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Evaluation of Soil Evolution After a Fire in the Southeast of Spain: A Multiproxy Approach

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Fire is considered as part of the ecological dynamic in Mediterranean forests and is strongly related to an anthropogenic origin. The aim of this study is to evaluate the evolution of soil properties after a fire in the short term (20 months) by the use of soil quality indicators. The work is based on a multiproxy approach about three basic aspects: 1) the study of changes in soil properties; 2) the estimation of erosion rates; and 3) the evaluation of colonization evolution by soil arthropods through ichnological analysis. Three sectors were selected for this study: a burned and intervened area, a burned and not intervened area, and a reference area. Soil samples were taken randomly from each plot and their main physico-chemical properties analyzed. The assessment of soil erosion was estimated for each plot from three transects (20 m in length) perpendicular to the maximum slope, and the same transects were used for the ichnological study to identify the different bioturbations and the producers. An increase in pH and K values and C/N ratio, and a decrease in total N, available P, CEC, and respiration rate were observed among the fire-affected areas and the reference area; however, there were no significant differences in soil organic carbon. According to erosion, the hydrological correction measures based on the construction of barriers with trunks and branches favored higher runoff and erosion rates in the intervened areas with respect to the not intervened areas. The ichnological analysis showed that arthropods of Formicidae family and Lycosidae sp. genre were the main organisms that recolonized post-fire scenarios; moreover, a lower ichnodiversity is observed in the not intervened area, although with a greater abundance, with respect to the intervened and reference area. According to our results, 20 months after the fire most soil physical-chemical properties did not experiment significant differences in relation to unburned reference area. Our erosion estimation suggested the hydrological correction measures were not appropriate to reduce erosion rates and led to higher soil losses. Moreover, our ichnological study supports the domination by pioneer and opportunist organisms in the recolonization of burned areas.

Keywords: soil properties, post-fire correction measures, soil erosion, tracemakers, bioturbations, recolonization

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INTRODUCTION

The first signs of fire as a natural disturbance of ecosystems date back to the Late Devonian, 400 million years ago (Bodí et al., 2012). In Mediterranean regions, fires have been part of the ecological dynamics of forests before the man appeared, with specific adaptations of the vegetation (Ojeda et al., 1996; Pausas et al., 1999; Pausas et al., 2009). The coincidence in the Mediterranean climate of the hotter and dryer season in summer, made the fires a recurrent event over time (Cerdà, 1993; Rodrigo et al., 2005; Mataix-Solera and Guerrero, 2007). Later, man used fire as a tool. In the Neolithic, societies become to have agricultural and livestock activities that required large areas for pasture and cultivation, and controlled fires began to be used (Cerdà, 1993; Mataix-Solera and Cerdà, 2009a; Giorgis et al., 2013). This has been maintained by both Spain and Mediterranean Europe until the 1960s. From the 1960s, there was a rural exodus in Spain and, consequently, a change in land use dominated by the abandonment of agricultural soils. In addition, reforestation with continuous monospecific stands and the extensive development of urban soils have favored a more prone scenario for the triggering of forest fires (Mataix-Solera and Cerdà, 2009a; Mataix-Solera et al., 2009). Therefore, this disturbance has become of an anthropogenic origin (FAO, 2001), with a strong increase since the 1970s (Pausas et al., 1999; Pedra, 2004; Bodí et al., 2012).

Fire has the ability to affect the physical, chemical and biological properties of the soil; and although the degradation caused by the fire could become irreversible in some cases (Almendros et al., 1984), especially in mountainous areas, the effects in relation to the changes in vegetation and the dynamics of nutrients and organic matter can be sometimes controversial. Soil pH, electrical conductivity, and phosphorous tend to increase after a fire as a consequence of the solubilization of various components from ash (González et al., 1992; Mataix-Solera and Guerrero, 2007; Bodí et al., 2012), although the increase in pH level is greater the higher the temperature reached, and depending on the soil type (Mataix-Solera et al., 2009). Mineral nitrogen concentrations tend to increase and become available in the soil surface after burning (Wan et al., 2001). Fire usually reduces the content in soil organic matter by mineralization (González et al., 1992; Cerdà, 1993; González-Pérez et al., 2004; Mataix-Solera et al., 2009; Mataix-Solera et al., 2011), but the intensity and severity of the fire plays a fundamental role in determining whether the amount of soil organic carbon increases or decreases. Low intensities, as in controlled fires, result in increases in soil organic carbon (Ibáñez et al., 1983; Mataix-Solera et al., 2009). Moreover, changes in soil organic carbon quality have been reported and special attention was paid to the formation of pyromorphic humus because promotes the resistance of organic matter against chemical and biological degradation (González-Pérez et al., 2004). When soil organic carbon is lost, a decrease in the cation exchange capacity occurs (Mataix-Solera and Guerrero, 2007), together with a loss of nitrogen proportional to the temperature reached (Mataix-Solera and Cerdà, 2009b; Bodí et al., 2012). According to physical properties, aggregate stability is also affected by fire, with highly variable effects; in this way, the type of fire is important, promoting this property when it is propagated by the aerial part of the vegetation (Úbeda and Sala, 1996; Mataix-Solera et al., 2009; Mataix-Solera et al., 2011). Otherwise, soil porosity also changes, increasing in clayey soils and decreasing in sandy textures (Úbeda and Sala, 1996). In addition, the microbial activity of the soil is also affected. Fungi show a higher sensitivity to temperature than bacteria, being also the largest fraction of the soil microbial biomass (González-Pérez et al., 2004; Mataix-Solera and Cerdà, 2009b; Mataix-Solera et al., 2009; Mataix-Solera et al., 2011). The recolonization by microorganisms will be more or less rapid depending on the temperature reached. According to Guerrero et al. (2005), those soils subjected to temperatures above 500°C experience strong impacts in relation to their recolonization by microorganisms, while other authors point out a rapid recovery of heterotrophic bacteria (Mataix-Solera and Guerrero, 2007).

