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Post-fire forest management effects on soil metal dynamics in Mediterranean forests

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Wildfires are an integral component of Mediterranean ecosystems. The forest management practices implemented following such forest fires can significantly influence soil chemistry and metal dynamics. This study investigates the effects of different forest management strategies, including natural regeneration, grading (e.g., gradoni terrace making), and subsoiling with ripper on soil levels of major, trace, and heavy metals in a fire-affected forest in the southwestern part of Türkiye. Soil samples were collected 2.5 years after the containment of the wildfire and analyzed for selected metals (Fe, Ca, Al, Mn, Cr, Ni, Zn, Cu, Pb, Co, As, and Hg) concentrations. The findings indicated that subsoiling with a ripper resulted in elevated levels of multiple potentially toxic metals, including Cr (223.22 ± 60.47 mg/kg), Ni (150.54 ± 27.33 mg/kg), Zn (156.18 ± 66.14 mg/kg), and As (6.72 ± 1.30 mg/kg), compared to other treatments. These findings demonstrate that management interventions such as subsoiling with a ripper can significantly alter the distribution and concentration of trace metals. Future research integrating topographic variation and earlier sampling would further strengthen our understanding of post-fire metal dynamics.

KEYWORDS

post-fire soil contamination, wildfire, forest management, heavy metal, soil disturbance

1 Introduction

Wildfires are becoming more frequent and intense across the world, driven by global climate change, land-use changes, and prolonged drought conditions (Furtak and Wolińska, 2023). These extreme events can significantly alter soil chemistry, ecosystem structure, and hydrological cycles. One of the most critical consequences of wildfire is the release and redistribution of heavy metals, which are known for their toxicity, persistence, and long-term environmental impacts (Ku et al., 2024; Rao et al., 2024). Elevated metal concentrations can impair the quality of air, soil, water, and agricultural products, posing significant risks to human and ecological health through direct exposure and trophic transfer (Cobbina et al., 2013; Waiker et al., 2022). Long-term ingestion or inhalation of heavy metals can lead to serious health problems, including cancer, developmental delays,

reduced growth, cognitive impairment, and various organ disorders (Jaishankar et al., 2014).

Wildfire-induced changes in soil properties, including pH shifts, loss of organic matter, and altered redox conditions, can increase the mobility and bioavailability of heavy metals such as Cd, Pb, Hg, As and Zn, thereby elevating risks to both ecosystems and human health (Arunrat et al., 2023; Salgado et al., 2024). Among these, Pb, Cd, and Hg are particularly concerning due to their potential to bioaccumulate in the food web and affect water and soil quality over extended periods (Tsui et al., 2019; Ding et al., 2022).

Vegetation loss and ash deposition following wildfires can introduce heavy metals into soils and nearby water bodies via wind dispersal and storm-driven erosion (Prats et al., 2014; Santín et al., 2015a). Post-fire runoffs can impact the mobility of metals, usually increasing metal leaching to nearby water sources (Burke et al., 2013; Rust et al., 2022). Therefore, post-fire forest management plays a critical role in shaping landscape recovery and determining whether these contaminants are stabilized or further mobilized (Abraham et al., 2017a).

To support vegetation recovery while keeping the soil stable, a range of forest recovery and management strategies are commonly applied after wildfires (Prats et al., 2014). These include reforestation, seeding, mulching, passive recovery, complete ripping with a ripper, terrace and erosion control measures (Gómez-Rey et al., 2013; Çalışkan and Boydak, 2017; White and Long, 2019; Papaioannou et al., 2023). While such interventions aim to reduce erosion and limit contaminant runoff (Robichaud, 2000; Wagenbrenner et al., 2006), they may also modify key soil processes, including redox dynamics, microbial activity, and organic matter input, which influence metal behavior (Certini, 2005). For example, reforestation may facilitate metal uptake by vegetation (Madejon et al., 2004). In contrast, plowing can redistribute metals within the soil profile, enhancing their mobility and potential for leaching or surface runoff (Kabala et al., 2013).

The Mediterranean region is highly vulnerable to large-scale wildfires due to its hot, dry summers and dense forest coverage (Özcan et al., 2018). For instance, in 2021, countries across the Mediterranean basin, including France, Greece, Italy, Spain, and Türkiye, experienced widespread wildfire damage, with Türkiye and Italy reporting the most extensive losses. Türkiye alone recorded 2,793 wildfires, which burned approximately 139,503 ha of forested land in 2021 (San-Miguel-Ayanz et al., 2023).

