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RESEARCH ARTICLE

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Mixture of winter cover crops reduces surface runoff and sediment production under no-tillage system for Oxisols

Miguel D. Fuentes-Guevara[1] | Jhonatan Spliethoff[1] | Edson L. Camilo[1] | Ernani Garcia Neto[1] | Chaiane Olanik[1] | Amanda Alves Pacheco[1] | Rodrigo Ferreira[2] | Leandro Rampim[1] | Marcelo M. L. Müller[1] | Cristiano A. Pott[1]

[1]Department of Agronomy, Universidade Estadual do Centro-Oeste (UNICENTRO), Guarapuava, Brazil
[2]Fundação Agrária de Pesquisa Agropecuária - FAPA, Entre Rios, Brazil

Correspondence
Miguel D. Fuentes-Guevara, Department of Agronomy, Universidade Estadual do Centro-Oeste (UNICENTRO), Guarapuava, Paraná 85040-167, Brazil.
Email: mdavidfuentes@gmail.com

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Abstract

One of Brazil's efficient soil and water conservation practices is the no-tillage system (NTS). Nonetheless, erosion during rainfall still causes soil and water losses in this system. Therefore, this study aimed to assess surface runoff in different cultivation systems and sediment production during rainfall events. In macro-plot 1 (non-terraced catchment [NTC]), we adopted the NTS management with up- and down-slope farming without including mechanical runoff control practices, which most regional producers use. In macro-plot 2 (best management practices [BMPs]), we optimized crop rotation by incorporating a mixture of cover crop species in autumn and implemented contour farming practices. In macroplot 3 (terraced catchment [TC]), we adopted the same soil management practices as the NTC macroplot, including mechanical runoff control using broad-based terraces. We used rainfall data to create hyetographs, hydrographs, and sedimentographs, aiming to evaluate the impact of management practices on surface runoff and sediment production. The surface runoff was reduced by 81% (BMPs) and 88% (TC) compared to the NTC system. There was also a reduction in suspended sediment concentration, around 33% (BMPs) and 63% (TC), compared to the NTC system. Despite conservation systems have shown effectiveness in reducing surface runoff and sediment production, monitoring these systems during periods not influenced by the La Niña phenomenon is necessary to assess the impact of rainfall events on soils with conservation practices in extreme events. The study findings provide guidance and recommendations for agricultural producers and field technicians globally, offering criteria for selecting optimal soil and water management practices in no-till systems. This promotes a conservation-oriented approach to agriculture.

KEYWORDS
crop rotation, runoff coefficient, soil conservation, soil loss, terraces, water loss

1 | INTRODUCTION

In recent years, the use of the no-tillage system (NTS) has increased in the United States, several South American and European countries, Southeast Asia, and Sub-Saharan Africa, where intensive agriculture is prevalent (Barreto et al., 2022; Silva et al., 2024; Wingeyer et al., 2015). The NTS involves complexes of technological processes aimed at exploiting productive agricultural systems. These processes involve soil mobilization exclusively within the planting row, continuous maintenance of soil cover, species diversification, and minimization or elimination of the time gap between harvesting and seeding (Derpsch et al., 2014; FAO, 2013; Phillips & Young, 1973). The main objective of this system was to reduce soil erosion, making it a conservation system that contributes to soil and water conservation (Kassam et al., 2018; Veresoglou et al., 2022). However, less attention has been given to the effect of this system on surface runoff (Barreto et al., 2022). Some studies have documented reduced runoff under NT attributed to increased crop residues and effective management practices (Blanco-Canqui & Lal, 2009; Thierfelder & Wall, 2009). In the same sense, in a study conducted on commercial farms in Argentina, a soybean (*Glycine max* (L.) Merr.)–corn (*Zea mays* L.)–wheat rotation on loamy soils with a 5% slope, researchers observed an 84% reduction in runoff under NTS. This reduction was, however, reached statistically significant only when the soil area covered with crop residue exceeded 80% (Crespo et al., 2010).

Implementing the NTS in the 1970s was one of the most significant advancements in Brazilian agriculture (Didoné et al., 2019; Fuentes-Llanillo et al., 2021; Kassam et al., 2018; Londero et al., 2021). From the 1990s, the NTS was adopted on a large scale in Brazil, experiencing exponential growth and causing a conservationist revolution in southern Brazilian agriculture (Bertol et al., 2004; Denardin et al., 2008; Didoné et al., 2019; Friedrich et al., 2012; Possamai et al., 2022). Thus, conservation agriculture significantly reduced soil losses caused by erosion (Casão Junior et al., 2012; Friedrich et al., 2012; Londero et al., 2021). However, the efficiency of NTS in controlling soil losses does not guarantee control over surface runoff (Deuschle et al., 2019; Didoné et al., 2019).

Recent studies have examined the effects of soil management practices on erosional and hydrological processes at the scale of watersheds and macroplots. These studies have identified significant soil and water losses in areas under NTS, demonstrating evident effects on sediment production (Deuschle et al., 2019; Londero et al., 2021; Tiecher et al., 2018; Utzig et al., 2023; Wang et al., 2023). These processes are directly related to the soil's physical-hydraulic attributes, which reflect the structural quality of the soil, the quantity, size, and continuity of pores (Deuschle et al., 2019; Pott & De Maria, 2003; Reichert et al., 2016). Therefore, issues associated with the alteration of these soil attributes in NTS, such as problems of surface soil compaction and reduced infiltration rate, can be directly related to increased soil erosion and surface runoff (Ambus et al., 2018; Deuschle et al., 2019).

Agriculture systems characterized by intensive use and inadequate management of natural resources, often accompanied by monocultures or continuous succession planting, have altered soil's physical, chemical, and biological properties. The continuous use of these practices contributes to the degradation of organic matter and, consequently, the reduction of soil fertility and the productive potential of crops. Furthermore, agricultural production systems have adopted larger and heavier agricultural machinery to achieve higher operational efficiency in crop cultivation. Nevertheless, this transition to mechanization in agricultural areas has increased soil compaction. Adopting best management practices (BMPs) that enhance soil physical and chemical quality has mitigated these issues. BMPs prioritize using a single strand of cover crops during intercropping periods and incorporating a mixture of cover plant species (Pott et al., 2023; Rosa et al., 2017; Spliethoff et al., 2019).

Studies have assessed the impact of NTS on surface runoff generation and sediment production (Deuschle et al., 2019; Didoné et al., 2019; Londero et al., 2017; Merten et al., 2015). However, Londero et al. (2021) recommended that researchers should conduct further studies on the significance of monitoring strategies at the macroplot scale to assess the impact of various crop, soil, and water management methods that can contribute to identifying the most effective conservation agricultural practices in diverse edaphoclimatic regions. In light of this, this study aims to assess the effectiveness of adopting conservation practices in representative NTS in the Central-Southern region of Paraná, Brazil, for reducing surface runoff and sediment production during rainfall events. These systems include conservation practices such as a mixture of cover crops, contour farming, and terracing, aiming to identify and refine technical recommendations for soil and water management and conservation in areas under NTS.

2 | MATERIALS AND METHODS

2.1 | Location and history of the study area

The study area is located in the rural zone of the Entre Rios District, Guarapuava, Paraná state, Brazil (25°32′12″S and 51°30′21″W; Figure 1). The region is situated at an altitude of 1070 m and has a Cfb climate type (humid subtropical, with no defined dry season). This climate is characterized by an annual mean temperature of 17°C with cool summers (mean temperature of 20.5°C in January) and winters with frequent and severe frost (mean temperature of 13°C in July) according to the Köppen climate classification (Alvares et al., 2013; Peel et al., 2007).

