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Microarthropod responses to fire: vegetation cover modulates impacts on Collembola and Acari assemblages in Mediterranean area

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Abstract

Background In the Mediterranean region, fire is a recurring disturbance that impacts both surface and underground organisms. While the effects on plants and surface animals are well-studied, the consequences for soil microarthropods are often overlooked. This research addresses the microarthropod responses to fire by comparing post-fire Collembola and Acari assemblages in soils with different vegetation covers. Three years post-fire, surface soils were sampled within the Vesuvius National Park (Southern Italy) from a total of 24 sites, comprising 6 sites each under holm oak (HO), pine (P), black locust (BL), and herbaceous (H) vegetation. Within each vegetation cover, sites were further categorized into three unburnt (NB) and three burnt (B) sites for comprehensive analysis. Collembola and Acari were extracted, identified at the family and suborder level, respectively and analyzed for density and taxa richness.

Results The results highlighted that fire alone did not impact microarthropod communities, but its effects varied according to the vegetation covers. Microarthropod abundance declined in burnt soils under P, and increased in burnt soils under BL. Furthermore, eu-edaphic organisms (Onychiuridae, Oribatida), typical of stable environments, decreased in soils under P, and increased in soils under black locust.

Conclusions Fire impact on microarthropod communities changed according to the vegetation covers, highlighting the importance of considering vegetation type when managing post-fire landscapes. The rapid recovery of microarthropod communities under some vegetation covers suggests that fire may not universally impair soil biodiversity in Mediterranean environments.

Keywords Soil fauna, Wildfire, Soil biodiversity, Community ecology, Anthropic disturbance

Resumen

Antecedentes En la región del Mediterráneo, el fuego es un disturbio recurrente que impacta a los organismos tanto de superficie como los que viven por debajo del suelo. Mientras que los efectos del fuego sobre las plantas y los animales que habitan su superficie han sido bien estudiados, sus consecuencias sobre los microartrópodos del suelo han sido muchas veces pasadas por alto. Esta investigación se enfoca en las respuestas de los microartrópodos al fuego mediante la comparación post fuego de los ensambles de colémbolos y ácaros en suelos con diferente cobertura vegetal. Tres años luego del fuego, el suelo superficial fue muestreado dentro del Parque Nacional del Vesubio (en el sur de Italia) en un total de 24 sitios, que incluían 6 sitios debajo de encinos (HO), pinos (P), algarrobo negro (BL), y

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vegetación herbácea. Dentro de cada cobertura de vegetación, los sitios fueron luego caracterizados en tres categorías de no quemados (NB), y tres de quemados, para un análisis más comprensivo. Los colémbolos y ácaros fueron extraídos de esas muestras, identificados a nivel de familia y suborden, respectivamente, y analizados para determinar densidad y riqueza de esos taxones.

Resultado Los resultados resaltan que el fuego "*per se*" no impactó la comunidad de microartrópodos, aunque sus efectos variaron de acuerdo a la cobertura vegetal. La abundancia de microartrópodos declinó en suelos quemados bajo vegetación de pino (P), y se incrementaron en suelos quemados bajo vegetación de algarrobo (BL). Además, los organismos eu-edáficos (*Onychiuridae*, *Oribatida*), típicos de ambientes estables, también decrecieron en suelos de P y se incrementaron en aquellos debajo de BL.

Conclusiones El impacto del fuego en comunidades de microartrópodos cambia de acuerdo a la cobertura de la vegetación, resaltando la importancia de considerar el tipo de vegetación cundo se manejan paisajes post fuego. La rápida recuperación post fuego de las comunidades de artrópodos bajo una misma cobertura vegetal, sugiere que el fuego no perjudica de manera universal la biodiversidad del suelo en ambientes mediterráneos.

Background

Soil microarthropods represent a substantial proportion of biodiversity in forest ecosystems that play fundamental and irreplaceable roles in ecosystem functioning, such as organic matter decomposition, humus formation, and nutrient cycling (Joimel et al. 2018; Leclercq-Dransart et al. 2018). Soil microarthropods are rather ubiquitous in nature but their distribution and assemblage are affected by various factors such as plant communities and properties of litter and soil (Kutáková et al. 2018). Acari and Collembola are dominant groups of soil-dwelling microarthropods (Jung et al., 2010; Huebner et al., 2012) that play an essential function in the keystone processes of decomposition and nutrient cycling. Changes in their abundance and community assemblage are used as indicators of the intensity of various disturbances, even long after the disturbance events (Coyle et al. 2017; Certini et al. 2021; Malloch et al. 2020).

In Mediterranean ecosystems, fire represents one of the most important factors of disturbance that periodically affects extensive areas (Ladd et al. 2005; Psomiadis et al., 2017). Because of the high temperatures on surface soils, fires directly impact the soil microarthropods (Auclerc et al. 2019), causing a reduction of their density (Malmström, 2012; Auclerc et al. 2019) and a shift of the community composition that favors taxa resistant to fire (Andersen et al. 2014; Vasconcelos et al. 2017). Several studies reported that fire reduces the frequency and the density of Acari and Collembola (Çakır et al., 2023), and alter their community assemblage after fire, as some organisms moving slowly were immediately destroyed, and other groups can become dominant (Huebner et al., 2012; Malmström et al., 2009). Fire occurrence can also indirectly impact on soil microarthropod communities, as it influences the vegetation cover and the soil abiotic properties (Ferrenberg, Wickey, and Coop 2019; Memoli et al. 2021; Santorufo et al. 2021). In fact, vegetation covers, mediating the impact of fire (Memoli et al. 2022), can differently influence the capability of microarthropod communities to establish, grow, and migrate (Meloni et al. 2020). Depending on their tolerance to disturbance, their ability to move away, and their strategies of recolonization (Coyle et al. 2017), the microarthropod assemblage post-fire can be different according to the spatial heterogeneity of surface, soil properties, and the kind of vegetation (Auclerc et al. 2019).

The recovery of soil organisms after a fire is variable and can take from a few years to decades or even longer, depending on fire severity, spatial heterogeneity, and soil characteristics (Zaitsev et al. 2016). During fire, the soil undergoes transformations such as pH increase due to ash addition, changes in soil albedo, addition of pyrogenic carbon, and depletion of organic matter via combustion and erosion and alteration of moisture regime (González-Pérez et al. 2004; Bird et al. 2015). These microhabitat transformations may affect the soil microarthropods, whose recovery is strictly linked to each taxonomic group. The groups suffering the most from fire are the slowly moving microarthropods, as they do not have the ability to descend to the soil as fast as needed to avoid burning. By contrast, large predatory animals, feeding on unevenly distributed resources, have more advantages in escaping such extreme events as fire (Gongalsky et al., 2012).

As, the impact of fire on microarthropods according to different vegetation cover and soil characteristics is scarcely studied, it is essential for the ecosystem conservation, to clarify how these factors modify the effect of fire on microarthropod community and their recovery. In this framework, the present research aimed to evaluate the effect of fire on soil microarthropods, Collembola and Acari assemblage, in heterogeneous Mediterranean area including four vegetation covers (holm oak, pine, black locust, and herbaceous vegetation). In particular, the present research aimed to examine (1) if fire modifies the differences among the vegetation covers, on the basis of soil properties, microarthropods, Collembola and Acari communities, (2) which soil characteristics were associated with differences in Collembola and Acari assemblages by vegetation cover and fire, and (3) which taxonomic groups were mainly responsible for the possible changes among unburnt and burnt vegetation covers. These findings will help clarify how the impact of fire on microarthropod communities is influenced by vegetation cover and identify the key soil abiotic properties that affect these communities after fire events in the Mediterranean region, a recognized biodiversity hotspot.

