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Changes in Soil Quality and Hydrological Connectivity Caused by the Abandonment of Terraces in a Mediterranean Burned Catchment

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Abstract: Wildfires and agricultural activities are relevant factors affecting soil quality, hydrological cycle and sedimentary dynamics. Land abandonment leads to afforestation, which increases fire risk and land degradation. However, no studies have yet evaluated the effect of combining the two factors, which occur frequently in Mediterranean ecosystems. This study assessed the changes in soil quality caused by the abandonment of terraces in two microcatchments (<2.5 ha) affected distinctly by wildfires (once and twice burned) and in an unburned control microcatchment by analyzing soil quality parameters, biochemical indices and spatial patterns of hydrological and sediment connectivity. Soil samples were collected in thirty-six plots (25 m^2) representing terraced and non-terraced areas within these microcatchments. Unburned non-terraced plots had higher organic matter content and higher microbiological and enzymatic activities than other plots. Plots in abandoned terraces had lower soil quality indices, regardless of the fire effect. Land abandonment induced changes in the spatial patterns of hydrological connectivity, leading to concentrated runoff, enhanced erosion and soil degradation. Fire also negatively affected soil quality in both terraced and non-terraced plots. However, microbiological communities had different positive post-fire recovery strategies (growth and activity), depending on the previous soil conditions and land uses, which is indicative of the resilience of Mediterranean soil ecosystems.

Keywords: soil quality; hydrological connectivity; terraces; wildfires; land abandonment

1. Introduction

Wildfires are an important ecogeomorphological agent that is intrinsic to Mediterranean ecosystems [1], as indicated by the fire adaptations of many of their endemic plant species [2]. However, increasing temperatures, along with land use changes and urban expansion over recent decades, have been identified as the most important drivers of increased wildfire occurrence, leading to soil degradation [3]. By reducing or temporarily eliminating vegetation cover, frequent wildfires increase exposure of soils to erosion agents. In addition, fire may induce changes in the water cycle by increasing soil water repellence, reducing infiltration capacity and therefore promoting higher overland flow and enhanced soil losses [4]. Depending on their recurrence, duration and severity, wildfires can also cause direct and significant changes in the chemical, physical and biological properties of soil [5,6].

Identifying the effects of fire on soils in the Mediterranean region is still a challenging issue because the wide heterogeneity of land uses and the long history of human impact add further complexity [7].

Wildfires' greater frequency in recent decades is largely due to the afforestation of abandoned agricultural areas, involving increased fuel load and greater continuity of forest areas [8]. Therefore, afforestation and preterit agricultural practices in these areas may have been important factors altering soil quality prior to wildfire occurrence. Tillage, fertilization and vegetation management can significantly affect chemical and biological soil properties, entailing negative effects on soil quality [9]. Moreover, in the Mediterranean region, these practices have very often been accompanied by the construction of terraces, which are a very effective measure for soil conservation [10]. The massive presence of these structures, as long as they are well-maintained, decouples hillslopes and the fluvial system significantly [11], decreasing the hydrological response [12] and reducing the sediment transfer at the catchment scale [13]. However, the lack of maintenance after land abandonment leads to the deterioration and subsequent collapse of terraces, reactivating erosion and soil degradation processes [11–14].

In recent years, sediment connectivity has been consolidated as a useful conceptual framework for understanding sedimentary processes at different spatiotemporal scales [15]. The concept of sediment connectivity indicates the physical linkage of sediment (in terms of transfer) and the potential for a specific particle to move through the system [16]. Closely connected areas within a catchment, with stronger links between different compartments, are related to greater runoff, enhanced erosion and soil losses [17]. However, the presence and configuration of sediment stores such as terraces may create low-connected areas by decoupling water and sediment flows [18]. Thus, spatial patterns of connectivity have been studied recently to detect hotspots of erosion and soil loss. These are attributed to various dynamics of global change related to wildfires [19], land use changes [20], vegetation patterns [21] or abandonment of cultivated terraces [22]. However, these studies, based on sediment connectivity at the catchment scale, are aimed at analyzing the effects of different dynamics on soils in quantitative rather than qualitative terms.

While the importance of the quantity and productive function of soils was recognized long ago, the study of essential soil quality parameters for sustaining many ecosystem services (such as water purification, groundwater recharge, carbon sequestration, control of pathogen populations, biological nitrogen fixation and biodiversity conservation) has been gaining in relevance in recent years [23]. The lateness of this interest is largely due to the complexity of soil processes, which makes it difficult to establish quantitative indices and reference levels for assessing soil quality [24]. According to Doran and Parkin (1996), the minimum dataset for soil quality assessment should include physical, chemical and biological parameters [25]. Nevertheless, in general, physical and physicochemical parameters only show clear alterations when very drastic disturbances occur [26]. In contrast, biological and biochemical parameters are highly suitable indicators due to their sensitivity to any slight change that soil may suffer due to any degradation agent [27].

Enzymatic activities and soil respiration have been used as indicators of soil quality to evaluate degradation of forest [28,29] and agricultural soils [30] in Mediterranean environments. Generally, more intensive agricultural activity is associated with decreasing organic matter [31] due to tillage, biomass removal and increased mineralization and decomposition of the exposed soils [32]. Land abandonment can further aggravate degradation processes by affecting soil microbial activity, biomass C and enzyme activities, although soils may begin to recover after the appearance of spontaneous vegetation [33]. Zonorza et al. (2009) observed increased microbial biomass C, richness and shifts in the microbial community structure of agricultural terraces after 10–15 years of abandonment [34]. Wildfires have also been identified as an important source of variation in soil quality, with negative effects on biochemical and microbiological parameters [35]. However, recent studies reported that microbiological soil properties and enzymatic activities in Mediterranean environments show great resilience, being able to recover pre-fire levels in fewer than 20 years [36]. Wildfire occurrence in abandoned agricultural areas is very common in Mediterranean catchments [8] and the effect of these combined factors on soil quality is still poorly understood. As studies addressing this issue through the analysis of soil microbiological parameters and enzymatic activities are scarce, more research into soil degradation and recovery processes in these environments is required.

This paper is part of a study series investigating the effects of terrace abandonment on soil quality in three Mediterranean microcatchments affected in different ways by wildfires [37]. This recent study evaluated soil degradation by means of physicochemical, biochemical and microbiological soil parameters, highlighting the need to further explore the relationships between biochemical soil properties, which can be used as simple indexes of soil quality. Moreover, changes in hydrological processes introduced by terracing may have a great influence on soil in terms of quantity and quality. The present study based on this previous research by Lucas-Borja et al. (2017) [37] incorporated several soil quality indices into the analysis, as these provide better understanding of the growth and activity of microbiological communities and the morphometric index of connectivity [IC] (17). These serve to evaluate: (1) whether abandoned terraces induce differences in sediment connectivity and in soil quality of three Mediterranean microcatchments under different wildfire regimes and (2) to what extent differences in soil quality can be attributed to the presence of agricultural terraces and their effects on connectivity, to the different wildfire regimes or to the combination of the two factors.

2. Materials and Methods

2.1. Study Area

Sa Font de la Vila catchment is a small catchment (4.8 km^2) located in the southwestern part of the Tramuntana Range on the island of Mallorca (Figure 1a,b).