Antalya has experienced some of the most destructive wildfires in the country's history. The 2021 Manavgat and surrounding fires in the city alone burned more than 75,000 ha. Despite the severity and frequency of such events, few studies have examined heavy metal concentrations in forest ecosystems following wildfires (Bartkowiak and Lemanowicz, 2017; Esen et al., 2023; Villarruel et al., 2024), to the best of our knowledge, no study has examined the impact of post-fire forest management practices on soil major, trace, and heavy metal levels. Therefore, our study aims to investigate the effects of post-fire forest management practices on the distribution and concentration of heavy metals in fire-impacted soils. By comparing managed and unmanaged burned sites, we aim to assess how post-fire management practices such as natural regeneration, seedling and seed sowing, *gradoni* terracing, and full-surface soil ripping (hereby referred to as subsoil ripping, RIP) influence both major and trace metal dynamics in soil.

2 Materials and methods

2.1 Study area

The study was conducted in Manavgat, Antalya (Figure 1), a region characterized by a Mediterranean climate with hot, dry summers and mild, wet winters (Kavgacı et al., 2010). In the summer of 2021, Türkiye experienced a series of catastrophic wildfires, the most severe of which occurred in Manavgat. Beginning on 28 July and lasting until 10 August, the fire burned approximately 40,000 ha of forest, making it the largest wildfire recorded in the history of the Republic of Türkiye (Atalay et al., 2024).

The affected landscape was primarily composed of *Pinus brutia* (Turkish red pine) forests, along with maquis shrublands and sclerophyllous forest (Kavgacı et al., 2017). In the aftermath, a range of post-fire forest management strategies was employed by the General Directorate of Forestry of Türkiye to mitigate erosion and promote vegetation recovery. These included passive approaches including natural regeneration, and active interventions like seed sowing in areas with limited seed sources and disruptive mechanical treatments, including *gradoni* terracing and subsoil ripping (RIP), followed by reforestation efforts (Yıldız et al., 2023).

To assess the impact of these strategies on heavy metal dynamics in soil, four distinct sites were selected, each representing a different post-fire management approach. The natural site (36.94450° N, 31.37040° E) was located on a slope and left to recover without human disturbance. Nearby this, the graded site (36.94430° N, 31.37030° E) was also sloped but underwent mechanical grading (e.g., *gradoni* terracing) and was planted with pine seedlings in 2023. The RIP site (36.94180° N, 31.37726° E), situated on flatter terrain, was subjected to full-surface soil ripping using heavy-duty dozers and then replanted following fire. Finally, the control site (36.95898° N, 31.35140° E), which was not impacted by the wildfire.

2.2 Sample collection

Soil sampling was conducted once on 4 January 2024, approximately 2.5 years after the fire, across four distinct land cover types representing both burned and unburned forest conditions. Within each plot, a representative 10 × 10-m area was defined. From each of these areas, surface soil samples were randomly collected at a depth of 0–5 cm using a stainless-steel shovel to prevent contamination. The samples were placed in clean, labeled Ziplock bags, stored on ice during transport, and transferred to the laboratory for processing. Upon arrival, soils were freeze-dried and passed through a 2 mm sieve to ensure homogeneity prior to analysis.

2.3 Sample analysis

Soil organic matter (SOM) was estimated using the loss-on-ignition (LOI) method, which serves as a proxy for SOM (Hereafter

