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Article

Short-Term Impact of Tillage on Soil and the Hydrological Response within a Fig (*Ficus Carica*) Orchard in Croatia

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Abstract: Tillage is well known to have impacts on soil properties and hydrological responses. This work aims to study the short-term impacts of tillage (0–3 months) on soil and hydrological responses in fig orchards located in Croatia. Understanding the soil hydrological response in the study area is crucial for soil management due to frequent autumn floods. The hydrological response was investigated using rainfall simulation experiments (58 mm h^{-1}, for 30 min, over 0.785 m^2 plots). The results show that the bulk density was significantly higher 3 months after tillage than at 0 and 1 months. The water holding capacity and amount of soil organic matter decreased with time. The water runoff and phosphorous loss (P loss) increased over time. The sediment concentration (SC) was significantly higher 3 months after tillage than in the previous monitoring periods, while sediment loss (SL) and carbon loss (C loss) were significantly lower 0 months after tillage than 3 months after tillage. Overall, there was an increase in soil erodibility with time (high SC, SL, C loss, and P loss), attributed to the precipitation patterns that increase the soil water content and therefore the hydrological response. Therefore, sustainable agricultural practices are needed to avoid sediment translocation and to mitigate floods and land degradation.

Keywords: soil properties; erosion; nutrient loss; undeveloped soil

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1. Introduction

Historically, tillage has been used as a soil management practice for various reasons. In Mediterranean permanent plantations, tillage is often used to control weeds and prevent competition for water by undesirable plants [1,2]. Tillage reduces soil compaction temporarily [3], but with soil consolidation, soil compaction increases over time [4,5]. However, tillage has some detrimental impacts on soil properties and hydrological responses [6–10], enhancing land degradation [11], such as aggregate breaking and exposure to the air as aggregates entrap soil organic matter (SOM). Aggregate exposure to air increases microbial activity and mineralization, enhancing SOM losses through CO_2 emissions [12–14]. For instance, tillage especially affects topsoil SOM [15], decreasing root biomass [16], water-extractable SOM [17] and nutrient availability (including soil phosphorous, P) [18,19]. Overall, tillage reduces soil quality [20].

Tillage alters the soil structure and decreases the aggregate size. Intensively tilled soils are more prone to consolidation, compaction, and surface crust [21]. Tillage induces temporal changes in the bulk density (BD), structure, and differential porosity, affecting hydrological properties [22–26]. Shortly after tillage, soils have a high water storage capacity, which decreases during re-compaction [27]. The soil pore system is modified by tillage, which creates large macro-pores that are temporally unstable and susceptible to compaction [28,29]. The hydrological response of tilled soils is tied to soil structure [16,19].

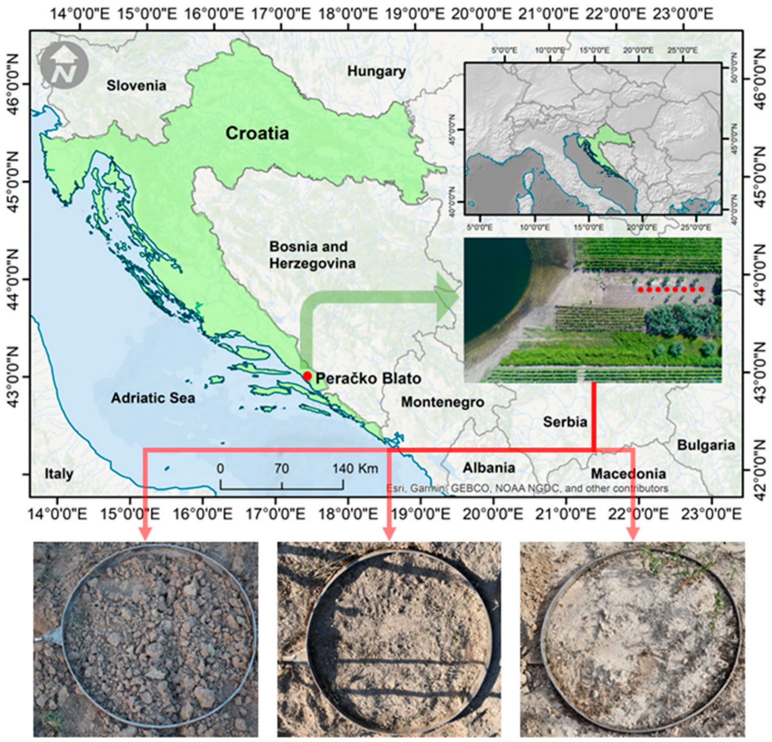
So far, the literature has shown that tillage strongly modifies the soil system and has residual effects in the following weeks [30]. In this context, it is clear that overland flow and erosion are tied to soil properties and their spatial and temporal variability [31–34]. Previous research focusing on soil erosion was carried out in cereal croplands [3,35], vineyards [11,31,36], and olive [37,38], avocado [39], citrus [40], almond [41], persimmon [42], apple [43], and apricot [44] orchards. Nevertheless, to our knowledge, no study has been carried out in fig orchards, which is an essential issue since these types of orchards are traditional crops in the Mediterranean region [45,46].

This study aims to assess the short-term impacts of tillage on soil properties and hydrological response in a fig orchard installed in young and underdeveloped soils with very high calcareous content. Therefore, the current work is highly novel and relevant for understanding the impact of tillage on land degradation in this type of soil.

