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Erosion Control Performance of Improved Soil Management in Olive Groves: A Field Experimental Study in NE Portugal

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Abstract: Olive groves rank among the cropping systems facing higher erosion risk in Mediterranean Europe. The adoption of erosion control soil management practices is key for reducing such risk and driving olive production towards sustainability. This field experimental study aimed to quantify the erosion control performance of improved soil management as compared to conventional soil management in olive groves of NE Portugal. The design aimed to compare the effects of introducing no-tillage (NT) to a conventionally managed (T) olive grove and those with complementing ground cover by adventitious species (NS) with a sown cover (S) and comprised four treatments: TNS (reference for conventional), TS, NTNS and NTS. Erosion microplots (4 m^2) were installed (two per treatment), recording soil loss, runoff and ground cover in seven erosion events throughout one year. The best erosion control performance was found in NTNS (low-cost improved soil management treatment) with 50% and 85% reductions in soil loss, respectively, in the annual total and in erosion events following large precipitation periods. Plots with adventitious vegetation ground cover performed better in soil loss control than the sown ones. Converting to no-tillage, as compared to sowing herbaceous vegetation to increase ground cover, proved more performant and less hazardous for improving erosion control in olive groves.

Keywords: soil loss; surface runoff; soil cover; soil tillage; ground cover management; soil conservation

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Citation: Santos, R.; Fonseca, F.; Baptista, P.; Paz-González, A.; de Figueiredo, T. Erosion Control Performance of Improved Soil Management in Olive Groves: A Field Experimental Study in NE Portugal. *Land* **2023**, *12*, 1700. https://doi.org/10.3390/land12091700

Academic Editors: Lea Wittenberg and Hanoch Lavee

Received: 26 July 2023
Revised: 23 August 2023
Accepted: 28 August 2023
Published: 30 August 2023

1. Introduction

The tradition and symbolism surrounding the olive tree are remarkable, as it has been a key part of several ancient cultures. Its fruit can be eaten whole or used to produce olive oil, a venerated product that, together with bread (wheat) and wine (vine), make up the sacred triad, which considered one of the foundations of the Roman Empire for its contribution to the dissemination of these products around the Mediterranean [1,2]. While considered one of the oldest crops in the world, the olive tree also presents a growing landscape of soil degradation in the Mediterranean region, with a mean rate of erosion measured at a field plot scale of 1.7 t ha^{-1} year^{-1}, second only to vines [3]. However, values that were six times higher were presented by Gomez et al. [4] in their study in Southern Spain, where estimates based on the Revised Universal Soil Loss Equation (RUSLE), adapted for olive groves, predicted erosion rates exceeding 10 t ha^{-1} year^{-1}, which are beyond soil loss tolerance, even under less restrictive standards [5]. These estimates highlight the threat to soil resources that prevails in the main olive-oil-producing region in the world (Andalusia), therefore questioning the sustainability of the olive chain under current farming practices.

In Mediterranean areas, olive cultivation is commonly carried out in shallow and sloping soils, where soil loss tolerance should be set at a much lower rate than that mentioned above. This, in association with non-conservative soil management practices that deeply disturb the dynamics of the soil-plant-atmosphere system, including heavy mechanization and frequent tillage operations leaving poor ground vegetation cover, potentiates soil degradation and the resulting environmental impacts. Most often, the damage is only noticed in the long term with decreases in crop productivity and, in more severe cases, the loss of soil productive potential, leading to increased desertification susceptibility [6–10].

It is estimated that more than 75 billion tons of soil are lost annually due to the erosive process across the globe, and in Europe, these losses result almost entirely (90%) from anthropic action [11–13]. In addition to losses in agricultural productivity, with major economic impacts on-site, erosion can cause water eutrophication and, in more severe cases, can lead to the siltation of reservoirs, flooding, landslides and the formation of gullies, generating major socio-environmental off-site impacts [14,15].

Besides the environmental ground, farming systems' sustainability in the olive production chain relies on social and economic grounds, where the costs of soil degradation are often missing in farm accountancy. Some authors [14,16–21] report that it is difficult to quantify the indirect financial losses due to the erosive process because these affect agricultural production and the ecosystem. For example, with the loss of soil resilience, ecosystem services such as habitat and biodiversity are very likely to suffer impacts that can profoundly alter the intra- and interspecific interactions that occur in the edaphic environment, and quantifying, in economic terms, the amount that would be lost by reducing and/or changing these relationships is complex. Thus, from an economic point of view, there is a trade-off, where it is simpler to understand the opportunity cost of what it would be possible to "save" by not investing in erosion control measures to the detriment of what would be lost, which, in this case, is soil quality.

Keeping the soil covered by vegetation is one of the principles of soil protection against erosion because vegetation reduces the impact of raindrops onto the soil surface, the runoff water velocity and the particle drag [22–24]. However, in spite of its low cost, this practice is not widespread among farmers due to negative perceptions of cover crops, especially spontaneous herbaceous vegetation, which is seen as a detrimental competitor of the main crop, and due to the lack of practical results that effectively demonstrate soil conservation gains that translate into productivity gains [25].

In this sense, as compared to model estimates, field experimental assessments of soil loss rates should be most effective in demonstrating the effects of improved soil management practices in controlling erosion. This is the case of those conducted by Gómez et al. [26] and Martínez et al. [27] on erosion plots in olive groves in Spain subjected to different soil management treatments: barley sown as a cover crop, conventional tillage and the application of herbicides for weed control. Both studies observed that herbicide application while keeping a bare soil surface generated the highest soil loss rates. Barley as a cover crop was the best-performing treatment, with conventional tillage showing intermediate results. These studies were conducted as a response to the growing awareness of the need to conserve soil in farmland, and they are part of the research effort on mastering cover crops' role in reducing soil degradation in permanent crops, as shown in a recent review [28], where the contributions and challenges to be overcome in the management of cover crops and water conservation in vineyards and olive groves are presented and discussed. However, this review also shows that information is still scarce in regard to the effects of adventitious herbaceous vegetation grown between olives on erosion control, which would be, economically, far more interesting than a sown cover. On the other hand, field research results are not commonly translated into erosion control performance indicators of a certain practice, which limits the perception of its advantage by non-technical target audiences. In fact, soil loss rates vary sharply according to local conditions, and the effects of improved soil management practices can only be perceived in relative terms by comparison with a reference, which is commonly conventional tillage-based soil management.

Gómez [29] analyzed farmers' perceptions of soil management under olive groves in southern Spain and found that most farmers understood the need to protect the soil, particularly against erosion, by using some form of cover. A smaller but significant proportion did not use practices that could make their production more sustainable because they were less concerned about the impact of erosion and other forms of soil degradation on the ecosystem. Similarly, the authors found that rainfed farmers were more reluctant to adopt cover crops because they did not see the economic benefits in addition to the added difficulty of accessing seeds.

Quantifying the costs and benefits of improved soil management through reducing tillage frequency and intensity and through ground vegetation management would certainly be helpful to change farmers' perceptions towards their adoption. The basic data for such an exercise are the erosion control performance indicators that quantify the effective reduction in soil loss (or other erosional response parameters such as runoff or sediment concentration) determined by the adoption of a certain practice. Such benefits can be translated into economic benefits and, therefore, be better perceived by farmers. Adopting improved soil management practices is key for protecting soil resources and reducing the threat to sustainability that the olive sector is facing in many Mediterranean olive production regions. This is also the case in NE Portugal, where olive oil production booms and olive groves are an important part of the social, economic and cultural landscape. Most olive groves are rainfed and grown under semiarid climates over shallow soils and in sloping areas [30,31], where the adoption of improved soil management practices is required.

In this context, the present study aimed to quantify the erosion control performance of improved soil management approaches compared to conventional tillage-based soil management approaches in olive groves in NE Portugal under field experimental conditions. The soil management improvements tested were no-tillage and herbaceous vegetation ground cover (adventitious or sown).

2. Materials and Methods

2.1. Study Area

The study was carried out in an olive grove located in Suções, Municipality of Mirandela (41°29′19.81″ N 7°14′53.2″ W) (Figure 1). The local relief is gently undulating with moderate slopes, approximately 345 m in elevation. According to the Köppen–Geiger classification [32], the climate is Csa, humid temperate with hot dry summers. Climatological normal at Mirandela weather station (ca. 8 km straight line from Suções) for the period 1971 to 2000 (the most recent published) recorded an average annual rainfall of 508 mm, with a typical Mediterranean seasonal distribution, meaning dry summers and rainfalls concentrated in fall and winter. Average annual temperature is 14.3 °C [33]. The soil is a Schist-derived Eutric Leptosol, following the FAO/UNESCO legend [34] applied in the Soil Map of Northeast Portugal [35]. In NE Portugal, these soils are generally sandy loam, which have very high rock fragment content and sub-acid and are poor in organic matter.