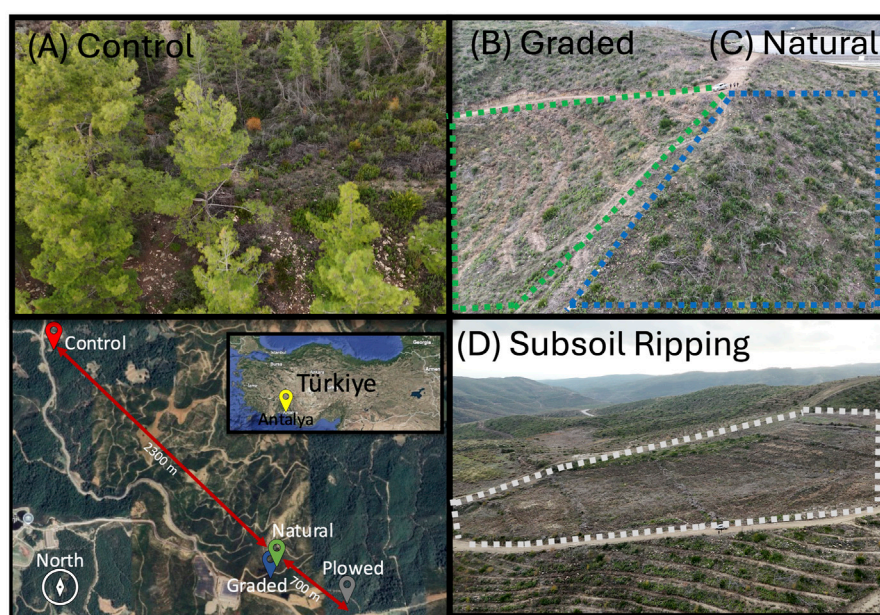


FIGURE 1 Study area located in Manavgat, Antalya, Türkiye, including four forest plots: Control (A), Graded (B), Natural (C) and Subsoil Ripping (D).

referred to as SOM), by combusting soil samples in a muffle furnace. Approximately 5 g of freeze-dried, homogenized soil was weighed into pre-cleaned ceramic crucibles. The samples were then combusted in a muffle furnace at 500 C for 4 hours to oxidize the organic material. After cooling, crucibles were reweighed, and organic matter content was calculated based on the mass loss during ignition (Ulus et al., 2022).

Total mercury (Hg) concentrations in soils were measured at the Biogeochemistry Laboratory of The Chinese University of Hong Kong using a Nippon MA-3000 solid-phase mercury analyzer (NIC, Japan). For each analysis, approximately 50 mg of soil sample was weighed into a pre-cleaned sample boat. Calibration curves were constructed using the IAEA-456 certified reference material (Costal Sediment). Analytical accuracy and quality control were further ensured by including the MESS-4 (Marine Sediment) reference material during each analytical session.

Soil samples were analyzed at the Joint School of Nanoscience and Nanoengineering for the quantification of other heavy metals. Samples preparation following EPA Method 3052 for total soil digestion using a microwave digestion system (CEM Mars 6 microwave digester). Specifically, 0.5 g of dried, homogenized soil was placed in Teflon vessels with 9 mL of concentrated HNO_3 and 3 mL of HF. Following microwave-assisted digestion, 10 mL of 4% boric acid solution was added to neutralize residual HF. The resulting solution was filtered using syringe filters and diluted accordingly. A final dilution factor of 1:6000 was applied and considered in the final concentration calculations. Elemental concentrations were measured using Inductively Coupled Plasma Mass Spectrometry (Agilent 7900). Internal standards and multi-point calibration curves were used to ensure analytical quality. Procedural blanks and certified reference materials (e.g., SRM

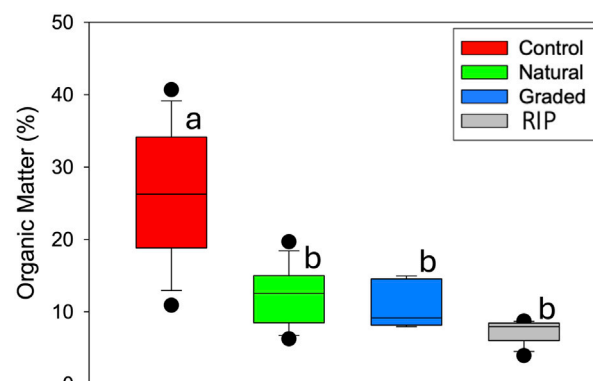


FIGURE 2 Loss-on-ignition (LOI) content (%) across four sites: Control, Natural, Graded, and Subsoil Ripping (RIP). Different letters on the boxplots indicate statistically significant differences between groups ($P < 0.05$).

2711a) were included to monitor both precision and accuracy throughout the analysis.

2.4 Statistical analysis

Statistical analyses and data visualization were performed using SigmaPlot software. One-way repeated measures ANOVA was applied to assess differences among treatments, followed by Tukey's *post hoc* test for pairwise comparisons. Linear regression analyses were conducted to evaluate the relationships between metals and SOM.

