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Post-fire recovery of temperate and mediterranean ecosystems: An interplay between fire severity, soil nutrients, and vegetation from early-stage to decadal-scale dynamics

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A R T I C L E I N F O

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A B S T R A C T

Wildfires strongly alter soil properties, which in turn affect ecosystem recovery over extended periods, though long-term impacts are less certain. This study investigated a 14-year post-fire chronosequence in Chile's mediterranean and temperate humid forests, revealing ecosystem-specific soil properties and nutrient recovery mechanisms. By analysing sites at successional stages, the chronosequence approach assessed temporal changes and ecosystem recovery, revealing long-term wildfire effects on soil dynamics and nutrients recovery.

Wildfires raised soil bulk density to 0.9 g cm^{-3} in humid temperate and 1.2 g cm^{-3} in mediterranean ecosystems. Mediterranean soils experienced greater compaction from organic matter loss, soil aggregate destruction, ash-clogged pores, and topsoil erosion. Soil texture shifts were ecosystem-dependent: mediterranean soils increased 10–12 % in clay and silt through ash redistribution and aggregation, while temperate soils saw sand content rise by 0.74 % and 0.32 % yearly at 0–5 and 5–10 cm depths from thermal disaggregation and erosion. Ground vegetation recovers quickly, but physical soil properties like bulk density require over 14 years to return to pre-fire conditions.

In humid temperate forests, ash input initially increased soil pH (4.8 to 5.8), reducing acidity, mitigating aluminium toxicity, while increasing nutrient availability. Base cation stocks increased in mediterranean woodlands (e.g., Ca: up to 0.41 Mg ha^{-1} y^{-1}) due to ash retention, lower leaching, and ash infiltration into subsoil. Nutrient stocks in humid forests recovered slowly (Ca: 0.087–0.13 Mg ha^{-1} y^{-1}) due to rainfall-driven leaching and low subsoil reserves. Carbon and N losses were restricted to the litter horizon in temperate forests, recovering via fire-resistant tree inputs, whereas mediterranean soils suffered severe C and N depletion from vegetation loss, erosion, and low N fixation.

Fire effects and recovery are ecosystem-specific, shaped by landscape, geology, hydrology, and vegetation resilience. Understanding how fire regimes affect soil and nutrient recovery is vital for improving projections in fire-prone regions.

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1. Introduction

Wildfires are one of the major ecological disturbances that play a fundamental role in Earth system dynamics, with numerous ecological consequences on the spatiotemporal patterns of the biosphere and geosphere in burned landscapes (North et al., 2015; Pausas and Keeley, 2009; Mataix-Solera and Cerdà 2009; Ling et al., 2021). They occur across almost every biome, climatic zone and all vegetation zones (Archibald et al., 2013) and are broadly categorized as low-, moderate-, and high-severity wildfires (Raison et al., 2009; Cerdà and Robichaud 2009). Low-severity fires consume ground litter and understory vegetation, while moderate- to- high-severity fires defoliate but spare overstory trees, and high-severity fires lead to the mortality of most vegetation, including most woody material (Raison et al., 2009; Mclauchlan et al., 2020).

Generally, wildfires have several direct impacts on soil. They affect soils physically, chemically, and biologically through the combustion of organic matter, soil heating, and deposition of (hot) ash. Indirectly, wildfires also influence the soil by reducing vegetation cover, producing partially burned and pyrolyzed plant residues (charcoal) and ash, and leading to changes in the soil flora (Pausas and Verdú 2005; Raison et al., 2009; Cerdà and Robichaud 2009). After a wildfire, the dynamics, species composition, and structure of at least the understory are affected, but only the changes in the dynamics, such as the succession rates and species interactions, are likely to have lasting impacts on the ecosystem in the long-term (Prestes et al., 2020). Fire-derived charred deposits elevate soil temperatures post-burning by reducing albedo, but the loss of canopy may even have a greater impact: it eliminates shading, exposing soil to direct sunlight and amplifying diurnal temperature fluctuations, thus drastically altering the microclimate. These effects can persist for up to two years until the understory vegetation has recovered (Cerdà and Robichaud 2009).