With an average annual rainfall (*R*) of 1936 mm and a warmest month's average temperature remaining below 22°C (Salton et al., 2016), the soils in the study area are highly weathered and deep. These soils, classified as Oxisols (Embrapa, 2008; Soil Survey Staff, 2014), have a high clay content (>700 g kg^{-1}). The area's historical context is a typical agricultural region with rural properties cultivating grains in the summer (soybeans and corn) and cereals in winter (wheat, barley, and oats). The primary management system employed in this region centers on a NTS coupled with upslope and downslope tillage practices. It is worth noting, however, that the system lacks mechanical practices for controlling surface runoff and erosion. Additionally, the region's producers discontinued this practice during the 1980s–1990s when they implemented the NTS in the area. These land use and management types represent the current traditional model agricultural producers adopt in the State of Paraná Central-Southern region.

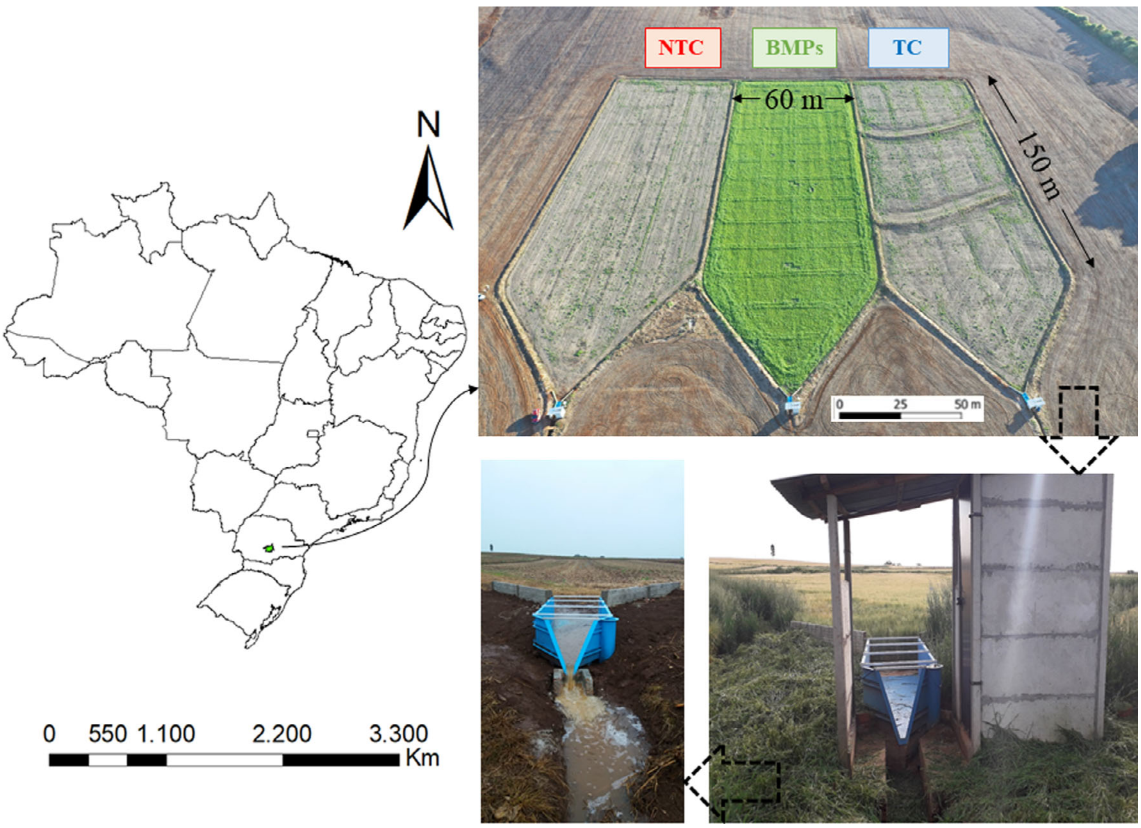

FIGURE 1 Location of the study area and view of the macroplots. BMPs, best management practices; NTC, non-terraced catchment; TC, terraced catchment. Entre Rios District, Guarapuava, Paraná, Brazil. [Colour figure can be viewed at wileyonlinelibrary.com]

2.2 | Characteristics of the macroplots

The study was conducted in the agricultural region with the previously mentioned land use and management history. At this location, we installed three paired large plots called macroplots, each with an area of 11,000 m^2. A topographic survey was conducted through aerial photography using a drone, followed by the creation of a digital elevation model of the terrain to ensure similarity in topography among the macroplots. To isolate the areas of each macroplot, we constructed ridges at the lateral, upper, and lower limits. These ridges avoid the entry and exit of water and drive runoff toward the monitoring site.

The digital model shows the variation in elevation along the terrain profile of the macroplots (Figure 2), ranging from 1062 to 1078 m, with an average elevation of 1070 m. The predominant slope in the area varies between 0% and 8%, and the average slope of the topographic profile was 4%. The slope is more pronounced in the upper third of the macroplots, and the rill formation and the installed terrace are evident.

Based on the region's history and current production systems, the study evaluated three soil management systems under NTS: (i) up- and down-slope farming, (ii) contour farming, and (iii) contour farming with terraces (Figure 1).

To assess the effects of the soil management systems, we organized the three macroplots as follows:

- Macroplot 1: This plot was named the standard macroplot (non-terraced catchment [NTC]) since it represents the production system carried out by most regional producers, characterized by the absence of mechanical runoff control practices and terracing. Additionally, within this system, the most commonly employed crop rotation by agricultural producers was adopted, which involves cultivating grain crops under NTS, as depicted in the chronogram in Figure 3 for NTC.
- Macroplot 2: This was named the BMPs plot. In this one, a set of conservation practices was employed, aiming to improve the physical soil conditions and reduce soil and water losses in the agricultural fields of the producers. Among the adopted practices is crop rotation, incorporating a permanent mixture of cover crops in the soil, particularly during summer and winter intercropping periods, as illustrated in the chronogram in Figure 3 for BMPs. Furthermore, in this system, agricultural practices such as sowing, applications, and harvesting were carried out on contour, promoting soil conservation.
- Macroplot 3: This plot was named the terraced catchment (TC). In this one, the same rotation system as in macroplot 1 (NTC) was adopted, but with the addition of mechanical runoff control practices, including two broad-based terraces and contour farming. We used the Terraço 4.1 software (Pruski et al., 1996) to design the terraces with adjustments based on the method by Lombardi Neto et al. (1994), which includes factors related to soil use and