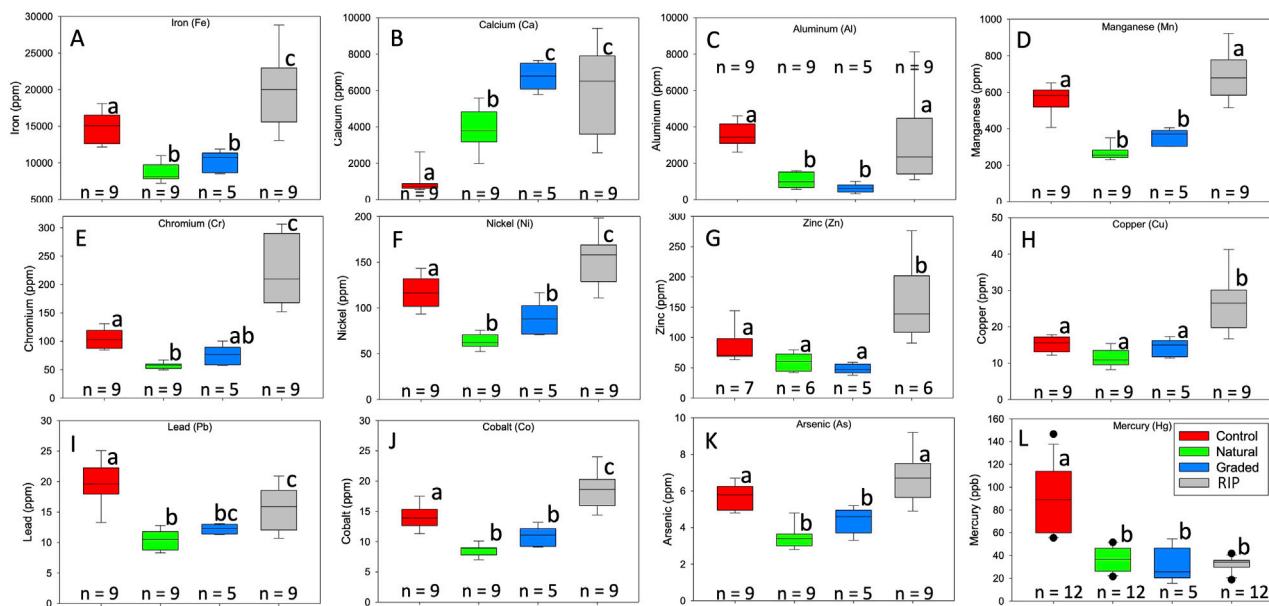


FIGURE 3
Boxplots showing concentrations of twelve metals in surface soils across three post-fire forest management treatments (natural, graded, and subsoil ripping (RIP) and control). Each subplot (A–L) represents a different metal: (A) Iron (Fe), (B) Calcium (Ca), (C) Aluminum (Al), (D) Manganese (Mn), (E) Chromium (Cr), (F) Nickel (Ni), (G) Zinc (Zn), (H) Copper (Cu), (I) Lead (Pb), (J) Cobalt (Co), (K) Arsenic (As), and (L) Mercury (Hg). Different letters indicate statistically significant differences among treatments ($p < 0.05$). Please note that the unit for mercury is different from the other metals and is indicated accordingly in the boxplots.