Methods

Site description

The study area is located inside the Vesuvius National Park, near Naples (Campania region, Southern Italy). The climate of the area is typically Mediterranean, with hot and dry summers and rainy cold autumns and winters (mean annual temperature: 13.2 °C, mean hottest temperature: 30 °C, mean coldest temperature: 5 °C; annual precipitation: 960 mm, data from the reports of the Osservatorio Vesuviano and from www.ilmeteo.it).

Vesuvius National Park represents a complex mosaic of Mediterranean vegetation types with different areas characterized mainly by holm oaks (*Quercus ilex* L.), others by pines (*Pinus pinea* L., *Pinus nigra* L.), others by grass and shrubs (such as *Myrtus communis* L., *Laurus nobilis* L., *Viburnum tinus* L., Cistus sp., Ginesta sp.) (Memoli et al. 2018), and some patches by black locust (*Robinia pseudoacacia* L.) (Anna De Marco et al. 2013). From 2 July to 31 August 2017, several wildfires occurred at the Vesuvius National Park. Eleven percent of the total forested area burned at high fire severity, 13% burned at moderate-low fire severity, 33% burned at low fire severity, and 12% remained unburned (Saulino et al. 2020). Fire caused the consumption of more than 50% (approximately 3000 ha) of the existing plant cover (Saulino et al. 2020) and leaving burnt and unburnt areas inside each plant cover typology.

Soil and microarthropod sampling

Approximately 3 years after the fire occurrence, in October 2020, soil and microarthropod samplings were performed, after 15 days without rainfall, to minimize the effect of climatic variability. The soil, developed on volcanic products, is characterized by andic properties (Imperato et al. 2003). The soil was collected at 24 sites (Table 1 and Fig. 1) equally divided into four different vegetation cover types: herbaceous (H), black locust (BL), pines (P), and holm oak (HO). Within each vegetation cover type, three sites (all affected by moderate-high fire intensity level) were collected in burnt (B) and three in unburnt (NB) areas. Distances between the sampled burnt and unburnt sites ranged from minimum of 200 m to a maximum of 4000 m (Table S1).

For each site, five soil cores (depth: 10 cm, diameter: 5 cm) used for the soil physical and chemical analyses and five soil corers (depth: 5 cm, diameter: 5 cm) used for the microarthropod analyses, were collected at the four corners of the site and one at the centre, after removing litter at unburnt areas, and after removing ash or the litter accumulated after fire, at burnt areas. The soil corers collected for the soil physical and chemical analyses were mixed to obtain a homogeneous sample, whereas those collected to extract microarthropods were kept separated. The soil samples were put in sterile bags and transported refrigerated to the laboratory.

Soil chemical analyses

In the laboratory, the homogenized soil sample was sieved (2 mm mesh size) to measure the pH, water holding capacity (WHC), water content (WC), total carbon (C), nitrogen (N), and organic carbon (C_{org}), NH_4^+ and NO_2, total and available P concentrations. Briefly, pH was measured in a soil:distilled water suspension (1:2.5 = v:v) by an electrometric method. WC was determined by gravimetrically drying fresh soil at 105 °C until constant weight, and WHC was measured gravimetrically after release of gravitational water and oven-drying at 75 °C to a constant weight. The total C and N concentrations were evaluated in oven-dried soil samples by Elemental Analyser (Thermo Finnigan, CNS Analyzer). The organic carbon (C_{org}) was measured in soil samples previously treated with HCl (10%) to exclude carbonates (Pribyl 2010), by Elemental Analyser (Thermo Finnigan, CNS Analyzer).

NH4 + and NO2 − concentrations were measured after extraction of fresh soil samples in a solution of KCl (2 M) according to the Italian Law DM 13/09/99. For the determination of the NH4 + concentration, an aliquot of sample was diluted with phenol solution, sodium nitroprusside solution, and sodium hypochlorite. For color development, the solution was left at room temperature for 1 h in the dark, and the absorbance at 640 nm was read using the spectrophotometer UV–Vis (Cary50, Varian). To determine the NO2 − concentrations, an aliquot of sample was diluted with dye solution. For the color development, the solution was left 10 min and the absorbance at 543 nm was read using the spectrophotometer UV–Vis (Cary50, Varian).

The total P concentration was determined on fresh soil treated with H_2SO (96%, Sigma Aldrich), H_2O_2 (30% wt, Honeywell), and HF (47%, VWR Chemicals) for acid digestion (Olsen et al., 1980). The solution was placed

Table 1 Surface area, dominant vegetation cover, and altitude of each site sampled on Vesuvius National Park

Site	Surface area (m^2)	Dominant vegetation	Altitude (a.s.l.)
NB-HO1	200	*Quercus ilex* L	600
B-HO1	400	*Quercus ilex* L	600
B-HO2	300	*Quercus ilex* L	600
NB-HO2	400	*Quercus ilex* L	600
B-P1	300	*Pinus pinea* L., *Pinus nigra* L., *Pinus sylvestris* L	600
NB-HO3	400	*Quercus ilex* L. approximately 80% of vegetation	600
NB-P1	200	*Pinus pinea* L., *Pinus nigra* L., *Pinus sylvestris* L	600
NB-P2	300	*Pinus pinea* L., *Pinus nigra* L., *Pinus sylvestris* L	600
NB-P3	200	*Pinus pinea* L., *Pinus nigra* L., *Pinus sylvestris* L	600
B-P2	500	*Pinus pinea* L., *Pinus nigra* L., *Pinus sylvestris* L	600
B-HO3	200	*Quercus ilex* L. approximately 80% of vegetation	600
B-BL1	400	*Robinia pseudoacacia* L., *Laurus nobilis* L., *Viburnum tinus* L., *Rosmarinus officinalis* L., *Cistus sp.*, *Ginesta sp.*	600
NB-BL1	300	*Robinia pseudoacacia* L., *Laurus nobilis* L., *Viburnum tinus* L., *Rosmarinus officinalis* L., *Cistus sp.*, *Ginesta sp.*	600
B-H1	200	*Centranthus ruber* L., *Valeriana officinalis* L., *Helichrysum italicum* R., *Artemisia campestris* L., *Rumex scutatus* L	600
NB-H1	200	*Centranthus ruber* L., *Valeriana officinalis* L., *Helichrysum italicum* R., *Artemisia campestris* L., *Rumex scutatus* L	600
NB-BL2	300	*Robinia pseudoacacia* L., *Laurus nobilis* L., *Viburnum tinus* L., *Rosmarinus officinalis* L., *Cistus sp.*, *Ginesta sp.*	600
NB-H2	400	*Centranthus ruber* L., *Valeriana officinalis* L., *Helichrysum italicum* R., *Artemisia campestris* L., *Rumex scutatus* L	900
NB-BL3	300	*Robinia pseudoacacia* L., *Laurus nobilis* L., *Viburnum tinus* L., *Rosmarinus officinalis* L., *Cistus sp.*, *Ginesta sp.*	900
B-BL2	200	*Robinia pseudoacacia* L., *Laurus nobilis* L., *Viburnum tinus* L., *Rosmarinus officinalis* L., *Cistus sp.*, *Ginesta sp.*	900
B-H2	400	*Centranthus ruber* L., *Valeriana officinalis* L., *Helichrysum italicum* R., *Artemisia campestris* L., *Rumex scutatus* L	900
B-BL3	300	*Robinia pseudoacacia* L., *Laurus nobilis* L., *Viburnum tinus* L., *Rosmarinus officinalis* L., *Cistus sp.*, *Ginesta sp.*	900
B-H3	200	*Centranthus ruber* L., *Valeriana officinalis* L., *Helichrysum italicum* R., *Artemisia campestris* L., *Rumex scutatus* L	900
B-P3	200	*Pinus pinea* L., *Pinus nigra* L., *Pinus sylvestris* L	900
NB-H3	300	*Centranthus ruber* L., *Valeriana officinalis* L., *Helichrysum italicum* R., *Artemisia campestris* L., *Rumex scutatus* L	600