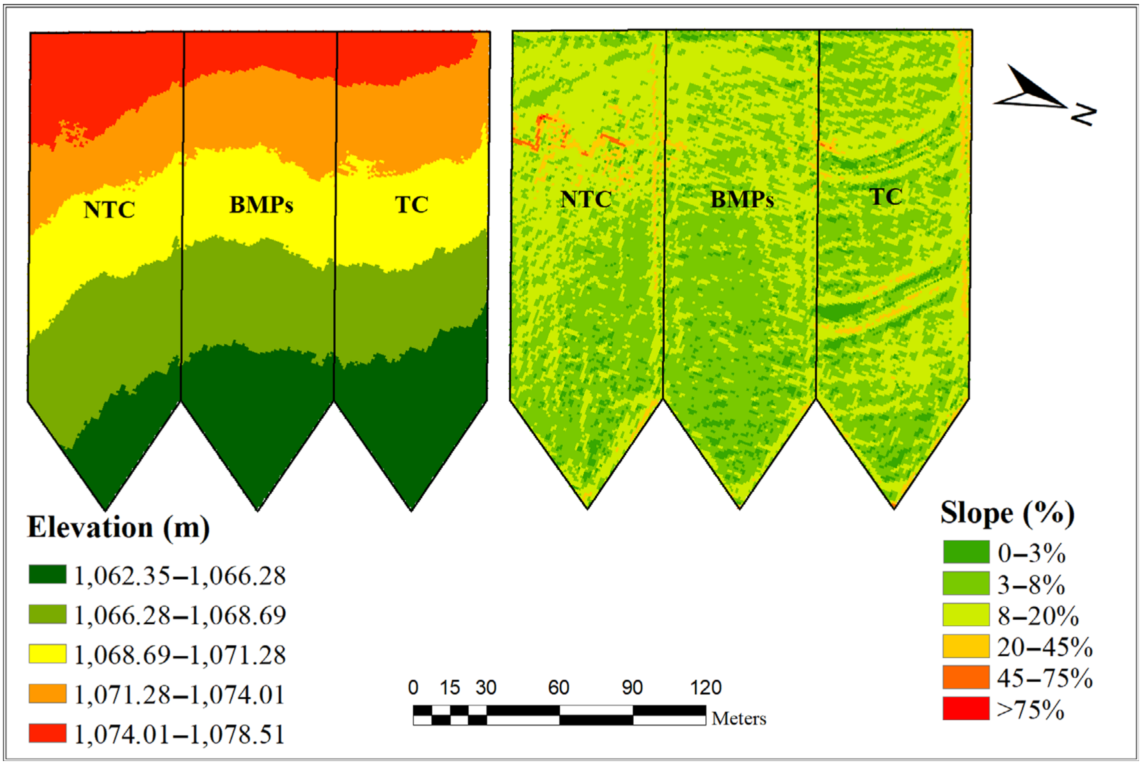

FIGURE 2 Digital elevation model and slope maps of the study area. BMPs, best management practices; NTC, Non-terraced catchment; TC, terraced catchment. [Colour figure can be viewed at wileyonlinelibrary.com]

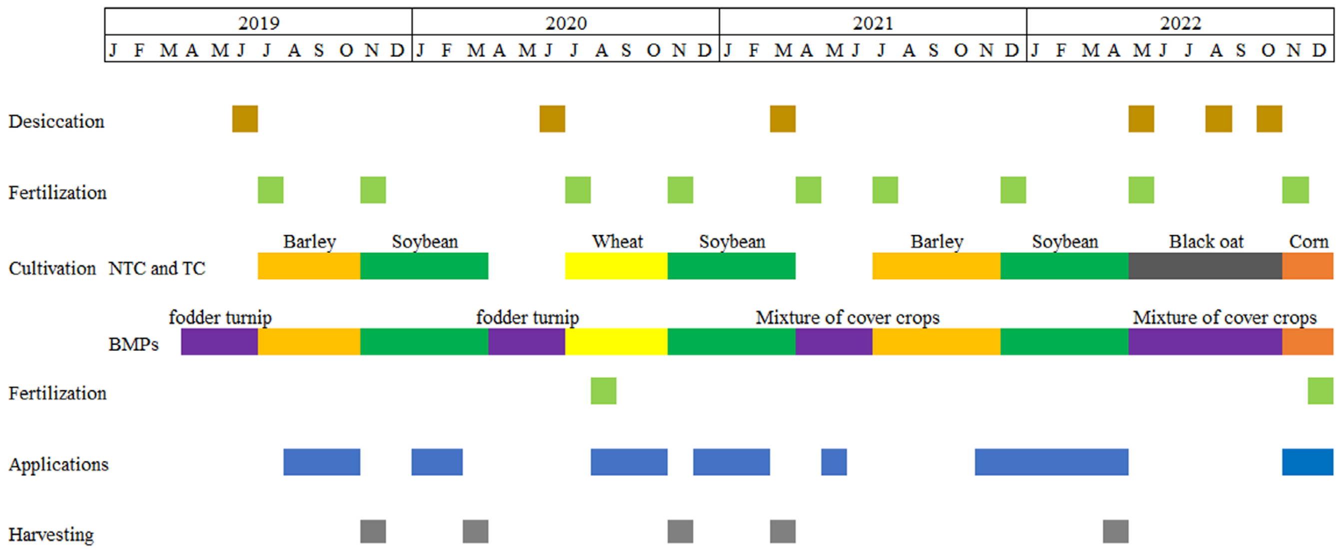

FIGURE 3 Chronogram detailing the crops, soil management, and agriculture practices implemented in each macroplot. The mixture of cover crops consisted of the cultivation of black oat (*Avena strigosa*), rye (*Secale cereale*) + vetch (*Vicia sativa*), and grass pea (*Lathyrus hirsutus*). Corn (*Zea mays*), fodder turnip (*Raphanus sativus*), barley (*Hordeum vulgare*), soybean (*Glycine max*), and wheat (*Triticum aestivum*). BMPs, best management practices; NTC, non-terraced catchment; TC, terraced catchment. [Colour figure can be viewed at wileyonlinelibrary.com]

management. Furthermore, the infiltration rate used as an input parameter in the software was determined using a pressure infiltrometer with concentric rings.

The macroplots were installed in April 2019, 5 months before starting the monitoring, aiming to assess the macroplot installation's potential effects on the system's hydrological dynamics. The agricultural practices carried out after the installation of the macroplots are presented in Figure 3. This figure shows the rotation systems adopted by the agricultural producer of the region in the NTC macroplot. The proposed conservation systems are presented, including BMPs in the BMPs macroplot, with cover crops during autumn, and the TC macroplot with contour farming.

2.3 | Monitoring

The strategy of this study was to assess the effects of soil management practices through monitoring water and soil losses during rainfall (*R*) events. Hydrological parameters were measured simultaneously in the three macroplots and used to assess the effectiveness of each conservation system in controlling water runoff and soil erosion. The monitoring was conducted between September 2019 and October 2022, a period characterized by a low number of significant *R* events due to the strong influence of the La Niña phenomenon in the southern region of Brazil. During the 38 months, we monitored 19 rainfall events. However, only 13 events were manually monitored for sediment loss evaluation, and a water loss assessment was conducted for all events. The monitored events encompassed various *R* intensities, volumes, and soil moisture conditions.

Water discharge (Q) and suspended sediment concentration (SSC) were monitored at a control point established in the drainage accumulation section in each macroplot. This control point was built with a channel attached to an H-type flume for water level monitoring and *Q* estimation. The dimensions of the flume and channel were determined based on the maximum estimated *Q* (2379 L s^{-1}) for the contributing area of the macroplots using the rational method (McCuen, 1998). This determination considered factors such as the basin area, topography, soil type, land use, and maximum rainfall duration in 24 h with a 10-year return time.

Rainfall (*R*, mm) was monitored using a pluviograph with discretization every 2 min and a pluviometer for measuring the total accumulated rainfall over 24 h. The antecedent soil moisture condition (θ, cm^3 cm^{-3}) was characterized using a soil moisture sensor installed in the area of the macroplots. From this data, the characterization of rainfall events was possible by obtaining rainfall variables such as rainfall intensity (*I*, mm h^{-1}) and maximum rain intensity in 30 min (I_{30}, mm h^{-1}).

The water level (*H*, m) during surface runoff in the macroplots was manually monitored in the H-type flume using a hydrometric ruler, with measurements depending on the variation in the surface runoff depth (1 cm). A person was present beside the H-type flume during some events, taking notes of the water level. The *Q* (L s^{-1}) was determined using the specific key curve for the H-flume, which requires measuring water level in meters. Moreover, we monitored the surface runoff depth using a pressure sensor (linigraph) installed in a stilling well attached to the H-type flume at 2-min intervals. The SSC (g L^{-1}) was measured through manual sampling during the events (Utzig et al., 2023). Samplings were conducted at different intervals, depending on the water level variation, to cover the event's entire time interval and record the hydrograph's rise and recession. The samples collected for SSC determination per rainfall/runoff event were analyzed using the evaporation method (Shreve & Downs, 2005). The SSC data were linearly interpolated to the same time interval as the *Q* data.

The evaluation of rainfall/runoff events over time was conducted through the analysis of rainfall (*R*, mm), surface runoff discharge (*Q*, L s^{-1}), and SSC (g L^{-1}), represented in hyetographs, hydrographs, and sedimentographs, respectively. From these graphs, a set of variables representing the behavior of each event was generated, such as (i) surface runoff volume (V_{Total}, m^3), (ii) peak water discharge (Q_{peak}, L s^{-1}), (iii) runoff coefficient (RC, %), (iv) maximum and mean SSC (g L^{-1}), and (v) total sediment yield (SY, kg; Equation 1).

$$SY = k \sum (Q_i \cdot SSC_i). \tag{1}$$

The subscript *i* represents the instantaneous values of *Q* and SSC, and *k* is a unit conversion factor.