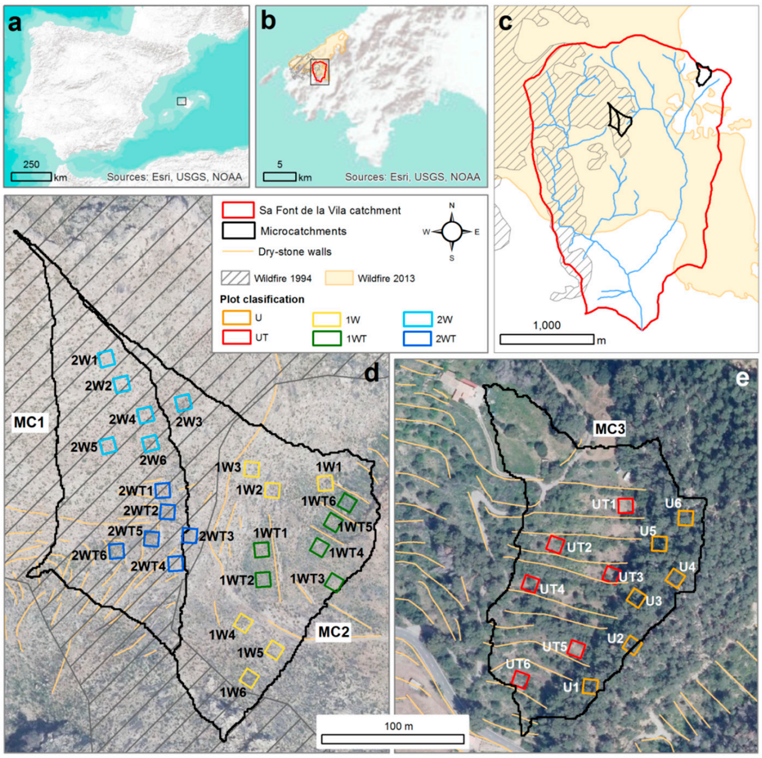

Figure 1. (**a**) Location of Mallorca island; (**b**) Location of Sa Font de la Vila catchment and wildfires in 1994 and 2013, (**c**) Burned areas in sa Font de la Vila catchment and location of the microcatchments. (**d**) Location of the representative plots on the burned microcatchments (i.e., MC1 and MC2). (**e**) Location of the representative plots in the unburned microcatchment (i.e., MC3). U = Unburned; UT = Unburned with Terraces; 1W = Burned in 2013; 1WT = Burned in 2013 with Terraces; 2W = Burned in 1994 and 2013; 2WT = Burned in 1994 and 2013 with Terraces.

This county is a paradigmatic case of cultural Mediterranean landscape with important interactions between natural dynamics and ancient human activities. Over the centuries, its morphology has been shaped by intensive agricultural activity [38], resulting in a massive presence of terraces, i.e., 37% of the catchment surface area. The catchment's morphology is complex, with height ranging between 63 and 517 m.a.s.l. (above sea level) and a mean gradient slope of 38%. Currently, agricultural activities are restricted to the valley bottoms, where the slope is less pronounced (<10%). Lithology consists mainly of Upper Triassic (Keuper) clays and loams. In the upper parts, where Rhaetian dolomites and Lias limestones predominate, slope gradients are steeper than 30%. Under the Soil Taxonomy System, soils can be classified as Entisols at the catchment headwaters and Alfisols in the lower parts. These underdeveloped soils do not exceed 20 cm and do not show defined horizons, as they consist mainly of slightly altered regolithic parent material. The climate is Mediterranean sub-humid and ranges between temperate and warm on the Emberger climate scale [39]. The mean annual temperature is 16.5 °C and the mean annual precipitation is 532 mm y-1 with an inter-annual coefficient of variation of 23% (1970–2010, data provided by the Spanish Meteorological Agency, AEMET). High-intensity rainstorms with a recurrence period of 10 years may reach 85 mm in 24 h. Since the mid-twentieth century, important socio-economic changes have caused the gradual abandonment of farmland in marginal areas, leading to increased afforestation. In the early 1990s, forest areas reached 77% of the entire catchment, with only 15% remaining as an agricultural area [39]. The increased availability of biomass, together with the lack of management, favored the occurrence of two large wildfires in 1994 and 2013. In 1994, the first wildfire affected 25% of the catchment's surface area and reduced the forest cover to 52%. In July 2013, the wildfire affected 71%, with 30% of this overlapping with the area burned in 1994 (Figure 1c).

At the headwaters of the Sa Font de la Vila catchment, three afforested microcatchments were selected (Figure 1c) under the following criteria: (1) similar area and comparable characteristics (see Table 1); (2) representative presence of abandoned terraces and (3) distinct fire regimes. Using multitemporal mapping based on aerial photography, terrace abandonment in microcatchments 1 and 2 (MC1 and MC2) was identified in the early 1960s and afforestation processes in 1980s. Terraces in microcatchment 3 (MC3) were progressively abandoned since the 1970s and no clear afforestation processes were observed. In the study area, two types of terraces can be identified, based on the technical and constructive characteristics of terraces and their position relative to the fluvial drainage network [40]: (i) check-dam terraces that cut across first-order thalwegs orthogonally and refilled their original incision in a series of stepped plans retained by walls, (ii) step terraces, mainly built as narrow horizontal surfaces (<5 m wide) on steep hillslopes (>30%) to cultivate marginal areas. MC1 was completely burned in 1994 and 2013. MC2 was also burned in 2013 (100%) and partially affected (40%) by the 1994 fire. MC3 was selected as a control microcatchment since it was not affected by these fires.

Table 1. Main characteristics of the selected microcatchments.

		MC1	MC2	MC3
Area (ha)		1.7	2.2	2.2
Altitude range (m.a.s.l)		306–398	283–400	281–344
Average slope gradient (%)		47	44	32
Lithology		Rhaetian dolomites and Lias limestones		
Soils		Alfisoils		
Terraces	Area (%)	27	19	61
	Walls (m/ha)	288	183	407
Vegetation (prior to the wildfires)		Western Mediterranean forest and scrubland. Tree strata: *Quercus ilex*, *Pinus halepensis*, *Olea europaea var. Sylvestris.* Scrub strata: *Pistacia lentiscus*, *Ampelodesmus mauritanica*, *Chamaerops humilis*, *Erica multiflora*, *Cistus albidus*, *Cistus monspeliensis*, *Calicotome spinosa*, *Rhamnus alaternus*, *Rosmarinus officinalis*, *Cneorum tricoccon*, *Phillyrea angustifolia*.		
Occurrence of wildfires		1994 (100%); 2013 (100%)	1994 (40%); 2013 (100%)	Non-affected

a.s.l: above sea level.

2.2. Experimental Design and Sampling

At each microcatchment, 12 plots (5 m × 5 m) were established, in line with both the fire occurrence described and the terracing: six on terraced and six on non-terraced areas (Figure 1d,e). It should be noted that the plots selected in MC2 were only those in areas burned in 2013, avoiding those areas also burned in 1994. Thirty-six samples (one per plot) were collected in January 2016 (i.e., 2.5 year since the last wildfire in 2013), following the same procedure used by Lucas-Borja et al. (2010; 2012) [28,29]. Each sample consisted of six replicates (200 g), randomly distributed in each plot, which were mixed to obtain a composite sample. After manual exclusion of litter, samples were taken from the top 5 cm of soil because the largest portion of microbial biomass and activity fall within this horizon. In addition, differences associated with vegetation cover (through leaf fall) should be at their strongest, as opposed to the deeper horizons. Following the removal of plant remains, the samples were sieved at 2-mm Ø and kept at 3 °C prior to the analyses. Species composition, vegetation cover and the main morphological characteristics of plots are shown in Table 2.

2.3. Soil Quality Parameters

2.3.1. Physical and Chemical Parameters

Soil samples were immediately analyzed for pH and electrical conductivity (EC) in a 1:5 (w/v) aqueous solution. Total organic carbon (TOC) was determined by the potassium dichromate oxidation method [41]. The soil organic matter (SOM) was determined by multiplying soil organic carbon by 1.72. Total nitrogen (N) was determined by the Kjeldahl method [42]. Calcium carbonate content ($CaCO_3$) was measured according to Porta et al. (1986) [43].