One of the main problems in Mediterranean areas is that post-fire effects can also lead to higher soil erosion rates. Soil erosion is strongly controlled by soil properties, slope, climate and vegetation cover (Martínez Martínez, 1979; Cerdà-Bolinches, 2001), being the reduction or elimination of the vegetation cover a key factor in these areas. Soil erodibility plays also an important role, and it is related to granulometry, structure and stability of the aggregates; being the soils with higher content in fine sands and silts more erodible than clayey soils. Some authors also emphasize the importance of organic matter in relation to the soil erodibility by conditioning greater stability of the aggregates (Cerdà, 1993; García-Fayos, 2004). In this way, soils with organic matter content below 4% have significantly high erosion rates (Benito et al., 2014). Another key factor is the hydrophobicity or water repellency; depending on the temperature reached in a fire, this repellency can be high and contribute to increase runoff and erosion rates (Úbeda and Sala, 1996; De Luis et al., 2003; Mataix-Solera et al., 2009; Mataix-Solera et al., 2011). In semi-arid areas into the Mediterranean climate, these runoff losses can be problematic in view of the water balance of the edaphic environment (Mataix-Solera and Cerdà, 2009b). The post-fire measures in order to promote the ecological recuperation and avoid the soil losses are decisive. In some cases, the cut down of burned trees and the removal of the burned wood is carried out, but some authors point out that sometimes avoid this type of intervention could be more beneficial for the recuperation of a post-fire scenario, due to the reduction of the hydric stress and the insolation rate over the seeds, the higher input of nutrients from the mineralization of the burned wood or the colonization facilitation of some organisms (Castro et al., 2006; Castro and Leverkus, 2013; Leverkus et al., 2013; Marañón-Jiménez et al., 2013).

Our study is focused in the southeast of the Iberian Peninsula, one of the most fire affected area in the Mediterranean region, where the occurrence of fires in summer is very frequent and followed by autumn characterized by torrential rains. The absence of adequate intervention strategies produces intense erosive processes and soil losses (Alberdi et al., 2008), that are evident in between 45–50% of this area (Lozano-García and Parras-Alcántara, 2011) and may compromise the soil and

FIGURE 1 | Location of the different studied areas and sampling plots.

ecological recovery of the zone. The aim of this study is to evaluate the evolution of the soil after a fire occurred in Sierra de Lújar (SE, Spain) by the use of soil quality indicators. This work is based on a multidisciplinary approach by the combination of soil physico-chemical studies, soil erosion estimation and the evaluation of the degree of recolonization of soil invertebrate organisms based on ichnological studies.

MATERIAL AND METHODS

Study Area

The study area corresponds to the Sierra de Lújar, located in the southeast of the Iberian Peninsula (**Figure 1**). In July 2015, there was a fire where a total of 2,147 ha were burned, most of them (1,580 ha) corresponded to forest land. After the fire, the removal of wood from the affected areas, the construction of barriers with cut branches and trunks, and the removal of some burnt dead wood, were carried out in some sectors to prevent soil erosion. The study area is located between 800 and 1,300 m of altitude (both Thermo and Mesomediterranean bioclimate), has mean annual precipitations ranging from 200 to 600 mm (semi-arid/dry ombrotype) and relatively high mean temperatures ranging from 17 to 19°C (Moreno, 1994; Valle et al., 2005). Three experimental plots by sector were selected for this study. In all cases, selected plots presented similar conditions, characterized by an abrupt topography, with very steep slopes (between 18–34%), similar orientation (south-facing), same lithology (a mixture of schists and quartzites) and soil type (eutric Regosols) (LUCDEME, 1993). The serie of vegetation is *Myrto-Querceto suberis* with the presence of pines revegetation and being *Cistus ladanifer* the most abundant species (Valle et al., 1993). The presence of cork oaks (*Quercus suber*), more typical of the western region of Andalusia, where rainfall is more abundant and the geological substrate is siliceous in many areas, has been considered as the most singular ecological element of the region (Cabezudo et al., 1995). These populations of cork oaks could be located in this area due to an extreme advance of the species to the east or to the remains of an older distribution that corresponded to the entire Mediterranean coast, constituting in any case one of the most sensitive communities because they are far from their ecological optimum (Díaz-Fernández et al., 1996; Latorre and Artero, 1997; Úbeda et al., 2009).