Apparent infiltration (Ia) was monitored in each macroplot to assess each system's capacity to increase water infiltration. The Ia evaluation is crucial since rainfall can influence subsurface runoff and base flow processes. Ia (Equation 2) was determined during rainfall events by monitoring the runoff volume and rainfall in each event, using the expression

$$Ia = R - Q, \tag{2}$$

where *R* and *Q* are in mm.

2.4 | Data analysis

The measured variables were analyzed to assess the differences between the macroplots. Therefore, descriptive statistics were used, including dispersion and central tendency measures. Considering all events, the *Scott-Knott test* for multiple comparisons was employed. This test evaluated the differences among hydrosedimentological variables (V_{Total}, RC, Q_{Peak}, and SY) and inferred the effects of different soil management and conservation practices on erosive and hydrological processes. In this situation, the test compares the mean of all variables across the macroplots, considering that each event in a macroplot can be compared to observations in other macroplots (Londero et al., 2017). This approach aimed to identify differences in the distinct temporal behaviors of *Q* and SSC during *R*-runoff events, which may reflect critical processes and factors governing sediment loss in the studied systems (Deuschle et al., 2019). The statistical analysis was conducted using R software version 4.3.2 (R Core Team, 2023).

3 | RESULTS AND DISCUSSION

Figure 4 presents the mean monthly rainfall in the macroplots during the monitoring period (2019–2022). The climate normal precipitation

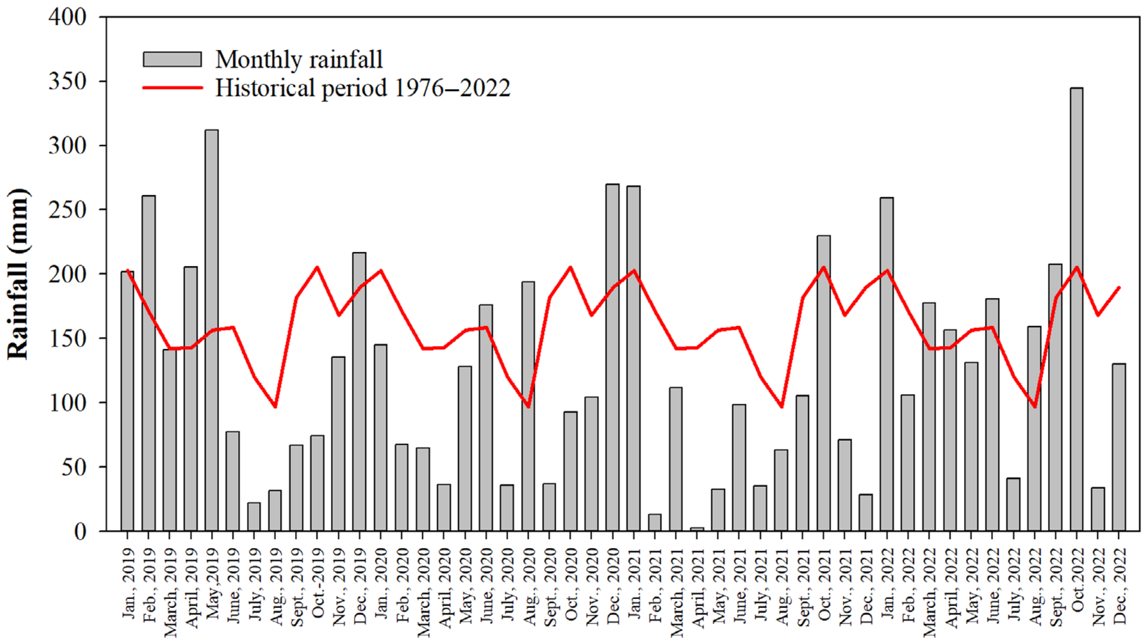

FIGURE 4 Monthly rainfall total during the monitoring period (2019–2022) and historical monthly rainfall (1976–2022). [Colour figure can be viewed at wileyonlinelibrary.com]

for Guarapuava is 1936 mm. The strong impact of the La Niña phenomenon on the rainfall regime is observed in the reductions of annual rainfall by 14%, 27%, and 35% for the years 2019, 2020, and 2021, respectively. These reductions correspond to 277, 515, and 685 mm less for these years. During the monitoring period, the negative effect of the La Niña phenomenon on precipitation is evident in the few significant rainfall events that generated surface runoff in the macroplots during the monitoring period.

The results of the hydrological monitoring showed that the evaluated management systems exhibited differences in the temporal variation of *Q* and SSC for *R* events but with a rapid hydrological response. These results enabled the analysis and identification of differences in factors causing water and soil losses in the studied production systems. The total accumulated rainfall from the 19 monitored events was 472.4 mm under different antecedent soil moisture (θ) conditions and rainfall intensities (*I*; Table 1).

Figure 5 presents the results of the hydrological variables monitored in the 10 events with the highest RC in the macroplots. The most significant losses occurred in the standard macroplot (Macroplot 1: NTC), with a total of 41 m^3 of water loss (Figure 5a) during all evaluated events. This macroplot stood out for exhibiting water loss in all events. The total water in the other macroplots (Macroplot 2: BMPs and Macroplot 3: TC) were 40 and 7 m^3 (Figure 5a), respectively.

The significant role of antecedent moisture in generating water losses is evident, as demonstrated in Table 1. Notably, soil moistures above 0.40 $m^3\ m^{-3}$ were capable of producing the highest water loss volumes in all systems, even with I_{30} ranging between 14 and 30 mm h^{-1} (Table 1), as observed in the events of June 02, 2022 and October 30, 2022 (Figure 5). Furthermore, monitoring Ia revealed that the soil, regardless of the management system, exhibited a high capacity for Ia, resulting in fewer significant surface runoff events, even during events of high rainfall intensity (Table 1).

The higher water and soil losses in the NTC macroplot are associated with the absence of conservation mechanical practices that create physical impediments to surface runoff. Additionally, the practices and management carried out by producers in the region, following the up- and down-slope farming, led to greater soil disaggregation, transport, and surface runoff during rainfall events, even with the inclusion of NTS and I_{30} < 10 mm h^{-1} (Table 1). Some studies have documented that NTS can reduce erosion to low levels (Kurothe et al., 2014; Williams et al., 2014); however, it is observed that water and soil losses are still higher in the no-till system without additional soil conservation practices.

The findings from this study are consistent with areas where cultivation is implemented following the up- and down-slope direction, as demonstrated in other studies (Luciano et al., 2009; Rocha Junior et al., 2018). Significant Surface runoff volumes in this soil management practice can remove crop residues and provoke rill erosion, where runoff water can concentrate on the downstream parts of the landscape, dissolving and carrying the soil with greater energy. Moreover, this system can accelerate water erosion with increased slope steepness (Londero et al., 2017; Luciano et al., 2009; Wang et al., 2016).

When evaluating the inclusion of BMPs in macroplot 2—BMPs, which includes a mixture of cover plant species in the autumn period under a NTS and contour farming, this system showed a reduction in water and soil losses in most of the monitored events when compared to macroplot 1—NTC (Figure 5). The use of cover crops and contour farming allowed for an increase in soil infiltration capacity, as evidenced by a decrease in water losses by 59% and soil losses by 82%

TABLE 1 Characteristics of monitored rainfall events.