2. Materials and Methods

2.1. Study Area, Climate, and Soil Properties

The study area is located in Peračko Blato, Croatia (43°4′ N, 17°26′ E, average 7 m a.s.l.), and has an average slope of 5.5° (Figure 1). The climate is Mediterranean, with an average annual precipitation (1998–2018) of 1123.6 mm, and the intra-annual differences range between July as the driest month (26.7 mm) and November as the wettest month (148.3 mm) (Figure 2). The average annual temperature is 16 °C, with the coldest weather in January (6.9 °C) and the warmest in July (26 °C) [47].



0 months **1 month** **3 months**

Figure 1. Location of the Peračko Blato study area, the eight experimental plots, and temporal changes in the soil surface within the fig orchard.

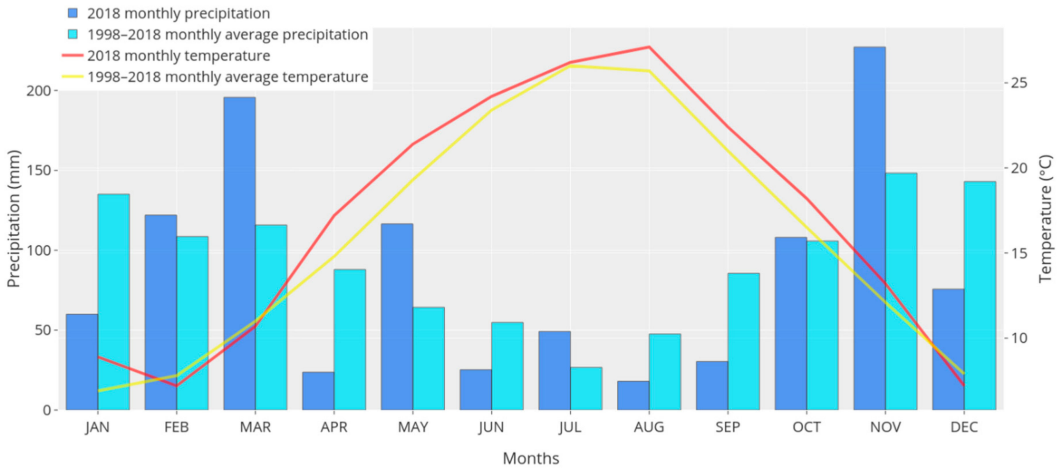


Figure 2. Monthly average precipitation and temperature between 1998 and 2018 and during the study year (2018). Data from the Ploče city meteorological station (43°2′ N, 17°26′ E, 2 m a.s.l.). The meteorological station is located 2.9 km from the studied fig orchard.

The soil in the study area is classified as a Calcic Fluvisol [48], developed on calcareous lake sediments with a high content of carbonates (>80%) and cation exchange capacity saturation (90% domination of exchangeable Ca^{2+}). The general soil properties are summarized in Table 1. The research area was formerly under a freshwater lake, which was partially drained in 1912 when a tunnel connecting the lake with the sea was constructed. After the construction of this infrastructure, the lake water level was reduced by ~12 m. However, floods often affect the lands near the lakes in the autumn-winter period. The new areas uncovered by water were used for cropping vegetables, vines, olives, figs, and citrus.

Table 1. General soil properties of the study location. Abbreviations: carbonates ($CaCO_3$), soil organic matter (SOM), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and cation exchange capacity (CEC).

Properties	**Texture (%)**			**pH**	**$CaCO_3$ (%)**	**SOM (%)**	**Exchangeable Cations ($cmol\ kg^{-1}$)**				**CEC ($cmol\ kg^{-1}$)**
	Sand	**Silt**	**Clay**				**Ca**	**Mg**	**K**	**Na**	
Value	11.6	77.2	11.2	7.52	83.45	2.68	18.91	0.70	0.30	0.25	20.16

2.2. *Experimental Design, Treatments, Sampling, and Rainfall Simulations*

Eight plots separated by 4 m were established in a 5-year-old fig (*Ficus carica*) orchard. The fig variety is Petrovača bijela, planted with a distance of 7 × 8 m. The plots had a similar slope (mean 5.5°) and north exposition. The fig orchard is managed with shallow rotation tillage (manually guided rotating spading machine) 2 times a year (spring and late summer or early fall) as a weeding method to a depth of 10 cm. No herbicide was applied in this orchard. All plant protection, soil management, and pomo-technical practices were performed manually without the use of machinery. Field experiments were carried out in 2018 during August (2 days after tillage—0 months), September (one month after tillage), and November (three months after tillage). During the experiments, the soil was bare. A set of rainfall experiments was carried out using a pressurized rainfall simulator (UGT Rainmaker, Müncheberg, Germany), previously calibrated using a plastic vessel of known dimensions. Rainfall simulations were 30 min long, with the rainfall intensity set to 58 mm h^{-1} because 93% of the annual soil loss was measured in a single rainstorm event at a rainfall intensity of 59 mm h^{-1} [31]. Before the simulations, undisturbed soil samples (0–10 cm) and soil core samples (0–10 cm) were taken in the vicinity of each plot. To enclose the plot catchment area, a metal ring (0.785 m^2) with a faucet was stuck 5 cm into the soil with the faucet facing downslope. At the end of the faucet, a plastic canister was connected to collect the overland flow. During each simulation, the time to ponding (TP) and time to runoff (TR) were measured using a chronometer. The experimental rainfall events were performed in August 2018, 2 days after shallow rotational tillage management (0 months). The measurements in September and November were performed in the same orchard 1 and 3 months after tillage. In each rainfall experiment, the catchment area was established in the vicinity of the previous measurement area (2 m).

