soil systems

Article

Long Term of Soil Carbon Stock in No-Till System Affected by a Rolling Landscape in Southern Brazil

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Abstract: In the 1960s, a conservationist agricultural practice known as a "no-tillage system" was adopted. Several benefits such as soil erosion reduction and soil carbon sequestration, among others, could be ascribed to no-till systems. Therefore, it is important to evaluate the long-term sustainability of this agricultural system in different environments. This study has the objective to evaluate the soil organic carbon dynamic in a no-till system (40-year) and on a rolling landscape in Southern Brazil. A systematic grid with four transversal–longitudinal transects was used for soil sampling. Soil samples from 0–20, 20–40, and 40–60 cm depths were collected (16 trenches × 3 depths × 1 sample per soil layer = 48), and a forest nearby was used as control (4 trenches × 3 depths × 1 sample = 12). The soil at the forest site showed 20% more carbon stock than no-till at the 0–20 cm soil depth. However, the entire no-till soil profile (0–60 cm) showed similar soil carbon as forest soil. The soil carbon stock (0–20 cm) in no-till was depleted at a rate of 0.06 kg C m^{-2} $year^{-1}$, summing up to a carbon loss of 2.43 kg C m^{-2}. In addition, the non-uniform hillslope affected the soil carbon redistribution through the landscape, since the convex hillslope was more depleted in carbon by 37% (15.87 kg C m^{-2}) when compared to the concave sector (25.27 kg C m^{-2}). On average, the soil carbon loss in the subtropical agroecosystem was much lower than those reported in literature, as well as our initial expectations. In addition, the no-till system was capable of preserving soil carbon in the deepest soil layers. However, presently, the no-till system is losing more carbon in the topsoil at a rate greater than the soil carbon input.

Keywords: soil-geomorphology; oxisols; soil conservation; sustainability; food system; food security

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1. Introduction

Contemporary society is challenged with the crucial paradox of producing more food, fiber, and biofuel to supply for an increasing global population, especially on increasingly degraded soils and agroecosystems worldwide [1–3]. The conversion of forest and natural grassland to a cropping system is detrimental to soil carbon stock [4–6]. Opting for an intensive agricultural system can increase crop production. However, this may decrease the ecosystem services including water quality, biodiversity, and carbon sequestration. A cropland with restored ecosystem services may mitigate the effects of agriculture intensification, and guarantee sustainable development [7,8].

In the 1960s, the no-tillage system was adopted as a conservationist agricultural practice. The basic background principles of this system are: (1) avoid soil disturbance; (2) keep the residue (mulching) over the topsoil; (3) plan crop rotations (i.e., not only double crops such as wheat–soybean); and (4) contour tillage practices and soil conservation according to the terrain [9,10]. Many benefits were ascribed to the no-till system, especially when compared to conventional tillage (CT), such as enhancement of soil aggregate stability [11,12], soil organic matter improvement and carbon sequestration [13,14], and reduction of runoff and soil loss [8,15].

Soil organic matter and carbon stock are of the utmost importance to soil functions, ecosystem productivity, and soil carbon sequestration. Despite the disagreement about the capacity of the no-till system to sequester carbon [16,17], the no-till system is recognized as an agricultural conservationist practice that ensures conservation of carbon, soil, water, and sustainability of the agroecosystem [10,18].

Soil carbon is very sensitive to land conversion and can therefore be lost in a few decades in temperate regions, and in a few years in tropical regions [19–21]. Even with advances in the past few years regarding soil carbon dynamics in agricultural systems, some research priorities need to focus on long-term soil resilience on soil organic carbon (depletion or conservation), assessment of actual carbon stock in space-time, assessment of soil carbon stock beyond the topsoil limit (0–10 or 0–20 cm), and effect of soil management and soil erosion on carbon stock [6,22,23]. In addition, it is necessary to understand the carbon dynamics across the landscape, i.e., source, transport, deposition, and export [24,25]. Therefore, study of the hillslope system under long-term land conversion and the no-till system is crucial to understand the soil carbon depletion–maintenance interaction in the soil system.

We conducted this research to address some of these priorities or scarcity of studies pointed out above, particularly the long-term effect of land conversion on soil carbon stock. The objectives of this study are (1) to estimate the soil organic carbon stock on the long-term (40-year) no-till system; (2) to explore the effect of landforms on soil organic carbon redistribution; and (3) to put the local no-till system in a long-term (69-year) land conversion context through a literature review.