on a heated plate at 150 °C for 15 min. After cooling, the solution was filtered with Whatman® quantitative filter paper, ashless, Grade 42. An aliquot of 500 µL of sample was made up to 5 mL with ultrapure water, and five drops of pnitrophenol indicator (0.25% in water) and NaOH solution (5 N, in water) were added to change the color of the indicator to yellow. For color development, sulfomolybdic reagent was added and the solution was brought to a final volume of 50 mL with ultrapure water. After 10 min, the absorbance at 882 nm was read using the spectrophotometer UV–Vis (Cary50, Varian).

The P_{avail} concentration was determined for fresh soil mixed with activated carbon and sodium bicarbonate solution (0.5 M in water). Each solution was stirred for 30 min and filtered with Whatman® quantitative filter paper, ashless, Grade 42. Successively, an aliquot of 1 mL of sample was made up to 5 mL with ultrapure water, and five drops of p-nitrophenol indicator (0.25% in water) H2SO4 solution (2.5 M, in water) were added to change the color of the indicator to yellow. For color development, sulfomolybdic reagent was added and the solution was made up to a final volume of 25 mL with ultrapure water. After 10 min, the absorbance at 882 nm was read using the spectrophotometer UV–Vis (Cary50, Varian). The detailed methods used in our study follow those reported in Memoli et al. (2022).

Microarthropod sampling and analyses

In the laboratory, the microarthropods were extracted through the MacFadyen extractor over a 1-week period (Cortet et al. 2007) and identified using a stereomicroscope. Microarthropods were sorted in Acari that were further identified to the suborders of Oribatida, Gamasida, and Astigmata, in Collembola further identified through different keys (Gisin 1943; Bretfeld 1999; Potapov 2001) to the family level and in other groups including Symphyla, Pauropoda, insect larvae… The data were reported as density (n. org. m^{-2}) and richness (mean taxa number) for total microarthropods, Acari and Collembola. The abundances of Acari suborders and Collembola families and their percentages within the community were also reported.

Statistical analyses

To assess the impact of fire (positive or negative) on each soil abiotic property, the percentage differences between

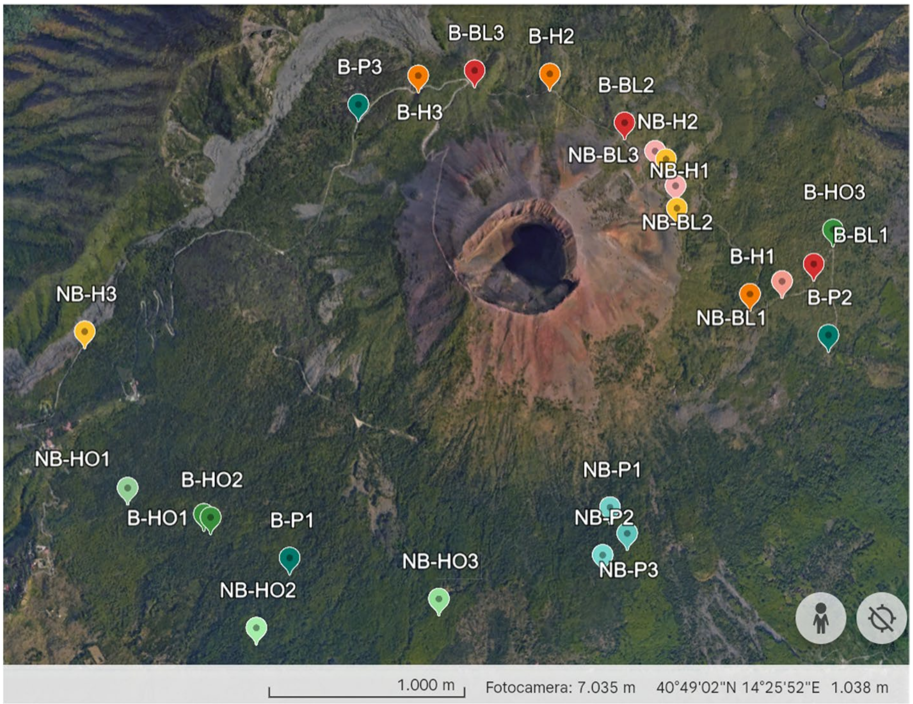


Fig. 1 Map of the sites collected under unburnt holm oak (HO, light green), pine (P, light blue), black locust (BL, light red), herbaceous vegetation (H, gold), and under burned holm oak (dark green), pine (dark cyan), black locust (dark red), and herbaceous vegetation (orange) inside Vesuvius National Park

unburnt (control) vegetation and the respective burnt (treatment) vegetation were calculated and the Wilcoxon tests (considered significant when $P < 0.05$) were performed to assess significant differences. Additionally, to assess variations in soil abiotic properties within unburnt and burnt vegetation groups separately, Kruskal–Wallis rank-sum tests with Bonferroni adjustments were conducted, also considering $P < 0.05$ as the threshold for significance.

To examine the impact of fire on the microarthropod community, the Bray–Curtis dissimilarity index (vegan package, Oksanen et al. 2022) was calculated between burnt and corresponding unburnt vegetation, based on the abundances of Collembola families and Acari suborders. To assess community differences within the unburnt and burnt vegetation groups separately, permutational multivariate analyses of variance (PERMANOVA) using Bray–Curtis distance matrices, with the ADONIS function and 999 permutations applied to the community parameters, were also performed.

For a more comprehensive analysis of fire, vegetation covers, and their interactions, PERMANOVA (Bray–Curtis distance, ADONIS and pairwise.perm.manova functions, 999 permutations) and non-metric multidimensional scaling (NMDS, Bray–Curtis distance, vegan package) were performed on the entire microarthropod community. This included parameters such as microarthropod density and richness, Collembola and Acari density and richness, and Collembola family and Acari suborder abundances, across unburnt and burnt vegetation covers.

To further investigate the effects of fire, vegetation cover, and their interactions on individual community parameters, Negative Binomial Generalized Linear Models (GLMs; MASS package, Venables and Ripley 2002) were applied to microarthropod density and richness, Collembola and Acari density and richness and Collembola family and Acari suborder abundances. This approach helped reduce overdispersion in the data. Significance of the factors (fire and vegetation cover) was determined using the ANOVA function from the lmerTest package (Kuznetsova et al. 2017), with post hoc Tukey tests ($P < 0.05$) performed using the car package (Fox et al., 2019).