2.3. Laboratory Analyses

The soil water content (SWC), bulk density (BD), and water holding capacity (WHC) were analysed according to the soil core method (weighting, wetting, and drying) [49]. For the undisturbed soil samples, we followed soil structure assessment preparation guidelines, according to Diaz-Zorita et al. [50]. Samples were carefully manipulated by hand, ensuring that the formed aggregates were not broken. During this preparation, all stones, roots, and other non-soil fragments were removed. Following aggregate separation, the samples were air-dried in the greenhouse at ~30 °C for 3 days and sieved with an auto-sieve shaker for 30 seconds [46] to separate particle fractions with diameters >8, 5, 4, 2, 1, 0.5, 0.25 and <0.25 mm. After weighing, the mean weight diameter (MWD) was determined using the following equation:

$$\sum_{i=1}^{n} xi \times wi \tag{1}$$

where "*xi* is the mean diameter of any particular size range of aggregates separated by sieving, and wi is the weight of aggregates in that size range, as a fraction of the total dry weight of soil used" [51]. The 1–2 mm fraction was separated after weighing for water-stable aggregate (WSA) analyses, while the rest of the sample was milled and passed through a 2 mm sieve in preparation for chemical analyses. The WSAs were determined on Eijkelkamp's wet sieving apparatus following Kemper and Rosenau [52]. The chemical analyses were performed as follows: SOM using the Walkley and Black [53] method and soil and sediment available P (P_2O_5) by the ammonium lactate (AL) method [54].

Canisters filled with the overland flow were weighed, and the sediment was filtered through filter paper (0.45 microns) to calculate the mass of sediment loss (SL) after air drying for 72 h. The sediment mass was subtracted from the mass of the overland flow to obtain the water runoff (WR). The sediment concentration (SC) was calculated by dividing the mass of the sediment by the mass of the water in overland flow. Data were converted to g L^{-1}. Sediments collected from the filter paper were finely milled and passed through a 2 mm sieve to evaluate carbon loss (C loss) and P loss. C in sediments was measured using dry combustion with an Elementar Vario Macro CHNS analyser.

2.4. Data Analyses

Data normality and homogeneity of the variances were assessed using Shapiro–Wilk and Levene's tests, respectively. Data were considered a normal distribution, and heteroscedasticity was considered at $p > 0.05$. Natural logarithm (Ln), logarithm (log), and Box Cox (BC) were applied to normalize the data (SWC, WSA, P_2O_5, TP, SC, SL, C loss, and P loss). Except for the SWC and WSA, all other variables followed a normal distribution after BC transformation. One-way analysis of variance (ANOVA) was applied to identify significant differences between sampling dates. In the case of SWC and WSA, the non-parametric Kruskal–Wallis ANOVA test was applied. In the figures, the original data are shown. If significant differences were observed at $p < 0.05$, a Tukey Least Significant Difference (LSD) post hoc test was applied to identify differences within treatments. In the case of SWC and WSA, a multiple comparison mean rank test was applied. Principal component analysis (PCA) based on the correlation matrix was performed using BC transformed datasets. No rotational procedures were applied. Statistical analysis was carried out using Statistica 12.0. Graphical representation of the results was performed using Plotly software [55].

3. Results

3.1. Rainfall Patterns

During the study period, lower rainfall was observed in August and September 2018 than in the monthly average from 1998–2018 (Figure 2). In November 2018, however, rainfall was substantially higher than that observed in the climatological normal. Regarding the temperature, the monthly average in 2018 was slightly higher than that in 1998–2018 (Figure 2).

3.2. Topsoil Properties

The SWC was approximately four times higher in month 3 than in months 0 and 1 ($p < 0.05$), following the precipitation pattern (Figure 2). The BD was also significantly higher at month 3 than before. No significant differences were identified in either the SWC or BD between 0 and 1 month after tillage (Figure 3A,C). The WHC had an inverse dynamic; it was significantly higher 0 months after tillage than at 1 and 3 months (Figure 3B). Additionally, no differences were identified between 1 and 3 months. The MWD was significantly higher 1 and 3 months after tillage than at 0 months (Figure 3D). Although the WSA content showed a decreasing tendency over the study period, no differences among the different months were observed in the WSAs. Finally, SOM and P_2O_5 had similar behaviour. In both cases, the values observed were significantly higher at 0 than at 1 and 3 months after tillage (Figure 4A,B).