Experimental Design

Three sectors were selected for this study. A burned area where no intervention measures were implemented (NA), a burned area where intervention measures were made (IA), and an unburned reference area (RA) (**Figure 1**). **Figure 2** shows the intervened and not intervened area, respectively. The intervention measured consisted principally in the cut of trees and construction of barriers with cut branches and trunks; according to this, the original tree density in NA was [mean (standard deviation)] 1733 (564) trees ha-1, while the tree density in IA was 300 (66) trees ha-1; additionally, the removal of burnt dead wood was carried out as well in the intervened area. In each one of the three areas, three plots of 20 × 20 m (400 m^2) were randomly delimited, in which three test pits were also randomly carried out, to sample and characterize the representative soils of each area.

Soil samples were taken to characterize the soil properties affected by fire. In each one of the three sectors (IA–NA–RA), three plots (20 × 20 m) were selected, and composite samples

FIGURE 2 | Intervened area (left) and not intervened area (right).

(composed of five sub-samples thoroughly homogenized) were taken at three depths (0–5; 5–10; 10–30 cm) to obtain three representative plots for each sector. The total number of samples in the field was: 3 sectors x 3 plots x five sub-samples x 3 depths = 135 samples. This study uses as a preliminary methodology to be applied in larger areas, so we homogenized the five sub-samples per depth to obtain a representative sample per depth for each plot, so the total number of samples analyzed was: 3 sectors x 3 plots x 3 depths = 27 samples; where samples represent the average conditions per plot to characterize (in triplicate) each sector. The assessment of soil erosion was calculated for each plot from three transects of 20 m length perpendicular to the maximum slope (n = 9); each transect was located every 5 m. The estimation was made by measuring the width and maximum depth of the rills found into each plot over the transect line. According to these measures, an estimate of the erosion was calculated in terms of kg of soil lost by plot area. The same transects used for quantify soil erosion were used for the ichnological study, in order to identify and characterize the different bioturbations and the producers. Special attention was paid to the morphology of the trace, including size, shape of the opening and presence of some distinctive element; when possible, the family of the tracemarker was identified by visual observation and photographs taken in field. Relative abundance of trace morphotypes in each transect was calculated by the ratio between the total number of bioturbations found for each morphotype in the transect and the number of bioturbations found of the same morphotype each area. The establishment of plots, soil sampling and erosion measures, were carried out 20 months after the fire, while the ichnological study was realized 3 months later the previous study.

Laboratory Analysis

Soil samples were dried at room temperature in the laboratory and sieved through a mesh size of 2 mm, separating the fine fraction (<2 mm) and the gravel (>2 mm). Additionally, grinding of a small portion of the fine fraction of each sample was made to carry out some specific analyzes. The main soil physicochemical properties were analyzed according to standard methods (MAPA, 1994): granulometric analysis was determined by the Robinson's pipette method; electrical conductivity (EC) was measured in a soil:water extract in a ratio 1:5; pH was measured in a soil:water suspension in a ratio 1:2.5; calcium carbonate content ($CaCO_3$) was determined in a calcimeter after reaction with hydrochloric acid (HCl 1:1); exchangeable bases (Ca^{2+}, Na^+, K^+ and Mg^{2+}) were extracted with ammonium acetate (1N and pH 7.0); and cation exchange capacity (CEC) was measured after saturation with sodium acetate (1N and pH 8.2). Total carbon (C) and total nitrogen (N) were determined on a LECO TruSpec CN instrument; additionally, organic carbon (OC) was calculated by the difference between total carbon and the carbon in carbonates, and the easily oxidizable fraction of organic carbon (OC_{ox}) was evaluated with potassium dichromate ($Cr_2O_7K_2$) in cold 0.1 N according to Sierra et al. (2013); available phosphorus was measured by the Olsen method (Olsen et al., 1954). Available water was determined by the Richards membrane method (Richards, 1945) by the difference of the water retained at 33 kPa (field capacity) and 1,500 kPa (wilting point). To estimate the microbiological activity in laboratory, basal respiration was measured according to ISO International Organization for Standardization, 2002 and measured in a SY-LAB respirometer, model μ-Trac 4,200, previously to the respiration measures the humidity was adjusted to field capacity.

Statistical Analysis

Statistical programs R and SPSS were used for the data analyses. According to this, significant differences ($p < 0.05$) were evaluated by the non-parametric test of Kruskal-Wallis. This test was applied in order to determine significant differences among sectors (NA, IA, and RA) for the physical-chemical properties of soils analyzed in laboratory. Special attention was paid to the first 5 cm of the soil, where the fire influence and changes in soil properties are more evident. The same test was carried out to establish significant differences related to the estimation of soil erosion between the burned areas. In regard to the ichnological study, relative abundance was calculated for each morphotype and, moreover, Kruskal-Wallis test was applied for the number of morphotypes identified in field in relation to the producer. Additionally, Principal Components Analyses (PCA) were

TABLE 1 | . Mean values (0–5 cm) of some soil parameters measured in the not intervened burned area (NA), intervened burned area (IA), and unburned reference area (RA) (n = 9). Easily oxidazible carbon (OC_{ox}), total organic carbon (OC), total nitrogen (N), available phosphorous (P), exchangeable potassium (K), cation exchange capacity (CEC) and respiration rate. Lowercase letters indicate significant differences between areas (Kruskal-Wallis test, p < 0.05).