Ash wettability is intricately linked to combustion temperature, with low-temperature/severity fires producing hydrophobic ash and high temperature fires yielding hydrophilic ash (Bodí et al., 2011). Ash hydrophobicity increases with organic material content (Dlapa et al., 2013). Post-fire water repellence influences runoff dynamics, thereby causing an increase in overland flow during rainfall in case of enhanced soil hydrophobicity. The deposition of ashes exacerbates this effect by clogging soil pores, generating erosion-pavement, and decreasing water infiltration rates (Doerr and Thomas, 2000; Matus et al., 2023).

Furthermore, the consumption of soil organic matter during fires alters the soil structure, leading to reduced aggregate stability and a tighter arrangement of soil particles. This process increases soil bulk density and subsequently reduces porosity, water-holding capacity, and infiltration rates, while also increasing runoff and erosion (Certini 2005; Granged et al., 2011). In areas affected by high-intensity fires, soil bulk density also increases due to the intense heating and subsequent loss of fine soil particles up to the loss of the entire topsoil through erosion, exposing the mineral subsoils with their higher bulk densities (Kim et al., 2005; Guillaume et al., 2015). Besides direct alteration of the mineralogy due to intense heat (Shakesby and Doerr, 2006), post-fire erosion of fine particles is the major reason for altered particle size distributions as a consequence of fires (Fayos 1997; Certini 2005; Granged et al., 2011). The extent and duration of these changes in soil physical properties are determined by fire intensity, duration, pre-fire soil moisture, and initial soil physical properties (DeBano, 2000). Soil physical properties may require several years to decades to fully recover following a wildfire (Agbeshie et al., 2022).

Besides its impact on soil physics, fire results in nutrient losses during combustion (gaseous and particulate) and further losses through accelerated erosion and leaching due to a lack of vegetation cover (Raison et al., 2009) and increased surface hydrophobicity. The heating of soil does not only directly mineralize certain nutrients, but it also triggers biological processes that enhance decomposer activity. This often results in significant depletion of topsoil nutrient stocks, which can be replenished by several processes during the vegetation recovery phase after fire. These include element weathering in subsoils and parent materials and thereafter uplift of nutrients, re-accumulation via litterfall from unburned trees, or dust transport onto the topsoil (Wittenberg 2021; Jobbágy and Jackson, 2004). All of these processes depend strongly on climatic factors and occur alongside simultaneous changes in the recovering vegetation, as well as changing soil temperature and moisture regimes that induce shifts in the microbiome and its decomposer activity (Christensen 1994, MacLean and Wein 1977; Raison et al., 2009; Jiang et al., 2017; Fang et al., 2023). Such altered rates of soil nutrient turnover affect ecosystem productivity i.e., having implications on weathering by deep roots and the nutrient uplift, etc., by creating feedbacks on biological processes involved in nutrient turnover (Neary 1999; Gao et al., 2019).

Specifically, when climatic conditions are hypothesized as significant drivers of a process, such as a post-fire recovery of soil properties, transects along climatic gradients offer ideal study scenarios. Chile has a wide range of climates, from extremely arid conditions in the north to humid ones in the south with decreasing temperatures and increasing precipitation along this eco-sequence (Bernhard et al., 2018; Oeser et al., 2018). Interannual climate variability controls the wildfire activity in central and south-central Chile, which is characterized by woodlands and forests, frequently replaced by pine and eucalyptus plantations (Urrutia-Jalabert et al., 2018). The climate–fire linkage is modulated by vegetation type and its associated fuel characteristics (Holz et al., 2012). The number of wildfires, the length of the fire season, and the duration of wildfires have all increased in the last decades (González et al., 2018). Chile experienced an average of 5,647 wildfires per year, burning 54,438 ha annually between 1984 and 2004. From 2004 to 2024, these numbers rose to 6,268 fires and 108,990 ha per year, with total area burned reaching 2.2 million hectares (CONAF Corporación Nacional Forestal, 2024).