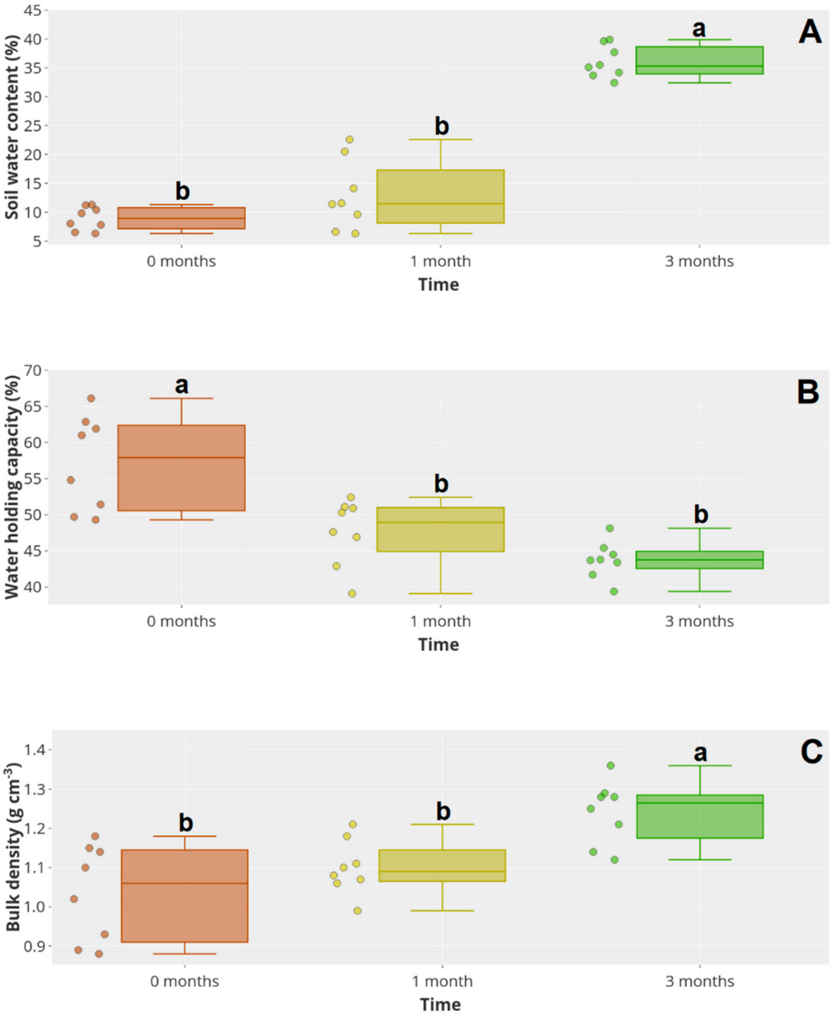


Figure 3. *Cont.*

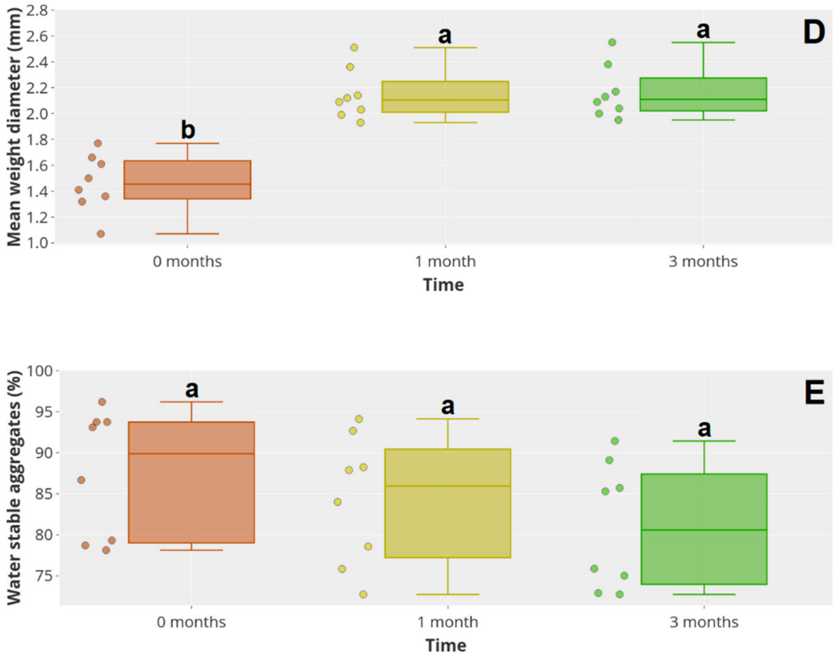


Figure 3. Differences in soil physical properties within the fig orchard study site over the study period: (**A**) soil water content, (**B**) water holding capacity, (**C**) bulk density, (**D**) mean weight diameter, and (**E**) water-stable aggregate distribution. Upper hanging bar (maximum), lower hanging bar (minimum), upper box line (quartile 3), line (median) and lower box line (quartile 1). Different lower-case letters represent significant differences between monitoring periods ($p < 0.05$). Dots next to a boxplot represent measured values.