Herein, explanation of soil carbon dynamics on the long-term no-till system is important to evaluate the sustainability of the agroecosystem in subtropical regions, as well as to support soil conservation practices. Moreover, the study area is one of the oldest under the no-till system in Southern Brazil.

2. Materials and Methods

The study area is located at the center-south of the state of Paraná, Brazil at 1120 m (above sea level). The zero-order catchment (hollow) is around 5 ha and is located at the Agricultural Foundation for Agricultural Research–FAPA (Figure 1). The hillslopes are gently ranging from 3% to 5% inclination, while the slope is 5% along the thalweg with 270 m. The soil consists of brown aluminum Oxisols (Ferralsols are high-weathering, resulting in oxic horizon [26]) developed over basalt rock. Kaolinite is the main type of clay, followed by subsidiary gibbsite and iron oxides including hematite and goethite (clay 657 g kg^{-1}, silt 266 g kg^{-1}, and sand 77 g kg^{-1}). Additionally, the pristine horizon is rich in soil organic carbon >40 g kg^{-1} [27].

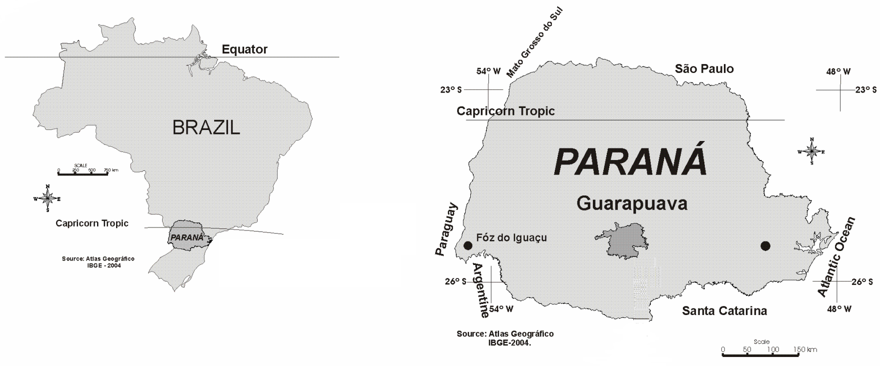

Figure 1. Study area in the context of Southern Brazil and the southern center of the state of Paraná, municipality of Guarapuava.

The annual rainfall ranges from 1800 to 2000 mm. The rain is distributed along the year (i.e., there is no seasonality), with the lowest rainfall during winter (August, 80–100 mm) and the highest rainfall during spring (October, 200–220 mm). The annual temperature is around 17 °C–18 °C. During winter (June to August), the average temperature is 13.5 °C, and during summer (December to February), the average temperature is 21.5 °C [28].

2.1. Soil Sampling

Soil samples were collected from an area with an agricultural land use history of 69 years. In addition, several experiments and case studies were revisited to put the long-term soil carbon history into context (see Table 1). The sampling area has been transited from different levels of land conversion and intensification (Figure 2). Herein, the focus is on the last phase of conversion from conventional tillage to a no-till system in a 40-year term. From 1968 to 1978 (10 years), the area was cultivated with conventional soil preparation such as plowing and harrowing. The crops were grown in simple succession (i.e., double crops), with wheat cultivated during winter and soybeans cultivated during summer [29]. Since 1978, the area has been cultivated with seeding a mulch-based cropping system (DMC), and thereafter, the no-till system was adopted. Within 40 years of cultivation, a total of 82 summer–winter harvests occurred in the area. During summer, soybean (*Glycine max*) (80%) is the most cultivated crop followed by corn (*Zea mays*) (20%). During winter, the most cultivated crop or cover crops are wheat (*Triticum aestivum*) (30%), barley (*Hordeum vulgare*) (26%), oat (*Avena sativa*) (18%), vetch (*Vicia vilosa*) (13%), and turnip (*Raphanus raphanistrum*) (13%) [30].

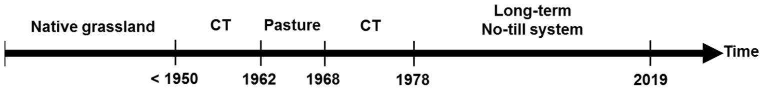

Figure 2. Long-term land use history of the study area modified from Jaster et al. (1993) [29] and the present study. Note: CT (Conventional Tillage).