To explore the contribution of each abiotic properties and community parameters in each burnt and unburnt vegetation covers, two distinct Random Forest analyses (RandomForest package, Breiman, 2001) based on 500 trees with random splitting and out-of-bag prediction errors, were conducted separately on soil properties and the community parameters. Variable importance was estimated using the Breiman-Cutler permutation importance algorithm. The minimal depth algorithm was applied to identify the most influential predictors by determining the depth at which a variable was used to make a split, with shallower depths indicating higher importance.

To assess how soil characteristics impacted microarthropods, Collembola and Acari communities, Spearman's regression tests were performed to investigate the significant (at least $P < 0.05$) relationships.

All the graphs and statistical analyses were performed using the R 4.0.3 programming environment.

Results

Differences in soil properties in unburnt and burnt sites under different vegetation covers

Differences between the unburnt and burnt soil under the same vegetation covers highlighted that, in soils under HO, WHC decreased (40%), contents of N and NO_2 increased (approximately 40% both), and content of P_{avail} increased of about 60% (Fig. 2, Table S2). In soils under P, slight variations in properties occurred (Fig. 2, Table S2). In soils under BL, contents of C and N increased (approximately, 35% for both) as well as content of P_{avail} increased of about 70% (Fig. 2, Table S2). In soils under H, WHC decreased (50%), contents of C, C_{org}, and N increased (approximately, 50% for all), where contents of NO_2 and NH_4 decreased (approximately, 100% for both) (Fig. 2, Table S2).

Among the soil properties, pH, WHC, WC, contents of C and N mainly influenced the unburnt and burnt soils under BL and P and the burnt soils under H (Fig. 3); pH, contents of C, N, and C_{org} mainly influenced the unburnt soils under H (Fig. 3); pH and WC mainly influenced the unburnt soils under HO, and WC and contents of N mainly influenced the burnt soils under HO (Fig. 3).

Soil microarthropod, Collembola and Acari community in unburnt and burnt sites under different vegetation covers

In the investigated area, the microarthropod community accounted for 13 taxa in total, with Acari and Collembola accounted for approximately 90% of the collected organisms.

According to PERMANOVA analysis, the abundances of microarthropods, Acari and Collembola as well as microarthropod diversity, were significantly impacted ($P < 0.001$) by the interaction between fire and vegetation covers (Table 2, Fig. 4). Moreover, only the burnt soils under P and BL showed significant differences ($P < 0.01$) with the respective unburnt soils (Table 2). The Bray–Curtis dissimilarity index, based on Acari and Collembola abundances, highlighted that the lowest value was found between unburnt and burnt soil under HO (0.14) and highest between unburnt and burnt soil under P and BL (0.42 and 0.39, respectively) (Fig. 5).

While microarthropod, Acari, and Collembola abundances showed no significant differences across different vegetation covers in unburnt soils ($P = 0.07$, PERMANOVA analysis), the impact of vegetation became more pronounced in burnt soils, where significant variations were observed ($P < 0.01$, PERMANOVA analysis). In unburnt sites, microarthropod, Acari and Collembola density (6000 to 16,000 individuals m^{-2}; 1358 to 3566 Collembola m^{-2}; 3113 to 9511 Acari m^{-2},

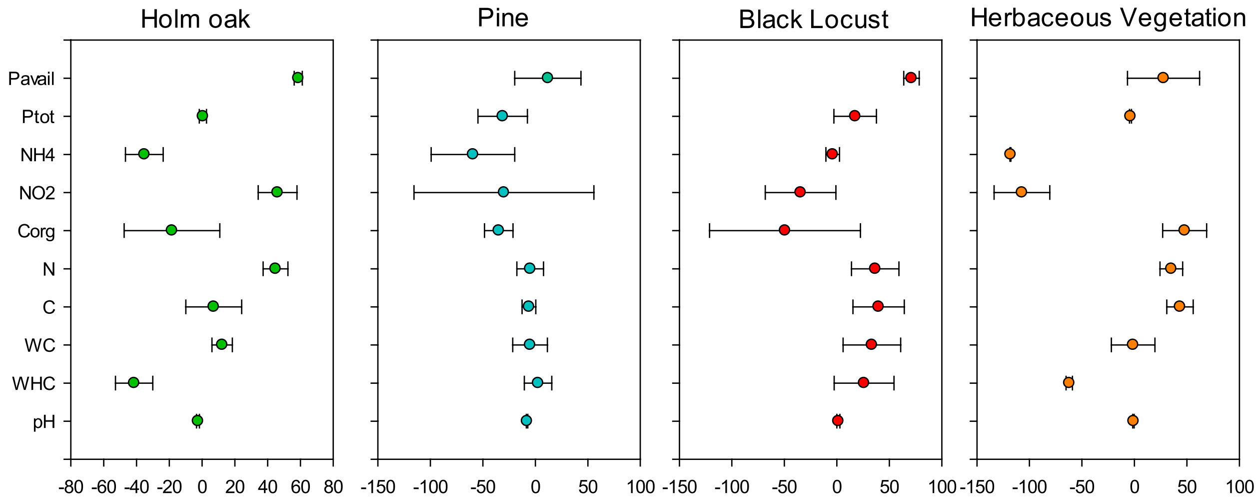
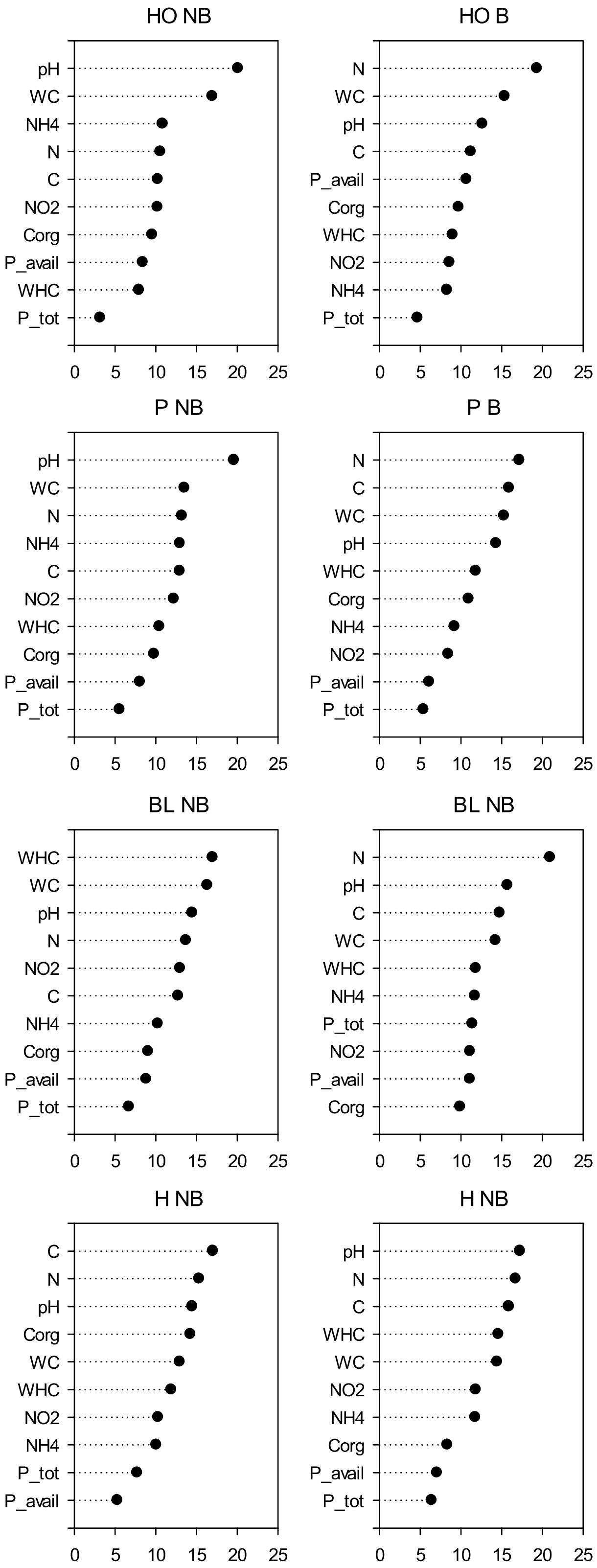