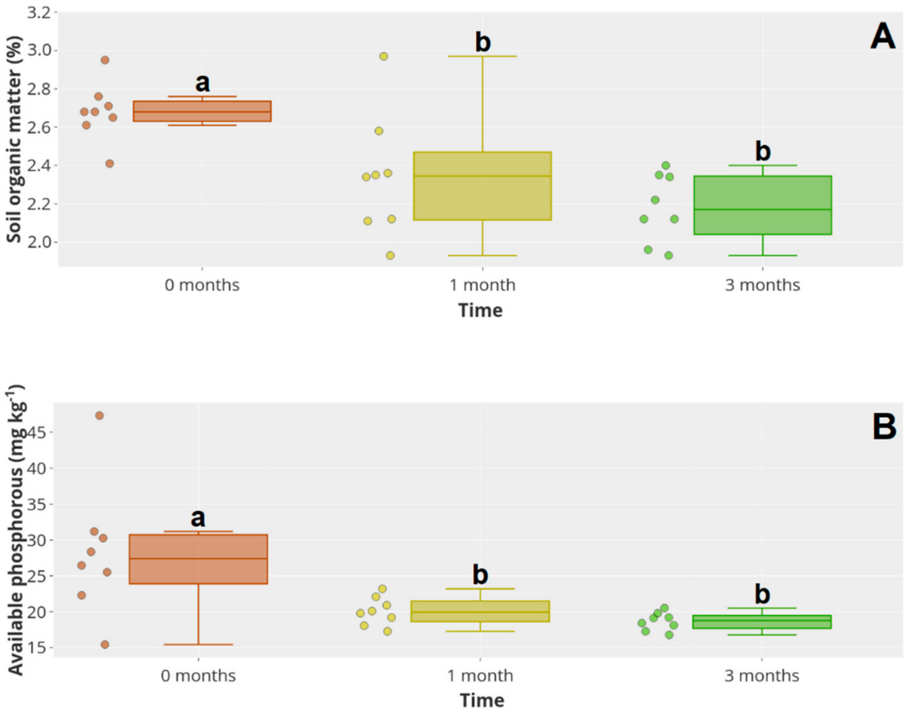
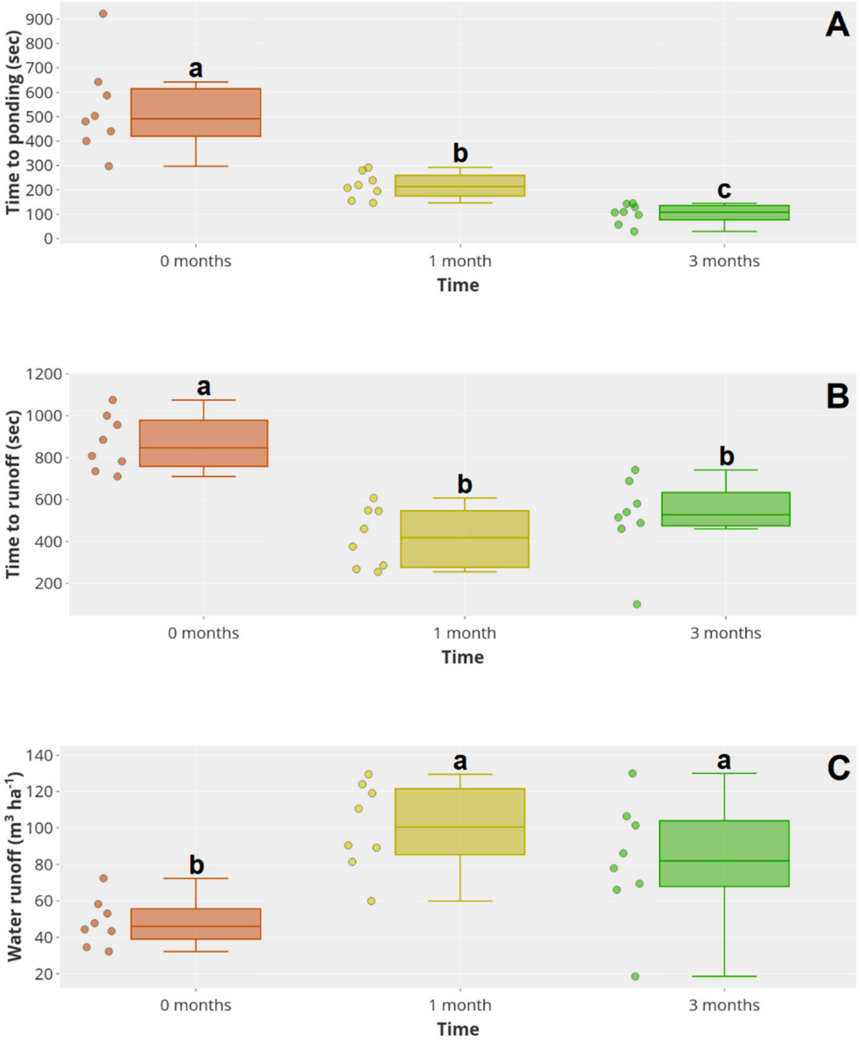


Figure 4. Differences in soil chemical properties within the fig orchard study site over the study period: (**A**) soil organic matter and (**B**) available phosphorus according to the time after tillage. Upper hanging bar (maximum), lower hanging bar (minimum), upper box line (quartile 3), line (median), and lower box line (quartile 1). Different lower-case letters represent significant differences between treatments ($p < 0.05$). Dots next to a boxplot represent measured values.

3.3. Overland Flow Properties

The hydrological response to rainfall simulation on the different study dates is summarized in Figures 5 and 6. The TP was significantly higher 0 months after tillage than 1 and 3 months after tillage. Additionally, the PT was significantly lower 3 months after tillage than 1 month after tillage (Figure 5A). The TR decreased significantly from 0 months to 1 and 3 months after tillage (Figure 5B). One and 3 months after tillage, the WR was significantly higher than at 0 months (Figure 5C). The SC and SL were significantly higher 3 months after tillage than at 0 and 1 month (Figure 5D,E). C loss was significantly lower at 0 than at 3 months after tillage (Figure 6A). Finally, P loss was significantly lower at 0 than at 1 and 3 months after tillage (Figure 6B).