2.3.2. Biochemical and Microbiological Parameters

The basal soil respiration (REB) related with microbial activity was measured in a multiple sensor respirometer (Micro-Oxymax, Columbus, OH, USA). The microbial biomass Carbon (MBC), related with the number of soil microorganisms, was determined by the fumigation-extraction methods [44]. Urease activity was measured according to the method of Tabatabai (1994), using urea as substrate [45]. Alkaline phosphatase and β-glucosidase activities were determined using ϱ-nitrophenyl phosphate disodium and ϱ-nitrophenyl-β-D-glucopyranoside, respectively, as substrates. The assay is based on the release and detection of ϱ-nitrophenol (PNP). The metabolic quotient (qCO2) has been used by various authors and expresses the amount of CO_2-C produced per unit of biomass and time. Llorente and Turrión (2010) used it as an indicator of the adversity of the environmental conditions [46]. The mineralization coefficient (Qcm) was calculated as the fraction of basal soil respiration (REB) and total organic carbon (TOC), as proposed by Pinzari et al. (1999) [47]. The carbon ratio of microbial biomass with TOC (hereafter, MBC/TOC) is an indicator of the potential mineralization of organic matter [48]. The study of basal respiration, microbial biomass and ratios (metabolic and MBC/TOC) gives a rough idea of the microbiological communities present in soil and their response to distinct ecosystem perturbations. The synthetic enzymatic index (SEI) was calculated following Dumontet et al. (2001) and with the above-mentioned enzyme activities (urease, phosphatase and β-glucosidase) releasing the same reaction products [49]. From the activities of these three enzymes, soil functional diversity was determined by the Shannon Index of diversity (H) ($H = -\sum p_i \, log2 \, p_i$), where p_i is the ratio of the activity of a particular enzyme to the sum of activities of all enzymes [50].

Table 2. Species composition, vegetation cover and morphological characteristics of plots under different representative conditions: U = Unburned; UT = Unburned with Terraces; 1W = Burned in 2013; 1WT = Burned in 2013 with Terraces; 2W = Burned in 1994 and 2013; 2WT = Burned in 1994 and 2013 with Terraces.

PLOTS (n)	Main Tree Species			Shrub and Herbaceous Vegetation	Vegetation Cover	Slope	Stoniness
	Composition (%)	*Ø (mm, (mean))*	*Height (cm, (mean))*	*Main Species*	*(% (mean))*	*(% (mean))*	*(% (mean))*
U (6)	*Quercus ilex* L. (60%), *Pinus halepensis* Mill. (25%), Olea europeae (15%)	8–250 (155)	80–400 (256)	*Pistacia lentiscus*, *Genista* sp, *Cistus albidus*	30–90 (60)	5–25 (19)	5–25 (13)
UT (6)	*Quercus ilex* L. (20%), *Pinus halepensis* Mill. (60%), Olea europeae (20%)	8–155 (47)	80–300 (216)	*Pistacia lentiscus*, *Cistus albidus*, *Chamaerops humilis*, *Erica multiflora*, *Ruscus aculeatus*, *Juniperus oxycedrus*	60–80 (70)	14–33 (19)	3–11 (6)
1W (6)	*Pinus halepensis Mill.* (100%)	8–155 (47)	47–162 (89)	*Pistacia lentiscus*, *Ampelodesmus mauritanica*, *Chamaerops humilis*, *Cistus albidus*, *Erica multiflora*,	20–50 (40)	38–64 (50)	20–40 (25)
1WT (6)	*Pinus halepensis Mill.* (100%)	7–23 (15)	40–161 (89)	*Ampelodesmus mauritanica*, *Pistacia lentiscus*, *Chamaerops humilis Arisarum vulgare*, *Brachypodium retusum*, *Cistus albidus*, *Erica multiflora*,	45–90 (50)	12–25 (17)	5–20 (9)
2W (6)	*Pinus halepensis Mill.* (100%)	4–25 (11)	17–159 (64)	*Ampelodesmus mauritanica*, *Pistacia lentiscus*, *Chamaerops humilis*, *Cistus albidus*, *Erica multiflora*	7–35 (22)	36–59 (46)	40–75 (56)
2WT (6)	*Pinus halepensis Mill.* (100%)	4–24 (11)	18–150 (64)	*Ampelodesmus mauritanica*, *Pistacia lentiscus*, *Chamaerops humilis*, *Arisarum vulgare*, *Brachypodium retusum*, *Cistus albidus*, *Erica multiflora*	10–80 (44)	6–30 (18)	5–35 (19)

2.4. Morphometric Index of Connectivity

Analysis of connectivity patterns is particularly important in this study because they are closely related to sediment transfer processes (e.g., erosion, transport and deposition) leading to impoverishment of soil quality. The Index of Connectivity (IC), originally defined by Borselli et al. (2008), measures the potential linkage between different compartments of a catchment and indicates the probability of a particle at a certain location reaching a defined target area [17]. In this study, the targets were set at the outlet of each microcatchment. Thus, the most connected areas are those potential sediment sources that may be transferred through the catchment and delivered out of the system. IC was computed from a 1-m LiDAR-based DTM (Instituto Geográfico Nacional, 2014) following the approach of Cavalli et al. (2013), which is especially suitable for assessing the topographic influence of features on hydrological and sediment processes [51]. The enhanced algorithms proposed by Cavalli et al. (2013), incorporating important improvements for their application to mountainous catchments, were implemented by using the stand-alone freely available software SedInConnect 2.3 [52]. For each cell of the catchment, the IC was calculated by the upslope component Dup (i.e., the characteristics of the drainage area) and the downslope component Ddn (i.e., the characteristics of the flow path to the selected target):

$$\mathrm{IC} = \log 10\left(\frac{Dup}{Ddn}\right) = \log 10\left(\frac{\overline{WS}\sqrt{A}}{\sum_i \frac{d_i}{W_i S_i}}\right) \quad (1)$$

where $\overline{W}$ is the average weighting factor (the impedance to runoff and sediment fluxes, using the roughness index IR [53]) of the contributing area upslope (dimensionless), $\overline{S}$ is the average slope gradient of the contributing area upslope (m/m), A is the contributing area upslope (m^2) computed with the D-Infinity algorithm [54], d_i is the length of the flow path along the ith cell according to the steepest downslope direction (m), and W_i and S_i are the weighting factor and the slope gradient of the ith cell, respectively.