Area	pH	OC_{ox} (%)	OC (%)	N (%)	C/N	P (mg/kg)	K (cmol+/kg)	CEC (cmol+/kg)	Soil respiration rate (mg CO2/h/g soil)
NA	6.9a	1.29a	3.19a	0.11a	11.78a	0.54a	1.40b	14.40a	0.0063a
IA	6.6a	1.82a	3.98a	0.12a	16.3 ab	0.58a	1.67b	16.79a	0.0064a
RA	5.9b	2.62a	5.29a	0.27b	19.6b	2.65b	0.55a	22.07b	0.0090b

performed to analyse the relationship among the soil parameters in relation to the fire influence (burned or not burned area).

RESULTS

Soil Characterization and Properties

Considering the entire soil profile sampled (0–30 cm) at the three areas (NA, IA, and RA), the physicochemical analysis presented similar values in the main properties (n = 27). In all cases, soils were classified as eutric Regosols (LUCDEME, 1993). Soils have a high content in gravel in all areas, ranging between 50–58%, with textures dominated by the "loam" class, with a clay content ranging between 12–15%; the burned areas (NA and IA) presented a higher content in silt (around 50%), and the reference area (RA) presented a higher content in sand (around 51%), but without significant differences between soil samples. In all areas, soil pH is moderately acidic (6.0–6.7), without significant differences in the deeper soil samples between areas. Soils do not have calcium carbonate in any case. The cation exchange capacity (CEC) is moderate in all cases (Hazelton and Murphy, 2007), with values ranging between 12.4–16.4 $cmol_+ kg^{-1}$, and is strongly related to the low content in organic matter and clay of these soils. The base saturation degree (V) of the soils is moderately low, with values ranging from 55–76%, indicating a partial desaturation of the exchangeable complex of the soils.

The mean values of the 0–5 cm samples among the three selected areas were compared (**Table 1**). The organic carbon content, both total (OC) as readily oxidizable (OC_{ox}) were slightly lower in burned areas (NA and IA) in relation to the reference area (RA), although these differences were not statistically significant. C/N ratio was lower in burned areas than in the reference area; however, significant differences were identified only between the not intervened are and the reference area. The comparison between burned and unburned areas showed a significant increase in pH and exchangeable potassium, while the content in total nitrogen and available phosphorous decreased. In our case, the respiration rate 20 months after the fire was reduced around 30% in burned areas relation to the unburned ones.

In our study, we observed that there are no statistically significant differences in the main physical-chemical properties between the two burned areas (NA and IA), indicating that 20 months after the fire, the effect of the actions of cutting trees and building barriers on the soil properties is not significant.

The principal component analysis (PCA) showed that in burned areas the soil respiration is directly related to the OC, OC_x, N, C/N, exchangeable Ca and available water (AW), while in the unburned areas, the soil respiration is directly related to the same parameters with the exception of Ca and AW, and other properties like available P, exchangeable K, and cation exchange capacity (CEC) also appear with significant influence on soil respiration (**Figure 3**).

Soil Erosion

The reference area (RA) presented a very high vegetation cover and no signs of erosion were detected. In the burned areas, signs of rill erosion appear in the surface, with a higher defined pattern in the intervened areas in relation to the not intervened ones. Significant differences were observed for the maximum depth of rill measured in field; the mean value in IA was 12.80 cm, while in NA was 5.40 cm. The intervened area (IA) showed higher erosion value than not intervened area (NA), with a total soil loss measured in all transects up to 56.61 and 17.34 kg, respectively, being these differences statistically significant (p < 0.05) by Kruskal-Wallis test (**Figure 4**). According to UNEP (1997) criteria, plots were grouped depending on their slope range; values among 12–20% correspond to steep slopes and those between 20–35% to very steep slopes. In relation to this, the intervened area showed greater erosion values in all cases, with a statistically significance (p < 0.1) for steep slopes and without significant differences for very steep slopes, both by Kruskal-Wallis test (**Figure 5**). However, higher erosion rates were found in the steep slopes. In accordance with the not intervened area, the erosion rates were higher in very steep slopes than those of steep ones.

Ichnological Study

Ichnological field study was conducted in the three studied areas (NA, IA, and RA) and in the same three plots used for the soil and erosion characterization. Bioturbations were identified, and several morphotypes (Mph) differentiated according to their morphology and the presence or not of the producers (**Figure 6**). Specimens of ants from the Formicidae family, belonging to *Aphaenogaster* sp. and *Tetramorium* sp. gender, were found. Moreover, one spider species from the Lycosidae family was detected. Once identified and described the different