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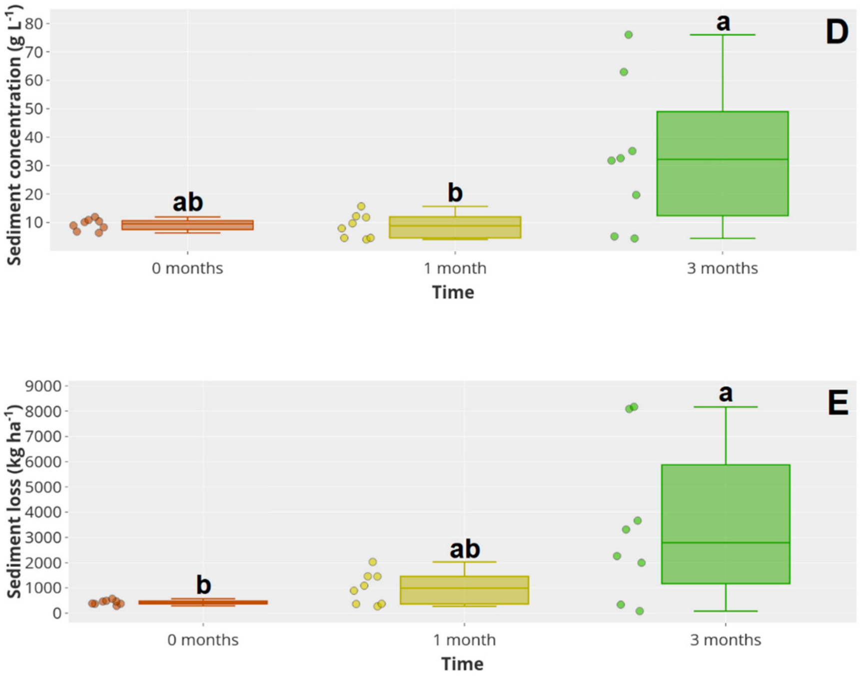

Figure 5. Hydrological response over the study period: (**A**) time to ponding, (**B**) time to runoff, (**C**) water runoff, (**D**) sediment concentration, and (**E**) sediment loss distribution according to the time after tillage. Upper hanging bar (maximum), lower hanging bar (minimum), upper box line (quartile 3), line (median), and lower box line (quartile 1). Different lower-case letters represent significant differences between treatments ($p < 0.05$). Dots next to a boxplot represent measured values.

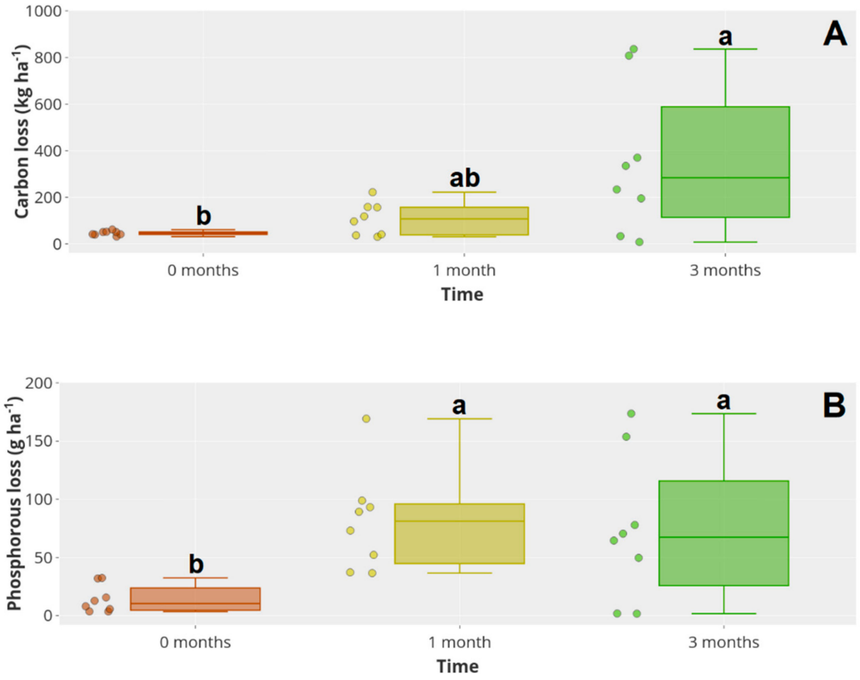

Figure 6. Nutrient loss during the rainfall simulation experiments: (**A**) carbon loss and (**B**) phosphorus loss distribution according to the time after tillage. Upper hanging bar (maximum), lower hanging bar (minimum), upper box line (quartile 3), line (median), and lower box line (quartile 1). Different lower-case letters represent significant differences between treatments ($p < 0.05$). Dots next to a boxplot represent measured values.

3.4. Principal Component Analyses

PCA identified four major factors that explained 84.99% of the total variance. Factor 1 explained 49.08%, while Factor 2, Factor 3, and Factor 4 explained 16.44%, 10.79%, and 8.69% of the total variance, respectively (Appendix A, Table A1). Most of the variables were explained by the factor 1 (Appendix A, Table A2). The relation between Factor 1 and Factor 2 is shown in Figure 7A. The BD, SWC, MWD, WR, SC, SL, C loss, and P loss were highly associated. On the other hand, these variables exhibited the opposite behaviour of the WSA content, SOM, P_2O_5, WHC, TR and TP. The differences between variables are more marked between 0 and 1/3 months after tillage. Between the last two months, the differences are minimal (Figure 7B).