2.5. Statistical Analysis

A first comparison of all soil quality parameters for each representative condition (different combinations of fire and presence/absence of terraces) was performed by a post-hoc Least Significant Difference (LSD) test using Statgraphics Plus 6.0® software (Statpoint Technologies, Inc.; The Plains, Virginia 20198, USA). For this previous analysis, a significance level of $p < 0.05$ was adopted. A CLUSTER analysis using Primer v6 (Massey University, Albany, Auckland 0632, New Zealand) [55] was used to identify whether representative plots could be grouped on the basis of their soil quality characteristics as well as their hydrological and sediment connectivity. Additionally, the ANOSIM (ANalysis of SIMilarities) routine, also in Primer v.6 (Massey University, Albany, Auckland 0632, New Zealand), compared within- and between-group similarities [56]. In a robust classification, similarities between plots within the same group should be substantially greater than similarities between those from different groups. A key output from this analysis is the R statistic coefficient, which ranges from −1 to 1. When the R statistic tends to 1, all plots within classification groups are more similar to each other than to any plots from different groups. When R approaches 0, similarity between and within classification groups may be considered statistically irrelevant. R negative values indicate that plots within a classification group are more similar on average to plots in the other groups than those in their own group. Although the R statistic is a useful comparative measure of the differences between plots, a Monte Carlo permutation test with 999 replicates was used to assess the significance (p) of each value. In this study, the established level of significance was $p = 0.001$. Finally, for the purpose of interpreting differences between the groups, a SIMPER (SIMilarity PERcentage) analysis was performed using Primer v6 (Massey University, Albany, Auckland 0632, New Zealand) [56]. This analysis identifies the most characteristic parameters of each group by calculating their contributions by means of similarity percentages (one-way analysis). Moreover, the SIMPER analysis identifies the most differing parameters between groups. The percentage contribution of each of them to these differences can also be calculated (pairwise tests). Based on the SIMPER analysis, close similarity between plots of the same group or between groups would result in low values of mean square distance (R), over a range of (0, 100). Conversely, important differences would be expressed with high values of mean square distance. The statistical significance in this analysis, also set at $p = 0.001$, was assessed by the same method as in the ANOSIM analysis.

3. Results

3.1. Soil Quality

3.1.1. Physical and Chemical Parameters

Significant differences ($p < 0.05$) were observed between physical and chemical parameters of the distinct plots (Table 3). Terraced plots, both unburned ones and those burned once, showed significantly lower soil organic content (5.6 ± 0.4) than non-terraced plots (10.2 ± 0.6). All terraced plots also had lower EC (1548 ± 5.6) than other plots (242 ± 16.9). N content (0.27 ± 0.01) was also significantly lower in terraced and burned plots. However, $CaCO_3$ content was significantly higher in most terraced areas (25.9 ± 1.4 in terraced plots; 15 ± 1 in non-terraced plots). On the other hand, burned plots showed higher C/N ratios (12.9 ± 0.3) and pH (8.3 ± 0.1) than unburned plots (9.7 ± 0.4 and 8.1 ± 0.1, respectively). In non-terraced plots, a steady decrease in organic matter was detected as a result of the successive fires. On the contrary, in terraced plots, the higher occurrence of fires was associated with an increase in organic matter. Fire recurrence also seems to involve a steady decrease in $CaCO_3$ content. However, no significant differences were observed for EC, C/N or pH between once- or twice-burned plots.

3.1.2. Biochemical and Microbiological Parameters

Terracing and fire occurrence influenced greatly the biochemical and microbiological soil parameters, with significant ($p < 0.05$) differences found between plots with distinct representative conditions (Table 3).

Non-terraced unburned plots, still covered by natural holm oak forest, showed greater soil respiration (REB = 2.4 ± 0.5) and enzymatic activities (UA = 2.7 ± 0.4; UPH = 2.9 ± 0.3; βGLA = 2.9 ± 0.3; SEI = 9.2 ± 0.7) than the rest of the plots (REB = 0.8 ± 0.04; UA = 0.5 ± 0.04; UPH = 1.5 ± 0.07; βGLA = 1 ± 0.1; SEI = 3 ± 0.1). Low soil biomass carbon was associated with terraced plots (MBC = 383 ± 42), while non-terraced plots had much higher values (1197 ± 264). The MBC/TOC ratio was significantly different in terraced and non-terraced plots: it was lower when combined with wildfires. On the other hand, all unburned plots showed higher Qcm (0.3 ± 0.03) and Shannon Index values (1.54 ± 0.01) than burned plots (0.2 ± 0.01 and 1.5 ± 0.01, respectively). However, differences in the Shannon Index values cannot be considered statistically significant. The effects of fire on qCO_2 appeared to be different in terraced plots and non-terraced plots. Non-terraced unburned plots had higher metabolic activity (0.027 ± 0.002) than non-terraced burned plots (0.009 ± 0.001). In contrast, terraced unburned plots showed very low qCO_2 values (0.014 ± 0.002), which were much higher in terraced burned plots (0.033 ± 0.006).

Table 3. Soil quality parameters for each representative condition: U, unburned non-terraced plots; UT, unburned terraced plots; 1W, Non-terraced plots burned once; 1WT, terraced plots burned once; 2W, non-terraced plots burned twice; 2WT, terraced plots burned twice. Physical and chemical parameters: SOM, soil organic matter (%); EC, electrical conductivity (µS/cm); N, % of Nitrogen; C/N ratio; pH, % of $CaCO_3$. Biochemical and microbiological parameters: REB, basal soil respiration (mg CO_2 soil kg^{-1}); MBC, microbial biomass C (mg C BM kg^{-1}); UA, urease activity (µmoles PNP g^{-1} dry soil h^{-1}), PHA, phosphatase activity (µmoles PNP g^{-1} dry soil hr^{-1}), β-GLA, β-glucosidase activity (µmoles PNP g^{-1} dry soil h^{-1}); qCO_2, metabolic quotient (mg C-CO_2 g^{-1} Cmic h^{-1}); Qcm, mineralization coefficient (mg C-CO_2 g^{-1} C h^{-1}); MBC/TOC (mg Cmic g^{-1} Corg); SEI, Synthetic Enzyme Index; H, Shannon Index. Data followed by the same small letter are not significantly different according to the Least Significant Difference (LSD) test ($p < 0.05$).

		U		**UT**		**1W**		**1WT**		**2W**		**2WT**		**ALL PLOTS**	
		Range	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*
Physical and chemical parameters	SOM	6.1–15.8	11.6a	3.3–4.7	3.9e	6.6–12.2	10.2b	3.9–7	5.6d	7.9–10.1	8.7c	5.7–8.4	7.3c	3.3–15.1	7.9
	EC	229–435	308a	118–161	138c	187–207	197b	139–165	151c	177–329	221b	140–214	176c	118–435	198
	N	0.3–1.02	0.69b	0.21–0.29	0.24b	0.31–0.61	0.46a	0.19–0.31	0.24c	0.37–0.46	0.41b	0.3–0.36	0.34c	0.19–1.02	0.4
	C/N	8.6–11.7	10.0c	7.4–11.7	9.4c	11.63–15.28	13.0a	11.2–16.6	13.5a	11.54–12.89	12.3b	11.1–14	12.6b	7.4–16.6	11.8
	pH	7.9–8.1	8.0c	8.1–8.3	8.2b	8.2–8.3	8.3a	8.2–8.3	8.2a	8.1–8.4	8.3a	8.2–8.3	8.3a	7.9–8.4	8.2
	$CaCO_3$	18.6–18.6	18.6b	33.6–33.6	33.6a	17.1–17.1	17.1b	23.7–23.7	23.7b	9.3–9.3	9.3c	20.3–20.3	20.3b	9.3–33.6	20.4
Biochemical and microbiological parameters	REB	1.04–3.88	2.42a	0.47–1.05	0.71b	0.44–1.01	0.82b	0.64–0.87	0.74b	0.6–1.6	0.99b	0.52–1.06	0.84b	0.4–4.6	1.09
	MBC	403–1532	893b	356–707	545c	351–5516	1624a	145–408	247c	858–1415	1074b	63–537	356c	63–5516	790
	UA	1.72–3.88	2.65a	0.51–1.03	0.77b	0.17–0.72	0.42b	0.39–0.61	0.51b	0.35–0.79	0.62b	0.26–0.57	0.42b	0.17–3.88	0.9
	PHA	3.05–4.01	3.61a	1.32–1.78	1.50b	0.89–2.73	1.83b	1.03–1.34	1.16c	1.13–1.63	1.48b	1.09–1.82	1.42b	0.89–4.01	1.83
	β-GLA	1.58–3.76	2.93c	0.88–1.44	1.15b	0.65–1.7	1.14b	0.66–0.87	0.74b	0.71–1.1	0.87b	0.83–1.31	1.02b	0.65–3.76	1.31
	qCO_2	0.021–0.033	0.027a	0.008–0.024	0.014b	0.002–0.013	0.009b	0.016–0.061	0.034a	0.007–0.015	0.009b	0.016–0.083	0.032a	0.002–0.083	0.021
	Qcm	0.04–0.52	0.29a	21–0.45	0.31a	0.12–0.16	0.14b	0.18–0.28	0.23b	0.13–0.32	0.2b	0.16–0.23	0.2b	0.04–0.52	0.23
	MBC/TOC	9.1–17.5	12.9b	14.4–29.8	24.2a	9.1–94.4	27.2a	4.1–17.8	8.4b	18.3–26.9	21.2a	1.9–12.3	8.2b	1.9–94.4	17
	SEI	6.46–10.86	9.2a	3.17–3.97	3.42b	1.71–5.01	3.39b	2.09–2.82	2.41b	2.19–3.34	2.97b	2.25–3.7	2.86b	1.7–10.9	4.04
	H	1.51–1.58	1.55a	1.47–1.57	1.52a	1.35–1.42	1.37a	1.44–1.54	1.5a	1.43–1.56	1.48a	1.38–1.48	1.43a	1.3–1.6	1.48