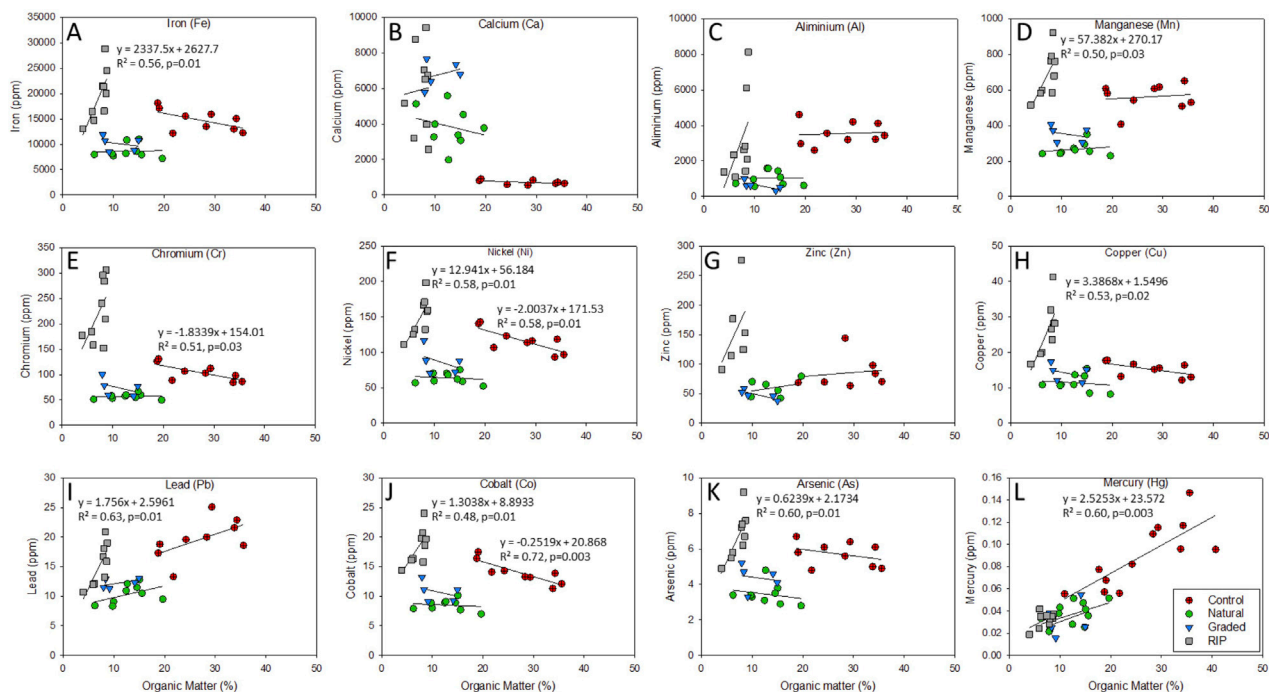


FIGURE 4
Relationships between soil organic matter (SOM) and selected metal concentrations in post-fire soils across control, natural, graded, and subsoil ripping (RIP) treatments. Panels show: (A) Fe, (B) Ca, (C) Al, (D) Mn, (E) Cr, (F) Ni, (G) Zn, (H) Cu, (I) Pb, (J) Co, (K) As, and (L) Hg. To keep each panel clear, only the regression equations for statistically significant relationships ($p < 0.05$) between SOM and metal concentrations are shown.

3 Results and discussions

3.1 Soil organic matter

SOM varied across treatments (Figure 2). SOM values were similar among the three post-fire treatments, RIP ($7.28\% \pm 1.48\%$), natural ($12.22\% \pm 3.93\%$), and graded ($10.90\% \pm 3.36\%$), with no significant differences. Only the control plot had significantly higher SOM ($26.19\% \pm 8.90\%$), indicating better organic matter retention in undisturbed soils. Esen et al. (2023) reported much lower SOM in *Pinus brutia* forest, in Antalya, with pre-fire values of $6.7\% \pm 2.5\%$, and post-fire levels of $6.0\% \pm 2.7\%$ in northern areas and $2.0\% \pm 0.38\%$ in southern sites. The higher SOM levels observed in our study may be due to the presence of organic material left after burning (such as twigs, bark, and needles), as well as newly grown vegetation based on field observation.

The noticeable decline in SOM from control to RIP plot highlights the vulnerability of soil carbon pools to both wildfire and land changes. Fire can consume substantial amounts of vegetation and organic-rich topsoil (Salgado et al., 2024), while plowing may further degrade SOM by mixing it with deeper, carbon-poor layers (Jiménez-Morillo et al., 2020).

3.2 Concentrations of major, trace and heavy metals in soil

We measured several major, trace and heavy metals and compared them across three post-fire forest management strategies: natural, graded, RIP treatments and control. Overall, metal concentrations varied significantly by both metal type and treatment. Figure 3 presents boxplots of metals (Fe, Ca, Al, Mn, Cr, Ni, Zn, Cu, Pb, Co, As, and Hg) in soil samples collected from all four study areas.

RIP soils consistently showed the highest levels for several metals, including Fe ($19,671.94 \pm 5,019.05$ mg/kg), Mn (688.57 ± 130.42 mg/kg), Cr (223.22 ± 60.47 mg/kg), Ni (150.54 ± 27.33 mg/kg), Zn (156.18 ± 66.14 mg/kg), Cu (26.24 ± 7.49 mg/kg), Co (18.4 ± 3.01 mg/kg), and As (6.72 ± 1.30 mg/kg), all significantly higher than those in Natural and Graded treatments ($p < 0.01$ for most comparisons). In contrast, the natural regeneration site had the lowest concentrations for most metals, including Fe, Mn, Cr, Ni, As, and Co (Figure 3). The graded treatment showed similar values, with Ca notably peaking here ($6,795.96 \pm 750.35$ mg/kg), significantly higher than in control or natural plots ($p < 0.001$). The control site, despite being unburned, exhibited the highest levels of Al ($3,547.96 \pm 645.08$ mg/kg), Pb (19.68 ± 3.38 mg/kg) and Hg (89.70 ± 28.25 mg/g).