Mirandela ranks first among the NE Portugal municipalities in regard to olive grove area; the municipality has about 1/4 (23%, 24,400 ha) of the total area of the NE dedicated to cultivation and therefore contributes significantly to the olive production chain in the region, which, in turn, ranks second among the olive production regions of Portugal, right after Alentejo [30]. The olive grove area has expressively expanded over the last decades toward regularly spaced and mechanized plantations, with the adoption of organic or integrated farming practices still having minor representation in the region. The olive grove where the experiment was carried out, which is 20 years old, is part of that expansion. It is non-irrigated, was planted with a 7 m by 7 m tree spacing and follows conventional farm practices that include a tillage operation in fall using plow or scarifier and another in spring for weed control using a scarifier or a chain shredder.

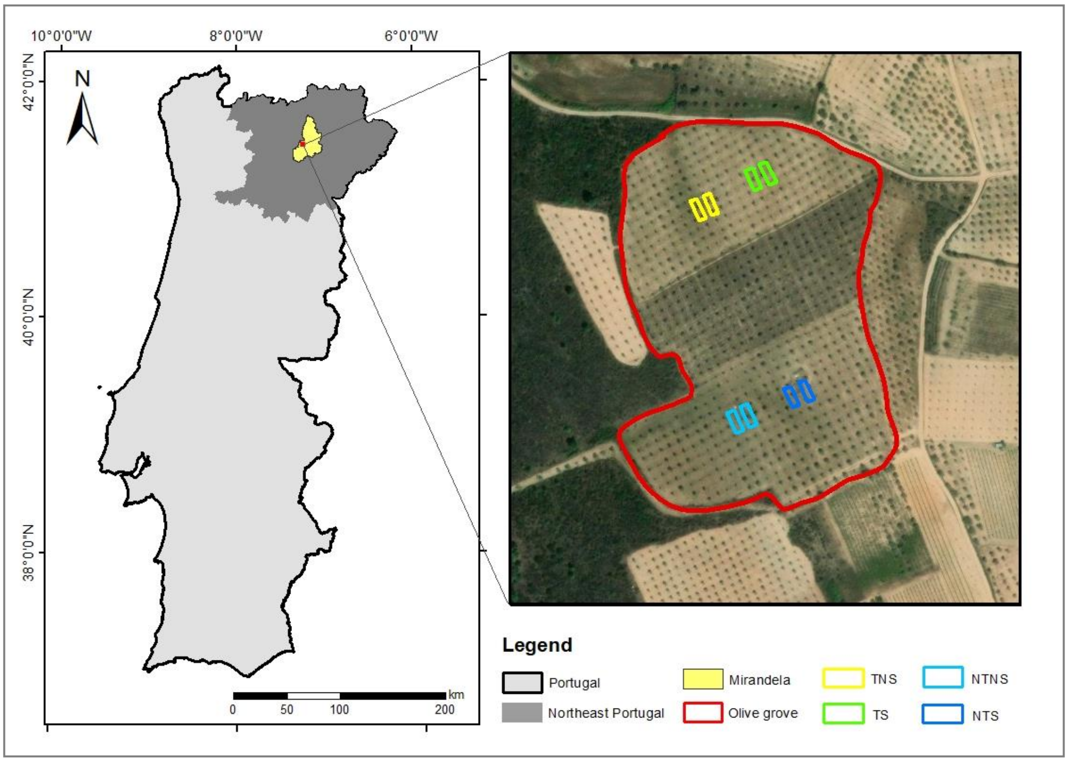

Figure 1. Location of the study area of Suçães, in Mirandela municipality, NE Portugal (**left**) and location of erosion plots (8) within the olive grove (**right**). Notes: experimental blocks (2): tilled at North and non-tilled at South; Treatments (4): TNS—tillage, not sown; TS—tillage, sown; NTNS—no-tillage, not sown; NTS—no-tillage, sown.

2.2. Experimental Design and Site Characterization

The study area is property of a private company that owns olive groves and produces olive oil in Suçães. The study area was made available to implement a research project focused on Man4Health. As such, the experimental design is justified by the project's broad objectives rather than those specific to the present paper.

The olive grove was divided into two blocks with different soil management practices: one with tillage (T) and one without tillage operations (NT), as shown in Figure 1 (right), as the northern and southern tracts of the study area, respectively. In each block, a sub-block was sown (S) with a biodiverse seed mixture (10 g m^{-2}), incorporating more than 10 species of Poaceae, Fabaceae and Asteraceae, and the other sub-block was not sown (NS). The experimental design aimed to compare the effects of introducing no-tillage on a conventionally managed olive grove and those of complementing herbaceous vegetation cover by adventitious species with a sown cover. The seed mixture composition aimed to cover a wide range of stress resistance levels (soil water, extreme temperatures, rooting constraints, soil fertility limitations) to allow us to achieve an effective ground cover under the highly variable weather conditions that characterize the Mediterranean climate.

Sub-blocks corresponded to the soil management treatments being compared: T NS—tillage not sown (taken as reference for representing the conventional); T S—tillage sown (representing a potential improvement to the conventional aimed at increasing ground vegetation density); NT NS—no-tillage not sown (representing a potential improvement to the conventional aiming to avoid tillage-borne soil structural disturbance); NT S—no-tillage sown (representing the combination of potential improvements to the conventional stated for T S and NT NS).

Sub-blocks were the spatial units adopted for the assessments or monitoring campaigns carried out in the study area. These comprised olive trees, ground vegetation cover and soil. Measurements of olive trees included diameter and maximum and minimum height of canopies and were performed with a tape on 12 trees randomly selected in each sub-block. Canopy foliage density was assessed from the interpretation of photos capturing canopy view from ground upward, taken in each selected tree (2 per tree) at fixed cardinal positions. Area covered by olive trees was calculated assuming a circular horizontal cross-section canopy shape, combined with the tree spacing arrangement and output a cover percentage of olive trees of 7%. This calculation outlines the observational evidence that soil cover by vegetation in an olive grove is very much dependent on herbaceous vegetation development in between olive trees.

Besides the botanical surveys of herbaceous vegetation (adventitious and sown) performed during the adequate season, which are not relevant to the present study, ground vegetation cover was periodically assessed, as described later in this section, for erosion plots.

For soil physical-chemical characterization of sub-blocks, a total of 72 topsoil samples were collected in the study area. In each sub-block, 6 sampling area replicates were randomly selected, consisting of the 49 m^2 square defined by 4 neighboring olive trees. The sampling scheme comprised 24 disturbed samples with soil depths of 0–10 cm for routine physical-chemical analyses and 48 undisturbed soil samples, 2 per sampling area, collected on 100 cm^3 rings at soil depths of 0–5 cm for physical testing. The soil sampling campaign was performed prior to the experiment implementation in two consecutive steps (first with disturbed samples and second with undisturbed samples) once the sub-blocks were defined in the field. Parameters analyzed on the sieved (<2 mm) disturbed samples were pH (H_2O and KCl), organic matter content and extractable P and K [36], as well as soil texture and other parameters included in Table 1. In the undisturbed soil cores collected, saturated hydraulic conductivity was determined in a closed-circuit constant head lab permeameter. As part of the lab protocols, other physical properties, such as bulk density, total porosity and water holding capacity, were also determined in the same soil cores following the hydraulic conductivity test. A summary of soil analytical data is presented in Table 1. The study area soil entirely matched the above-mentioned Eutric Leptosol characteristics, except for organic matter content, which was moderate in the study area (2.6%).

Table 1. Summary of soil analytical data of samples collected in the experimental blocks.

Parameters	**Tilled Block**		**No-Till Block**	
	Mean	**STDEV** [1]	**Mean**	**STDEV** [1]
pH H_2O	5.3	0.2	5.2	0.1
pH KCl	4.0	0.2	4.0	0.1
Soil Organic Matter (%)	2.4	0.7	2.8	0.4
N total (g kg^{-1})	1.4	0.3	1.5	0.2
Extractable P_2O_5 (mg kg^{-1})	31.0	21.5	32.4	13.5
Extractable K_2O (mg kg^{-1})	193.7	78.8	139.3	32.1
Base saturation (cmolc kg^{-1})	3.4	0.8	3.2	0.9
Exchangeable Al^{3+} (cmolc kg^{-1})	0.3	0.1	0.3	0.1
Cation Exchange Capacity pH 7.0 (cmolc kg^{-1})	7.1	0.9	8.7	2.2
Coarse sand (g kg^{-1})	367.5	23.7	439.9	80.5
Fine sand (g kg^{-1})	297.5	10.2	271.6	40.6
Silt (g kg^{-1})	214.5	21.3	173.3	36.3
Clay (g kg^{-1})	120.5	14.4	115.2	7.9
Texture class	Sandy loam			
Coarse fragments (%)	41.2	2.2	41.6	4.5
Bulk density	1.07	0.13	1.11	0.11
Total Porosity (%)	51.1	0.1	51.3	0.0
Field capacity (%)	39.8	0.1	40.9	0.1
Permeability class	Very rapid			

[1] STDEV—standard deviation.