3.2. Spatial Patterns of Connectivity

IC calculations identified the most connected and disconnected areas in the selected microcatchments and also analyzed the effect of terraces on their spatial distribution (Figure 2).

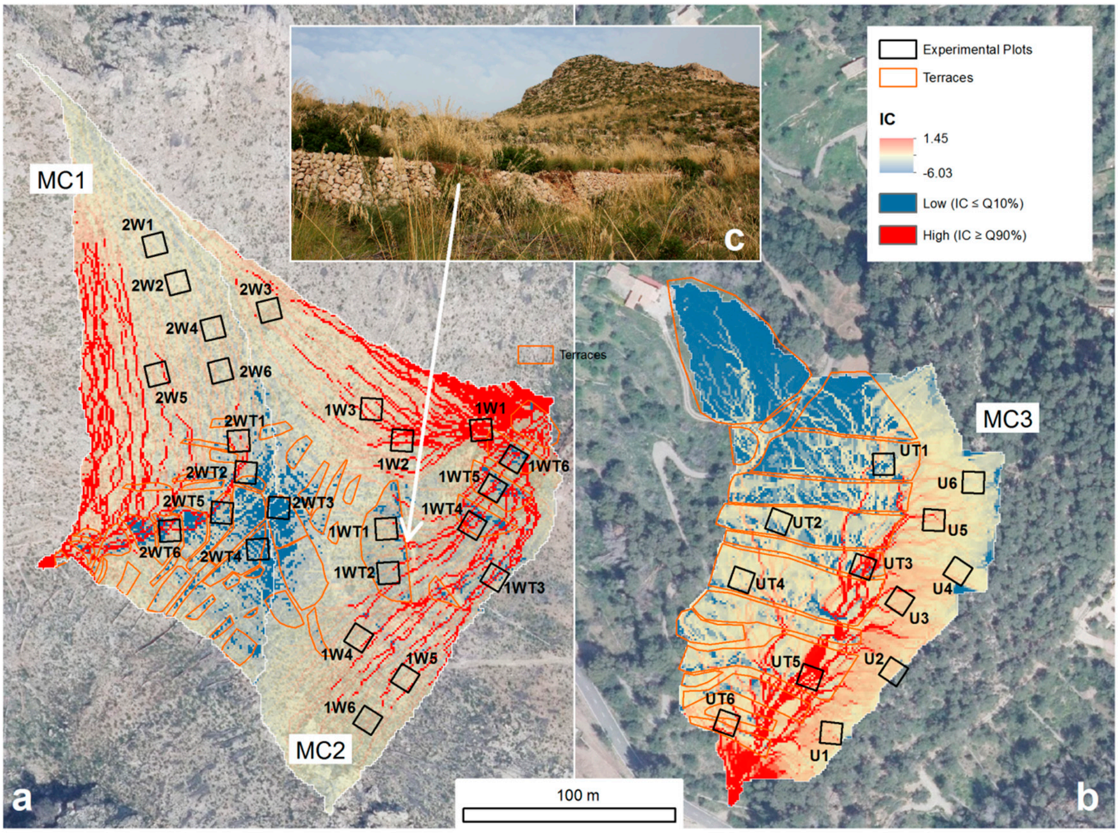

Figure 2. Spatial patterns of connectivity in (**a**) microcatchments MC1 and MC2 and (**b**) microcatchment MC3. (**c**) The collapse of dry-stone walls on abandoned terraces favours increased connectivity along preferential pathways.

Values lower than 10% IC distribution (≤ -4.27) were mainly located within terraces (78%), as well as in some flat areas near the drainage divide. Fieldwork confirmed the high disconnectivity of these areas, in which no evidence of overland flow was observed. Values higher than 90% IC distribution (≥ -3.09) formed highly-connected pathways along steep hillslopes and concave areas, especially in those closer to the catchment outlet. In many cases, these preferential lines of flow concentration run along terraced areas (32%), especially along check-dam terraces (e.g., plots 2WT2, 2WT5, 2WT6; 1WT4–1WT6), which were built on the natural thalweg. The failure of the dry-stone walls after the abandonment of crops showed a coupling effect that facilitated runoff concentration and increased erosion (Figure 2c). The greater variability of IC values in terraced areas (STD = 0.50) than in non-terraced areas (STD = 0.41) was fully consistent with the presence of well-connected pathways (i.e., high IC values) within very disconnected areas (low IC values). The main zonal statistics calculated by the selected plots reflected the same patterns (Figure 3). Plots located on non-terraced hillslopes (e.g., U1–U6; 1W1–1W6; 2W1–2W6) showed more homogeneous IC values (-4.24–-2.34), indicating lower concentration of the overland flow. On the contrary, plots on terraced areas showed a wider range of IC values (-5.59–-2.02), with higher maximum and lower minimum values, as well as a greater dispersion of the values included between Q25 and Q75 (in green in Figure 3).