Ca levels showed a generally increasing trend from the control to the natural and graded sites, except in the RIP site (Figure 3B). Given the high volatilization temperature of Ca ($\sim 1,240$ C; Pereira et al., 2011), it thermally mineralizes and remains in the soil after fire, often concentrated in ash. Ku et al. (2018) found significantly higher Ca in both black and white ash compared to unburned soils. The elevated and variable Ca in the RIP site likely reflects white ash accumulation, typical in *Pinus* plantations (Abraham et al., 2017b), and ash retention due to flat terrain. In contrast, ash in the sloped natural and graded sites may have been more easily displaced. Fe levels showed a different pattern, highest in the RIP site,

intermediate in the control, and lowest in the natural and graded sites (Figure 3A).

Mn and Al all exhibited similar distribution patterns, with the highest concentrations in the RIP and control site, and the lowest in the natural and graded sites. These elements are thermally stable. Mn and Al withstand temperatures exceeding $1,000$ C and tend to remain in the mineral matrix or ash after combustion (Pereira et al., 2011). The flat topography of the RIP area may have favored ash retention, unlike the sloped natural and graded plots, where erosion and runoff could reduce surface metal content.

Metals such as Cr, Cu, Zn, Pb, Ni, and As tend to increase in burned soils compared to unburned soils (Campos et al., 2016; Rao and Parsai, 2025; Ozgeldinova et al., 2025). This increase may be particularly pronounced in wildfires involving pine trees, which have been shown to elevate heavy metal concentrations in soil significantly (Santorufu et al., 2021; Rao et al., 2024). Pine trees are rich in organic compounds such as cellulose, hemicellulose, lignin, and proteins (Chen et al., 2022). These compounds contain functional groups, like hydroxyl and carboxyl, which can effectively bind and retain heavy metals (Sun et al., 2010). In our study, the concentrations of Cr, Cu, Ni, and As were highest in the RIP plot, with mean values of 223.22 ± 60.47 mg/kg for Cr, 26.24 ± 7.49 mg/kg for Cu, 150.54 ± 27.33 mg/kg for Ni, and 6.72 ± 1.30 mg/kg for As, this pattern likely reflects the combined effects of ash retention in flat terrain and mechanical disturbance, which brings metal-rich subsoil to the surface. Previous studies have also shown that salvage logging can lead to soil compaction (Gomez et al., 2002), which may help retain metals within the soil, especially in flat terrains, where topography limits runoff.

Cr showed the most pronounced increase, suggesting a strong influence from both ash input and soil mixing. Control plots also had relatively high Cr and Ni levels, indicating naturally elevated background concentrations in the area. In contrast, natural regeneration and graded sites exhibited lower metal concentrations, likely due to reduced disturbance and potential metal loss through erosion. The decline in heavy metal concentrations is generally linked to their transport from fire-affected areas to nearby soils and surface waters via wind, erosion, and runoff (Rao and Parsai, 2025). Esen et al. (2023) also reported a general increase in Cr and Ni concentrations in soils following wildfire events, indicating that fire may enhance the mobility or surface accumulation of these metals via ash deposition and changes in soil chemistry. Supporting this, a study by Guvenç et al. (2003) found high background levels of these metals in Antalya, with Cr concentrations averaging 190 ± 150 mg/kg in urban areas and 260 ± 100 mg/kg in rural areas, while Ni levels averaged 81.5 ± 57.6 mg/kg in urban sites.

Pb and Zn concentrations in soil varied across post-fire forest management treatments (Figure 3). Pb levels were highest in the control plots (19.68 ± 3.38 mg/kg), followed by the RIP (15.40 ± 3.56 mg/kg), graded (12.22 ± 0.80 mg/kg), and natural regeneration sites (10.34 ± 1.62 mg/kg). Elevated Pb in control plots may reflect natural background values or long-term atmospheric deposition, while lower concentrations in natural and graded plots likely result from post-fire erosion. Furthermore, previous studies have shown that Pb can be released as fine particulate matter ($PM_{2.5}$) during wildfires (Holder et al., 2023), which may contribute to its reduction in natural regeneration and graded sites due to atmospheric dispersion. The moderately high Pb levels in RIP soils may be attributed to the mechanical mixing of Pb-rich subsoil or the

accumulation of ash at the surface. Regional studies showed higher Pb levels in soil. For example, Öktüren Asri et al., 2024 reported Pb levels of 64.68 ± 33.24 mg/kg in fruit orchards, while Guvenç et al. (2003) found 36.5 ± 21.4 mg/kg in urban soils, considerably higher than those in forested areas.