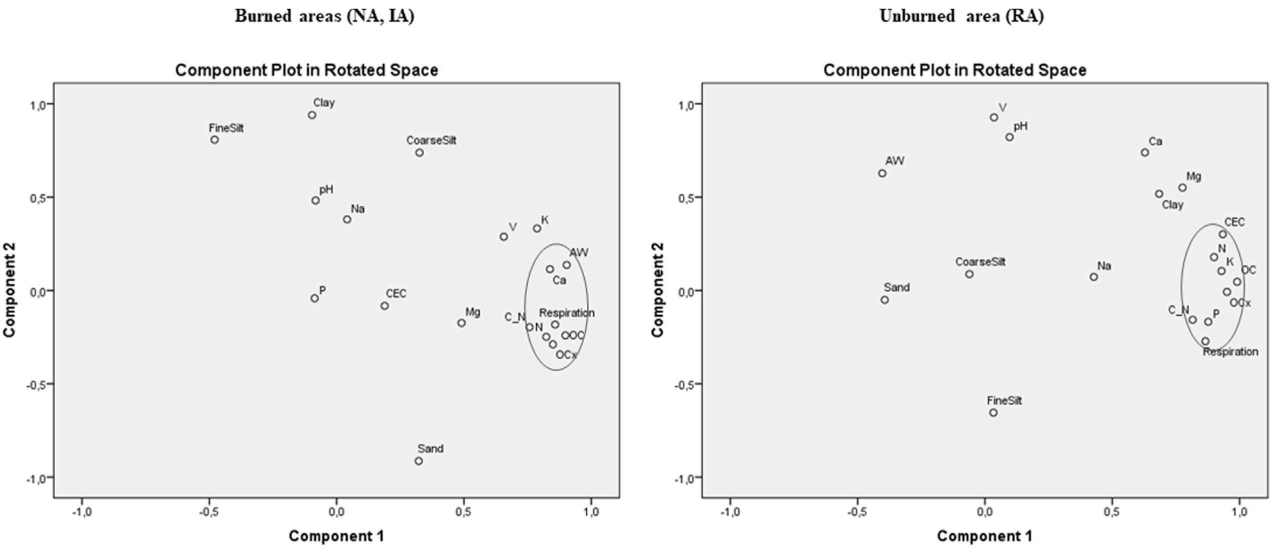

FIGURE 3 | Principal component analysis of the soil respiration rate and main soil properties for the burned (NA, IA) and unburned (RA) area.

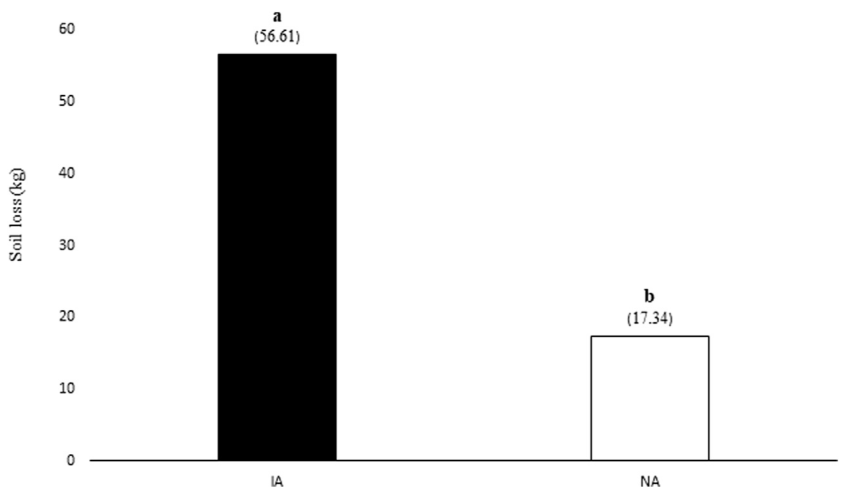

FIGURE 4 | Total erosion values (kg) in burned sectors [intervened (IA) and not intervened (NA) areas]. Letters indicate significant differences between treatments by Kruskal-Wallis test $p < 0.05$).

morphotypes, a count was carried out in order to estimate the amount of them by area and plot (**Table 2**). The Mph-1 is the most numerous, being recognized in any transect and in all studied areas, Mph-2 is frequent and registered in most transects, Mph-3 and 6 are common and observed in all areas, while Mph-4 and Mph-5 are scarce and registered only in transects 2 and 1, respectively.

The relative abundance was estimated for every morphotype among the three sampled areas (NA, IA, and RA) (**Table 3**). Our results indicate that morphotype 1 is the most abundant, and is mainly found in the intervened area (IA). Morphotype 2, was mainly identified in the not intervened area (NA) and rarely in the reference area (RA). Morphotypes 3 and 6 were more abundant in IA respect to the other studied areas; while morphotypes 4 and 5 were scarcely presented in all cases, and no detected in any plot of the not intervened area (NA).

Statistically significant differences were found between morphotypes, after grouping them in relation to the tracemarker (**Table 4**). In this case, morphotypes produced by arachnid biological activity (morphotypes 2, 3, and 5) were more abundant among the areas affected by fire (3.67 in NA; 2.67 in IA, without significant differences between them) in relation to the reference area (0.67 in the RA). On the contrary, significant differences were not found when ants were the producers (**Table 4**).

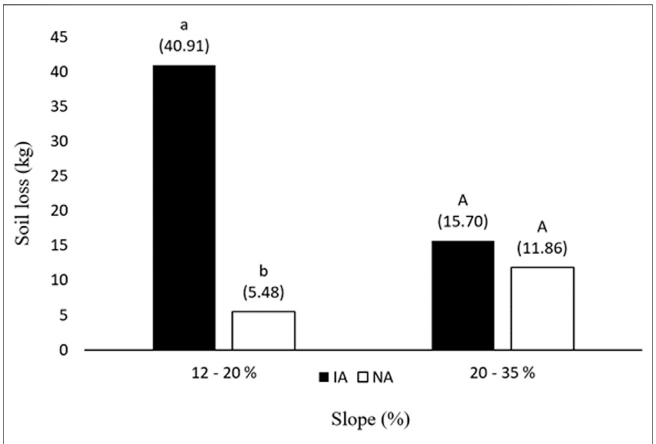

FIGURE 5 | Erosion values among treatments after grouping them by slope ranges. Diffenrent letters indicate significant differences between slopes (p < 0.1) by Kruskall-Wallis test.