A systematic grid with four transversal–longitudinal transects was used for soil sampling (Figure 3). In total, 16 trenches of 50 cm length and 60 m depth were dug. Soil samples were collected using a metal ring with 100 cm^3 (~5.03 cm of diameter and 5.03 cm of height) at the depths of 0–20 cm, 20–40 cm, and 40–60 cm for analysis of soil bulk density and carbon. A soil sample was collected from each depth (16 trenches × 3 depths × 1 sample per soil layer = 48). Through the systematic grid along the area, nine trenches were dug over convex hillslopes, while seven trenches were dug over concave hillslopes (Figure 3). Four trenches from a secondary forest in the same pedogeomorphic unit ~850 m of distance were used as a reference site. Native grass was not found near the study area to serve as a reference site. However, elsewhere, both areas of forest and native pasture might have an equivalent soil carbon stock at 0–25 cm soil depth 12.8 kg m^{-2} and 12.2 kg m^{-2}, respectively [31]. Furthermore, they were used for a general context and not for a direct comparison with the study area.

Total soil organic carbon in g kg^{-1} was determined according to the Walkley and Black method [32], and the soil carbon stock was estimated (Equation (1)) [33].

$$\mathrm{SCS} = (\mathrm{TOC} \times \mathrm{D} \times \mathrm{D})/100 \quad (1)$$

where

SCS = Soil carbon stock (kg m^{-2});
TOC = Total soil organic carbon at the sampled soil layer (g kg^{-1});
BD = Soil bulk density of the soil layer (kg m^{-3});
D = Soil layer sampled thickness (cm);
Soil carbon loss was estimated through (Equation (2)).

$$CL = \frac{CA - NT}{Time\ of\ conversion} \quad (2)$$

where

CL = carbon loss in kg C m^{-2} $year^{-1}$, CA = carbon stock in control area in kg C m^{-2} $year^{-1}$, and NT = carbon stock in no-till according to time of implantation in kg C m^{-2} $year^{-1}$.

Moreover, the soil carbon stock in the soil was used as a proxy to infer and estimate the long-term soil loss in the no-till system, since when erosion occurs, it transports sediment and carbon as well.

Figure 3. Systematic grid distribution of the soil collection points (16 trenches).

2.2. Data Analysis

In a previous study (i.e., literature survey), soil carbon content was collected up to 10 cm soil depth in the study area. Through an empirical model developed for the study area, it was estimated that the soil carbon decreases by 0.326 kg for every cm of soil depth increment (Figure 4). Overall, 75–85% of the total carbon from 0–20 cm depth is concentrated at 0–10 cm soil depth, and approximately 25% of the carbon is reduced at the deepest soil layer [30]. Here, this model was tested in two soil carbon profiles of the Southern Paraná region [12,34], and the model showed a similar soil carbon distribution pattern (data not reported). We used this model to transform (estimate) the total soil carbon content in 0–10 cm to 0–20 cm soil layer equivalent (see Table 1). This strategy was used to apply the no-till system in the local and regional contexts when the soil carbon content or stock was displayed only at the 0–10 cm soil layer.

Therefore, the no-till system was evaluated in two ways: (a) whole soil profile 0–60 cm depth, through the experiment of this study; (b) topsoil 0–20 cm depth, from the data of the present study and the data from the literature survey, as in most cases, soil carbon data were only obtained at the soil depth of 0–10 cm or 0–20 cm.

The Mann–Whitney U test was used to compare independent samples. In addition, the critical p-value established in the comparisons was unrestricted, and the maximum of $p \leq 0.05$ was adopted as significant.

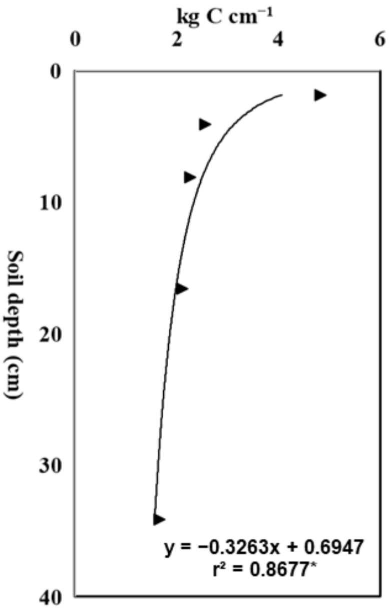

Figure 4. Soil carbon distribution in the study area according to soil depth modified from Silva (2013) [30]. (n = 3 soil profiles); * $p \leq 0.05$.

3. Results and Discussion

In this study, the soil organic carbon stock on the long-term (40-year) no-till system decreased, especially at 0–20 cm, but the carbon depletion rate was below our initial expectations, as well as that reported in the literature. Despite a long-term (69-year) conversion from grassland to a cropping system, the study area showed a soil carbon average above a critical limit.