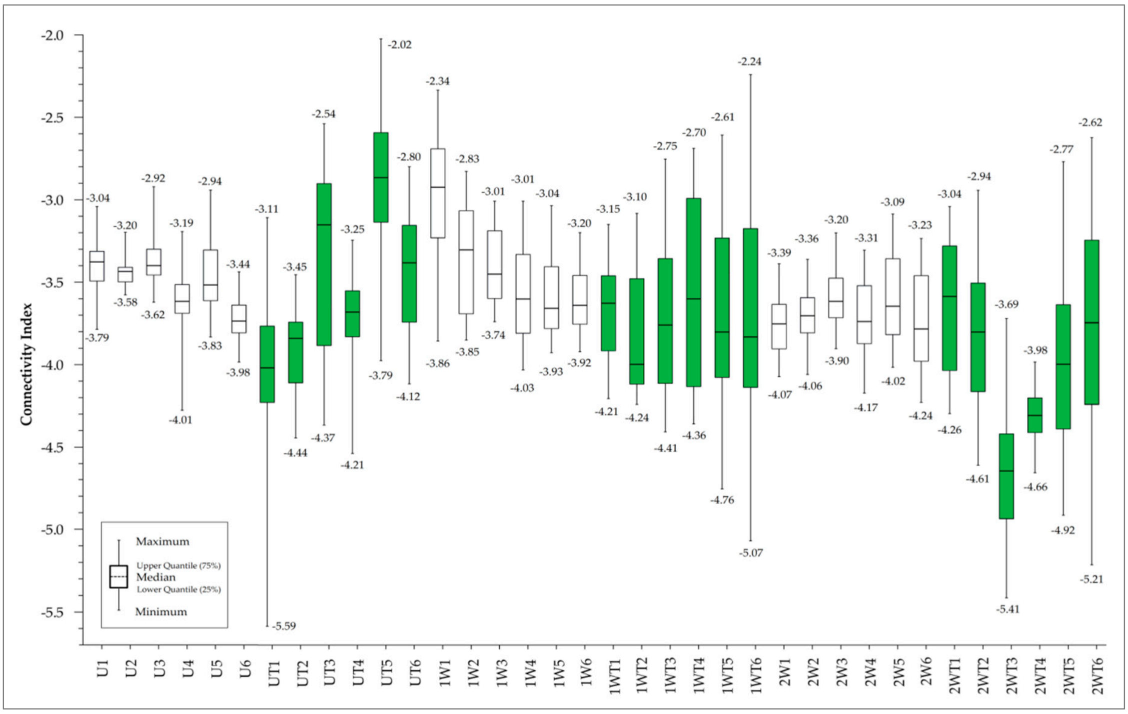

Figure 3. Range and mean IC values by plots with different representative condition: U, unburned; UT, unburned and terraced; 1W, non-terraced and burned once; 1WT, Terraced and burned once; 2W, non-terraced and burned twice; 2WT, terraced and burned twice.

3.3. Clustering and Characterization of Groups

The cluster analysis depicted the degree of statistical similarity of the parameters studied (soil quality and connectivity) in the different plots, which was graphically represented by the Euclidean distance separating them (Figure 4). Plots are classified into different groups on the basis of similarity criteria. If a distance of 11 is applied, plots are classified into three groups, whereas if the degree of similarity is higher (i.e., Euclidean distance = 5), the number of groups increases to 11.

Therefore, the ANOSIM analysis was used iteratively for different plot combinations based on the cluster analysis (applying different Euclidean distances). Groups with no significant differences were pooled to reduce classification into statistically distinct groups. As a result, four groups of plots were established, showing significant differences between all (Overall R = 0.56, $p < 0.001$) and between pairs of groups (Table 4).

These four groups showed a good relationship with the different combinations of terraced or non-terraced, burned or unburned plots (Figure 4). The first group (G1) included only unburned plots without terraces (i.e., U1–U6) and still covered by holm oak forest (30–90%). The second group (G2) mainly consisted of burned plots located on steep (30–64%) and stony (30–75%) non-terraced hillslopes and with low vegetation cover (i.e., 1W1–1W6; 2W1–2W6; 2WT1; 2WT3; 2WT4). The third group (G3) mostly consisted of unburned plots at abandoned terraces (i.e., UT1–UT6; 1WT1; 1WT2). Finally, the fourth group (G4) included only burned plots located at degraded check-dam terraces (i.e., 1WT3–1WT6; 2WT2; 2WT5; 2WT6). The ANOSIM analysis of the studied parameters did not reveal significant differences between plots differently affected by fire, including once- and twice-burned plots in the same groups.

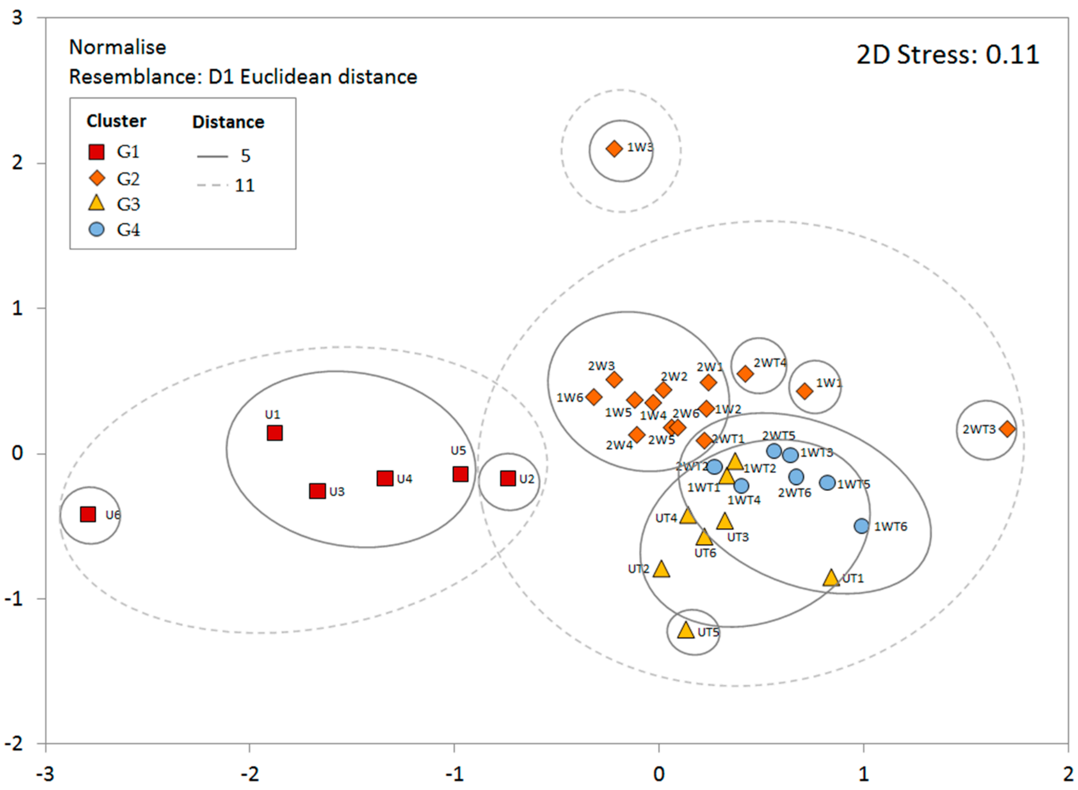

Figure 4. Cluster analysis. G1, unburned and non-terraced plots; G2, most of plots, burned and non-terraced; G3, most of plots, unburned and terraced; G4, burned and terraced plots.

Table 4. ANOSIM (ANalysis of SIMilarities), pairwise tests (Global R: 0.56; $p < 0.001$). Plot groups: G1—Group 1, unburned and non-terraced plots; G2—Group2, burned and non-terraced terraces (except 2WT2, 2WT3 and 2WT5); G3—Group 3, unburned and terraced plots (except 1WT1, 1WT2); G4—Group 4, burned and terraced plots.

Groups	R Statistic	Significance Level
G1 and G2	0.73	0.001
G1 and G3	0.92	0.001
G1 and G4	0.94	0.001
G2 and G3	0.44	0.001
G2 and G4	0.40	0.003
G3 and G4	0.48	0.001

The SIMPER one-way analysis assessed the similarity between plots belonging to each group, identifying the most characteristic parameters and the contribution in similarity percentages (Table 5).

