P, Sivapalan M. Climate, soil, and vegetation controls on the temporal variability of vadose zone transport. *Water Resour Res.* 2011;47:W00J13. <https://doi.org/10.1029/2010WR010194>
- IUSS Working Group WRB. World reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. Rome: Food and Agriculture Organization of the United Nations; 2015. (World Soil Resources Reports, 106).
- Kruschke JK. Bayesian estimation supersedes the t test. *J Exp Psychol Gen.* 2013;142:573-603. <https://doi.org/10.1037/a0029146>
- Lal R, Delgado JA, Gulliford J, Nielsen D, Rice CW, Scott Van Pelt R. Adapting agriculture to drought and extreme events. *J Soil Water Conserv.* 2012;67:162-6. <https://doi.org/10.2489/jswc.67.6.162A>
- Leuthold SJ. Understanding the effects of complex topography on cover crop dynamics and maize production in kentucky agroecosystems [thesis]. Lexington: University of Kentucky; 2021.
- Liang K, Qi J, Liu EY, Jiang Y, Li S, Meng FR. Estimated potential impacts of soil and water conservation terraces on potato yields under different climate conditions. *J Soil Water Conserv.* 2019;74:225-34. <https://doi.org/10.2489/jswc.74.3.225>
- Liu B, Chen X, Meng Q, Yang H, van Wart J. Estimating maize yield potential and yield gap with agro-climatic zones in China-Distinguish irrigated and rainfed conditions. *Agr Forest Meteorol.* 2017;239:108-17. <https://doi.org/10.1016/j.agrformet.2017.02.035>
- Lombardi Neto F, Belinazzi Junior R, Lepsch IF, Oliveira JB, Bertolini D, Galetti PA, Drugowich MI. Terraceamento agrícola. Campinas: Secretaria da Agricultura e Abastecimento do Estado de São Paulo; 1994.
- Londero AL, Minella JPG, Deuschle D, Schneider FJA, Boeni M, Merten GH. Impact of broad-based terraces on water and sediment losses in no-till (paired zero-order) catchments in southern Brazil. *J Soils Sediments.* 2017;18:1159-75. <https://doi.org/10.1007/s11368-017-1894-y>
- Londero AL, Minella JPG, Schneider FJA, Deuschle D, Menezes D, Evrard O, Boeni M, Merten GH. Quantifying the impact of no-till on runoff in southern Brazil at hillslope and catchment scales. *Hydrol Process.* 2021;35:e14094. <https://doi.org/10.1002/hyp.14094>
- Maetens W, Poesen J, Vanmaercke M. How effective are soil conservation techniques in reducing plot runoff and soil loss in Europe and the Mediterranean? *Earth-Sci Rev.* 2012;115:21-36. <https://doi.org/10.1016/j.earscirev.2012.08.003>
- Matzenauer R, Bergamaschi H, Berlato MA, Maluf JRT, Barni NA, Bueno AC, Didoné IA, Anjos CS, Machado FA, Sampaio MR. Consumo de água e disponibilidade hídrica para milho e soja no Rio Grande do Sul. Porto Alegre: FEPAGRO; 2002. (Boletim FEPAGRO, 10).
- Matzenauer R, Barni NA, Maluf JRT. Estimativa do consumo relativo de água para a cultura da soja no estado do Rio Grande do Sul. *Cienc Rural.* 2003;33:1013-9. <https://doi.org/10.1590/s0103-84782003000600004>
- McNeill K, Macdonald K, Singh A, Binns AD. Food and water security: Analysis of integrated modeling platforms. *Agr Water Manage.* 2017;194:100-12. <https://doi.org/10.1016/j.agwat.2017.09.001>

- Merten GH, Araújo AG, Biscaia RCM, Barbosa GMC, Conte O. No-till surface runoff and soil losses in southern Brazil. *Soil Till Res.* 2015;152:85-93. <https://doi.org/10.1016/j.still.2015.03.014>
- Miranda ACR, Silva DP, Mello EL, Pruski FF. Assessment of efficiency and adequacy of retention terraces. *Rev Bras Cienc Solo.* 2012;36:577-86. <https://doi.org/10.1590/s0100-06832012000200027>
- Morgan RPC. *Soil erosion and conservation*. 3rd ed. Oxford: Blackwell Publishing; 2005.
- Oliveira ADB, Rosa APSA. indicações técnicas para a cultura da soja no Rio Grande do Sul e em Santa Catarina, safras 2014/2015 e 2015/2016. Pelotas: Embrapa Clima Temperado; 2014.
- Pereira CA. Adaptações na teoria de Green-Ampt para modelar a infiltração de água no solo [dissertação]. Santa Maria: Universidade Federal de Santa Maria; 2017.