Fig. 2 Forest plot of the differences between burnt (considered as control) and burnt (considered as treatment) sites in pH, water holding capacity (WHC), water content (WC), organic carbon (C_{org}), carbon, nitrogen and phosphorus (C, N, and P), nitrite (NO_2^-), ammonium (NH_4^+), and available phosphorus (P_{avail}) measured in soil under different vegetation covers holm oak (HO, green), pine (P, blue), black locust (BL, red), herbaceous vegetation (H, orange) collected inside Vesuvius National Park



◀ **Fig. 3** Random forest derived variable importance, based on Breiman-Cutler algorithm, of soil properties measured in soil under unburnt (NB) and burnt (HO) vegetation covers (HO, green), pine (P, blue), black locust (BL, red), herbaceous vegetation (H, orange) collected inside Vesuvius National Park. Black lines represent the variables selected using the minimum depth algorithm

respectively) showed significantly higher values in soils under holm oak and pine (Table 3). The microarthropod, Acari and Collembola richness (3.2 to 4.2 mean taxa number; 2 mean suborder number; 1.4 to 2.6 mean family number, respectively) did not show significant differences among the vegetation covers (Table 3).

In burnt soil, microarthropod, Acari and Collembola density (4700 to 14,000 individuals m^{-2}; 2264 to 7699 Acari m^{-2}; 1188 to 3227 Collembola m^{-2}, respectively) showed the highest values under black locust (Table 3). The microarthropod richness (2.2 to 4.3 mean taxa number) showed significantly higher values in soils under HO, P, and BL, whereas Acari and Collembola richness (1.6 to 2.1 mean suborder number; 1 to 2.4 mean family number, respectively) did not show significant differences among the vegetation covers (Table 3). The effect of fire on microarthropod community under the same vegetation cover highlighted that, in burnt soils, microarthropod and Acari density significantly decreased under P and increased under BL, whereas Collembola density significantly decreased under HO, P, and H vegetation and increased under BL (Table 3).

The analyses of Acari suborder relative abundances highlighted that Oribatida and Gamasida were the most abundant in terms of individuals (Table 4). In unburnt soils, Gamasida (32 to 49%) showed the higher values under HO and P, whereas Oribatida (49 to 68%) and Astigmata (0 to 1%) did not show showed significant differences among the vegetation covers (Table 4). In burnt soils, Gamasida (32 to 45%) showed the higher values under P and BL than under HO, whereas Oribatida (55 to 64%) and Astigmata (0 to 1%) did not show significant differences among the vegetation covers (Table 4). The effect of fire on Acari relative abundances under the same vegetation cover highlighted that, in burnt soils, Gamasida relative abundance significantly increased under P (Table 4).

The analyses of Collembola family relative abundances included nine families of Collembola, with Onychiuridae, Entomobryidae, and Isotomidae the most abundant in terms of individuals (Table 4). In unburnt soils, Entomobryidae (0 to 21%) showed the higher relative abundance in soils under HO, Isotomidae (7 to 34%) under BL, Onychiuridae (21 to 68%) under HO, P, and H vegetation, Neanuridae (0 to 11%) showed the higher relative abundance in soils under BL (Table 4). In burnt

Table 2 Summary of PERMANOVA analysis (R square: R^2 and F-value: F) among (a) fire, vegetation, and their interactions and (b) pairwise PERMANOVA analysis (R square: R^2 and F-value: F) between b) burnt and unburnt vegetations based on microarthropod community sampled in soils collected at Vesuvius National Park

a) Factors	R^2	F	Pr(> F)
Fire	0.00894	0.7282	0.492
Vegetation	0.05862	1.5922	0.14
Fire *Vegetation	0.14707	3.9949	0.001
Residual	0.78538		
b) Fire within vegetation	R^2	F	Pr(> F)
HO_NB *vs* HO_B	0.0215	0.3521	0.705
P_NB *vs* P_B	0.3017	6.9115	0.005
BL_NB *vs* BL_B	0.2891	6.5067	0.001
H_NB *vs* H_B	0.0583	0.9907	0.343

sites, Entomobryidae (0 to 27%) showed the higher relative abundance in soils under HO, Isotomidae (0 to 22%) under P, Onychiuridae (39 to 56%) under BL, HO, and H vegetation, Neanuridae (0 to 15%) under BL, and Sminthuridae (0 to 6%) under P (Table 4). The effect of fire on Collembola family relative abundances under the same vegetation cover highlighted that, in burnt soils, Onychiuridae relative abundance significantly decreased in soils under P and increased in soils under BL, whereas Isotomidae relative abundance significantly decreased in soils under BL (Table 4).

Among the community parameters that mainly influenced the burnt and unburnt vegetation covers, Entomobryidae abundance mainly influenced in the unburnt HO, whereas Collembola and Acari densities and Entomobryidae abundance mainly influenced the burnt HO (Fig. 6). The Sminthuridae, Hypogastruridae, and Entomobryidae abundances mainly influenced the burnt P (Fig. 6). The Isotomidae abundance mainly influenced the unburnt BL, whereas Acari density, Oribatida, Onychiuridae, and Gamasida abundance mainly influenced the burnt BL (Fig. 6). The Entomobryidae abundance mainly influenced the unburnt H, whereas microarthropod density and richness and Isotomidae abundance mainly influenced the burnt H (Fig. 6).

The correlations among soil abiotic and community parameters highlighted that soil pH was negatively correlated with Neanuridae abundance ($P < 0.05$), the soil WC was positively correlated with Entomobryidae ($P < 0.05$) and with Sminthurididae ($P < 0.05$), the WHC was positively correlated with Sminthurididae abundance ($P < 0.01$) and the NH_4^+ was positively correlated with Entomobryidae ($P < 0.05$), Sminthuridae ($P < 0.05$), Sminthurididae ($P < 0.05$), Oribatida ($P < 0.05$) abundances and Collembola and Acari densities ($P < 0.05$).