Zn concentrations varied significantly, with the highest levels observed in RIP plot (156.18 ± 66.14 mg/kg), significantly higher than in the control (85.54 ± 28.37 mg/kg, $n = 7$), natural (59.68 ± 14.72 mg/kg), and graded (48.42 ± 8.04 mg/kg) plots, which did not differ statistically. Elevated Zn in the RIP soils likely reflects the retention of Zn due to the flat topography, which limits surface runoff, and mechanical disturbance, which brings Zn-rich subsoil back to the surface. In contrast, the graded and natural sites were more exposed to erosion, potentially leading to the loss or lateral transfer of Zn from the upper soil layers. The relatively consistent levels in the other treatments suggest that, without intensive intervention, Zn remains near background values.

For Zn, Güvenç et al. (2003) reported 189 ± 118 mg/kg in urban soils and 152 ± 61 mg/kg in rural sites. Esen et al. (2023) observed Zn concentrations of 62 ± 19 mg/kg pre-fire, rising to 70 ± 19 mg/kg on north-facing areas and 104 ± 11 mg/kg on south-facing areas post-fire. These values, especially post-fire, align with our RIP site data, suggesting that fire severity, slope, and soil disturbance play key roles in metal mobilization and retention.

Hg concentrations in soil differed significantly between the control and post-fire forest management treatments. The control site had the highest mean Hg level (89.70 ± 28.85 ng/g). In contrast, lower concentrations were found in the natural (36.73 ± 10.53 ng/g), graded (31.91 ± 15.05 ng/g), and RIP (32.68 ± 6.13 ng/g) sites. This suggests that wildfire caused substantial Hg loss or redistribution (Ku et al., 2018), likely through thermal desorption and volatilization for Hg (Burke et al., 2010). The similar Hg levels across all burned treatments imply wildfire, not management strategy, was the main driver of Hg reduction. These findings align with earlier research showing fire significantly lowers Hg in surface soils where organic matter and Hg are concentrated (Filimonenko et al., 2024; Li et al., 2022). Guvenç et al. (2003) also reported similar values in Antalya, with urban soils averaging 90 ± 100 ng/g and rural soils much lower (30 ± 30 ng/g).

Overall, our findings demonstrate that mechanical disturbance, particularly RIP, leads to a noticeable increase in surface soil metal concentrations. In contrast, metal levels in the natural and graded plots remained similar to or lower than those in the control site. This may be attributed to several factors, including (1) erosion-driven loss of surface materials due to their slope position (Prats et al., 2014), (2) the release of metals like Pb as fine particulate matter (PM_{2.5}) during wildfires (Holder et al., 2023), and (3) volatilization or particulate-bound release of metals such as Hg during combustion (Ku et al., 2024).

3.3 Potential roles of mineralogical transformations and charred material retention

Post-fire variations in soil metal concentrations are related to a complex factors, including the severity of the fire, the depth of the affected soil, mineralogical changes, formation of pyrogenic

materials, post-fire erosion, and hydrological transport processes (Fajković et al., 2022; Nørnberg et al., 2009). The heat can alter soil-mineral dynamics, generally leading to changes in soil properties like increased soil pH, reduced surface area and cation exchange capacity of clay (Fajković et al., 2022; Nørnberg et al., 2009), potentially reducing their capability to retain metals (such as Al, Cd, Co, Cr, Fe, Mn, Z) due to the loss of functional groups (i.e., hydroxyl and carboxyl) (Fajković et al., 2022; Guerin et al., 2024).

Wildfires produce charred residues and pyrogenic carbon (PyC), which may function similarly to engineered biochar by retaining metals through surface complexation, ion exchange, and electrostatic interactions (Bodí et al., 2014; Joseph et al., 2021; Lehmann and Joseph, 2012).

Furthermore, metals such as Cr, Cu, Zn, Pb, and Ni are known to exhibit increased sorption onto charred materials due to the presence of oxygen-containing functional groups and the high surface area of PyC (Ahmad et al., 2014; Mohan et al., 2007). However, after a fire, precipitation and runoff can quickly mobilize ash and particulate char, especially on sloped or disturbed terrains, leading to the physical removal or lateral redistribution of these metal-binding materials (Santín et al., 2015b; Wagenbrenner and Robichaud, 2014). This process might elucidate the seemingly paradoxical observation that unburned control plots occasionally exhibit higher concentrations of certain metals, such as Pb and Hg, compared to their burned counterparts.