- Pereira VR, Blain GC, Avila AMH, Pires RCM, Pinto HS. Impacts of climate change on drought: Changes to drier conditions at the beginning of the crop growing season in southern Brazil. *Bragantia.* 2018;77:201-11. <https://doi.org/10.1590/1678-4499.2017007>
- Pfister S, Bayer P, Koehler A, Hellweg S. Projected water consumption in future global agriculture: Scenarios and related impacts. *Sci Total Environ.* 2011;409:4206-16. <https://doi.org/10.1016/j.scitotenv.2011.07.019>
- Posthumus H, De Graaff J. Cost-benefit analysis of bench terraces, a case study in Peru. *Land Degrad Dev.* 2005;16:1-11. <https://doi.org/10.1002/ldr.637>
- R Development Core Team. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Vienna, Austria; 2018. Available online at <https://www.R-project.org/>.
- Rashid M, Rehman OU, Alvi S, Kausar R, Akram MI. The effectiveness of soil and water conservation terrace structures for improvement of crops and soil productivity in rainfed terraced system. *Pak J Agr Sci.* 2016;53:241-8. <https://doi.org/10.21162/PAKJAS/16.1502>
- Rattalino Edreira JI, Guilpart N, Sadras V, Cassman KG, van Ittersum MK, Schils RLM, Grassini P. Water productivity of rainfed maize and wheat: A local to global perspective. *Agr Forest Meteorol.* 2018;259:364-73. <https://doi.org/10.1016/j.agrformet.2018.05.019>
- Reichert JM, Albuquerque JA, Kaiser DR, Reinert DJ, Urach FL, Carlesso R. Estimation of water retention and availability in soils of Rio Grande do Sul. *Rev Bras Cienc Solo.* 2009;33:1547-60. <https://doi.org/10.1590/s0100-06832009000600004>
- Rockström J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D. Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resour Res.* 2009;45:W00A12. <https://doi.org/10.1029/2007WR006767>
- Rockström J, Karlberg L, Wani SP, Barron J, Hatibu N, Oweis T, Bruggeman A, Farahani J, Qiang Z. Managing water in rainfed agriculture - The need for a paradigm shift. *Agr Water Manage.* 2010;97:543-50. <https://doi.org/10.1016/j.agwat.2009.09.009>
- Rushton KR, Eilers VHM, Carter RC. Improved soil moisture balance methodology for recharge estimation. *J Hydrol.* 2006;318:379-99. <https://doi.org/10.1016/j.jhydrol.2005.06.022>
- Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumberras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. *Sistema brasileiro de classificação de solos*. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.
- Schwalbert RA, Amado TJC, Reimche GB, Gebert F. Fine-tuning of wheat (*Triticum aestivum*, L.) variable nitrogen rate by combining crop sensing and management zones approaches in southern Brazil. *Precis Agric.* 2019;20:56-77. <https://doi.org/10.1007/s11119-018-9581-6>
- Sentelhas PC, Battisti R, Câmara GMS, Farias JRB, Hampf AC, Nendel C. The soybean yield gap in Brazil - Magnitude, causes and possible solutions for sustainable production. *J Agr Sci-Cambridge.* 2015;153:1394-411. <https://doi.org/10.1017/S0021859615000313>
- Seyfried MS, Wilcox BP. Soil water storage and rooting depth: key factors controlling recharge on rangelands. *Hydrol Process.* 2006;20:3261-75. <https://doi.org/10.1002/hyp.6331>



- Shemdoe RS, Kikula IS, van Damme P, Cornelis WM. Tillage practices and their impacts on soil fertility in farmers' fields in semi-arid central Tanzania. *Arid Land Res Manag.* 2009;23:168-81. <https://doi.org/10.1080/15324980902817121>
- Silva JRM, Silva LL. Evaluation of the relationship between maize yield spatial and temporal variability and different topographic attributes. *Biosyst Eng.* 2008;101:183-90. <https://doi.org/10.1016/j.biosystemseng.2008.07.003>
- Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. *P Natl Acad Sci USA.* 2011;108:20260-4. <https://doi.org/10.1073/pnas.1116437108>
- Van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z. Yield gap analysis with local to global relevance-A review. *Field Crop Res.* 2013;143:4-17. <https://doi.org/10.1016/j.fcr.2012.09.009>
- Williams JD, Wuest SB, Long DS. Soil and water conservation in the Pacific Northwest through no - tillage and intensified crop rotations. *J Soil Water Conserv.* 2014;69:495-504. <https://doi.org/10.2489/jswc.69.6.495>
- Wrege MS, Steinmetz S, Matzenauer R, Radin B, Almeida IR, Reisser Júnior C, Maluf JRT, Bueno AC, Pasinato A, Cunha GR, Prestes SD, Dalmago GA, Pires JLF, Santi A, Berlato MA, Didoné IA. Atlas climático Rio Grande do Sul. Porto Alegre: Fepagro; 2018.
- Zanon AJ, Streck NA, Grassini P. Climate and management factors influence soybean yield potential in a subtropical environment. *Agron J.* 2016;108:1447-54. <https://doi.org/10.2134/agronj2015.0535>
- Zhang W, Cao G, Li X, Zhang H, Wang C, Liu Q, Chen X, Cui Z, Shen J, Jiang R, Mi G, Miao Y, Zhang F, Dou Z. Closing yield gaps in China by empowering smallholder farmers. *Nature.* 2016;537:671-4. <https://doi.org/10.1038/nature19368>