Event		Moisture ($m^3\ m^{-3}$)	I_{30}	Ia (mm)		
Date	P (mm)[a]	Previous[b]	mm h^{-1}	NTC	BMPs	TC
01/09/2019	13.20	0.35	23.6	13.18	13.19	13.18
09/06/2020	27.20	—	34.4	27.19	27.19	27.19
09/06/2020	18.20	—	18.0	18.18	18.19	18.19
10/06/2020	7.60	—	15.6	7.59	7.59	7.59
15/08/2020	9.60	0.45	14.4	9.59	9.59	9.59
15/08/2020	5.40	0.45	6.4	5.39	5.39	5.39
18/08/2020	13.60	0.47	9.6	13.59	13.59	13.59
04/12/2020	17.00	0.34	27.2	16.99	16.99	16.99
05/12/2020	15.20	0.43	19.2	15.19	15.19	15.19
05/12/2020	8.00	0.46	14.8	7.99	7.99	0.00
03/10/2021	12.05	0.38	13.7	12.02	12.04	0.00
23/10/2021	30.98	0.39	24.0	30.97	0.00	0.00
16/01/2022	69.02	0.36	46.7	68.84	69.00	69.01
25/02/2022	61.35	0.25	64.2	61.31	61.34	61.34
02/06/2022	32.06	0.42	16.5	31.29	31.41	32.00
02/06/2022	35.37	0.42	14.1	35.19	35.29	35.33
20/10/2022	35.86	0.38	41.7	35.32	35.55	35.68
29/10/2022	21.95	0.30	42.9	21.84	21.83	21.89
30/10/2022	37.34	0.43	37.8	35.60	34.91	37.02

Abbreviations: —, no available data; BMPs, best management practices; Ia, apparent infiltration; NTC, non-terraced catchment; P (mm), precipitation; TC, terraced catchment.
[a]Precipitation during the event.
[b]Antecedent soil moisture; I_{30} (mm h^{-1}): maximum rainfall intensity at 30 min intervals.

in most events. The mixture of cover crop species in cultivation systems has proven to be a management practice that improves the soil's physical quality. These improvements involve reducing soil bulk density and penetration resistance and increasing soil macroporosity (Pott et al., 2023; Spliethoff et al., 2019). Simultaneously, the cover crop mixture increased the water infiltration rate and structural quality of the soil, consequently reducing water and soil losses.

Regarding no-tillage (NTS) in contour farming, Rocha Junior et al. (2018) state that the low values of water and sediment losses in this system can be attributed to micro-depressions in the opposite direction of the slope. The soil management in this direction creates structures similar to micro-terraces, which act as a physical barrier to surface runoff, specifically reducing sediment losses (Luciano et al., 2009; Rocha Junior et al., 2016).

Despite effective control of water and soil losses under the BMP system in the majority of rainfall events, the results showed that during high-intensity rainfall events and high antecedent soil moisture conditions, such as those that occurred on June 02, 2022, October 29, 2022, and October 30, 2022 (Table 1), the cover crop mixture and contour farming were not sufficient to manage surface runoff (Figure 5a,d) and sediment production (Figure 5c). For these cases, the mean RC was 2.3%, corresponding to these four events (Figure 5b). The BMPs system was not efficient in controlling Q and SSC in these events because, before these events, there was a recent implementation or desiccation of the cover crop mixture using machinery that increased the exposed soil area (Figure 3). Furthermore, continuous periods of low-intensity rainfall prevented cultural management practices and the establishment of permanent vegetative cover, leaving the soil with desiccated crops without lodging for most of the time and a lower percentage of cover crop residues.

The system with mechanical erosion control practices, including broad-based terraces (TC), proved the most suitable technique for reducing water and soil loss in NTS (Figure 5a,c), mitigating soil degradation by water erosion. On average, this system decreased the total surface runoff volume (V_{Total}) and SY by 78.5% and 78.1%, respectively (Table 2). The use of terraces as the best conservation practice for controlling surface runoff and water management in agriculture has been recommended in various studies (Deuschle et al., 2019; Londero et al., 2017; Merten et al., 2015). These studies affirm that terraces positively impact agricultural production since this system enhances crop productivity due to more significant water and nutrient availability (Londero et al., 2017).

Nevertheless, agricultural producers in the region abandoned terracing due to the impracticality of conducting agricultural operations such as seeding, applications, and harvesting on the terraces. In light of this, the producers adopted the NTS with up- and down-slope farming as their cultivation method, believing it would be sufficient to control surface runoff and soil losses and reduce fuel consumption during management operations. As highlighted in other studies (Didoné et al., 2014, 2019; Merten et al., 2015), these changes

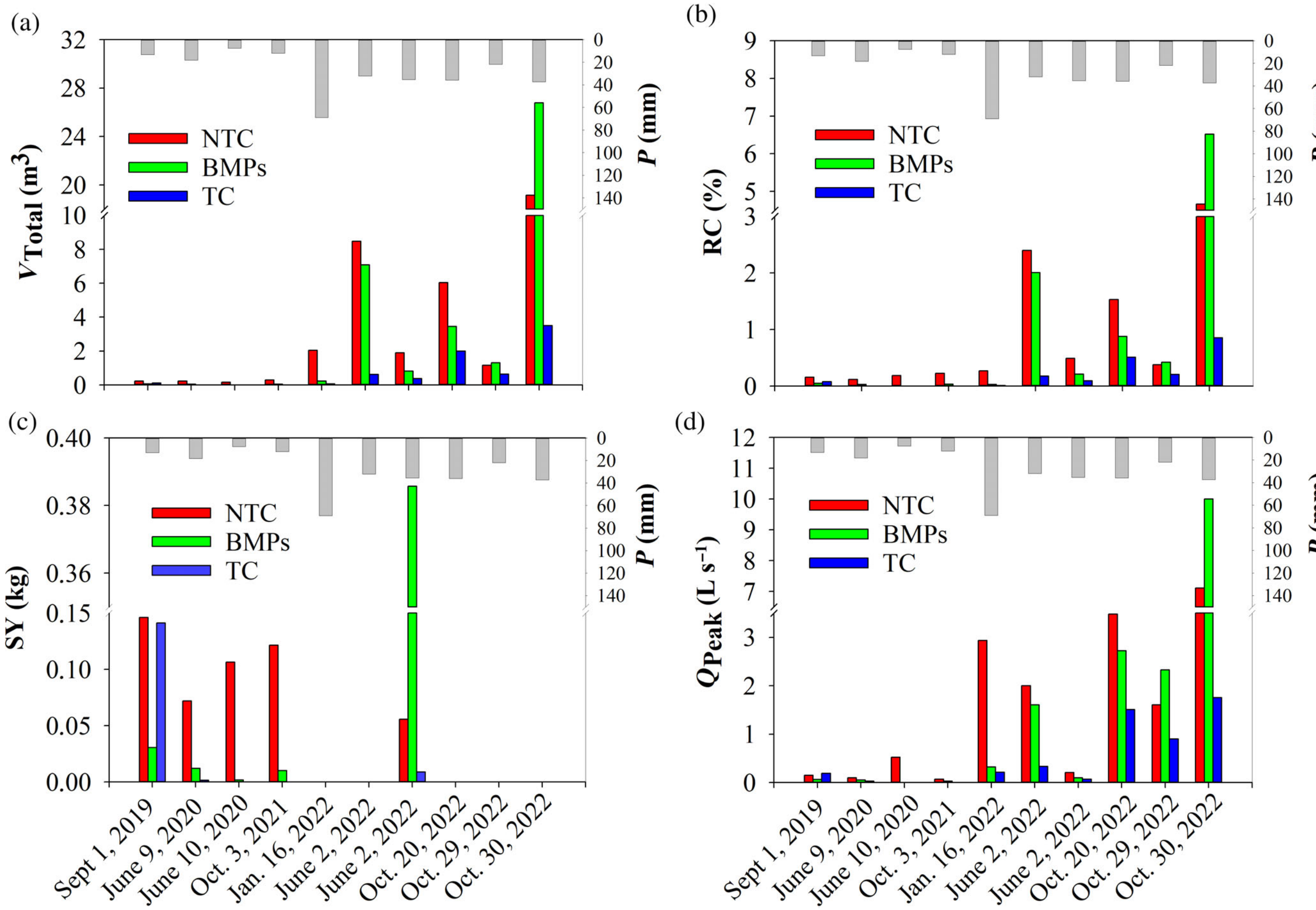

FIGURE 5 Hydrological variables measured during the monitored events: (a) surface runoff volume (V_{Total}), (b) runoff coefficient (RC), (c) sediment yield (SY), and (d) peak water discharge (Q_{Peak}) of events during the years 2019–2022. BMPs, best management practices; NTC, non-terraced catchment; *P*, precipitation; TC, terraced catchment. Entre Rios District, Guarapuava, Paraná, Brazil. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Statistical significance of mean differences for the monitored hydrological variables.