2.3. Erosion Monitoring

Eight erosion plots were installed in pairs, meaning two replicates in the four sub-blocks, in order to evaluate soil loss (kg ha^{-1}), surface runoff (mm) and sediment concentration in runoff (g L^{-1}) under the soil management treatments defined in the experimental design. The micro-plots, which had an area of 4 m^2 (1 m wide by 4 m long), were located in the area not covered by olive tree canopy, meaning they were in the inter-row lanes, draining in line with the local steepest slope to the front edge of water and sediment collecting devices. The average slope gradients of the erosion plots were 23%, 21%, 22% and 18%, respectively, for the TS, TNS, NTS and NTNS treatments.

Metal plates were inserted in the soil-defined plots' upper and lateral boundaries. In front of each plot, a metal gutter was installed to collect sediments carried by runoff during rainfall. The gutter was protected by an openable cover that allowed collection of the trapped eroded soil particles. A plastic hose was connected to the metal tube welded in the gutter's front edge to move runoff water and sediments to a plastic tank placed downslope (Figure 2). Each instance of water and sediment collection is named hereafter as erosion event. In each event, tanks were replaced by new ones, and runoff water volume and mass of eroded particles carried in suspension were assessed indoors. Soil particles trapped in the gutter were removed and carried to the lab in pots to assess deposited sediment dry mass. In each event, the percentage of ground cover by herbaceous vegetation of the erosion plot (%SCo) was visually estimated with the guiding charts found in Dissmeyer and Foster [37].

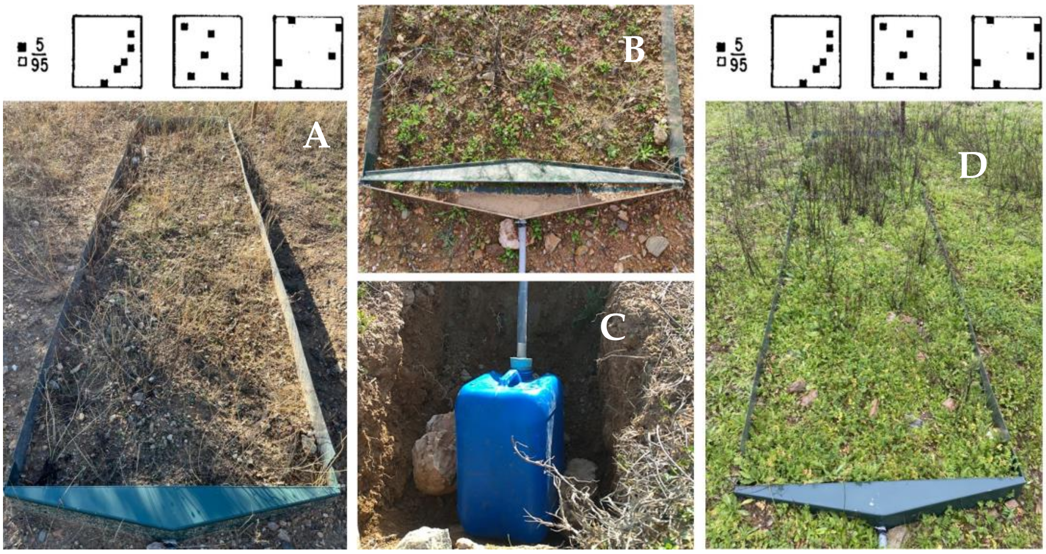

Figure 2. Erosion plots in the study area. (**A**)—TS plot with 5% soil cover (erosion event 30 September 2022). (**B**)—opening of the front device. (**C**)—reservoir designed to collect surface runoff water and sediments. (**D**)—NTNS plot with 95% soil cover (erosion event 12 December 2022).

To identify precipitation periods most likely to generate runoff and erosion and decide a collection date, daily rainfall from Mirandela weather station, made available by Institute of Sea and Atmosphere (IPMA, I.P.) [38], was monitored throughout the year. Collection dates, corresponding to erosion events, as defined above, followed significant precipitation periods and occurred on non-rainy days. Criteria adopted to decide a collection date were a cumulative precipitation since last erosion event exceeding 40 mm and, in the same period, daily rainfall exceeding 9 mm at least once. Seven erosion events were recorded over about one year (March 2022 to March 2023).

2.4. Laboratory Procedures and Data Treatment

Material collected in each erosion event was taken to IPB facilities for analysis, which consisted of determining water volume and, after decantation, determining sediment weight contained in the tank, labeled as suspended sediment. Dry weight of sediment trapped in the gutter, labeled as front sediment, was determined and summed to suspended sediment dry weight to calculate plot soil loss in the event. Sediment dry weight was determined in an oven at 105 °C for 24 h.

The calculation of soil loss, surface runoff and sediment concentration was performed based on the following expressions:

$$\text{Soil loss (SL)} = ((\text{Wss} + \text{Wsf})/\text{A}) \times 10 \ (\text{kg ha}^{-1}) \quad (1)$$

$$\text{Surface runoff (SR)} = \text{Vrw}/\text{A} \ (\text{mm}) \quad (2)$$

$$\text{Total sediment concentration (TSC)} = (\text{SL}/10)/\text{SR} \ (\text{g L}^{-1}) \quad (3)$$

$$\text{Suspended sediment concentration (SSC)} = \text{Wss}/\text{Vrw} \ (\text{g L}^{-1}) \quad (4)$$

Wss—dry weight of suspended sediments (g); Wsf—dry weight of front sediment (g); Vrw—volume of runoff water (L); A—area of the plot (m^2).

The data obtained were treated with the aid of the "Pivot Table" tool and submitted to analysis of variance (ANOVA) in Excel software (version 2307 Build 16.0.16626.20170). Means comparison for variables significantly affected by treatment was performed applying Tukey's Honestly Significant Difference (HSD) test, at 5% probability, using the calculator available on the VassarStats website [39].

3. Results

3.1. Distribution of Precipitation

The cumulative rainfall over the seven erosion events amounted to 584 mm in one year. Figure 3 highlights the character of Mediterranean climates, where rainfall is concentrated in fall and winter. In these seasons, soil cover may be poor due to either low herbaceous vegetation development during the colder months or to autumn tillage operations, which are traditional in Mediterranean farming systems and leave the soil surface more vulnerable to and less protected against concentrated rainfalls. In the study period, rainfall was concentrated from October to January. The erosion events with the highest cumulative precipitation occurred on 12 December 2022 (111 mm) and 6 January 2023 (138 mm).

Compared to the normal rainfall distribution throughout the year, which was given by the 30-year monthly averages, the monitoring period recorded a higher annual amount of precipitation (563.3 mm from 1 March 2022 to 28 February 2023, against 508.6 mm long-term average). However, the dry season, which was from late spring to early autumn, was longer than normal and received substantially less precipitation, in contrast with and compensated by the already mentioned concentration from mid-autumn until the end of winter. The annual number of days with precipitation > 10 mm in the monitoring period was approximately the same as the normal (16 against 15.3).

3.2. Soil Management Effects on Global Erosion

The average annual soil losses (SLs) were 605, 502, 350 and 252 kg ha^{-1} for treatments TS, TNS, NTS and NTNS, respectively (Figure 4). No-tillage treatments showed lower global SL than those with tillage, with a global reduction of about 46%. On the other hand, treatments where ground cover was only provided by adventitious herbaceous vegetation was shown to be more effective in reducing erosion (about 100 kg ha^{-1} lesser than the sown treatments) in both blocks, meaning that there was 17% and 28% less erosion in tilled and non-tilled treatments, respectively.

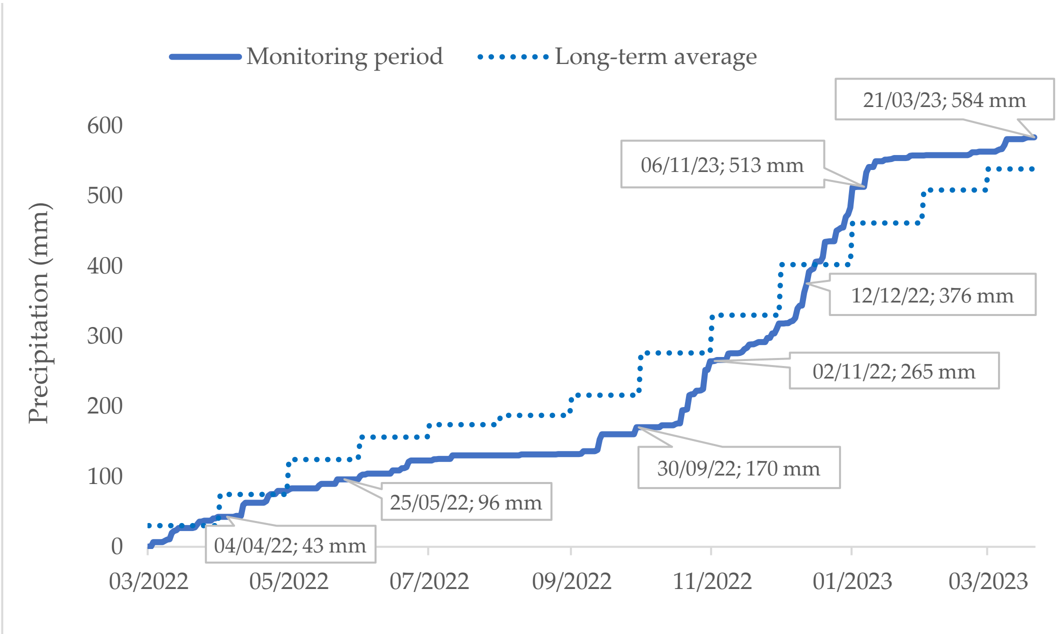

Figure 3. Cumulative precipitation during the erosion monitoring period (7 erosion events recorded in more than 13 months, dates and amounts in labels), as compared to the long-term average (1971–2000 climatological normal).