However, we observed that landforms (such as rolling landscape) affect soil erosion and soil carbon redistribution. Hillslopes (convex sectors) are more depleted in carbon (37%) than valley bottom (concave sectors). Presently, in the study area, the soil loss was estimated around 1.13 ± 0.17 Mg ha^{-1} year^{-1}, and the long-term soil carbon loss rate at topsoil was 0.06 kg C m^{-2} year^{-1}. The local conservationist agriculture is facing a critical phase related to soil carbon conservation, particularly at the topsoil.

3.1. Total Soil Carbon and Soil Carbon Stock on A 40-Year No-till System

The forest showed a higher concentration of total soil carbon at all depths compared to no-till (Figure 5). Overall, the soil carbon decreased with respect to the soil depth (Figure 5). In the no-till system, the soil surface displayed 17% and 28% more carbon when compared to the deepest soil layers at 20–40 and 40–60 cm, respectively ($p \leq 0.05$). However, the soil carbon at 20–40 and 40–60 cm was similar. Soil carbon content exhibits great variation along the area depending on the soil depth. At topsoil (0–20 cm), the soil carbon content ranged from 15.66 g kg^{-1} to 28.51 g kg^{-1}; at 20–40 cm depth, the soil carbon content ranged from 13.66 g kg^{-1} to 24.84 g kg^{-1}; and at 40–60 cm, the soil carbon content ranged from 12.87 g kg^{-1} to 23.80 g kg^{-1} (Table S1). For the three depths evaluated, the minimum and maximum soil carbon content maintained a constant amplitude ratio of 1.8 times.

Ribas (2010) evaluated a large sample of soil carbon content (n = 6534, soil depth 0–20 cm) from the southern state of Paraná, and about 85% of the soil samples came from areas with a no-till system. Overall, the soil in this region showed a total soil carbon ranging from 22.7 to 24.7 g kg^{-1}, with an average of 23.6 g kg^{-1}. In addition, 92.6% of the samples displayed a total soil carbon lower than 29.0 g kg^{-1}. Similarly, in the Guarapuava municipality, a total of 1212 samples was evaluated. The total soil carbon ranged from 23.5 to 24.9 g kg^{-1}, with an average of 23.7 g kg^{-1} [35]. Surprisingly, in this study, the 40-year no-till system showed a total soil carbon content (23.53 ± 3.63 g kg^{-1}) such as those of regional and local soils, considering the lag time of a decade than that in the study by Ribas.

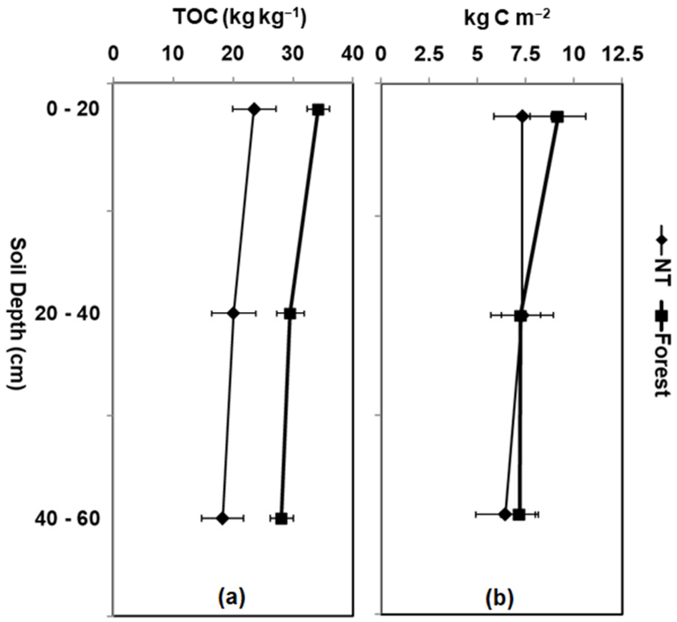

Figure 5. Total soil organic carbon (**a**) and soil carbon stock (**b**) in no-till and secondary forest according to soil depth. Note: no-till, n = 16 and forest, n = 4.

Despite a lower total carbon content (25% to 35%) compared to that of the soil forest ($p \leq 0.05$), the differences in soil carbon stock in the no-till system and forest along the profile were not significant (Figure 5). The soil bulk density in the no-till system was around 25% denser when compared to the forest soil, particularly in the deepest soil layers. The superior bulk density in the no-till system was compensated by the soil carbon stock. However, the forest showed 20% more carbon stock than the no-till system at the 0–20 cm soil layer. In contrast, at 20–40 cm and 40–60 cm, there was an equivalent soil carbon stock. Finally, considering the entire profile (0–60 cm), the no-till system showed similar soil carbon stock as the forest (Figure 5).