Macroplots	V_{Total} (m^3)	RC (%)	Q_{Peak} ($L\ s^{-1}$)	SY (kg)
NTC	2.14 a	0.572 a	1.00 a	0.073 a
BMPs	2.22 a	0.573 a	0.97 a	0.045 b
TC	0.46 b	0.125 b	0.32 b	0.016 b

Note: Different letters in the same column differ statistically at $p < 0.05$ by the *Scott-Knott test*.
Abbreviations: BMPs, best management practices; NTC, non-terraced catchment; Q_{peak}, peak water discharge; RC, runoff coefficient; SY, sediment yield; TC, terraced catchment; V_{Total}, runoff volume.

adopted by producers, combined with the implementation of an inadequate NTS with minimal residue and the absence of crop rotation, intensified erosive processes within this system. Therefore, we suggest conducting further studies to investigate different dimensions and structures of terracing that can address the challenges of agricultural operations and mitigate water and soil losses in these new systems.

Furthermore, we assessed the temporal variations of *Q* and SSC during rainfall events to comprehend the differences in hydrological processes within each monitored system and assess total soil and water losses. Figure 6 illustrates two significant that present hyetographs, hydrographs, and sedimentgraphs (September 01, 2019 and August 15, 2020). Overall, some systems showed reduced magnitudes of *Q* and SSC, but all exhibited a rapid hydrological response to intense rainfall events. The rapid rise and recession of the hydrographs and sedimentographs characterize this response. During the presence of barley and wheat culture, the NTC system could have been more efficient in controlling the runoff volume and velocity, regardless of antecedent moisture conditions and the magnitude of the *R* event.

The event monitored on September 01, 2019, stands out as an exception to the effectiveness of the TC system in erosion control. This exception occurred because the *R* event was the first event monitored close to the date of terrace installation, which occurred 5 months before monitoring began. This more significant generation of *Q* and SSC in the terraced system (Figure 6a) can be attributed to the recent soil disturbance in this system. In addition to this factor, it

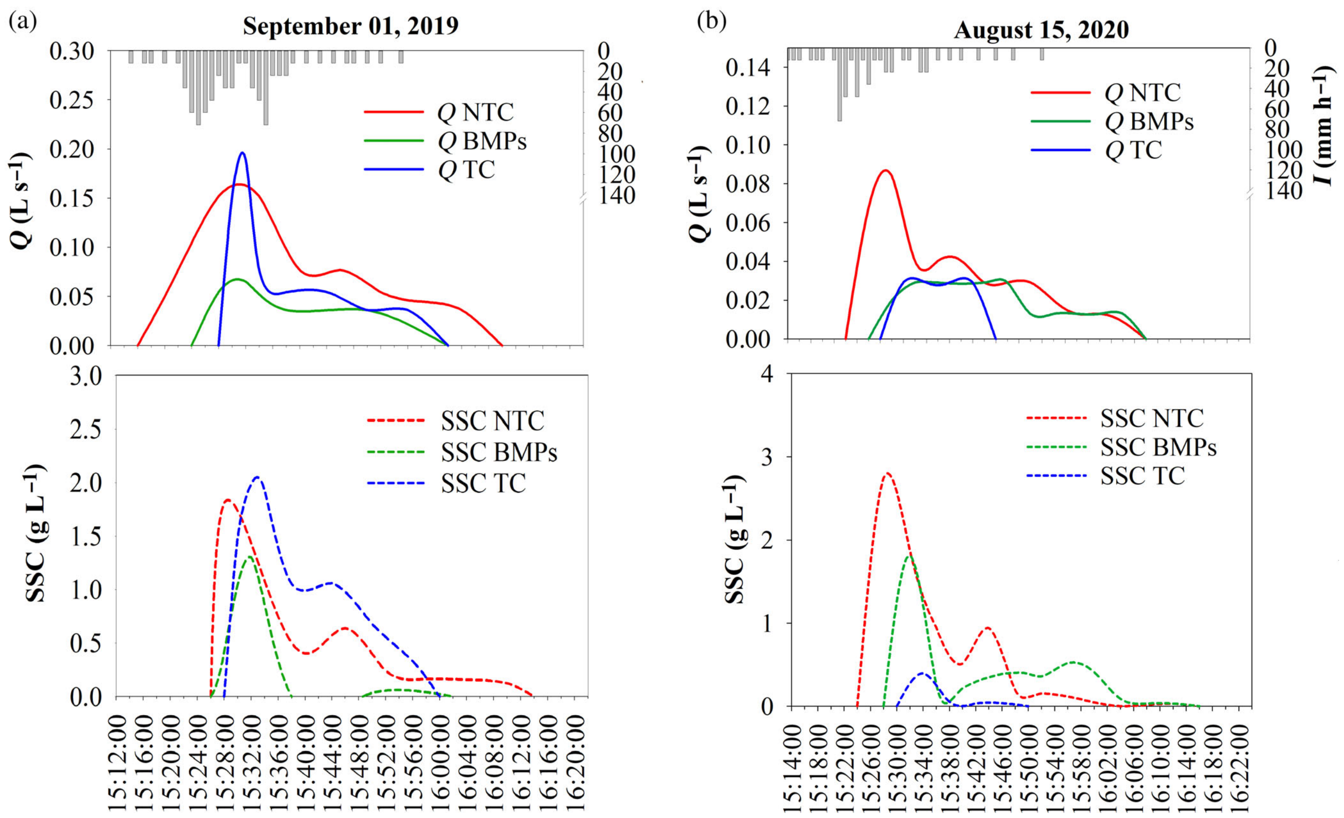

FIGURE 6 Hydrographs and sedimentograms in different measured precipitation events. [Colour figure can be viewed at wileyonlinelibrary.com]

is essential to mention that near this event, management practices were carried out in the barley crop, involving the application of agricultural pesticides using machinery. This activity may have reduced the soil cover along the wheel tracks left by the machines, allowing for a greater concentration of runoff in these areas. When installed, terraces require a period for stabilization to prevent soil disaggregation and subsequent erosive processes. This stabilization becomes evident during the event that occurred on August 15, 2020 (Figure 6b), ca. 1 year after the first event. Throughout this time, specifically in the phase of wheat cultivation, a notable reduction of 85% in maximum Q and 80% in SSC within the TC system is observed, highlighting the effective erosion control achieved by the terraces.

When evaluating the temporal variation of Q and SSC in all monitored events, it is possible to observe that the systems were inefficient in controlling the velocity and volume of surface runoff, regardless of soil management, antecedent moisture conditions, vegetation cover, and conservation practices for high magnitude precipitation events (R). This inefficiency is demonstrated by the rapid hydrological response to the stimulus of R, leading to sharp increases and decreases in the hydrographs. However, in events of lower magnitude, the TC system demonstrated the ability to prevent the generation of Q and SSC, as observed on December 05, 2020; October 03, 2021; and October 23, 2021 (Figure 5).

The peaks of Q and SSC exhibited different behaviors for the evaluated systems. Whitin the NTC system, the peak of SSC consistently preceded the peak of Q, implying its potential to enhance more significant sediment generation under NTS in the downslope direction. On the other hand, the BMPs and TC systems showed simultaneous peaks of SSC and Q, indicating decreased sediment generation when implementing crop management and mechanical soil conservation practices.