G1 plots showed great similarity (average square distance = 13.27). Soil mineralization (20%), soil respiration (18.8%) and average N% (12.3%), showing higher values than the average for all plots, represented more than 50% of the similarity. Conductivity (9.8%), urease activity (7.5%) and SOM (7.3%), also showing higher values than the average, were also parameters with significant contributions. The average square distance between G2 plots (12.65) was similar to G1. The characteristic parameters with a greater similarity contribution were microbial biomass (15.8%) and MBC/TOC (15.7%), with values higher than the average of all plots, and qCO_2 (11.8%), showing lower average values. Plots in this group, despite being located on very steep hillslopes, did not show high connectivity values: low mean IC (−3.68) and maximum IC values (−3.18) were characteristic parameters, contributing 11.7% and 7.3%, respectively. G3 plots were very similar to each other, with an average square distance of 8.46. The most characteristic parameters were related to connectivity. Mean IC, maximum IC, minimum IC and range IC values together explained more than 50% of group similarity. C/N and Qcm were also characteristic parameters, contributing 10.3% and 7.9%, respectively. G4 plots showed the greatest similarity within a group (average square distance = 4.39). This can be attributed to soil quality parameters such as C/N (23.9%), qCO_2 (16.8%) and Shannon Index (7.4%), but also to a wide range of IC values, with very high maximum IC values and very low minimum IC values. These three parameters contributed 13.4%, 9.9% and 7.1% to the similarity percentage of this group, respectively.

Table 5. SIMPER (SIMilarity PERcentage) one-way analysis. Average square distances between plots for each group and the most characteristic parameters contributing to their similarity.

	Average	**Contribution %**	**Cum. %**
G1: Average Square Distance = 13.27			
MBC—Microbial biomass carbon	0.29	20.03	20.0
REB—Basal soil respiration	2.42	18.78	38.8
N—Total Nitrogen (%)	0.69	12.26	51.1
EC—Electrical conductivity	307.8	9.79	60.9
UA—Urease activity	2.65	7.53	68.4
SOM—Soil organic matter (%)	11.56	7.27	75.7
G2: Average Square Distance = 12.65			
MBC—Microbial biomass carbon	1147	15.84	15.8
MBC/TOC ratio	20.91	15.71	31.6
qCO_2—Metabolic quotient	0.016	11.81	43.4
IC_{MEAN}—Mean IC values	−3.68	11.67	55.0
IC_{MAX}—Maximum IC values	−3.18	7.26	62.3
H—Shannon Index	1.42	6.52	68.8
G3: Average Square Distance = 8.46			
IC_{MEAN}—Mean IC values	−3.60	17.16	17.16
IC_{MAX}—Maximum IC values	−2.93	16.44	33.6
IC_{MIN}—Minimum IC values	−4.37	13.55	47.15
C/N—Carbon-Nitrogen rate	10.09	10.32	57.47
IC_{RANGE}—Range IC values	1.44	8.84	66.31
Qcm—Mineralization coefficient	0.30	7.92	74.23
G4: Average Square Distance = 4.39			
C/N—Carbon-Nitrogen rate	13.43	23.91	23.91
qCO_2—Metabolic quotient	0.034	16.78	40.69
IC_{RANGE}—Range IC values	2.10	13.36	54.05
IC_{MIN}—Minimum IC values	−4.76	9.91	63.96
H—Shannon Index	1.49	7.41	71.37
IC_{MAX}—Maximum IC values	−2.66	7.06	78.43

The SIMPER pairwise analysis evaluated differences between groups, identifying the most important parameters contributing to their dissimilarity (Table 6). G1 showed significant dissimilarity with the rest of the groups (Table 4). Accordingly, the SIMPER analysis also resulted in high values (G1 and G2 = 68.17; G1 and G3 = 73.59; G1 and G4 = 77.15). Enzymatic activities (i.e., urease, β-glucosidase, and phosphatase) were the most characteristic parameters in G1; they were always among those parameters with a higher dissimilarity percentage. In unburned and non-terraced plots, the Synthetic Enzyme Index, which encompasses all enzymatic activity, showed higher average values (9.2) than G2 (3.15), G3 (3.18) and G4 (2.51). Soil respiration in G1 was also higher than in the rest of groups. These were the most important parameters explaining the differences between G1 and burned areas. However, differences with G3 also included parameters such as N%, conductivity or SOM, contributing 10.1%, 9.7% and 9.2% to the dissimilarity percentage, respectively. Values of these former parameters in G3 were much lower (N = 0.24; EC = 139.6; SOM = 4.1) than in G1 (N = 0.69; EC = 307.8; SOM = 11.6). G2, G3 and G4, despite showing significant differences with each other (R > 0.4; $p \leq 0.003$, see Table 4), showed less dissimilarity than with G1 (Table 6). IC values in terraced plots (G3 and G4) had a wider range of values than in non-terraced plots, with higher maximum IC values and lower IC minimum values. Check-dam terraces in group G4, located in thalweg areas, showed especially high maximum and range IC values. Soil organic matter and total nitrogen content in G3 and G4, as well as MBC and soil respiration, were lower than non-terraced groups. On the contrary, high $CaCO_3$ content was a characteristic differential parameter of terraced areas, especially in G3 (31.15%), which was one of the parameters with the greatest contribution. High soil mineralization in G3 (0.3 mg C-CO_2 g^{-1} C h^{-1}) was also one of the most characteristic parameters of the group.

Table 6. SIMPER pairwise analysis. Average square distances between groups and parameters showing the most significant differences.

G1 and G2: Average Square Distance = 68.17	**Average G1**	**Average G2**	**Contribution %**	**Cum. %**
UA—Urease activity	2.65	0.50	10.0	10.0
SEI—Synthetic Enzyme Index	9.20	3.15	9.2	19.2
β-GLA—β-Glucosidase activity	2.93	1.02	9.1	28.3
pH	8.00	8.28	8.8	37.1
REB—Basal soil respiration	2.42	0.89	8.7	45.7
PHA—Phosphatase activity	3.61	1.64	7.7	53.5
G1 and G3: Average Square Distance = 73.59	**Average G1**	**Average G3**	**Contribution %**	**Cum. %**
N—Total Nitrogen (%)	0.69	0.24	10.1	10.1
EC—Electrical conductivity	307.83	139.63	9.7	19.7
REB—Basal soil respiration	2.42	0.70	9.3	29.0
SOM—Soil organic matter (%)	11.56	4.06	9.2	38.2
SEI—Synthetic Enzyme Index	9.20	3.18	8.4	46.5
β-GLA—β-Glucosidase activity	2.93	1.04	8.3	54.8
G2 and G3: Average Square Distance = 35.44	**Average G2**	**Average G3**	**Contribution %**	**Cum. %**
$CaCO_3$—Calcium carbonate content (%)	14.63	31.15	15.9	15.9
SOM—Soil organic matter (%)	8.97	4.06	8.3	24.2
IC_{MEAN}—Mean IC values	−3.68	−3.60	7.7	31.8
Qcm—Mineralization coefficient	0.17	0.30	7.5	39.4
C/N—Carbon-Nitrogen rate	12.67	10.09	7.4	46.8
H—Shannon Index	1.42	1.51	7.1	53.9
G1 and G4: Average Square Distance = 77.15	**Average G1**	**Average G4**	**Contribution %**	**Cum. %**
PHA—Phosphatase activity	3.61	1.18	9.7	9.7
SEI—Synthetic Enzyme Index	9.20	2.51	9.7	19.4
β-GLA—β-Glucosidase activity	2.93	0.86	9.1	28.5
UA—Urease activity	2.65	0.47	9.0	37.5
REB—Basal soil respiration	2.42	0.82	8.0	45.5
N—Total Nitrogen (%)	0.69	0.30	7.8	53.2
G2 and G4: Average Square Distance = 29.31	**Average G2**	**Average G4**	**Contribution %**	**Cum. %**
IC_{RANGE}—Range IC values	0.96	2.10	14.0	14.0
REB—Basal soil respiration	0.016	0.034	11.5	25.5
IC_{MAX}—Maximum IC values	−3.18	−2.66	9.9	35.3
MBC—Microbial biomass carbon	1146.79	273.19	9.7	45.0
MBC/TOC ratio	20.91	6.90	9.3	54.4
IC_{MIN}—Minimum IC values	−4.14	−4.76	9.0	63.3
G3 and G4: Average Square Distance = 22.30	**Average G3**	**Average G4**	**Contribution %**	**Cum. %**
C/N—Carbon-Nitrogen rate	10.09	13.43	19.6	19.6
IC_{RANGE}—Range IC values	1.44	2.10	10.2	29.8
qCO_2—Metabolic quotient	0.015	0.034	9.5	39.4
IC_{MIN}—Minimum IC values	−4.37	−4.76	9.0	48.3
IC_{MAX}—Maximum IC values	−2.93	−2.66	8.7	57.1
$CaCO_3$—Calcium carbonate content (%)	31.15	22.24	8.2	65.2