DISCUSSION

Soil Properties

The main impact on soil properties after fire is produced in the surface layer, and the maintenance of these properties after the fire will be decisive for the recovery of the area (Wan et al., 2001; Certini et al., 2011; Mataix-Solera et al., 2011; Novara et al., 2011; Zavala et al., 2014), so special attention to the first 5 cm of soil profile was paid. The greater values of pH measured in burned areas (NA and IA) are usually related to the release of high amounts of basic cations, which is in accordance with the results observed by other authors (Rashid, 1987; Tester, 1989; Kim et al., 1999; Nardoto and Bustamante, 2003); however, Úbeda et al. (2005) reported that more than 1 year after the fire pH values returned to pre-fire levels, which could be related to the OH- losses, the oxidation of organic matter and the leaching of cations after fire (Alcañiz et al., 2018). Additionally, Knicker (2007) argued that significant increases in the pH values are related to the high temperatures (>450°C) of an intense fire. The cation exchange capacity (CEC) is lower in the burned area as a result of organic matter losses (Ulery et al., 2017). The partial desaturation of the exchangeable complex of the soils (ranging from 55–76%) is mainly related to the loam textures, the moderately acidic conditions, the relative high precipitation in the area and the high slopes, that produce a partial loss of nutrients by runoff waters (Martín-García et al., 2004; Miralles et al., 2007). The content in calcium carbonate is very low in all cases and related to small carbonate inputs coming from runoff waters from nearby carbonated areas (Sanz de Galdeano et al., 2014).

In relation to the organic carbon content, we found no significant differences in total (OC) and readily oxidizable (OC_{ox}), among the studied areas, although the values were lower in the burned areas. This could be due, on the one hand, to losses associated to the mineralization of a fraction of the carbon and, on the other hand, as a consequence of the possible high intensity of fire, to the accumulation of recalcitrant forms of carbon, which are more resistant to biodegradation and could affect the recovery of soil respiration rates (González-Pérez et al., 2004; Knicker et al., 2006; González-Vázquez, 2011; Verma and Jayakumar, 2012). Total N is significantly lower in the burned area than in the reference area, indicating the loss of this element in soil after fire due to increase in N mineralization rate (Gillon and Rapp, 1989; Wang et al., 2014). According to the values of carbon and nitrogen reported, the C/N ratios are lower in the burned areas than in the reference area, even though these differences were only significant among the not intervened area and the reference area, what could be due to a high-intensity fire (Pereira et al., 2012). The available P content reported a significant decrease in burned soils respect to the reference area, although the reduction of this element is not a common process; this reduction could be related to volatilization occurred at higher temperatures (>700°C; Pourreza et al., 2014), or to losses of soluble inorganic forms of P from the soil by runoff (Merino et al., 2019). Fonseca et al. (2017) observed losses of P 2 months after the fire, probably, due to leaching by runoff waters and erosion, and reported that the increases in P content after the fire can be ephemeral and no last more than 1 year. The significant increase in exchangeable K observed in the burned areas (NA and IA) in relation to the unburned areas (RA) is commonly related to the release of this cation during the combustion of the soil organic matter and the incorporation of ashes to the soil (Certini, 2005).

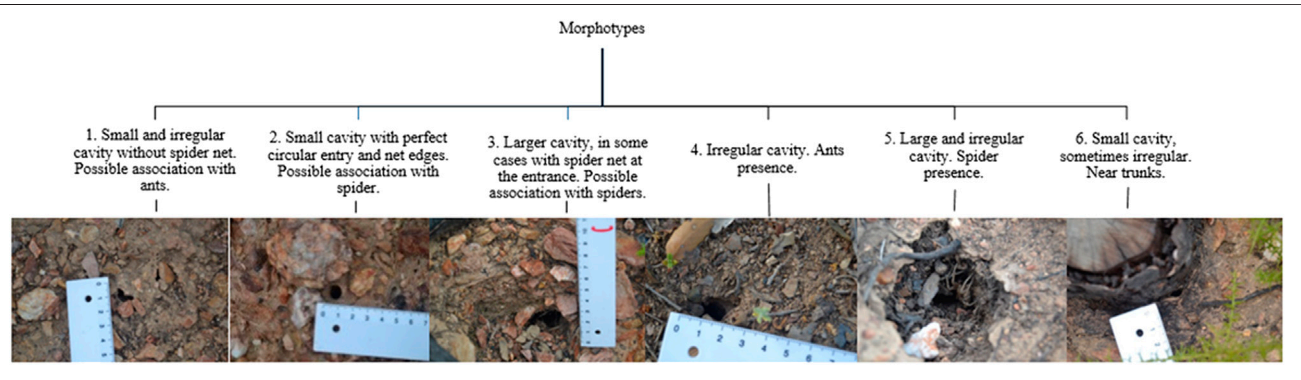

FIGURE 6 | Classification of the different trace morphotypes identified on field.