In general, the results demonstrate that regardless of the event intensity and its effect on the response of Q and SSC, systems implementing crops under NTC conditions have a higher tendency toward vulnerability in controlling surface runoff and soil erosion. The higher volume of water discharged in the NTC system has significant erosive potential, promoting the mobilization of nutrients and pesticides in water resources and exacerbating other environmental challenges such as eutrophication and water contamination. In this regard, it is crucial to prioritize the principles of conservation practices in the region's agricultural areas. This includes implementing strategies like incorporating crop rotation with a mixture of cover plant species in the NTS, adopting agriculture operations conducted in contour farming practices (Rocha Junior et al., 2016, 2018), and constructing terraces (Londero et al., 2017; Merten et al., 2015). The results of this study highlight the need to prioritize soil conservation practices since BMPs and TC systems demonstrated their effectiveness in reducing and controlling surface runoff and sediment production during high- and low-magnitude rainfall events. These practices will contribute to improving soil quality, reducing natural resource degradation, lowering the cost of soil recovery, and enhancing societal well-being (Deuschle et al., 2019).

4 | CONCLUSION

The NTS implemented in up- and down-slope farming, adopted by the agricultural producers, demonstrated a more significant potential for water loss through surface runoff and higher soil loss due to the high concentration of sediments.

The BMPs system, including crop rotation, a mixture of cover plant species, and contour farming, proved effective for controlling soil erosion in most rainfall events. It is an alternative for producers who wish to refrain from constructing terraces in their fields. The BMPs system can potentially reduce water losses by ca. 60% and soil losses by 82%.

The conservationist mechanical management system that includes terracing efficiently reduces surface runoff and sediment production during rainfall events. This system can decrease the total runoff volume and total sediment production by an average of 78% compared to the NTS with up- and down-slope farming.

Despite being conducted during the period influenced by the La Niña phenomenon, the systems exhibited a rapid hydrological response to rainfall events, resulting in hydrographs with pronounced runoff peaks and significant SSCs. Furthermore, this phenomenon impacted monthly total rainfall, falling below the historical monthly averages in most monitored months and for the annual total precipitation, consequently reducing the number of monitored rainfall events in the macroplots.

The findings of this study serve as a guide and recommendation for agricultural producers and field technicians in the region and around the world to have a criterion for choosing the best soil and water management and conservation practices to be implemented in areas under no-till systems, aiming for more conservation-oriented agriculture. Among these practices are a NTS with contour farming, including a mixture of cover plant species, and constructing terraces. However, using and evaluating the combination of other conservation practices to control surface runoff, soil erosion, and the mobilization of nutrients and pesticides that could degrade or contaminate water resources is also recommended.

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CONFLICT OF INTEREST STATEMENT

The authors report no declarations of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Miguel D. Fuentes-Guevara https://orcid.org/0000-0002-8735-8499

REFERENCES

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Leonardo, J., Gonçalves, M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711–728. https://doi.org/10.1127/0941-2948/2013/0507

Ambus, J. V., Reichert, J. M., Gubiani, P. I., & Carvalho, P. C. D. F. (2018). Changes in composition and functional soil properties in long-term no-till integrated crop-livestock system. *Geoderma*, *330*, 232–243. https://doi.org/10.1016/j.geoderma.2018.06.005

Barreto, P., Ernst, O., Bidegain, M. P., & Perdomo, C. (2022). Effects of grazing, rotation, and tillage on surface runoff in a heavy textured Uruguayan soil. *Soil Science Society of America Journal*, *86*, 1096–1112.

Bertol, I., Albuquerque, J. A., Leite, D., Amaral, A. J., & Zoldan Júnior, W. (2004). Physical soil properties of conventional tillage and no-tillage, in crop rotation and succession, compared with natural pasture. *Revista Brasileira de Ciência do Solo*, *28*, 155–163. https://doi.org/10.1590/S0100-06832004000100015

Blanco-Canqui, H., & Lal, R. (2009). Crop residue management and soil carbon dynamics. *Soil Carbon Sequestration and the Greenhouse Effect*, *57*, 291–309.

Casão Junior, R., De Araújo, A. G., & Llanillo, R. F. (2012). *Plantio direto no Sul do Brasil: Fatores que facilitaram a evolução do sistema e o desenvolvimento da mecanização conservacionista*. FAO/IAPAR.

Crespo, R. J., Ares, G., Sfeir, A., Wingeyer, A. B., & Usunoff, E. (2010). Efecto de la labranza y la cobertura vegetal sobre el escurrimiento y la pérdida de suelo en la región central de la provincia de Buenos Aires. *Revista de La Facultad de Ciencias Agrarias*, *42*(1), 93–106.

Denardin, J. E., Faganello, A., & Santi, A. (2008). Falhas na implementação do sistema plantio direto levam a degradação do solo. *Revista Plantio Direto*, *18*, 33–34.

Derpsch, R., Franzluebbers, A. J., Duiker, S. W., Reicosky, D. C., Koeller, K., Friedrich, T., Sturny, W. G., Sá, J. C. M., & Weiss, K. (2014). Why do we need to standardize no-tillage research? *Soil and Tillage Research*, *13*, 16–22. https://doi.org/10.1016/j.still.2013.10.002

Deuschle, D., Minella, J. P. G., Hörbe, T. A. N., Londero, A. L., & Schneider, F. J. A. (2019). Erosion and hydrological response in no-tillage subjected to crop rotation intensification in southern Brazil. *Geoderma*, *340*, 157–163. https://doi.org/10.1016/j.geoderma.2019.01.010

Didoné, E. J., Minella, J. P. G., Reichert, J. M., Merten, G. H., Dalbianco, L., De Barros, C. P. P., & Ramon, R. (2014). Impact of no-tillage agricultural systems on sediment yield in two large catchment in southern Brazil. *Journal of Soils and Sediments*, *14*, 1287–1297. https://doi.org/10.1007/S11368-013-0844-6

Didoné, E. J., Minella, J. P. G., Schneider, F. J. A., Londero, A. L. L., Lefè, I., & Evrard, O. (2019). Quantifying the impact of no-tillage on soil redistribution in a cultivated catchment of southern Brazil (1964–2016) with 137Cs inventory measurements. *Agriculture, Ecosystems & Environment*, *284*, 106588. https://doi.org/10.1016/j.agee.2019.106588

Embrapa. (2008). *Mapa de solos do estado do Paraná: Legenda atualizada* (p. 74). Embrapa Floresta, Embrapa Solos, IAPAR.

FAO. (2013). *Basic principles of conservation agriculture*. http://www.fao.org/ag/ca/1a.html

Friedrich, T., Derpsch, R., & Kassam, A. (2012). Overview of the global spread of conservation agriculture overview of the global spread of conservation agriculture. *Field Actions Science Reports*, *6*, 1–7. http://journals.openedition.org/factsreports/1941

Fuentes-Llanillo, R., Telles, T. S., Soares Junior, D., De Melo, T. R., Friedrich, T., & Kassam, A. (2021). Expansion of no-tillage practice in conservation agriculture in Brazil. *Soil and Tillage Research*, *208*, 104877. https://doi.org/10.1016/J.STILL.2020.104877

Kassam, A., Friedrich, T., & Derpsch, R. (2018). Global spread of conservation agriculture. *International Journal of Environmental Studies*, *76*(1), 29–51. https://doi.org/10.1080/00207233

Kurothe, R. S., Kumar, G., Singh, R., Singh, H. B., Tiwari, S. P., Vishwakarmaa, A. K., Sena, D. R., & Pande, V. C. (2014). Effect of tillage and cropping systems on runoff, soil loss and crop yields under semiarid rainfed agriculture in India. *Soil and Tillage Research*, *140*, 126–134. https://doi.org/10.1016/j.still.2014.03.005

Lombardi Neto, F., Belinazzi Junior, R., Lepsch, I. F., Oliveira, J. B., Bertolini, D., Galeti, P. A., & Drugowich, M. I. (1994). *Terraceamento agrícola*. Secretaria da Agricultura e Abastecimento do Estado de São Paulo, CATI (Boletim Técnico, 206).