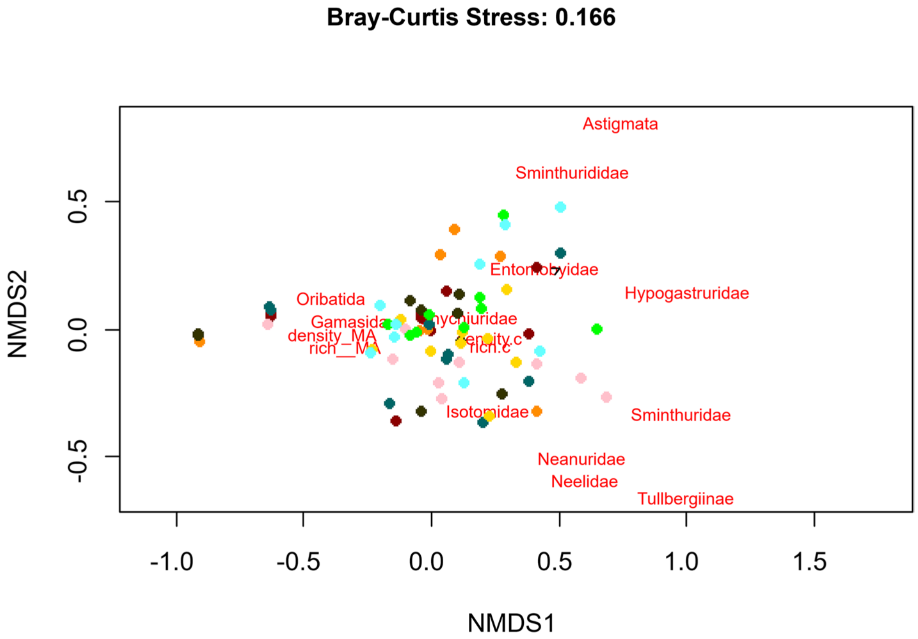


Fig. 4 Graphical displaying the first two axes of the non-metric multidimensional scaling (NMDS) on Collembola and Acari community composition found in soils collected under unburnt holm oak (HO, light green), pine (P, light blue), black locust (BL, light red), herbaceous vegetation (H, gold) and under burned holm oak (dark green), pine (dark cyan), black locust (dark red), and herbaceous vegetation (orange) inside Vesuvius National Park. The soil abiotic properties significant correlated with the Acari and Collembola community composition were plotted

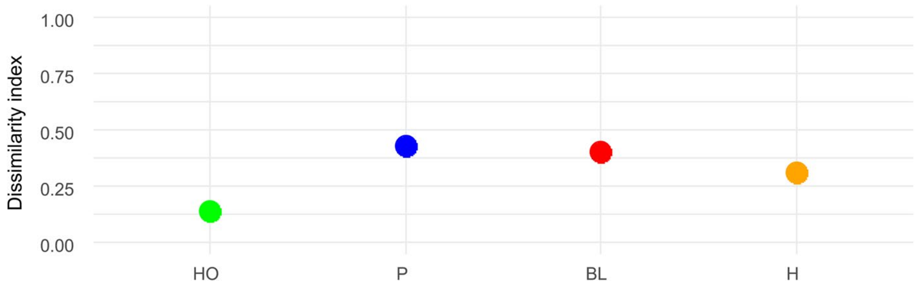


Fig. 5 Values of dissimilarity index (Bray–Curtis distance) calculated for Acari and Collembola community composition between unburnt (considered as control) and burnt (considered as treatment) sites within holm oak (HO, green), pine (P, blue), black locust (BL, red) and herbaceous vegetation (H, orange) collected inside Vesuvius National Park

Table 3 Mean values (± s.e.) of density (expressed as n° of organisms m^{-2}), taxa richness (expressed as n° of taxa), calculated for microarthropod (ar), collembola (C), and Acari (aca) communities in unburned (NB) and burned (B) soils collected inside Vesuvius National Park under holm oak (HO), pine (P), black locust (BL), and herbaceous vegetation (H). Different small and capital letters indicate significant differences (at least, $P < 0.05$) respectively, among NB and B soils under different vegetation covers. Asterisks indicate significant differences ($P < 0.05$) between NB and B soils within the same vegetation cover type

	Density-ar	Taxa richness-ar	Density-C	Richness-C	Density-aca	Richness-aca
NB HO	12,682 A (± 2994)	4.22 A (± 0.54)	3171 A * (± 818)	2.11 A (± 0.45)	6568 A (± 1778)	2.11 A (± 0.11)
B HO	10,361 ab (± 2380)	4.33 a (± 0.41)	1585 b (± 445)	2.11 a (± 0.45)	5888 b (± 1673)	2.11 a (± 0.20)
NB P	16,532 A * (± 3342)	4.00 A (± 0.40)	3567 A * (± 883)	2.67 A (± 0.50)	9512 A * (± 2405)	2.00 A (± 0.16)
B P	6285 b (± 1263)	3.78 a (± 0.40)	1755 b (± 426)	2.44 a (± 0.70)	2265 b (± 408)	1.67 a (± 0.17)
NB BL	5945 B * (± 1053)	3.22 A (± 0.40)	1359 B * (± 416)	1.56 A (± 0.41)	3114 B * (± 632)	2.00 A (± 0.17)
B BL	13,815 a (± 2495)	3.56 a (± 0.47)	3227 a (± 1337)	1.56 a (± 0.41)	7700 a (± 962)	1.78 a (± 0.15)
NB H	8323 B (± 2283)	3.22 A (± 0.49)	2774 B * (± 1271)	1.44 A (± 0.53	3510 B (± 566)	2.00 A (± 0.17)
B H	4699 b (± 1109)	2.22 b (± 0.27)	1189 b (± 457)	1.00 a (± 0.28)	2944 b (± 749)	2.11 a (± 0.20)

Discussion

In the investigated area, the fire alone did not impact the soil microarthropod, Acari and Collembola communities (PERMANOVA analysis). The lack of differences between microarthropod communities in burnt and unburnt soils already after 3 years since fire is surprising, as some research (Zaitsev et al. 2016; Malmström et al., 2008; Fusco et al. 2023b) reported that microarthropods took several decades to recover after fire. Even though this result needs to be confirmed with longer surveys, it suggests that the heterogeneity of landscape and the vegetation covers could have played a role in modifying and mitigating the impact of fire on microarthropod community, accelerating their recovery. In the present research, it can be excluded that the recovery in the microarthropod abundance in burnt soils could be due to the movement of these organisms from the unburnt soils (fire refugia) as the distance between the unburnt and burnt investigated points of sampling were too large (minimum 200 m) to allow their re-colonization in only 3 years, because microarthropod dispersal is generally slow and only occurs at short distances (Juan-Ovejero et al. 2023). Also slope and aspect can be excluded as they are quite comparable among the sites. By contrast, altitude and vegetation covers would seem to be the main difference responsible for the variations in microarthropod abundance after only 3 years. The accumulation of nutrients and organic matter in soils located at lower altitudes (De Marco et al. 2022), where are located the sites mainly covered by trees, could have accelerated the recovery after fire, confounding the results between burnt and unburnt soils. Finally, vegetation covers, influencing the

Table 4 Relative percentage of Acari suborder and Collembola family composition in unburnt (NB) and burnt (B) soils collected inside Vesuvius National Park under holm oak (HO), pine (P), black locust (BL), and herbaceous vegetation (H). Different capital and small letters indicate significant differences (at least, $P < 0.05$) in community composition, respectively, among NB and B soils under different vegetation covers. Asterisks indicate significant differences (at least, $P < 0.05$) between NB and B soils within the same vegetation cover type