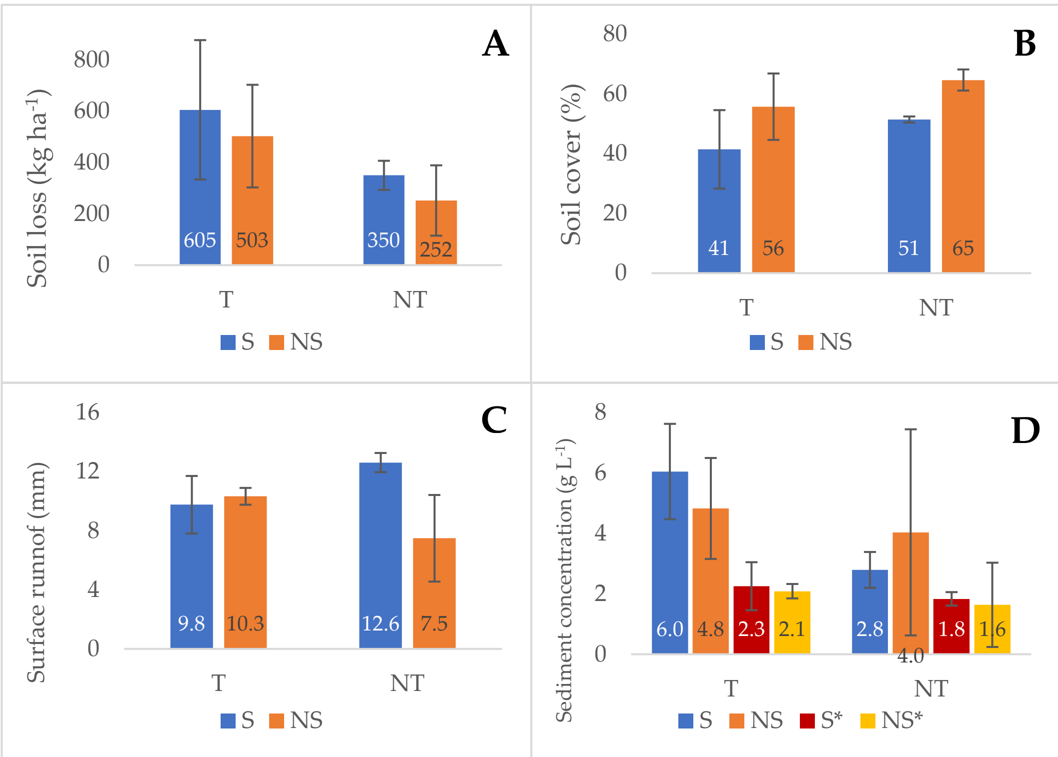

Figure 4. Annual means of soil loss (**A**), soil cover (**B**), surface runoff (**C**) and sediment concentration (**D**). Notes: sediment concentration legend marks with * refer to the suspended sediment concentration (SSC). Notes: T—treatments with tillage; NT—treatments with no-tillage; S—treatments sown; NS—treatments not sown.

The global average soil cover by herbaceous vegetation during the erosion monitoring period was higher in treatments where no sowing was performed. NTNS and TNS had 65 and 56%, respectively, and ground cover was provided only by adventitious vegetation (Figure 4). In the sown treatments, those figures were 15% lower, while in no-tillage treatments, the soil cover was, on average, 10% higher than in tilled treatments.

The surface runoff (SR) in tilled treatments was very similar in the sown and not sown sub-blocks, with 9.8 mm in TS and 10.3 mm in TNS. The surface runoff in the NTS treatment was 30% higher (12.6 mm) than in TS, while in NTNS, the runoff was 27% lower (7.5 mm) than TNS (Figure 4).

The total sediment concentration (TSC), meaning the sum of the eroded soil particles deposited in the plot front's edge gutter and the ones conveyed in suspension to the runoff tank, was highest in the tilled treatments, averaging 6 and 4.8 g L^{-1}, respectively, for TS and TNS. The no-tillage treatments showed lower averages, as NTNS had 4 g L^{-1} and NTS had 2.8 g L^{-1}. The suspended sediment concentration data (labeled with * in block D of Figure 4), as expected, showed lower averages than TSC, with 2.3, 2.1, 1.8 and 1.6 g L^{-1} for the TS, TNS, NTS and NTNS treatments, respectively. Differences between the treatments were far more subtle in SSC than in TSC, with tillage treatments being ahead of non-tilled ones and sown treatments being ahead of not sown ones. It should be noted that the treatments' effects on SSC depicted the same pattern of variation as that of SL.

In spite of the differences found in the SL, %SCo, SR, TSC and SSC global mean values, which were affected by the treatments being compared, the ANOVA results showed that the differences were not statistically significant for any of the indicated variables.

3.3. Soil Management Effects on Erosion at Event Level

Table 2 depicts the distribution of the global averages (all plots accounted for) of soil loss and soil cover for each erosion event, together with the respective precipitation characteristics (total in the event, daily maximum and number of days with precipitation $\geq$ 9 mm). The highest event soil losses were observed in the 30 September 2022 erosion event (228 kg ha^{-1}) and the following erosion event on 2 November 2022 (56 kg ha^{-1}). For these two events, the total amounts of rainfall were 74 and 95 mm, respectively, and the average soil cover percentages were 17% and 81%, respectively. The precipitation that generated the most erosive event recorded a daily peak of 15 mm and 2 days with more than 9 mm of rainfall, whereas in the second most erosive event, these figures were 27 and 4, respectively. In the former event, the daily rainfall did not reflect the actual rainfall erosivity and was seemingly more dependent on short-duration intensity than on the rainfall amount.

Table 2. Soil loss, soil cover and precipitation in each erosion event recorded during the study period.

Erosion Event Date	Soil Loss (kg ha^{-1})	Soil Cover (%)	Precipitation Characteristics		
	Global, All Plots, Averages		P [1] (mm)	Ppeak [2] (mm)	NDP [3] $\geq$ 9 mm
4 April 2022	41	38	43	9	1
25 May 2022	25	49	53	15	1
30 September 2022	228	17	74	15	2
2 November 2022	56	81	95	27	4
12 December 2022	22	45	111	19	5
6 January 2023	46	64	138	29	7
21 March 2023	10	80	71	21	1

[1] P—total event precipitation; [2] Ppeak—maximum daily precipitation; [3] NDP $\geq$ 9 mm—number of days with 9 mm precipitation or more.

Furthermore, the two events with the highest total amounts of rainfall, which were 138 mm on 6 January 2023 and 111 mm on 12 December 2022, generated significantly lower average soil losses (34 kg ha^{-1} in both), with the soil cover percentages being, respectively, 64% and 45%. The highest daily rainfall recorded during the erosion monitoring period occurred in the January 2023 event, which also had the highest number of days where the rainfall exceeded 9 mm (7). In the December 2022 event, the daily maximum recorded was much lower (19 mm), while the number of days when the rainfall exceeded 9 mm was 5, the second-highest of all the events recorded during the erosion monitoring period. The other erosion events (April 2022, May 2022 and March 2023) were described by moderate to low values of soil loss, soil cover and precipitation (total, daily peak and number of days when rainfall exceeded 9 mm). Some exceptions were the soil cover and daily maximum precipitation in March 2023 (80%), which were the second- and third-highest throughout the erosion monitoring period, respectively.

The global SL mean values per treatment presented in the previous Section 3.2 are the sum of the SL values recorded at the event level on each plot. The seven erosion events yielded a large range of SL, and the largest one (30 September 2022) had a very important contribution to total soil loss in the erosion monitoring period, with the total SL increasing from 49% to 56%, meaning that around half of the total loss in about one year was due to one erosion event. The summed contribution of the largest and the second-largest erosion events (2 November 2022) reached 63% to 76% of the total loss (Figure 5). The heavy SL concentration in a few erosion events was larger in not sown treatments than in the sown ones, with the tilled block showing a narrower difference between the sown and not sown treatments. The contribution of these two events to global SR was expressively lower than that observed in SL (40% to 52% for the two largest events and 20% to 27% for the largest one) (Figure 5).