Consequently, graded and naturally regenerating plots, which undergo less mechanical disruption and are more prone to post-fire erosion, may show lower concentrations of most metals. This phenomenon is likely attributable to the removal of fine adsorptive materials, which have previously adsorbed metals, through processes such as surface runoff and leaching (Rhoades et al., 2011). This supports the hypothesis that, while fire initially increases metal availability through combustion and ash deposition, subsequent hydrological processes may deplete surface metal pools. In conclusion, charred materials produced by wildfires can adsorb and temporarily retain metals, particularly in areas where ash and PyC accumulation is prevalent. Nevertheless, these materials are rapidly displaced by runoff and erosion, especially in disturbed or sloped environments, potentially leading to lower post-fire metal concentrations compared to undisturbed controls.

3.4 Relationship between soil organic matter and heavy metal concentrations

A surprising distinction emerged in the relationship between SOM and metal concentrations in RIP treatments post-fire. As shown in Figure 4, a consistent positive correlation was observed between several metals exclusively in the RIP plots. However, only a few metals showed trends in the control (Hg: $R^2 = 0.60$, $p = 0.003$), natural regeneration, or graded sites, without consistent correlations across all treatments. For instance, strong positive correlations were detected in RIP soils for Fe ($R^2 = 0.56$, $p = 0.01$), Pb ($R^2 = 0.63$, $p = 0.01$) Ni ($R^2 = 0.58$, $p = 0.01$), As ($R^2 = 0.60$, $p = 0.01$), and Co ($R^2 = 0.48$, $p = 0.01$), indicating that heavy metal concentrations increased with rising organic matter content in these disturbed plots (Figure 4).

Previous studies have similarly reported positive associations between SOM and heavy-metal levels across diverse environments. For example, Coquery and Welbourn (1995) documented significant correlations with Fe and Pb in lake sediment, Ulus et al. (2022) reported the same trend for Hg in wetlands, and Li et al. (2018) further extended this pattern to Ni and As in mining areas. Fire can destroy organic matter, potentially leaving behind certain metals and altering metal–organic matter (Ku et al., 2018) relationships compared to pre-fire conditions. Therefore, further investigation is needed to understand these postfire dynamics.

A positive correlation between SOM and heavy metals at the RIP site likely reflects the mechanical mixing of ash residues and organic-rich topsoil during subsoiling with ripper. Deep ripping with heavy excavators mechanically mixed wildfire-derived ash residues (enriched in Fe, Ni, As, Co) with the underlying organic-rich topsoil. This homogenization dispersed metal-rich particulates throughout the subsoiling layer, directly increasing metal concentrations in coincidence with SOM. Moreover, the physical disruption of soil aggregates during tillage may have exposed fresh sorption sites on organic particles (Jastrow et al., 1996), enhancing metal complexation with SOM. This is particularly evident for Hg, Pb, and Fe, which are known to form stable organo-metallic complexes under aerobic conditions (Majumdar et al., 2024).

4 Conclusion

This study provides valuable insights into the effects of post-fire forest management strategies on heavy metal concentrations in soils. Our findings demonstrate that management interventions such as subsoiling with ripper can significantly alter the distribution and concentration of trace metals, with the RIP plot exhibiting the highest levels of several elements, including Co, Cu, Ni, Zn, and As. These results highlight the importance of considering soil contamination risks when planning forest restoration and land management practices after wildfires. Furthermore, while charred materials resulting from wildfires can temporarily sequester heavy metals through sorption processes, their rapid removal by post-fire runoff and erosion, particularly in disturbed or sloped areas, ultimately reduces surface metal concentrations. Collectively, these underscore the transient and spatially variable nature of metal enrichment following fires. This study has some limitations. Limited soil samples prevented detailed analysis of physical properties affecting metal mobility (e.g., porosity and bulk density). Ash was not collected due to the 2.5-year post-fire delay, and downslope samples from regenerating and graded plots, where metal runoff may accumulate, were not taken. Future studies should include ash and hydrologically active areas to understand post-fire metal dynamics in Mediterranean forests better.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YU: Conceptualization, Funding acquisition, Investigation, Validation, Visualization, Writing – original draft, Writing – review and editing. SW: Investigation, Writing – review and editing. MT-K: Investigation, Writing – review and editing, Resources. NL: Funding acquisition, Investigation, Writing – review and editing. OL: Funding acquisition, Investigation, Writing – review and editing. TB: Investigation, Writing – review and editing. HU: Investigation, Writing – review and editing. FA: Investigation, Project administration, Resources, Writing – review and editing. AK: Writing – review and editing.

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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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