Sites	Gamasida	Oribatida	Astigmata	Entomobryidae	Hypogastruridae	Isotomidae	Neanuridae	Neelidae	Onychiuridae	Sminthuridae	Sminthurididae	Tullbergiidae
NB HO	35.1 A (± 5.09)	64.4 A (± 4.94)	0.44 A (± 0.44)	21.4 A (± 8.37)	0.00 A (± 0.00)	6.85 B (± 4.01)	0.00 C (± 0.00)	0.00 A (± 0.00)	66.4 A (± 11.3)	2.22 A (± 2.22)	3.08 A (± 2.27)	0.00 A (± 0.00)
B HO	32.2 b (± 5.52)	63.6 a (± 6.67)	4.21 a (± 3.67)	27.5 a (± 11.4)	11.1 a (± 11.1)	2.77 b (± 2.77)	4.36 b (± 2.03)	0.00 a (± 0.00)	48.9 a (± 14.4)	1.58 b (± 1.58)	3.70 a (± 2.12)	0.00 a (± 0.00)
NB P	32.1 A (± 6.16)	67.5 A * (± 6.13)	0.33 A (± 0.33)	3.24 B (± 2.17)	0.00 A (± 0.00)	19.2 B (± 7.67)	4.56 B (± 3.30)	0.00 A (± 0.00)	67.7 A* (± 11.0)	5.30 A (± 3.25)	0.00 A (± 0.00)	0.00 A (± 0.00)
B P	43.7 b (± 9.28)	56.30 b (± 9.28)	0.00 a (± 0.00)	0.00 b (± 0.00)	13.42 a (± 7.47)	22.2 a (± 12.1)	6.02 ab (± 3.19)	0.00 a (± 0.00)	39.4 b (± 12.7)	6.02 a (± 3.19)	0.00 a (± 0.00)	1.85 a (± 1.85)
NB BL	49.7 A (± 7.55)	48.8 B (± 7.61)	1.58 A (± 1.58)	2.77 B (± 2.77)	5.55 A (± 5.55)	34.3 A * (± 12.6)	11.1 A (± 8.44)	0.00 A (± 0.00)	21.3 B * (± 11.0)	0.00 A (± 0.00)	0.00 A (± 0.00)	2.77 A (± 2.77)
B BL	44.9 a (± 10.9)	55.1 a (± 10.9)	0.00 a (± 0.00)	1.81 b (± 1.40)	0.00 a (± 0.00)	1.85 b (± 1.85)	15.3 a (± 9.87)	2.77 a (± 2.77)	56.1 a (± 14.3)	0.00 b (± 0.00)	0.00 a (± 0.00)	0.00 a (± 0.00)
NB H	43.9 A (± 7.59)	54.2 B (± 8.45)	1.85 A (± 1.85)	0.00 B (± 0.00)	5.00 A (± 1.98)	11.6 B (± 8.67)	0.46 C (± 0.46)	0.00 A (± 0.00)	60.7 A (± 15.4)	0.00 A (± 0.00)	0.00 A (± 0.00)	0.00 A (± 0.00)
B H	38.1 b (± 7.29)	59.8 b (± 7.77)	2.12 a (± 1.49)	2.22 b (± 2.22)	0.00 a (± 0.00)	0.00 b (± 0.00)	0.00 c (± 0.00)	0.00 a (± 0.00)	49.2 a (± 15.5)	0.00 b (± 0.00)	5.55 a (± 5.55)	9.72 a (± 9.72)

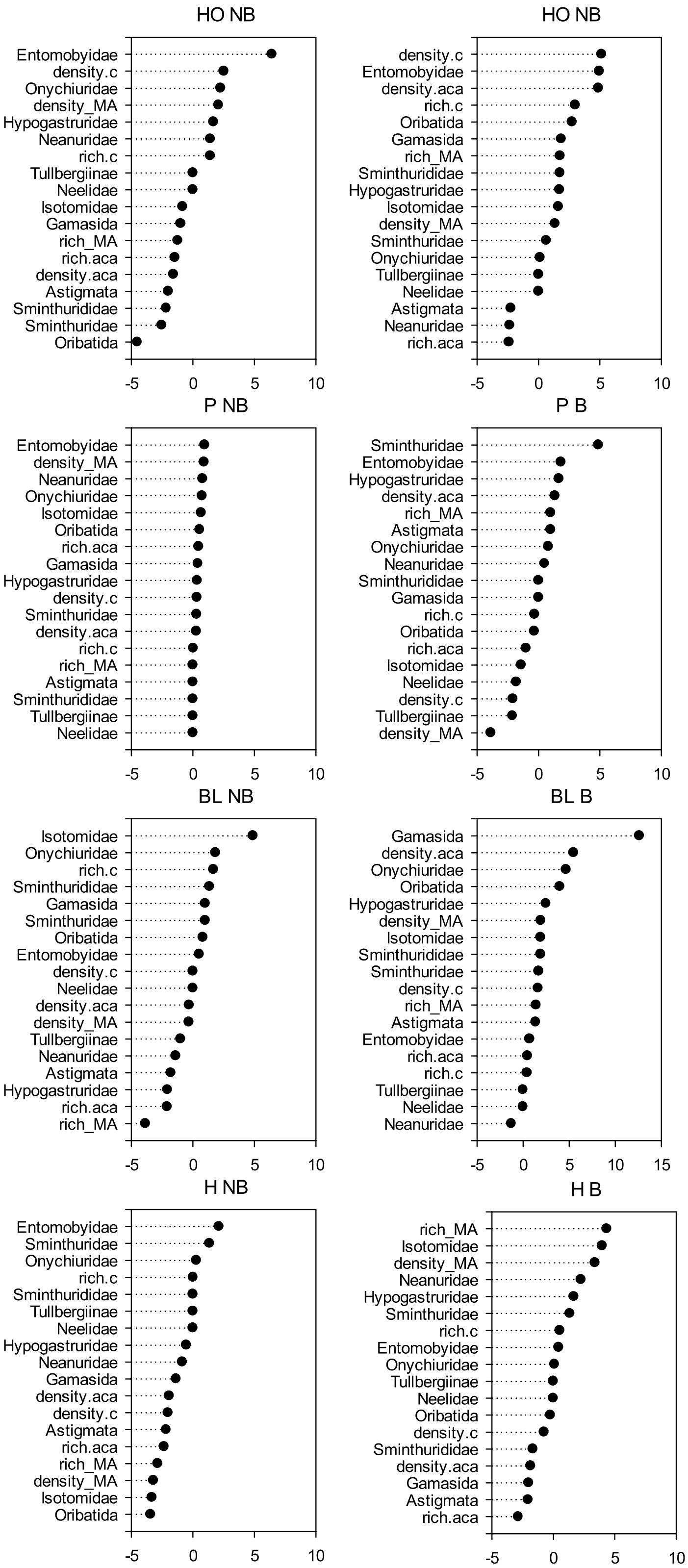


Fig. 6 Random forest derived variable importance, based on Breiman-Cutler algorithm, of soil microarthropod community parameters measured in soil under unburnt (NB) and burnt (HO) vegetation covers (HO, green), pine (P, blue), black locust (BL, red), herbaceous vegetation (H, orange) collected inside Vesuvius National Park. Black lines represent the variables selected using the minimum depth algorithm

fire impact on soil properties (Zhai et al. 2023), played the major role in recovery of the microarthropod community in a so brief time after fire occurrence (Meloni et al. 2020).