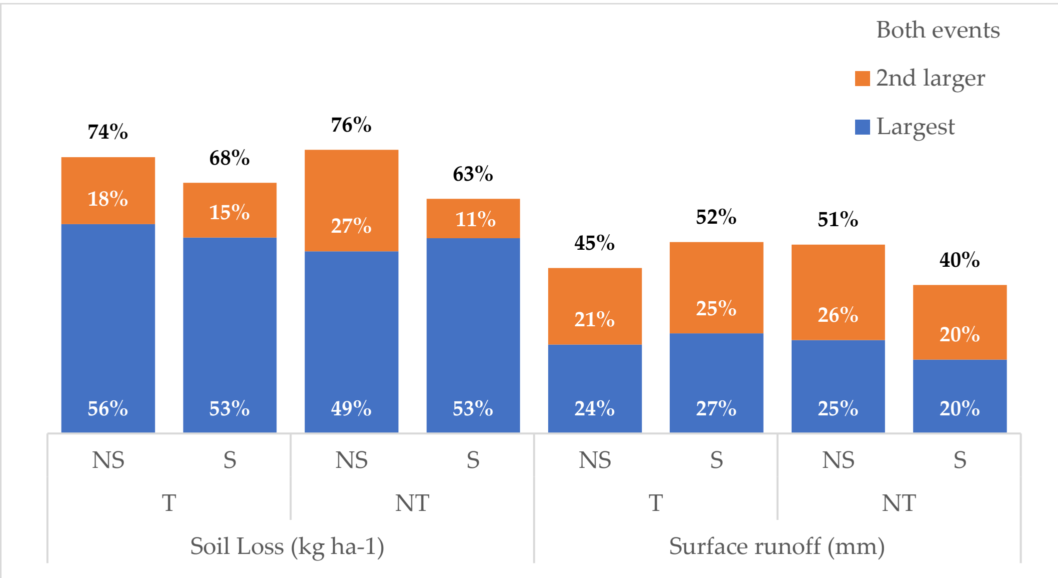

Figure 5. Relative contribution of the two larger erosion events to total soil loss and runoff in the erosion monitoring period, as affected by soil management treatment. Notes: T—treatments with tillage; NT—treatments with no-tillage; S—treatments sown; NS—treatments not sown.

For TNS, the treatment that was referenced as conventional soil management, the largest event amounted to 284 kg ha^{-1}, and the second-largest to 90 kg ha^{-1}. Although there were differences in the relative contribution of these events to the total SL, the events' ranks in terms of the SL magnitude were similar in the other treatments, meaning that there was a parallel erosional response to rainfalls in all plots, although with different magnitudes. In fact, the correlation between the event SL in TNS and in the other treatments was strong and highly significant ($p < 0.05$) (Figure 6). The slope of the regression line, with an intercept at the origin, represents, in global terms, the ratio between SL in a treatment and that in TNS. This ratio indicates that TS yielded 12% more SL than TNS, while the non-tilled treatments showed a reduction to 63% and 43% of the SL recorded under conventional soil management (TNS), with the stronger reduction being in NTNS treatment. The confidence intervals of the regression coefficient overlap the 1:1 straight line representing TNS in Figure 6, meaning that the erosional responses of the two treatments cannot be judged as statistically different. The same occurs for the non-tilled treatments in spite of the large difference in the regression coefficient for NTS and NTNS. In contrast, the upper confidence limit of the regression coefficient for NTS (0.769 at 95% probability) does not overlap with the 1:1 straight line, meaning that the tilled and non-tilled treatments responded to erosive rainfalls with significantly lower SL magnitudes than that of the tilled treatments. A soil loss data analysis at the event level also added significance to the differences between treatments that were already identified at a global level.

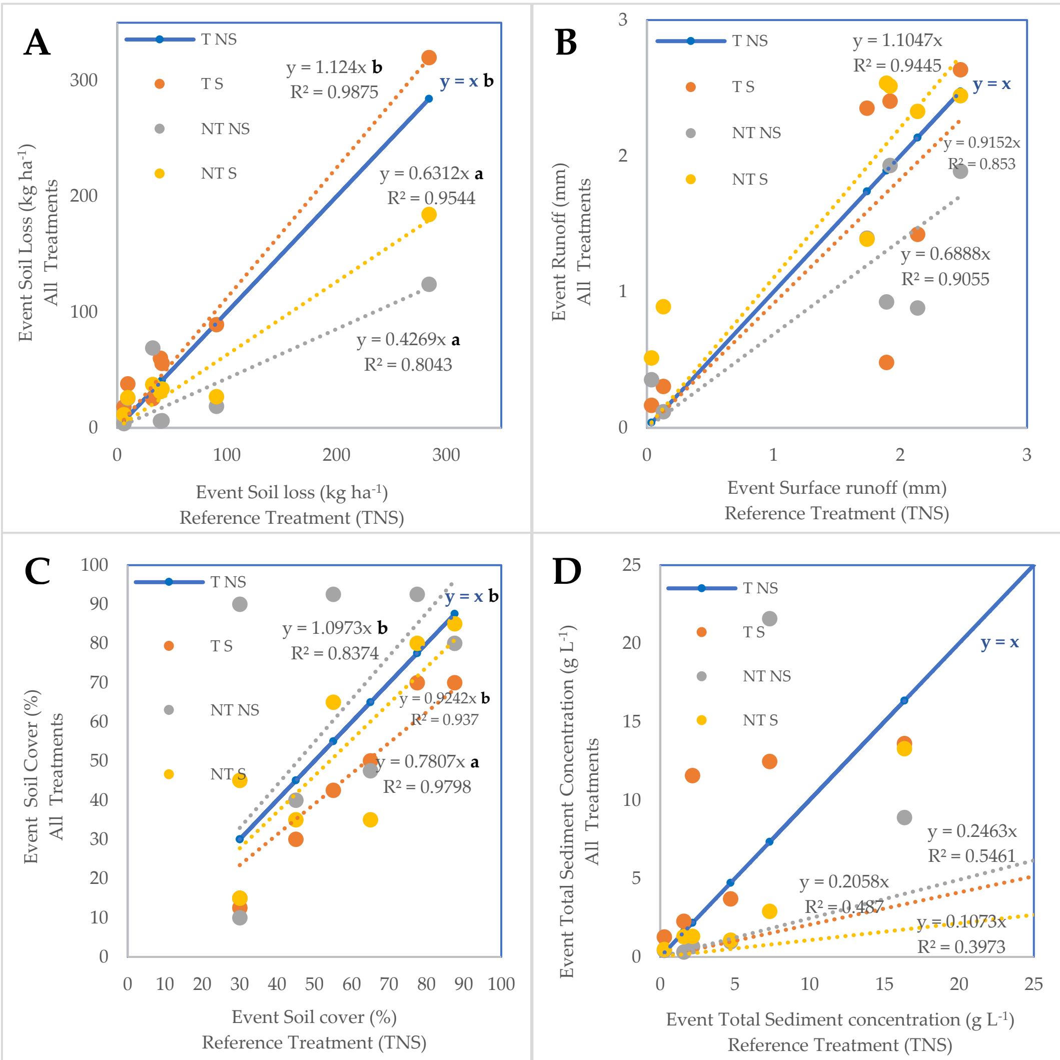

Figure 6. Event soil loss (**A**), surface runoff (**B**), soil cover (**C**) and total sediment concentration (**D**) under different soil management treatments as related to the reference treatment representing conventional soil management (TNS). Notes: different letters following the regression equations highlighted in bold indicate significantly different regression coefficient (at 5% probability); T—treatments with tillage; NT—treatments with no-tillage; S—treatments sown; NS—treatments not sown.

Although the ranks of the treatments are the same for event soil loss and surface runoff (Figure 6), the treatments are not statistically discriminated in the latter case. In fact, the confidence intervals of the regression coefficients of the fitted linear functions describing the relation between each treatment and the reference for conventional soil management all overlap. As is the case of the global results for the erosion monitoring period, NTNS imposed the most expressive reduction in runoff as compared to the conventional treatment (31% lower). The soil cover at the event level in the conventional soil management treatment is also well and significantly correlated with the same variable recorded in the other treatments throughout the erosion monitoring period. A significantly lower regression coefficient was obtained in TS compared to the remaining treatments, for which their confidence intervals overlap. Figure 6A–C depict the linear functions fitted to event data that are statistically significant ($p < 0.05$), with determination coefficients that range from 0.860 to 0.988. This demonstrates a consistent and parallel plot response to rainfall throughout the erosion monitoring period, as well as a consistent and parallel ground vegetation cover response to the prevailing weather conditions in both cases that were affected by the soil management treatment. On the contrary, the total sediment concentration in runoff throughout the experiment (Figure 6D) did not show important differences between treatments, so poor and non-significant linear fits were obtained when relating the conventional treatment to the other three treatments.