TABLE 2 | Number of traces belonging to all morphotypes (Mph) found in the different plots (P1, P2, and P3) in all studied areas (NA, IA, and RA).

Sample	Mph-1	Mph-2	Mph-3	Mph-4	Mph-5	Mph-6
NA-P1	1	2	3	0	0	1
NA-P2	8	4	0	0	0	0
NA-P3	3	2	0	0	0	1
Total (NA)	12	8	3	0	0	2
IA-P1	10	2	0	0	0	1
IA-P2	5	1	3	0	0	1
IA-P3	7	0	1	0	1	1
Total (IA)	22	3	4	0	1	3
RA-P1	9	1	0	3	0	0
RA-P2	3	0	1	0	0	1
RA-P3	4	0	0	1	0	1
Total (RA)	16	1	1	4	0	2
TOTAL	50	12	8	4	1	7

TABLE 3 | Relative abundance values in the different sampled areas (NA, IA, and RA) and for all morphotypes (Mph) found in the field study.

Area	Mph-1	Mph-2	Mph-3	Mph-4	Mph-5	Mph-6
NA	0.24	0.67	0.38	0	0	0.29
IA	0.44	0.25	0.50	0	1	0.43
RA	0.32	0.08	0.13	1	0	0.29

TABLE 4 | Mean values (standard deviation) of morphotypes produced by arachnid (2, 3, and 5) and ant (1, 4, and 6) biological activity for each treatment. Lowercase letters show significant differences among studied areas by Kruskal-Wallis test ($p < 0.05$).

Organism producer	NA	IA	RA
Arachnid	3.67a (4.04)	2.67a (1.53)	0.67b (0.58
Ant	4.67a (6.43)	8.33a (11.93)	7.33a (7.57)

The soil respiration is directly related to the biological activity of the soil ecosystem and is a good indicator of the impact of fire on soil microorganisms (Yiqi and Zhou, 2006). In our study, the reduction in the respiration rate in burned areas indicates a moderate impact on soil biological activity. Similar results were obtained by Amiro et al. (2003), who reported a reduction of CO_2 flux for a 15-year period after the fire, with the highest reduction to around 25% in relation to control areas during the first year following the fire. According to the principal component analysis, the soil respiration in the burned areas is directly related to the availability of water and exchangeable Ca content. Soil moisture is the principal factor controlling the soil microbial activity, so there is a direct correlation between the availability of water and the soil respiration in burned zones (Marañón-Jiménez et al., 2011; Plaza Álvarez et al., 2017). Moreover, the respiration rate can be affected by inputs of exchangeable cations as Ca (Rodríguez et al., 2017), coming from the combustion of the soil organic matter and the incorporation of ashes to the soil.

Soil Erosion

In our study case, the erosion between burned areas showed significant differences for IA in relation to NA, indicating that measures implemented in order to reduce runoff and erosion rates in IA were not appropriate and lead to higher soil losses. Robichaud (2000) reported greater sediment generation rates after fire in intervened areas by the construction of barriers than in control areas. Some authors have pointed out that barriers are effective in order to reduce runoff waters when precipitations are low intensity, but not when high intensity events occur (Wagenbrenner et al., 2006; Robichaud et al., 2008; Fernández and Vega, 2016a; Sánchez et al., 2019). In some studies, negative effects derived from the construction of barriers with dead trunks and branches have been observer 5 years after the fire (Fernández et al., 2007; Fernández and Vega, 2016b). Moreover, Wilson (1999) estimated that under some conditions, logging will cause greater runoff and on-site erosion than wildfire.

Besides the construction of barriers with trunks and branches, the removal of burned dead wood was carried out in some burned areas. This intervention usually involves the access of heavy machinery into the affected zone, which could be related to an increase of the soil compaction, a reduction of the infiltration and a rise of the runoff waters (Inbar et al., 1997; Fernández et al., 2007; Fernández and Vega, 2016b; Wagenbrenner et al., 2016). According to this, Wagenbrenner et al. (2015) observed a greater sediment generation regarding to the increase of the perturbation associated to the use of machinery and equipment after fire. Also, a compaction of the soil up to 10 cm of depth was estimated by other authors, even when the soil was dry and only a moderate use of equipment has occurred (Malvar et al., 2017). On the other hand, out the study area is south facing and the vegetation development usually slower and, consequently, the increase of bare soils contributes to greater erosion rates that were identified in post-fire scenario conditions. In relation to this, Marques and Mora (1998) determined higher erosion rates in the south facing areas than in the north facing areas, probably, associated to a faster development of the shrubs in the north facing zones. Finally, the cork oak forest, considered the most characteristic ecological element of the studied areas, is principally located in private lands. According to this, the participation of the different owners with the responsible administration seems to be determining for the recovery of the post-fire scenario.