Wildfires in Chile occur not only in the mediterranean climatic zone, but also often in the more humid temperate one. However, both lack studies of fires impacts on soil properties and recovery (Úbeda and Sarricolea, 2016; Rivas et al., 2012; Matus et al., 2023). A study of *Nothofagus glauca* forests analyzed post-fire soils of 2, 9, 14, and 21 months and concluded the requirement of long-term studies for a better understanding of the impact of fires on native forest soils (Litton and Santelices 2003). Globally, studies such as those in Australian eucalyptus forests (Bowd et al., 2019) show that soil recovery can span decades—far longer than traditionally assumed—highlighting the urgency of similar long-term research in Chile's fire-prone ecosystems. However, despite the high fire abundance, our knowledge of endemic mediterranean and humid temperate forests in Chile is scarce, which makes it challenging to predict the long-term impacts of the intensified fire regime.

To close these gaps in understanding of post-fire belowground recovery processes, this research examines fire-induced changes in soil properties and their recovery at the ecosystem level along post-fire chronosequences of vegetation and soils. Specifically, the recovery of the nutrient stocks was quantified over approximately 14-year period of vegetation recovery. This study aimed to identify contrasts and similarities in re-accumulating of nutrients in the soils of ecosystems of two climatic zones – a mediterranean woodland and a humid temperate forest, – both on similar parent material in the Chilean Coastal Cordillera.

We hypothesized that i) the impact of fire on soil physical properties is greater in the mediterranean than in humid temperate ecosystems, due to lower vegetation density and pre-fire organic matter content. The reduced post-fire organic matter input is expected to result in a longer recovery period for mediterranean than for temperate systems; ii) fire induces changes in soil chemical properties, including alterations in pH, carbon and nitrogen stocks, and base cations content, which will recover alongside the vegetation succession; iii) Soil nutrient mobilization and re-accumulation proceed more rapidly in humid temperate than in mediterranean ecosystems, due to higher rainfall and the resilience of fire-surviving, tall, deep-rooted trees. These trees uplift nutrients from the deep subsoil and saprolite—acting as a driver of increased weathering—and support rapid vegetation recovery.

2. Materials and methods

2.1. Site description

The study sites are located in the Coastal Cordillera of Chile between 31° and 38°S and were selected based on their wildfire history. Nahuelbuta represents a humid temperate ecosystem characterized by a temperate rain-oceanic climate (Cfb), whereas La Campana features a Mediterranean ecosystem under a cold-summer Mediterranean climate (Csb) (Köppen, 1900; Kottek et al., 2006; Fig. 1). A tall evergreen mixed forest dominated by broadleaf *Nothofagus dombeyiand* and conifer *Araucaria araucana*re presents Nahuelbuta, where Umbrisols are the dominant soil type (Oeser et al., 2018). A patchy deciduous forest and evergreen *sclerophyllous* shrubs on Cambisols represent La Campana (Bernhard et al., 2018). The dominant vegetation formations of Nahuelbuta and La Campana belong to the "coastal temperate forest of *A. araucana*" and "coastal mediterranean sclerophyllous forest of *Lithraea caustica* and *Cryptocaryaalba*", respectively (Luebert and Pliscoff, 2006; Oeser et al., 2018). The mean annual precipitation is 1084 mm yr^{-1} in Nahuelbuta and 436 mm yr^{-1} in La Campana. The mean annual air temperatures are 6.6 °C and 14.1 °C, respectively (Oeser et al., 2018). Detailed descriptions of the study sites are available in Bernhard et al., (2018) and Oeser et al., (2018).

2.2. Historical fires and chronosequences

Chile is characterized by a high natural fire regime in its mediterranean ecosystems but also in large areas of the humid temperate zones, which both have enough plant biomass as fuel sustaining large wildfires. Fires are less frequent in protected natural reserves such as the Nahuelbuta (humid temperate ecosystem) and La Campana National Parks (mediterranean ecosystem), where anthropogenic impacts are minimized compared to the surrounding buffer zones. These parks were chosen as the control state, as there is no record of fires in the last three decades. In contrast, the buffer zones, which have similar vegetation to the parks, are frequently affected by fires during the dry season, often caused by human activities. Recent fires in the buffer zones were compared to the reference/control site within the park. Fires, that occurred in agricultural fields and plantations, were not included.