Londero, A. L., Minella, G. P. G., Deuschle, D., Schneider, F. J. A., Boeni, M., & Merten, G. H. (2017). Impact of broad-based terraces on water and sediment losses in no-till (paired zero-order) catchments in southern Brazil. *Journal of Soils and Sediments*, *18*, 1159–1175. https://doi.org/10.1007/s11368-017-1894-y

Londero, A. L., Minella, G. P. G., Schneider, F. J. A., Deuschle, D., Merten, G. H., Ervard, O., & Boeni, M. (2021). Quantifying the impact of no-till on sediment yield in southern Brazil at the hillslope and catchment scales. *Hydrological Processes*, *35*, e1428. https://doi.org/10.1002/hyp.14286

Luciano, R. V., Bertol, I., Barbosa, F. T., Vázquez, E. V., & Fabian, E. L. (2009). Water and soil losses through water erosion under oat and vetch sown in two directions. *Revista Brasileira de Ciência do Solo*, *33*, 669–676.

McCuen, R. H. (1998). *Hydrology analysis and design* (2nd ed.). Prentice-Hall.

Merten, G. H., Araújo, A. G., Biscaia, R. C. M., Barbosa, G. M. C., & Conte, O. (2015). No-till surface runoff and soil losses in southern Brazil. *Soil and Tillage Research*, *152*, 85–93. https://doi.org/10.1016/j.still.2015.03.014

Peel, M. C., Finlayson, B. L., & Mcmahon, T. A. (2007). Update world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, *11*(5), 1633–1644. https://doi.org/10.5194/hess-11-1633-2007

Phillips, S., & Young, H. (1973). *No-tillage farming*. Reiman Associates.

Possamai, E. J., Conceição, P. C., Amadori, C., Bartz, M. L. C., Ralisch, R., Vicensi, M., & Marx, E. F. (2022). Adoption of the no-tillage system in Paraná state: A (re)view. *Revista Brasileira de Ciencia Do Solo*, *46*, e0210104. https://doi.org/10.36783/18069657rbcs20210104

Pott, C. A., Conrado, P. M., Rampim, L., Umburanas, R. C., Conrado, A. M. C., Outeiro, V. H., & Müller, M. M. L. (2023). Mixture of winter cover crops improves soil physical properties under no-tillage system in a subtropical environment. *Soil & Tillage Research*, *234*(105854), 1–7. https://doi.org/10.1016/j.still.2023.105854

Pott, C. A., & De Maria, I. C. (2003). Comparison with field methods for assessing infiltration rates. *Revista Brasileira de Ciência Do Solo*, *27*, 19–27. https://doi.org/10.1590/S0100-06832003000100003

Pruski, F. F., Silva, J. M. A., Calijuri, M. L., & Bhering, E. M. (1996). *Terraço for windows, versão 1.0*. (Version 1.0). UFV – Departamento de Engenharia Agrícola.

R Core Team. (2023). *R: A language and environment for statistical Computing*. R Foundation for Statistical Computing www.R-project.org

Reichert, J. M., Rosa, V. T., Vogelmann, E. S., Rosa, D. P., Horn, R., Reinert, D. J., Sattler, A., & Denardin, J. E. (2016). Conceptual framework for capacity and intensity physical soil properties affected by short and long-term (14 years) continuous no-tillage and controlled traffic. *Soil and Tillage Research*, *158*, 123–136. https://doi.org/10.1016/j.still.2015.11.010

Rocha Junior, P. R., Bhattarai, R., Alves, R. B. F., Kalita, P. K., & Andrade, F. V. (2016). Soil surface roughness under tillage practices and its consequences for water and sediment losses. *Journal of Soil Science and Plant Nutrition*, *16*, 1065–1074. https://doi.org/10.4067/S0718-95162016005000078

Rocha Junior, P. R., Bhattarai, R., Fernandes, R. B. A., Kalita, P. K., & Andrade, F. V. (2018). Runoff sediment and P losses from various soil management practices: Modelling in hilly slopes. *Journal of Soil Science and Plant Nutrition*, *18*(1), 113–128. https://doi.org/10.4067/S0718-95162018005000502

Rosa, D. M., Nóbrega, L. H. P., Mauli, M. M., Lima, G. P., & Pacheco, F. P. (2017). Humic substances in soil cultivated with cover crops rotated with maize and soybean. *Revista Ciência Agronômica*, *48*(2), 221–230. https://doi.org/10.5935/1806-6690.20170026

Salton, F. G., Morais, H., Caramori, P. H., & Borrozzino, E. (2016). Climatology of the episodes of precipitation in three locations in the Paraná state. *Revista Brasileira de Meteorologia*, *31*(4), 626–638. https://doi.org/10.1590/0102-7786312314b20150108

Shreve, E. A., & Downs, A. C. (2005). *Quality-assurance plan for the analysis of fluvial sediment by the U.S. Geological Survey Kentucky Water Science Center Sediment Laboratory*. U.S. Geological Survey, Information Services.

Silva, T. P., Bressiani, D., Ebling, É. D., & Reichert, J. M. (2024). Best management practices to reduce soil erosion and change water balance components in watersheds under grain and dairy production. *International Soil and Water Conservation Research*, *12*, 121–136.

Soil Survey Staff. (2014). *Keys to soil taxonomy* (12th ed.). USDA National Resources Conservation Services.

Spliethoff, J., Rampim, L., & Pott, C. A. (2019). Performance of cover and corn plants in different mechanicaland biological management associations. *Revista Brasileira de Ciências Agrárias*, *14*(4), e6655. https://doi.org/10.5039/agraria.v14i4a6655

Thierfelder, C., & Wall, P. C. (2009). Effects of conservation agriculture-techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and Tillage Research*, *105*(2), 217–227.

Tiecher, T., Minella, J. P. G., Evrard, O., Caner, L., Merten, G. H., Capoane, V., Didoné, E. J., & Dos Santos, D. R. (2018). Fingerprinting sediment sources in a large agricultural catchment under no-tillage in southern Brazil (Conceição River). *Land Degradation and Development*, *29*, 939–951. https://doi.org/10.1002/ldr.2917

Utzig, D. L., Minella, J. P. G., Schneider, F. J. A., Londero, A. L., Dambroz, A. B. P., Barros, C. A. P., Tiecher, T., & Kaiser, D. R. (2023). Nutrient transport in surface runoff and sediment yield on macroplots and zero-order catchments under no-tillage. *Catena*, *231*, 107333. https://doi.org/10.1016/j.catena.2023.107333

Veresoglou, S. D., Chen, J., Du, X., et al. (2022). No tillage outperforms conventional tillage under arid conditions and following fertilization. *Soil Ecology Letters*, *5*, 137–141. https://doi.org/10.1007/s42832-022-0145-3

Wang, H., Chen, W., Zhou, M., Zuopin, Z., Zhang, Y., Jiang, F., Huang, Y., & Lin, J. (2023). Runoff and sediment characteristics of a typical watershed after continuous soil erosion control in the red soil region of southern China. *Catena*, *233*, 107484. https://doi.org/10.1016/j.catena.2023.107484

Wang, Y., Zhang, J. H., Zhang, Z. H., & Jia, L. Z. (2016). Impact of tillage erosion on water erosion in a hilly landscape. *Science of the Total Environment*, *551-552*, 522–532. https://doi.org/10.1016/j.scitotenv.2016.02.045

Williams, J. D., Wuest, S. B., & Long, D. S. (2014). Soil and water conservation in the Pacific northwest through no-tillage and intensified crop rotations. *Journal of Soil and Water Conservation*, *69*(6), 495–504. https://doi.org/10.2489/jswc.69.6.495

Wingeyer, A. B., Amado, T. J. C., Pérez-Bidegain, M., Studdert, G. A., Varela, C. H. P., Garcia, F. O., & Karlen, D. L. (2015). Soil quality impacts of current South American agricultural practices. *Sustainability*, *7*, 2213–2242.

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