Two consecutive events in late autumn–early winter (12 December 2022 and 6 January 2023) recorded significant differences between treatments in regard to soil loss, soil cover and total sediment concentration (Table 3). These events recorded the highest amounts of cumulative precipitation, 111 mm and 138 mm, respectively (Table 2). No statistically significant differences between treatments were found for SR and SSC. Also, in none of the other five events did ANOVA indicate significant differences between treatments for any of the parameters evaluated.

Table 3. Results of the two-factor analysis of variance performed for the parameters evaluated per erosion event (*p*-values for tested factors are highlighted in bold, if significant, $p < 0.05$).

ANOVA: Two-Factor with Replicates										
Erosion Events		**Parameters**								
		Soil Loss			**%SCo**			**Total SC**		
P (mm)	**Date**	**T**	**S**	**I**	**T**	**S**	**I**	**T**	**S**	**I**
		***p*-Values**								
111	12 December 2022	**0.009**	**0.025**	0.347	**0.0005**	**0.002**	**0.026**	**0.005**	**0.010**	**0.016**
138	6 January 2023	**0.018**	**0.045**	0.778	**0.005**	**0.020**	0.230	**0.026**	0.064	0.678

P—precipitation; T—tillage effect; S—sowing effect; I—interaction effect.

Figure 7 relates soil loss to soil cover percentage for the two events with the highest values of accumulated rainfall. There was a strong correlation between the two variables ($R^2 = 0.93$) in both events. The typical negative exponential function relating the two variables best fit the data, despite differences in the function parameters. In short, the losses due to the erosive process decreased as the soil cover increased.

The coefficient of the exponential function fitted to the data of the erosion event of 23 January (Figure 7) indicated that the soil loss for bare soil conditions would be 510 kg ha^{-1}, a value that represents the potential erosional response of the soil of the experimental area to rainfall that occurred prior to water and sediment collection on the mentioned date (138 mm in total). The average soil loss observed was 34 kg ha^{-1} (Table 2), which means that only 6% of the erosive potential actually occurred under the rainfall conditions of this event, outlining the high protective capacity of the herbaceous vegetation cover (64%) in this erosion event. The average soil loss computed for the immediately preceding event (22 December) was the same, although the cumulative rainfall was 30 mm lower. Also, the soil cover was lower (45%) (Table 2), resulting in much lower soil protection, as indicated by a much higher proportion of the erosion potential being actually observed, compared to that found in the subsequent event (33% of the coefficient of the exponential function, Figure 7).

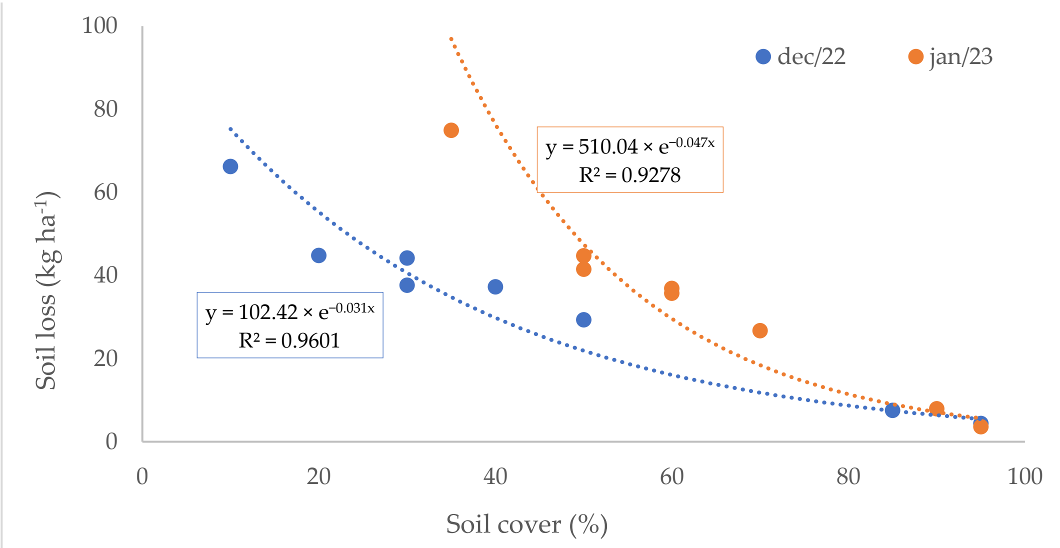

Figure 7. Relationship between soil loss and soil cover on 12 December 2022 (blue line) and 6 January 2023 (orange line).

Figure 8 depicts the means of SL, %SCo and TSC for the events that showed statistically significant differences between treatments in those parameters. As already mentioned, the SL global average (all plots accounted for) was the same in both erosion events. However, treatments' erosion responses were sharply different, with NTNS recording significantly lower values compared to the other treatments and a SL reduction of 85% in comparison with the reference conventional soil management (TNS). On the other hand, the highest SL values were recorded in the TS treatment and were significantly higher than in all other treatments throughout the January 2022 event (44% higher than NTS).

Soil cover changes between the two consecutive events indicated a high growth rate of herbaceous vegetation, which was seemingly associated with high soil water availability due to the large amounts of precipitation that fell during that period. NTNS treatment plots had the highest %SCo, which was significantly higher than all other treatments and steadily high during both events. Compared to TNS (the reference conventional soil management), the %SCo in NTNS was 60% and 38% higher in the two events, respectively, illustrating in practice the effects of tillage on ground vegetation development. Not sown treatments showed a much larger soil cover in that period of the year compared to the sown treatments (doubled in the December 2022 event and globally 35% higher in the January 2023 event).

The total sediment concentration in runoff followed the same pattern of differences between treatments as soil loss, with TS treatment showing the highest TSC in both events, significantly higher than in all other treatments. NTNS recorded the lowest TSC in both events, representing 30% and 18% of TSC in the reference for conventional soil management (TNS) during the December 2022 and January 2023 events, respectively. Not sown treatments were more efficient than the sown ones in limiting particle entrainment in runoff, as TSC in the former was globally 30% of that in the latter (for both tilled and non-tilled treatments and during the two events combined).

In summary, during the two erosion events (Figure 8) that best expressed the different erosional responses to erosive rainfalls affected by the soil management treatments under testing, the soil cover by herbaceous vegetation was key to determining the soil loss and the total sediment concentration in runoff. Additionally, using no-tillage treatments, avoiding disturbances determined by implemented actions in and machinery traffic over the topsoil and the limiting herbaceous vegetation clearance at the time of the operation output a significantly lower soil loss and total sediment concentration than the tilled treatments. Not sown treatments showed higher soil cover and lower soil loss and total sediment concentration in runoff than the sown ones. Adventitious vegetation that was partially disturbed and reduced by mechanized seedling operations performed in spring 2022, alone or combined with a prolonged soil water shortage due to below-normal precipitation during the dry season, generated poor plant emergence and a low growth rate in the early stages of development, which may have contributed to the differences between treatments in soil cover observed during the erosion monitoring period.