Here, the forest soil carbon stocks in the study area are consistent with those found in other regional studies by Sá et al. (2014) (0–40 cm, 15.9 kg C m^{-2}) and Pereira (2017) (0–20 cm, 8.72 kg C m^{-2}). Similarly, soil carbon stocks in no-till are comparable with other studies by Costa et al. (2004b) (0–20 cm, 7.34 kg C m^{-2}) and Sá et al. (2014) (0–40 cm, 13.7 kg C m^{-2}).

3.2. Long-Term Soil Carbon Stocks in No-till System: Local Context

A proper comparison of soil carbon content on a different agricultural system is fraught with difficulties, particularly due to methods of soil sampling and analysis, as well as depth assessment of soil layers [6]. Many studies have evaluated several distinct soil layers at 0–10 cm [36,37], 0–20 cm [14,35], and 0–30 cm [21,38]. Moreover, studies with soil collected at certain increment depths are typical [12,36]. During the use of the no-till system, the crop residue management causes the topsoil (0–10 cm) to be enriched with soil carbon [10,22] or even smaller depths at 0–5 cm [39]. Sometimes, in a layer of 30 cm, more than 70% of the total soil carbon could be concentrated on the first soil centimeters (e.g., <10 cm) (see Figure 3).

In Table 1, 6- to 40-year no-till systems were grouped to evaluate the carbon dynamics through periods of time. The data were obtained on the same pedogeomorphic climate landscape, as well as nearby the study area. Moreover, the local context no-till system was implemented in different phases, and several measurements were performed over time. At the yearly stage (6–15 years), the soil carbon was lower; however, at >21 years, the soil carbon in the no-till system increased by ~15% ($p \leq 0.05$). Data of soil carbon for the no-till system from 7 to 24 years were based on the topsoil (0–10 cm) [36,40] (Table 1).

The average total soil carbon (0–20 cm) in the no-till system was 23% lower than that of the forest ($p \leq 0.01$) (Table 1). In contrast, soil carbon content reached its peak at 21–25 years of the no-till system being implemented, which was similar to that of the forest. However, an absolute reduction by 12% in soil carbon stock was observed in the older no-till system (40 years) than the no-till system in the previous period ($p = 0.10$). On average, each soil cm of the no-till system was 0.412 kg C cm^{-1} lower than the forest soil (16%).

Over time, soil from the study area, i.e., the 40-year no-till system, lost 25% pristine soil carbon stock. The carbon loss was greater at the early phase (6–15 years), with the loss of 0.194 kg C cm^{-2} year^{-1}. The soil carbon loss ratio decreased drastically to 0.045 kg C cm^{-2} year^{-1} (>16 years). The soil carbon stock in the no-till system (40-year) was depleted at a rate of 0.06 kg C m^{-2} year^{-1}, summing up to a carbon loss of 2.43 kg C m^{-2}. The total organic carbon in the no-till system (40-year) was 16% lower when compared to the CT system applied before the conversion in year 1978 (Table 1).

Table 1. Context of the local long-term soil carbon dynamic in no-till system at topsoil (0–20 cm) based on the literature survey.

No-Till (Year)	**Average (Year)**	**TOC (g kg^{-1})**	**N**	**[1] TOC (g kg^{-1})**	**[2] Soil Carbon Stock**		**Source**
				(0–20 cm)	**kg C m^{-2}**	**kg C cm^{-1}**	
6–10	8	§ 34.75 ± 5.40	5	26.07	8.18	0.409	[36,41]
11–15	13	§ 31.48 ± 6.43	6	23.61	7.41	0.370	[36]
16–20	18	§ 36.83 ± 6.28	12	27.62	8.67	0.433	[36]
21–25	23	§ 40.88 ± 3.46	5	30.66	9.62	0.481	[27,34,40]
[3] 31	-	§§ 27.26	1	27.26	8.55	0.428	[30]
38	-	§§ 25.00 ± 1.26	4	25.00	7.84	0.392	[41]
40	-	§§ 23.53 ± 3.63	16	23.53	7.33	0.366	this study
Forest	-	§§ 34.72 ± 4.29	11	34.72	9.82	0.491	[29,39] and this study
[4] Conventional Tillage	-	§§ 28.00	1	28.00	-	-	[29]

Note: § (soil depth mostly 0–10 cm); §§ (soil depth 0–20 cm); [1] total soil carbon estimated for a 0–20 cm soil layer through local empirical model (Figure 4); [2] soil bulk density used to estimate soil carbon stock (no-till 0.91 g cm^{-3} and forest 0.82 g cm^{-3}); [3] composite sample; [4] soil carbon content in the conventional tillage previous to the conversion to no-till system in 1978 (composite sample).