4. Discussion

Significant differences in soil quality parameters and indices ($R > 0.73$, $p = 0.001$) were observed between unburned plots without terraces (G1) and the other plots under different representative conditions (G2, G3, G4). Plots belonging to G1, considered as reference plots, were characterized by high organic matter and MBC contents, balanced C/N ratios, greater soil respiration and a higher enzymatic activity than burned and/or terraced plots. The higher soil quality in these plots could be attributed to the presence of greater vegetation cover (60%) than in burned plots. However, unburned terraced plots (UT), with even greater vegetation cover (70%), also showed lower MBC/TOC, lower respiration, and enzymatic activity values closer to burned plots, indicating an important role of different factors such as species composition and agricultural activities during the past.

While reference plots were covered by natural forest mainly consisting of *Quercus ilex* (60%), vegetation on unburned terraced plots was mostly young *Pinus halepensis* (<10 year) and shrubs that colonized terraces after their abandonment. Rutigliano et al. (2004) observed that vegetation in more advanced stages of ecological succession leads to a greater contribution of organic matter and better conditions for microbiological and enzymatic activities [57]. Other authors have demonstrated that the accumulation of soil organic compounds in unburned and non-terraced mixed oak and pine forests was directly related to increased enzymatic activities [29]. Therefore, vegetation removal and changes in plant composition deriving from both wildfires and agricultural activities may be considered key factors [35,58] that explain the higher quality of the soil in the undisturbed plots in this study.

The significant differences between reference and terraced plots ($R \geq 0.92$, $p = 0.001$) cannot be attributed solely to vegetation composition, but also to the agricultural activities followed over decades. The conversion of natural ecosystems to agricultural systems drastically reduces the levels of soil organic matter [31–34], which is essential for the development of soil microbial activities [30,36]. In this study, plots located in terraced areas showed very low organic matter contents, hampering microbial biomass growth, which had much lower values than in non-terraced plots. Terraced plots showed lower nitrogen content, soil respiration and enzymatic activities. Although abandonment of agricultural activities enables the reestablishment of soil over time, the results of this study corroborate that its recovery can be slow, especially in Mediterranean environments suffering erosion processes [33]. IC calculations confirmed that the construction of terraces and their subsequent abandonment induced changes in the spatial patterns of hydrological and sediment connectivity [20], favoring enhanced concentration of surface runoff and, consequently, further development of erosion processes. Previous studies in the Sa Font de la Vila catchment showed that terrace abandonment triggered feedback dynamics in which the collapse of the walls generated increased connectivity, which in turn exacerbated the erosion processes leading to their collapse [11]. The most connected areas within terraces showed clear evidence of erosion along preferential pathways, which may be strongly related to soil and organic matter losses, with negative effects on microbiological communities and enzymatic activities. The high hydrological connectivity within terraces, especially in the check-dam terraces, was also related to increased soil carbonation processes, occurring especially as a result of the tillage and the remobilization of the soil [59]. The high $CaCO_3$ content in terraced plots, which slows down soil development processes [60], was one of the most significant factors of dissimilarity with the other plots.

Lombao et al. (2015) also pointed to vegetation as the key factor controlling soil quality in burned forests in Galicia (Spain) [36]. However, fire was also considered by these authors an important source of transformation with significant impacts on soil quality. The extent of the effects of fire can be highly variable depending on fire regime or local conditions [5,6], but generally fires cause partial or complete destruction of organic matter, deterioration of the soil structure, altered aggregate stability and marked quantitative and qualitative alterations of soil microbial communities [61]. In this study, burned plots without terraces showed slightly lower soil organic matter and nitrogen contents, higher pH and conductivity values, as well as reduced soil respiration and lower enzymatic activities than reference plots. However, burned terraced plots showed much lower contents of soil organic matter, regardless of whether they were burned once or twice. This suggests that wildfires had negative effects on soil quality in all burned areas, but previous soil conditions were more favorable in non-terraced than terraced plots.

Depending on the intensity and severity of fire, soil ecosystems can be transformed into different environments for microorganisms after a wildfire. Fire-induced changes in the quantity and quality of soil organic matter are a determining factor controlling the response of the system [62]. Changes in certain soil parameters (e.g., pH or nutrient availability) will also determine the recovery of microbial biomass, its composition and its activity during post-fire recolonization. Bárcenas-Moreno et al. (2011) showed that, despite the loss of organic matter from the soil after a fire, the increase in pH and the contribution of new nutrients may allow a significant recovery of C of microbial biomass after a few months and provide more favorable conditions for its activity [63]. However, the same authors emphasized that the conservation of a minimum content of SOM and N is essential for the recovery of microbial communities. Accordingly, fire-induced changes (e.g., pH increase) coupled with sufficient organic matter availability could have favored a large growth of microbial communities in burned and non-terraced plots, as indicated by the high values of MBC.

Burned and terraced plots, with significantly lower SOM and N contents, had higher qCO_2, which indicates enhanced metabolic activity of the smaller microbial communities. On the contrary, activity in plots with a greater presence of microorganisms could have been limited by the lower proportion of soil organic matter and nitrogen in relation to the microbial biomass. The higher metabolic activity of the smaller microbial communities, as well as their slightly higher mineralization capacity, could favor a faster recovery of the plots with lower soil quality, which is indicative of the great resilience of Mediterranean soil ecosystems [64].

5. Conclusions

This study provided valuable insight into the soil quality and hydrological connectivity of Mediterranean ecosystems by looking at the combined effects of agricultural terracing and wildfires. The following conclusions were reached:

(1) Non-terraced and unburned plots, with a vegetation cover dominated by natural oak forests, had much higher soil quality than all other plots. They had higher organic matter and nitrogen contents, as well as greater microbiological and enzymatic activity. Changes in vegetation cover and composition induced by both wildfires and terracing were therefore identified as determining differential factors.

(2) Terraced plots, regardless of fire effects, had much lower soil quality than other plots had. Low organic matter content and low microbial biomass in terraced plots indicated that agricultural activities in the past still had negative effects on soil quality before the occurrence of wildfires.

(3) Fire was significant, contributing to the worsening of most biochemical and microbiological parameters in both terraced and non-terraced plots. However, while burned non-terraced plots showed higher microbial biomass but lower metabolic ratios, burned terraced plots showed lower microbial biomass but higher metabolic activity, as well as slightly higher mineralization. Thus, microbiological communities in plots with different availability of organic matter and nitrogen due to agricultural activities reacted differently to fires.

(4) Although the construction of terraces has been recognized as a very effective soil conservation technique, the lack of maintenance caused changes in the spatial patterns of hydrological and sediment connectivity, favoring runoff concentration and enhanced erosion. Soil and organic matter losses in abandoned terraces is an added impact, hindering soil recovery after fires.

The complexity of Mediterranean ecosystems requires the integrated study of many factors interacting at different spatiotemporal scales. More research, from a multidisciplinary perspective, is needed to quantify land degradation processes, which would assist the design, implementation and evaluation of management and restoration plans.

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

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