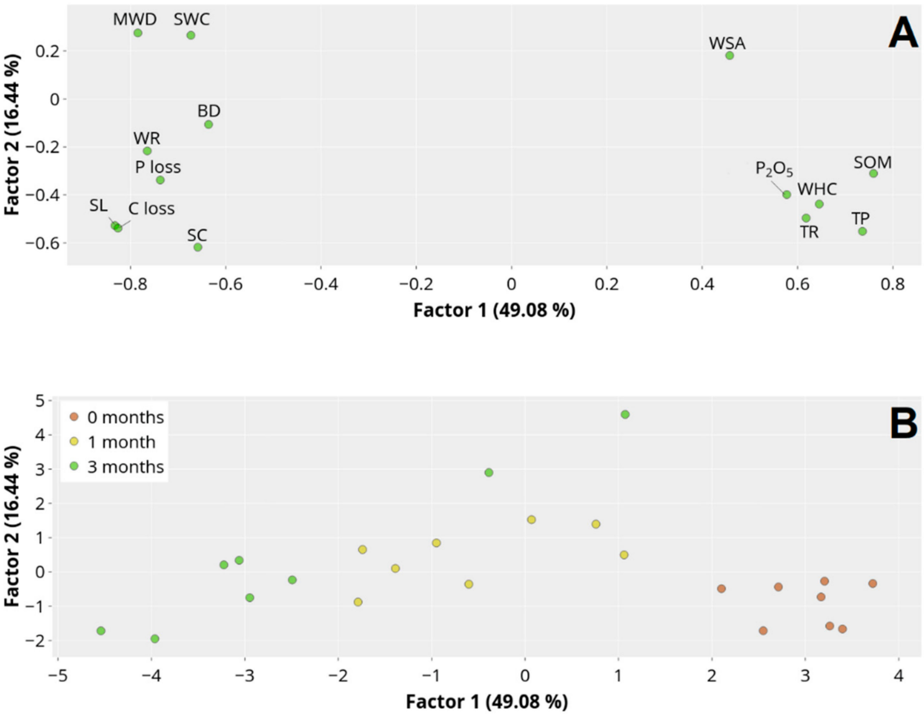

Figure 7. Results of the principal component analyses. Relation between Factors 1 and 2, (**A**) variables and (**B**) cases. Bulk density (BD); water holding capacity (WHC); soil water content (SWC); mean weight diameter (MWD); water-stable aggregate (WSA) content; soil organic matter (SOM); available phosphorous (P_2O_5); time to ponding (TP); time to runoff (TR); water runoff (WR), sediment concentration (SC); sediment loss (SL); carbon loss (C loss) and available phosphorous loss (P loss).

4. Discussion

The results obtained in this work show that there is an increase in soil consolidation over time (increasing BD), similar to that identified by others [56–58]. These previous studies reported the highest increases in BD a few weeks after tillage, while, in our case, we observed this effect only 3 months later.

Soil consolidation is affected by gravity, traffic, trampling, and rainfall [27]. No traffic or trampling occurred during the period studied. Therefore, the causes of the increase in soil consolidation 3 months after tillage are very likely due to the high precipitation that occurred in November. At 0 and 1 month after tillage, the precipitation was low (Figure 2). This effect may have contributed to the increase in the BD. It is well known that rain kinetic energy increases soil disaggregation, settling, and compaction [3,55]. Such a scenario supports the study of Busscher [59], who confirmed that 67–91% of re-compaction after tillage could be attributed to rainfall.

Changes in soil BD affected the relations between water and air in the soil pore system. In the present study, the WHC was significantly lower 3 months after tillage than at 0 months, which is likely a consequence of the increased BD modifying the pore size, shape, tortuosity, and continuity [23,24] but also affecting the MWD. In this study, the WHC had an inverse pattern when compared to BD and MWD. Tillage reduces aggregate sizes, which increase with time after disturbance. Usually, a reduced pore size and low MWD decrease water infiltration, while a high percentage of large pores reduces water retention [34]. This effect may explain the low WHC 1 and 3 months after tillage.

Despite the lack of statistical significance in the WSA content over the study period, there was a decreasing trend after tillage, which is very likely related to the SOM decrease and SWC increase [60]. The decreased amounts of SOM and P_2O_5 in the soil can be attributed to the mixture of vegetation cover with rotation-type tillage at 0 months after tillage. Later, the still-high temperatures during August, September, and October and tillage-induced oxidation contribute to SOM mineralization [61,62]. Additionally, SOM has a great capacity to hold water [63], and the decreasing SOM content may also contribute to the decreased WHC. Previous studies have shown relations between SOM and both MWD and WHC [64], as observed in this study. SOM acts as a binding agent for aggregates [21,65] and is considered a vital parameter in aggregate stability [66,67]. Such behaviour can be attributed to the initially low tillage-induced MWD and aggregation induced by consolidation and the high level of exchangeable Ca (93.8%) on the soil cation exchange capacity (Table 1), which acts as a cation bridge, connecting organic matter and clay minerals [68]. The decrease in SOM after tillage has implications for sediment loss (as discussed below).

The PT and RT were significantly higher at 0 than at 3 months after tillage. This result can be attributed to the WHC decrease and the increase in SWC (as a consequence of precipitation) that affects soil saturation, as reported in previous studies [69]. Tillage management that leaves crop residues on the soil surface reduces soil losses [3,31,44]. However, in the study site, this was not the case, and intensive tillage was applied. The soil was bare in all study periods. As a consequence of the high soil saturation and high BD, the overland flow properties (WR, SC, SL, C loss, and P loss) increased. Biddoccu et al. [31] identified a higher runoff in winter than in summer in Italian vineyards due to increasing antecedent soil moisture content. Another reason that may explain the high hydrological response 3 months after tillage is the decrease in soil roughness from 0 to 3 months after tillage (Figure 1). Additionally, even though not significant, the lower WSA content 0 months after tillage compared to 3 months after tillage may have influenced the increase in SL, SC, C loss, and P loss. A reduced aggregate stability increases the soil erodibility [46]. Previous studies observed that soil surface roughness constitutes an impediment to overland flow and retains sediments [70,71]. One month after tillage, an impermeable surface crust was observed in the soil within the fig orchard, likely created after the first rainfall events following tillage, and this crust became thicker 3 months later. This result may have reduced the infiltration capacity and increased overland flow, sediment transport, and nutrient losses, as identified elsewhere [72,73].