3.3. Long-Term Land Conversion and Its Effect on Soil Carbon

Land use changes, especially the intensification of agriculture, affect the ecosystem functions and services. Soil carbon is one of the most sensible properties that responds to land use conversion and intensification [20,22,37]. The conversion of the natural ecosystem to permanent agriculture in temperate zones can cause 50% of the original organic matter loss in the first 25 years of cultivation. In a tropical ecosystem, the loss of soil organic matter can occur within 5 years of cultivation [20]. In this study, the depletion of soil carbon did not follow this pattern (i.e., time and amount).

Here, before year 1950, the area was covered by native grassland. Afterwards, it was converted to conventional tillage (year 1950–1962) and pasture (year 1962–1968). Again, the area was converted from pasture to conventional tillage (year 1968–1978). Finally, the area was converted from conventional tillage to the no-till system, which remained the soil management system since 1978. In the present study, despite being in a subtropical region, the several conversions and intensification phases of the system seem to preserve a great amount of the soil organic carbon stock. Moreover, the soil carbon loss ratio did not follow the pattern suggested in literature [20,21]. If that had happened in any land conversion phase, most of the study area should have <17 g kg^{-1} total organic carbon.

It is difficult to explain the soil carbon dynamics in the study area prior to year 1978, and this is because there is no available soil data. However, some insights are discussed. The conversion from native grassland (i.e., extensive pasture) to conventional tillage with cultivation of rice (summer) and wheat (winter) may have caused the soil carbon loss from the year 1950–1962. Guo and Gifford (2002) estimated a 59% carbon loss on this type of land use change, and an improvement of 20% when crop is converted to pasture. The conversion from conventional tillage to pasture (year 1962–1968) may yield a gain in soil carbon [19].

Moreover, the pasture in the study area experienced an improvement with the cultivation of white clover (*Trifolium repens*) and winter grasses (the type was not defined) [29]. Again, from the year 1968 to 1978, the pasture was converted to a conventional crop system, with a succession of soybean (summer) and wheat (winter). Since year 1978, the area has been cultivated using the no-till system, with cultivation of wheat and cover crops such as oat (*Avena sativa*), barley (*Hordeum vulgare*), vetch (*Vicia vilosa*), and turnip forage (*Raphanus sativus*) during winter; during summer, corn and soybean are mainly cultivated [30,42].

Since the conventional tillage conversion to no-till, several local studies report an improvement in soil quality including the increase in soil carbon and aggregate stability [27,34,40], soil porosity, soil water retention and infiltration [30,43], soil temperature decrease and crop productivity enhancement [29,36], and soil erosion reduction [44]. The benefits of this system are recognized worldwide as a conservationist system that ensures soil erosion control, as well as water and soil carbon conservation [10,45,46].

In the study area, following a long-term cultivation, the soil carbon content was slightly above the critical limit. A concentration of 20 g kg^{-1} (~2% soil organic carbon) is recognized as the critical point to soil productivity and functions (e.g., microbial diversity) [17]. Therefore, the carbon input into the soil should be superior to its loss due to soil erosion and oxidation of organic matter.

Globally, the no-till system has the potential to sequester 0.030 kg C m^{-2} $year^{-1}$ [47] in Southern Brazil at the rate of 0.068 kg C m^{-2} $year^{-1}$ [48], as well as at the rate in a site with a similar pedogeomorphic climate landscape as the study area which was 0.043 kg C m^{-2} $year^{-1}$ [13]. Lastly, in the study area, a lower rate was registered as 0.015 kg C m^{-2} $year^{-1}$ [34].

Ferreira et al. (2018) argued that areas with a predominance of soybean in the cropping system characterized by a poor soil fertility management have a smaller soil carbon recovery rate [49]. In the study area, soybean (*Glycine max*) is the most cultivated in the cropping system. Moreover, when soybean is practiced as monoculture, without cover crops, it can cause a decline in soil organic matter, especially on the labile fractions [39]. This condition could be the most detrimental scenario to soil carbon depletion, but this is not the study area case. However, if our estimation was reasonable, the soil carbon in a 40-year no-till system (0–20 cm) would have been depleted (i.e., 0.06 kg C m^{-2} $year^{-1}$) above the rate of carbon input [49].