Among the unburnt sites the communities of microarthropods, Acari and Collembola seemed to be favored in soils under holm oak and pine. The sites covered by trees tend to have well-structured and stable micro-arthropod communities (Fusco et al. 2023a) that respond favorably to microhabitat conditions and soil properties. Holm oak and pine showed an abundant content of organic material, water retention, and nutrient content that provide wide habitat heterogeneity and great food resources (Meloni et al. 2020). This hypothesis is corroborated by the significant higher abundances of Acari Oribatida, and Entomobryidae and Onychiuridae (Collembola) that prefer to occupy deep soil or litter layer, where they found the great part of feeding resource (Susanti et al. 2021). The positive influence of holm oak and pine was particularly evident in the case of Collembola, rather than being universally applicable to the entire microarthropod community. Despite the high content of some nutrients (N, NH_4^+, and P_{avail}) in unburnt soils under black locust, densities of microarthropods, Acari and Collembola were low. Black locust is considered among the most invasive tree species in Europe (Campagnaro et al. 2018) and has a diverse impact on soil properties, such as the increase of nutrients and the secondary metabolites (e.g., phasin, robin, or toxalbumins) released from the leaf litter (Harta et al. 2021; Lazzaro et al. 2018). These substances, inhibiting protein synthesis and providing unfavorable conditions for less-tolerant species, might be the cause of the reduction in organism densities and the high presence of Isotomidae (Collembola), which can be more tolerant to other organisms. Unfortunately, the identification at level family cannot allow to identify which Isotomidae species are responsible for the high observed abundance.

The impact of fire on microarthropod communities exhibited discernible variations that were contingent upon the specific types of vegetation covers present (PERMANOVA analyses). Even though the microarthropod communities did not differ among unburnt vegetation types, fire exacerbated these differences (PERMANOVA analyses). Specifically, the impact of fire was not detectable in areas with holm oak and herbaceous vegetation, while it was negative in areas with pine and positive in areas with black locust. The decrease of microarthropod, Acari and Collembola densities, in soils under pine could be due to decrease of pH and NH_4^+ content. In fact, fire contributed to increase the soil water evaporation and nutrient volatilization that, likely, limited the presence of niches for microarthropods (Santorufo et al. 2021). As pH and NH_4^+ seemed to be important drivers of the microarthropod communities (as several correlations found), their alterations could have strongly impacted the organisms under pine. In soils under pine, the taxonomic groups mainly impacted by fire were Oribatida (Acari) and Onychiuridae (Collembola), eu-edaphic organisms that suffer fire occurrence as they slowly move with scarce ability to descend to the soil (Gongalsky et al., 2012). Although Oribatida are reported to be relatively fire-resistant due to their thick protective cuticle (Malmström, 2008), they were negatively impacted under pine. In the investigated area, microarthropods under pine strongly suffered fire occurrence both due to the direct effects of fire and to the changes in soil properties. This suggest that in burnt soils under pine, the microarthropod community undergoes a transition from one characterized by organisms typical of stable environments (eu-edaphic) to a community with organisms more aligned with dynamic environments (hemi-edaphic and epi-edaphic). This result agrees with other studies (Fattorini 2010; Catalanotti et al., 2018; Mantoni et al. 2021), suggesting that the use of pine, commonly used in Mediterranean areas for reforestation after fire, might have negative impacts on soil biodiversity and ecosystem functioning in Mediterranean areas (Mantoni et al. 2021). By contrast, in soils under black locust the post-fire increase of total and available nutrients (C, N, P, and P_{avail}) favored changed microarthropod community favoring them. It has been demonstrated that black locust is stimulated by fire disturbance, as it takes advantage by exploiting empty niches and persisting endemic vegetation stands (Saulino et al. 2023). The rapid growth of black locust after fire enriches soil of nutrients due to its capability to deposit high content of N and P in soils (Incerti et al. 2018). Several studies found a positive impact of black locust on microbial abundance and activities (Bolat et al. 2016; Liu et al. 2018); therefore, it can be hypothesized a similar impact on microarthropod community, likely due to the enrichment of nutrients in soils. Moreover, differently from what observed in soils under pine, Onychiuridae, the taxonomic group mainly impacted by fire, increased its abundance in soils under black locust. This suggests that in burnt soils covered by black locust, the microarthropod community shifts from one characterized by organisms typical of dynamic environments to a community displaying organisms indicative of stable environments (including Onychiuridae). This result challenges the simplistic view of invasive species as inherently harmful to ecosystem function.

Despite soils under holm oak and herbaceous vegetation experienced several changes in properties after fire occurrence, the microarthropod community did not appear to be strongly affected (PERMANOVA analyses and Bray–Curtis dissimilarity). This finding could be due to opposite reasons: soil under holm oak has been shown to be high resistant to fire (Memoli et al. 2021) and this could have less impacted also the microarthropod community, whereas the community of herbaceous vegetation was highly variable inside the burnt and unburnt soils, because of the heterogeneity of the sites, that made difficult to see any changes on microarthropod community due to the fire occurrence.

Conclusions

The study results highlighted that the sole occurrence of fire was insufficient to produce a significant impact on the microarthropod community within the investigated area. Topographic features, landscape heterogeneity, time since fire occurrence, and different vegetations contribute to mitigate the differences between unburnt and burnt sites. Particularly, the vegetation covers were the major responsible for discernible and specific effects on soil properties and then on the microarthropod community. Indeed, although the microarthropod communities under unburnt vegetation did not differ, fire exerted varying impacts depending on the type of vegetation. In soils under holm oak and herbaceous vegetation, the fire had a neutral effect. Conversely, fire negatively impacted the microarthropod community in soils under pine, while it exerted a positive impact under black locust, demonstrating how species-specific traits of vegetation significantly affect soil biodiversity. This contributed to increasing the differences among the microarthropod communities associated with different vegetation types. The decrease of pH and NH_4^+ in burnt soil under pine leads to shift in microarthropod community, with a decrease of eu-edaphic organisms typical of stable environments (Oribatida and Onychiuridae), whereas the increase of nutrients in burnt soil under black locust contributed to increase the abundance of organisms typical of stable environment.

In the investigated area, the impact of fire on the microarthropod community was not uniform but rather context-specific, probably associated with structural attributes of habitats. This highlights the importance of considering vegetation type when managing post-fire landscapes. Reforestation strategies, especially the use of pine in Mediterranean areas, should be revisited, as pine showed to be not suitable for soil biodiversity and ecosystem function in the long term.

While the 3-year recovery timeframe suggests resilience in microarthropod communities, the study emphasizes the need for longer-term monitoring to fully understand the temporal dynamics of recovery, helping biodiversity conservation efforts and forest management strategies.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-024-00332-5.

Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

Authors' contributions

LS, GM: Conceptualization. LS, VM, MZ, GDN, GS: Methodology. LS: Software. LS, MZ: Data curation. LS: Writing- Original draft preparation. ADM: Visualization. GM: Supervision. RB, GM: Funding. ADM, GM: Reviewing and Editing. All authors contributed critically to the drafts and gave final approval for publication.

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Data Availability

The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent of publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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