Ichnological Study

Fire can have a devastating effect on the organisms that develop in the soil, increasing the direct mortality and altering the structure of habitats (Moretti et al., 2004; Moretti et al., 2006). The recolonization after the fire is strongly influenced by the habitat structure, the dispersion, and the escape and migration capacity of the involved species. Usually, the post-fire scenario presents more open areas with a higher insolation grade and with lower soil moisture that could favor to xerophytic fauna (Swengel, 2001; Kiss and Magnin, 2003). The arthropods that live into the soil have more probabilities of surviving *in situ* to the effect of fire (Harper et al., 2000). In our case, no significant differences were found in relation to the number of morphotypes found at each area, which could be due to the number of replicates. In addition, the sampling was carried out 20 months after the fire and, as a result, changes in the populations can have occurred. Into adapted to fire environments, the greatest part of wildlife can recover in a short period of time (Moretti et al., 2004). According to this, Frizzo et al. (2012) found no significant differences in richness and composition species among the burned and unburned areas 12 months after the fire and attributed it to the low number of replicates by transect. On the other hand, our study showed significant differences in the number of trace morphotypes between treatments (mean values of 3.67 [NA], 2.67 [IA], and 0.67 [RA]) regarding to the producers and, specifically, when a spider (Lycosidae) was the tracemaker. The initial response to a bare soil and xeric conditions after a wildfire is the domination by pioneer organisms. Spiders, and specially Lycosidae species, are considered as part as pioneers of recolonization of post-fire scenarios and perturbed zones (Ferrenberg et al., 2006; Samu et al., 2010), they seem to be less dependent on the vegetal structures, and could seek refugees into the soil or under stones during the combustion (Moretti et al., 2002), although the immediately recolonization after fire is more probable (Bell at al., 2001). Moreover, some authors reported that depredators arachnids are predominant in open environments (Athias-Binche et al., 1987), and Underwood and Quinn (2010) observed an increase of vagrant and desiccation-tolerant spiders after the fire.

Besides of spiders, Formicidae, specifically of the *Tetramoriun* sp. and *Aphaenogaster* sp. genders, were found and identified on field, although no significant differences were found for the bioturbations produced by ants. They are considered as resilient and resistant organisms to fire because of their adaptations to xeric conditions, social behavior and nets into the soil, and it have been observed that they are the first organisms to recolonize a burned zone (Ahlgren, 1974). Furthermore, fire eliminates possible obstacles to locomotion and can promote an increase in the nutrient availability (Barrow et al., 2007). According to Arnan et al. (2006), the resilience of some ant communities in the Mediterranean region is related to the environmental condition and, as a result, the differences between burned and unburned areas are little when water deficit on summer exists. Moreover, Formicidae family is considered a very resilient taxon to the effect of fire (Pryke and Samways, 2012). Mateos et al. (2011) determined that the Formicidae family was the most abundant in all treatments, including logging, subsoiling, re-burnt and unburned. Other authors found that the diversity of ants was similar among burned and unburned steppe zones after the fire (Farji-Brener et al., 2002). In general, no significant differences were found between intervened and not intervened burned zones, so leaving the burned dead trunks could help to recover the abundance of several insect groups (Elia et al., 2012).

Observed results support the ichnological information obtained in the last years about the initial recovery by opportunistic tracemakers immediately after different-scale paleoenvironmental disasters. At the ecological scale, less than 10 years after the environmental contamination disaster of Aználcollar (province of Sevilla, southern Spain), the ichnological record revealed the colonization of the polluted substrate; nests of the ant *Tapinoma nigerrima* (Nylander), an opportunistic species, were observed through the tailing layer (Rodríguez-Tovar and Martín-Peinado, 2009; Martín-Peinado and Rodríguez-Tovar, 2010). At the geological range this fact has been recognized in "minor" and "major extinctions". In relation with minor extinctions, the record of the trace fossil *Halimedides* immediately after the Toarcian Oceanic Anoxic Event has been related with the opportunistic behaviour of the tracemaker after improvement of oxygen conditions and nutrient availability (Rodríguez-Tovar et al., 2019; Fernández-Martínez et al., 2020). In the order of major extinctions, the so-called "Big Five," a clear example is obtained from the end-Cretaceous (K-Pg) mass extinction event. Ichnological studies conducted in several K-Pg sections evidenced the rapid colonization of the K–Pg boundary layer, classically interpreted as an inhabitable substrate, by opportunistic organisms with a high independence with respect to substrate features (i.e., *Chondrites* tracemakers) (Rodríguez-Tovar and Uchman, 2004; Tovar and Uchman, 2006; Rodríguez-Tovar and Uchman, 2008; Labandeira et al., 2016).

CONCLUSION

According to our results, 20 months after the fire most soil physical-chemical properties did not experiment significant differences in relation to unburned reference area, although a significant decrease in total N content, CEC, and respiration rate was observed in affected areas. On the other hand, our erosion estimation suggested the hydrological correction measures were not appropriate to reduce erosion rates and, on the contrary, leaded to higher soil losses. Moreover, the implementation of these measures has an additional economic cost for the administration. Therefore, and in accordance with other authors, the not intervention and leaving the cut burned dead wood could have been an interesting alternative option in order to reduce possible economic costs, erosion rates and facilitate the vegetation recovery. Respect to the ichnological study, no significant differences were found in relation to the number of trace morphotypes found at each area; this could be related to the low number of replicates of the sampling. On the contrary, significant differences were observed in the number of morphotypes between treatments. Our results support the domination by pioneer and opportunist organisms in the recolonization of burned areas. Specifically, Lycosidae spiders and ants of the Formicidae family were the main groups identified on field and are considered as part of the most abundant organisms after a fire.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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