3.4. Effects of Landforms on Soil Erosion and Soil Carbon Redistribution

Here, and in most parts of Southern Brazil, the basalt rocks form assemblages of landforms known as plateaus. Regionally, a plateau is a flat terrain; however, at a local scale (i.e., farm-land level), the basalt rocks produce a rolling landscape with a non-uniform slope (e.g., convex, straight, concave, hollow) [50] (see Figures S1 and S2). In addition, the geomorphological surface was stable for a long geological time, and the weathering operated mostly on transport-limited conditions, developing deep soils such as Oxisols and Nitisols, and soils with moderate depth such as Cambisols [51].

Consequently, no-till is usually practiced on non-uniform hillslopes. Moreover, the slope shape is prone to different shear stress due to interrill and rill initiation, as well as due to soil erosion rate. For instance, uniform and convex-linear slopes produce 3.4 to 4 times more sediment, respectively, than concave-linear slopes [52]. Therefore, in a rolling landscape, the sediment carbon redistribution occurs through a net with different transport and deposition rates.

In the study area, the hollows (zero-order catchment) are frequently activated as ephemeral streams within the year, especially during prolonged duration and a large volume of rainfall (personal observation). If the concave slope and hollows are sensible to produce convergent runoff in a basaltic plateau landscape [53], then this may affect the local soil carbon redistribution and exportation from the system as well.

In Brazil, a no-tillage system reduced the runoff and soil loss by 70% and 90%, respectively, when compared to that of conventional tillage [48]. Between the years 2001 and 2012, the conservation agriculture in Brazil reduced soil erosion by 20%. However, the national soil erosion average (>20 Mg ha^{-1} year^{-1}) was above the soil loss tolerance threshold (T value 10 Mg ha^{-1} year^{-1}) [54]. Despite the benefits of conservation agriculture, FAO global assessment indicated that the main threats to Brazilian soils are soil erosion and soil organic carbon change [55].

Soil erosion involving aggregates and particle detachment of soil mass, aggregate breakdown during transport, as well as transport and deposition is an important mechanism for lateral flux of carbon redistribution through the landscape [24,25]. In the present study, the convex slope was more depleted in carbon (15.34 to 19.80 g kg^{-1}) compared to the concave slope (20.79 to 20.43 g kg^{-1}) ($p \leq 0.05$). The soil carbon redistribution followed the rolling landscape, that is, non-uniform slopes. Similarly, the convex hillslope (15.87 to <20.57 kg C m^{-2}) showed lower carbon stock in the entire 60 cm profile than the concave hillslope (>20.57 kg C m^{-2}) (Figure 6).

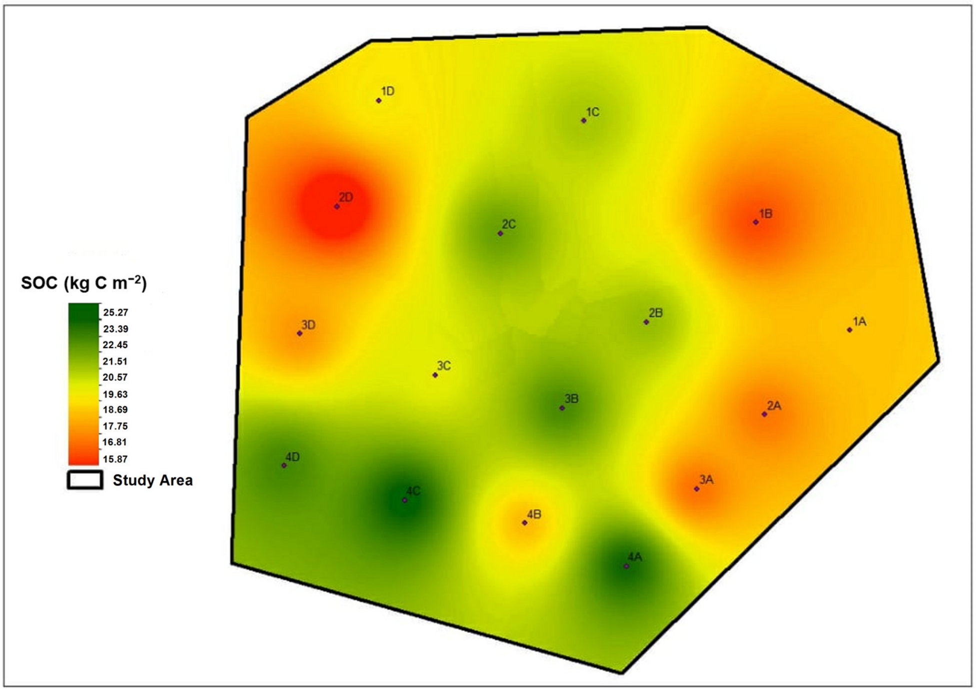

Figure 6. Effects of landforms on soil carbon redistribution in no-till system (0−60 cm soil profile). Note: convex slopes predominate in red to orange colors, while concave slopes (i.e., valley bottom) predominate in yellow to green colors.