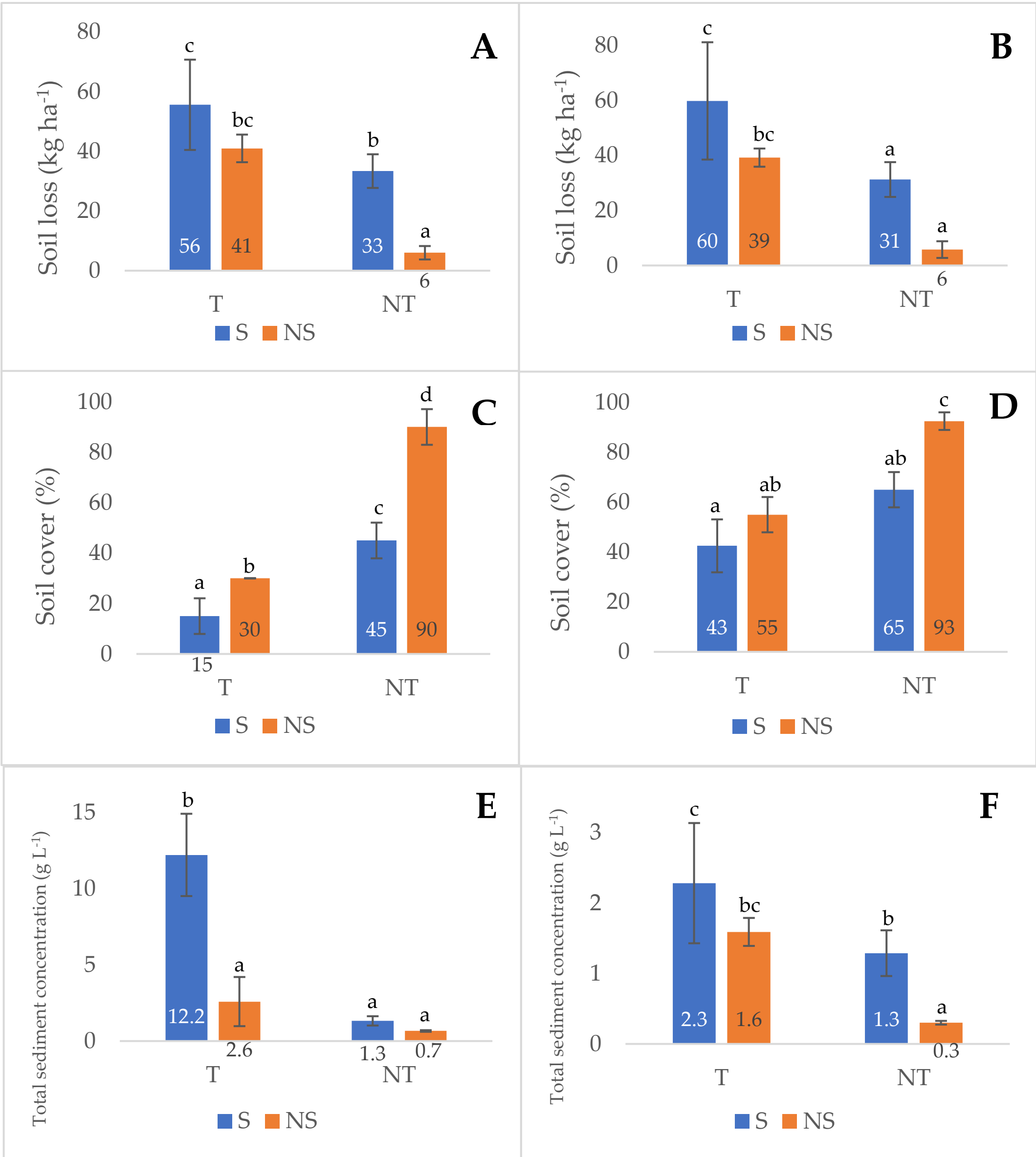

Figure 8. Mean values of soil loss, soil cover and total sediment concentration for the erosion events of 12 December 2022 (**A**,**C**,**E**) and 6 January 2023 (**B**,**D**,**F**). Notes: different lowercase letters indicate a statistical difference according to Tukey test ($p < 0.05$); T—treatments with tillage; NT—treatments with no-tillage; S—treatments sown; NS—treatments not sown.

4. Discussion

4.1. Soil Management Effects on Global Erosion

The soil loss measured over about one year of records reached a maximum of 600 kg ha^{-1} in 4 m^2 tilled and sown microplots. This is a low rate when considering the 2-ton ha^{-1} year^{-1} soil loss tolerance defined for non-renewable soil substrate, as is the case of the study area [40]. This tolerable rate is far higher than the range of soil formation rates, which are between 300 and 1400 kg ha^{-1} year^{-1} for most of Europe [41]. Soil loss rates measured in the present study (250–600 kg ha^{-1} year^{-1}) mostly fit within the range of soil formation rate mentioned above and did not surpass soil loss tolerance. However, the study area soil is shallow with moderate to low organic matter content, indicating the need for improvements in soil quality that recommend soil loss below the range of tolerance, as was the case of the non-tilled not sown soil management treatment tested. Gómez et al. [26] and Martínez et al. [27] reported much higher soil loss rates in olives groves under different soil management in Southern Spain. In both studies, values of soil loss of 0.8 to 6.9 t ha^{-1} year^{-1} [26] and between 1.0 to 40.7 t ha^{-1} year $^{-1}$ were observed [27].

In a context similar to the experiment, namely permanent crops (vineyard) on sloping Leptosols in the same region, annual rates lower than 0.5-ton ha^{-1} were recorded in a long-term experiment [42]. Such rates could only be explained by the soil's very high rock fragment content and cover, greatly reducing the splashed particle availability for entrainment due to the low proportion of the exposed soil surface area, reducing the runoff amount and overland flow velocity due to the soil surface roughness and, consequently, increasing infiltration and reducing the transport of eroded particles [43]. Furthermore, a faster particle exhaustion driven by wash occurs in soil surfaces with high rock fragment content, which leads to steady, very low erosion rates in the long run on such surfaces [44]. The high mass percentages of coarse fragment contents reported in Table 1 actually correspond to a larger rock fragment volume percentage (59%) and cover percentage (76%), according to Figueiredo [45].

Erosion studies in olive groves commonly report the highest degree of surface soil degradation in the Mediterranean region due to the limited vegetation cover, which tends to be realized only by canopies under conventional soil management. The result is large poorly covered space between the trees that is completely exposed to erosive rainfalls, with potentially or actually high losses of soil and organic matter and, consequently, of nutrients and water [46–49] (Figure 9). However, Fleskens and Stroosnijder [50] summarized the causes contributing to the common low soil loss rates found at the field erosion plot scale, among which rock fragment cover and content play major roles. This is a common characteristic of Mediterranean sloping olive groves where soil contains high rock fragment contents on the surface and in the topsoil, strongly limiting interrill erosion. In cases where rainfall generates large runoff amounts, according to the slope and hydrological contribution area, the overland flow shear stress over and unvegetated and tillage-disturbed soil may develop linear erosion features such as rills and gullies [51,52] (Figure 9). Linear erosion processes determine much higher soil losses than those recorded in the present research, whose experimental setup, namely the erosion plot size, was meant to measure interrill erosion. In the case of either interrill or linear erosion processes, few events or even a single erosion event can generate most of the soil loss each year, as was found in the Suçães study area and corroborated by other studies on permanent crops in NE Portugal. For example, in steep, sloping vineyards, ten-year averages of 39% and 62% of the annual soil loss occurred in the major erosion event of the year and in the two most erosive ones, respectively, and these figures rose to 49% and 86%, respectively, in the year with the maximum annual soil recorded in ten years [53].

Although no statistically significant differences were found between treatments for any of the parameters assessed, the overall results suggest that spontaneously formed vegetation cover had the best effects in terms of soil cover (NTNS and TNS) and that treatments without tillage outperformed those with tillage in terms of soil loss (NTNS and NTS). A 50% efficiency in soil loss reduction was observed for the NTNS treatment compared to the conventional (TNS), and 42% efficiency was observed for the NTS compared to the TS. An overview showing how the reduction of activities that negatively affect the soil, such as excessive tillage, heavy mechanization and low vegetation cover, highlighted the potential to reduce soil losses [54–58]. This information can be very positive for the agricultural environment, as it would allow lower economic expenditure by farmers, who tend to be very reticent about investing in soil conservation measures unless they have subsidies [25]. The concern here is directed toward the management of inter-row soil vegetation, which needs attention when it begins to consume too much water. In addition, it is important to ensure that the system does not enter self-management and develop levels of occupation of the area that are very difficult to control [17,59,60].

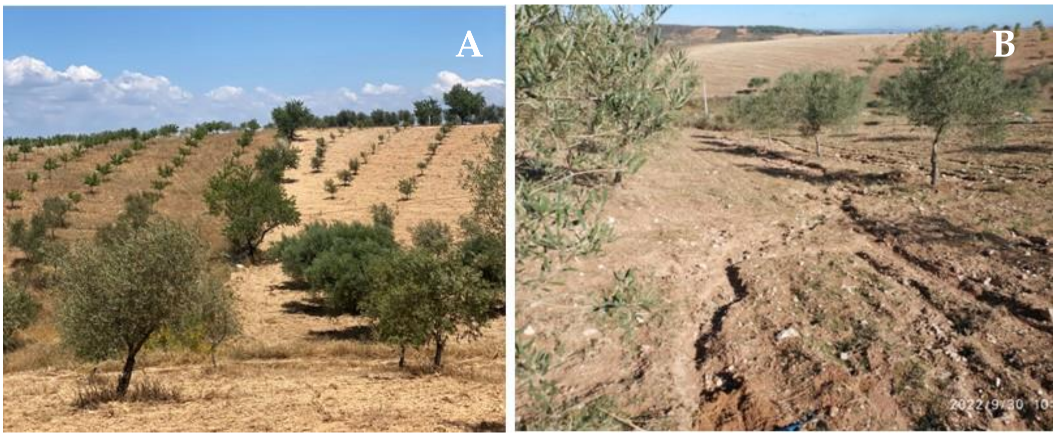

Figure 9. Contrasting permanent crop fields in the study area: well-developed ground cover by herbaceous vegetation (**left**) beside bare soil with ground cover removed by tillage (**right**) (**A**) and rills in a bare tilled soil (**B**). Notes: photos taken in the study area in summer 2023 (**A**) and following the largest soil loss event (22 September) (**B**).