The PCA results highlight that tillage impacts on the soil are different between 0 and 3 months after tillage. At 0 months after tillage, the PT, RT, WSA, WHC, SOM, and P_2O_5 had high values. In contrast, 3 months after tillage, the BD (as a result of soil consolidation), MWD (as a consequence of time after tillage), and SWC (due to the precipitation pattern) were high. The soil consolidation (compaction), roughness reduction, crust formation and moisture content increased the hydrological response and nutrient losses (WR, SC, SL, C loss, and P loss) (Figure 7A). The variability was high 1 and 3 months after tillage, showing that the soil properties and hydrological response heterogeneity increased after disturbance. This effect is likely influenced by rainfall patterns, especially in month 3, after tillage (Figure 7B). The kinetic energy impact from seasonal rainfall on the soil surface affects the spatial variability of the soil properties [74–76].

The present results highlight the importance of precipitation in the impact on soil properties. The change in soil properties and surface conditions altered the hydrological response and erosion. In the case of this fig orchard, the combination of high rainfall and intensive management was revealed to be very damaging for the soil properties, sediments, and nutrient losses. For instance, 3 months after tillage, we observed a loss of >3 t ha^{-1} of soil in a single rainstorm event. This finding reveals unsustainable soil management practices at the study location considering other data describing tolerable soil loss in Europe at a rate of 1 t ha^{-1} year^{-1} [77]. The loss of sediments and nutrients implies decreased soil fertility, which enhances land degradation [78,79]. Additionally, the P losses in soils with a low content of this element may negatively impact plant growth and yields since phosphorus is a crucial nutrient [80]. In these soil types, with high exchangeable Ca and high pH (Table 1), the P availability is naturally low [81]. With current practices, the presence of this element will likely be reduced, limiting plant growth. Intensive management is likely to have offsite impacts such as the siltation and eutrophication of surface water bodies [82,83]. More sustainable practices (e.g., cover crops, reduced tillage) are needed to ensure that these soils continue to provide long-term ecosystem services and avoid the disservices (e.g., high erosion rates) produced by the current practices [84]. This short-term study reveals that improved soil management is required to mitigate land degradation, and more research is needed in fig orchards, which have been overlooked by the scientific community. Further research will focus on studying a large temporal scale and applying different types of management to reduce the impacts of agriculture on the soil properties and hydrological response.

5. Conclusions

This short-term study shows that the SWC, BD, MWD, TP, and TR were significantly higher 3 months after tillage than immediately after tillage. The WHC, WSA (despite the lack of statistical significance) SOM, P_2O_5 content, WR, SC, SL, C loss, and P loss showed the opposite dynamics. With time, the variability in the parameters studied increased, and the seasonal rainfall kinetic energy impact increased. Overall, with time, there was an increase in post-tillage consolidation that, together with soil saturation, a reduction in surface roughness, and crust formation, augmented the loss of sediments and nutrients. The current management practices have negative impacts on soil properties, which lead to increasing land degradation, with potential site impacts on fig yields and offsite environmental impacts, such as lake siltation and eutrophication. It is urgent to apply more sustainable agricultural management practices to avoid runoff, nutrient translocation, and floods.

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Disclaimer: text.

Appendix A

Table A1. Principal component analysis (PCA): eigenvalues of the correlation matrix and related statistics.

Factors	**Eigenvalues of Correlation Matrix and Related Statistics**			
	Eigenvalue	**% Total**	**Cumulative**	**Cumulative**
1	**6.870559**	49.07542	6.87056	49.0754
2	**2.301528**	16.43948	9.17209	65.5149
3	**1.509930**	10.78521	10.68202	76.3001
4	**1.216229**	8.68735	11.89825	84.9875
5	0.921799	6.58428	12.82004	91.5717
6	0.373413	2.66723	13.19346	94.2390
7	0.331562	2.36830	13.52502	96.6073
8	0.210259	1.50185	13.73528	98.1091
9	0.150673	1.07624	13.88595	99.1854
10	0.059838	0.42742	13.94579	99.6128
11	0.034298	0.24498	13.98009	99.8578
12	0.012329	0.08806	13.99242	99.9458
13	0.007493	0.05352	13.99991	99.9994
14	0.000091	0.00065	14.00000	100.0000

Bold values represent the factors that at least explain one variable.

Table A2. PCA: factor weight of the variables.

Variable	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**
BD (g cm^{-3})	−0.635970	−0.106389	**−0.671890**	0.289905
WHC (%)	**0.645557**	−0.438237	0.297301	0.179958
SWC (%)	**−0.673038**	0.265434	−0.624049	−0.025846
MWD (mm)	**−0.784366**	0.275267	−0.033961	0.425271
WSA (%)	0.457684	0.181181	0.000951	**0.669754**
SOM (%)	**0.759445**	−0.310617	−0.178819	0.323267
P_2O_5 (mg kg^{-1})	**0.577460**	−0.398762	−0.358618	0.272733
PT (sec)	**0.736282**	−0.552068	0.038546	0.017696
RT (sec)	**0.618064**	−0.496640	−0.414612	−0.148541
WR (m^3 ha^{-1})	**−0.764620**	−0.216738	0.422021	0.351363
SC (g kg^{-1})	**−0.658483**	−0.618021	−0.128423	−0.232881
SL (kg ha^{-1})	**−0.832526**	−0.527928	0.056611	−0.050388
C loss (kg ha^{-1})	**−0.826036**	−0.538793	0.069739	−0.051622
P loss (g ha^{-1})	**−0.737336**	−0.338006	0.207075	0.292488

Bold values represent the variables explained by each factor.

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