The study area is suffering from soil erosion and lateral flux of soil carbon. The long-term soil loss during the land conversion which depletes the soil carbon is estimated at 0.06 kg C m^{-2} year^{-1}. In the southern state of Paraná, the no-tillage system showed a soil loss ranging from 0.4−1.0 Mg ha^{-1} year^{-1}, with an average of 0.73 Mg ha^{-1} year^{-1} [44]. Generally, soil loss rates under conservation tillage on moderate slopes are very low (<1 t ha^{-1} year^{-1}) [8]. We estimated that the long-term soil erosion in the study area was 1.13 ± 0.17 Mg ha^{-1} year^{-1}, considering the soil carbon content average in the forest (n = 11) as a baseline (see Table 1).

In this study, the soil loss was slightly greater than its counterpart's average [8,44]. Globally, cropland shows the highest soil carbon loss annually (0.023 kg C m^{-2} year^{-1}). Considering the upper limit for crop and grassland, the soil carbon loss may range from 0.03 kg C m^{-2} year^{-1} to 0.05 kg C m^{-2} year^{-1} [5]. The rate of soil carbon loss in the study area was above that reported in meta-analysis. However, our data were estimated within a 40-year term, while the data from Abdalla et al. (2020) were registered in the field by means of experimental plots operating no longer than 14 years.

Probably, the conservationist agriculture (i.e., no-till) in Southern Brazil is facing a critical phase, since the agriculture in the region is vulnerable to climate change, and there is a tendency of rising temperature and rainfall in the region [56]. Therefore, climate change could affect the soil erosion rates, soil carbon dynamics, and stock [6,10]. In a climate change scenario, conservationist agriculture, soil management practices, and food system adaptations (e.g., climate-smart agriculture) are needed more than ever [8,57].

Farms, stakeholders, and scientists should highlight the basic principles of the conservationist agriculture in order to avoid disturbing the topsoil (no-till); keep mulching on the ground; plan a crop rotation system and not only a crop succession (e.g., wheat–soybean); replace fallow by cover crops; and use contour tillage and terraces wherever necessary. These practices are of the utmost importance, particularly on the rolling landscape such as that of the study area and elsewhere, especially in Southern Brazil.

4. Conclusions

In this study, the objectives were to estimate the soil organic carbon stock on a long-term no-till system, and to apply it to the land conversion historical context over a rolling landscape. We observed that land conversion reduced the soil organic carbon stock at the topsoil (0–20 cm) by 20%. Overall, soil carbon has been depleted by 0.06 kg C m^{-2} $year^{-1}$ above the rate of carbon input. Soil carbon loss in the subtropical agroecosystem was much lower than our initial expectations, as well as that reported in literature. In addition, the no-till system was able to conserve soil carbon in the deepest soil layers.

Land conversion from conventional tillage to the no-till system seems to increase the soil organic carbon up to 25 years or <30 years. Possibly, the no-till system is currently losing more carbon due to soil erosion and organic matter mineralization at a rate greater than the soil carbon input. However, over the long term, the no-till system acted as a buffer, reducing the accelerated soil carbon loss, supposing the conventional tillage was kept in use.

The rolling landscape (i.e., hillslopes) affected the total soil organic carbon content and, consequently, the soil carbon stock. The convex hillslope was more depleted in carbon than the concave sectors. Therefore, at the farm or catchment level, carbon redistribution could show sites with critical limits of soil carbon content. The hollow sites are hydro-geomorphologically dynamic, and the soil conservation should be cautious of this sort of terrain. Moreover, studies about validation of the cropping system and soil carbon dynamic evaluation are mostly conducted on homogeneous or uniform slopes that are not coinciding with a rolling landscape. It is therefore difficult to extrapolate data from experimental areas in space-time to a rolling landscape.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/soilsystems7020060/s1, Figure S1. The study area MDT greyscale displaying the hollow (zero-order catchment), notice the ephemeral rill in the center; Figure S2. Aspect of the rolling landscape; Table S1. Soil Carbon Forest.

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