From data found in the studies by Gómez et al. [26] and Martínez et al. [27], the soil loss reduction efficiency of the soil management option tested by these authors (barley as a cover crop) was estimated to be 72% [26] and 64% [27], displaying the better performance of sown cover (under no-tillage) compared to that obtained in the present study. It should be stressed that the soil loss rates recorded in these studies were globally much higher than those found in the present study, where the reference treatment for conventional soil management (TNS) recorded about 0.6 t ha^{-1} $year^{-1}$, as already presented above, against 2.9 and 5.7 t ha^{-1} $year^{-1}$, respectively, for the two above-cited studies.

Analyzing the sediment concentration can help in appraising the magnitude of soil particle entrainment due to precipitation. The accumulation and transport of sediments, mainly in suspension, over long distances from the eroding source causes great damage to aquatic ecosystems, especially during large rainfall events associated with soils with high susceptibility to erosion, which can cause the siltation of reservoirs, the eutrophication of water bodies and the contamination of different forms of aquatic life, in addition to economic damage [61,62]. The correlation between the sediment concentration and surface runoff in the treatments considered in the present study was poor. This finding is consistent with that observed by Merchán et al. [61], who concluded that suspended sediment concentration is seasonal, highly variable and influenced by large rainfall events. Tian et al. [63] observed that sediment concentration is highly correlated with runoff but also strongly influenced by rainfall and that subtle changes in some relationships between variables may occur depending on the period of the year considered. However, both authors observed the influences of agricultural land use and practices on sediment concentration, which are corroborated by the present study results, where higher SC values (total and suspended) were found in treatments with tillage.

4.2. Soil Management Effects on Erosion at Event Level

Erosion rates are influenced by several factors, such as soil type, climate, topography and land cover and use and encompass ecological disasters [3,64]. The production and concentration of sediments are also influenced by variables such as soil moisture, rainfall duration, intensity and surface runoff, among others [63,65]. Despite the high variability of the factors influencing the erosion process, in general, arable land represents the highest soil losses by erosion [66], and when the soil is bare, the rates of interrill and rill erosion are higher [3]. Thus, there is a greater accumulation and transport of sediments that are exported to other locations and cause negative environmental impacts [61].

The increase in SL and TSC rates and the decrease in %SCo in TS and TNS treatments are directly related to tillage, which exposes organic matter, stimulates its mineralization and reduces the concentration of nutrients, in addition to disturbing soil structure. A disturbed soil structure affects the shape and architecture of herbaceous vegetation root systems that are also important for soil protection [67,68]. Therefore, the soil is unprotected and needs much more time to restore vegetation growth, lower cover percentages are reached and, consequently, high soil loss rates may occur [69,70]. In fact, the susceptibility of soil particles to transport by runoff increases with the degree of soil disturbance, as found in the present study, where soil disturbance is represented by tillage. Such a result confirms that of Merchán et al. [61], who observed an increase in sediment concentration with the intensity of agricultural land use and practices.

The exponent of the fitted functions that relate SL and %SCo (Figure 7) is at the upper end of the range of values found in the literature. For example, Wischmeier and Smith [71] give a value of -0.035. In Renard et al. [72], values of the order of -0.025 are found. The higher values are usually found for stony soils and/or arid areas (see e.g., [43]), which fit well with the local study area conditions (semi-arid Mediterranean climate and soils with high rock fragment contents). Relating this information to the results obtained in this study and also considering the trends observed for SL and %SCo, the overall picture shows a reduction in the transport of eroded particles in the NTS and NTNS treatments. Even for the TS treatment, which presented the highest TSC values, there was a 90% decrease between the erosion events in question, which was justified by the increase in soil cover. This is considered a positive aspect, as it shows that there was a greater resistance of the soil to the drag of particles, even with the increase in rainfall. Therefore, the parameters observed are responsive to soil conservation measures, as was also noted by Cerdà et al. [73] in their research on the potential of weed cover in olive groves in Spain.

Among the factors associated with soil cover for erosion control, at least half of the reduction in erosive processes in pastures can be attributed to the contribution of living roots [74]. Root systems favor the creation of a complex soil environment with beneficial interactions because root exploration of the soil volume promotes positive effects on living biota, porous architecture and soil aggregation, thus favoring a water infiltration increase and the reduction of surface runoff and sediment concentration [67,75–78].

The results obtained on the consecutive dates and the interpretation of the possible causes for the greater or lesser susceptibility of the soil to losses are in line with what was revealed by some authors [67,79,80]. They explained that conventional systems (TNS and TS), that is, systems in which there is a high degree of soil disturbance due to constant tillage, are most likely to suffer losses due to erosion. In contrast, the no-till system (NTNS and NTS), where soil disturbance is minimal and the topsoil remains in place, can be very effective in reducing surface runoff and the amount of sediment transported by water.

The results of the present study can provide a starting point for improving soil management and conservation in olive groves, despite the continuous soil disturbances associated with farm management and operations that prevail in permanent cropland. A balance should be set between soil management techniques and soil conservation techniques to achieve the more efficient and lasting use of the scarce soil resources available. In this context, soil cover by herbaceous vegetation for as long as possible during the crop cycle should be encouraged through conservation instead of conventional soil management, reducing tillage to on that which is essential.

While olive trees represent a crop that is well-adapted to regional soil and climatic constraints [30,31], they also represent the current unsustainable scenario of soil degradation induced by conventional soil management practices [10]. Such a scenario requires a shift in farming purpose and focus that will effectively allow us to protect and improve the soil quality. The results show that soil cover, combined with reduced soil disturbance, can be key to mitigating erosion processes.

5. Conclusions

Although it can be considered common sense in terms of scientific and technical grounds, no-tillage treatment has not yet been widely adopted in actual olive growing systems. In this sense, our experimental results confirmed the basic hypothesis that soil loss and surface runoff rates are, as expected, lower in non-tilled plots compared to those under conventional tillage-based soil management. On the contrary, the hypothesis that sowing herbaceous vegetation in a large proportion of area not protected by olive trees canopy would improve soil cover and, as a result, contribute to reducing soil loss and surface runoff, was not confirmed. In fact, sowing is hazardous in Mediterranean environments, as the emergence and growth of herbaceous vegetation are very much dependent on rainfall seasonal distribution, which shows very high inter-annual variability. In this context, managing adventitious herbaceous vegetation in olive groves is seemingly a more effective and less costly option.

The global performance of no-tillage plots demonstrated a 46% soil loss reduction (50% in the not sown plots), halving the erosion risk in olive groves when converting from conventional to no-tillage soil management. The performance was considerably higher during erosion events associated with higher amounts of rainfall in late autumn and winter, when non tilled plots reached a 60% reduction in soil loss, while in the not sown plots, the reduction was 85%. This research outcome is encouraging, as it indicates the high performance of no-tillage soil management in the critical erosive season in Mediterranean agri-environments.

Conservation soil management practices were far more effective in reducing soil loss than in reducing surface runoff. For the Mediterranean environment, characterized by systematic summer soil water shortage, this should be taken as an important difference, meaning that the performance indicators obtained for soil loss should not be expected for runoff or for soil water storage purposes.

Author Contributions: R.S. was in charge of the implementation of the research carried out whose results are the object of the present manuscript, performing field and lab tasks, treating data and writing the draft paper; T.d.F. designed the experimental research, participating and supervising all associated tasks, sketched the elaboration of the manuscript, wrote parts of the manuscript and revised the draft version; F.F. contributed to the design of the experimental research, participating and co-supervising all associated tasks; P.B. contributed to the design of the experimental research and, as PI of the project that supported the experiment, made available the means to carry out the research; A.P.-G. gave scientific support to the design of the experiment and for sketching the manuscript elaboration; T.d.F., F.F. and A.P.-G. are supervisors of R.S., a UDC PhD student at CIMO. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for the financial support of the research carried out and of the publication of this paper, respectively by project "Man4Health—New management strategies in olive groves for improving soil health and crop yield", NORTE-01-0145-FEDER-000060, and by CIMO—Centro de Investigação de Montanha, through UIDB/00690/2020 funding. Authors are also grateful to the Foundation for Science and Technology (FCT, Portugal) for the financial support through national funds FCT/MCTES (PIDDAC) to CIMO (UIDB/00690/2020 and UIDP/00690/2020) and SusTEC (LA/P/0007/2020). Renecleide Viana dos Santos thanks the national funding by FCT, the Foundation for Science and Technology, through the individual research grant 2022.13246.BD.

Data Availability Statement: All relevant data is already presented in this article.

Acknowledgments: The authors would like to thank their collaborates (Cristiano Santos, Brenda Bueno, Yumi Munetiko, Ana Caroline Royer, Tamires Bertocco, Arthur Janoni Lima, Israel Santos, Leonardo Alves and Eduardo Cattuci) for their support in field work and sample collection, as well as for helping with lab sample treatment.

Conflicts of Interest: The authors declare no conflict of interest.

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