The chronosequence approach was used to reconstruct the post-fire changes in soil parameters (Walker et al., 2010; Nájera De Ferrari et al. 2024). This approach involves selecting a collection of sites that have contrasting ages since being abandoned or disturbed, but share similar soil types and environmental conditions within the same climatic zone and historical land use. Utilizing spatial locations of sites substitutes for temporal alternatives, enabling the study of succession stages and facilitating the sampling of more sites than traditional long-term studies allow. Chronosequence studies assume that sites disturbed at different times in the past underwent comparable changes, processes, and conditions during their formation. This assumption enables us to assess the changes in soil parameters over time and understand the dynamics of post-fire recovery when compared to the control site.

Recent fire data were obtained from archives of MODIS C6 (Terra and Aqua; 1 km spatial resolution) and VIIRS 375 m NRT (375 m spatial resolution) open access FIRM Earth data from NASA (https://earthdata.nasa.gov/firms). Before selecting the fire site, the affected areas were cross-checked for signs of vegetation fires, e.g. charcoal traces, and fire incidents were verified with locals and authorities whenever possible. Upon verification, it was confirmed that there were no fire recurrences in the same place as the selected site. The selected fires (Fig. 1) were all medium-intensity based on field observations, which means, we found moderate burn traces, indications for partial but not necessarily full vegetation loss, and charcoal presence. In mediterranean ecosystem (La

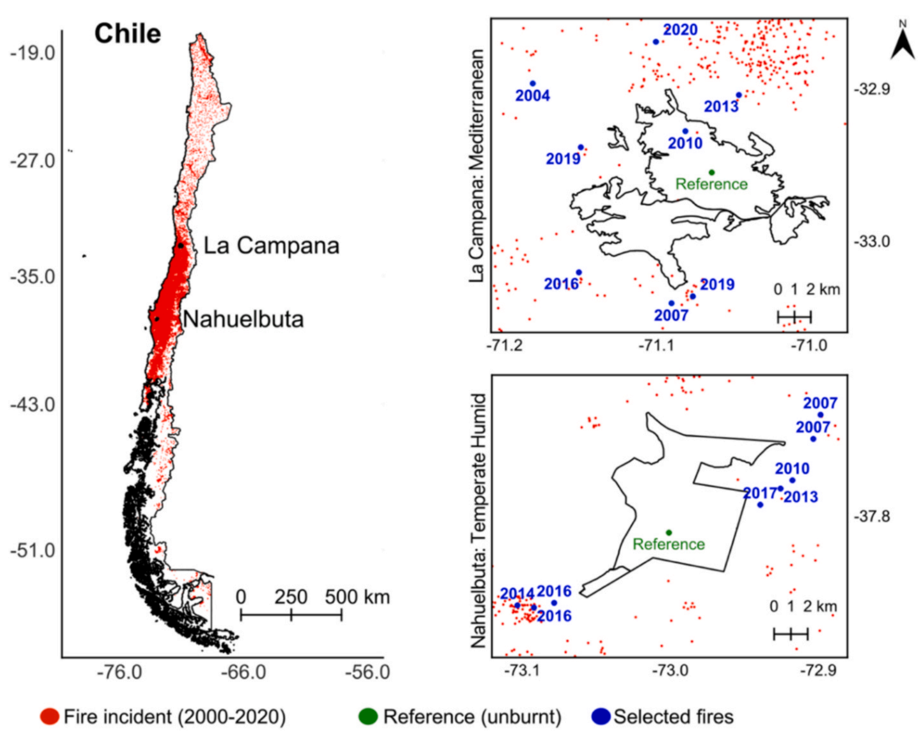

Fig. 1. Map of Chile with wildfires since the year 2000 (red dots) and the two study sites (black dots) (left), enlarged study site maps on the right for Nahuelbuta (top) and La Campana (bottom), in which the selected chronosequences are shown in blue and the control sites (no historical fire) in green (right). Fire data was obtained from open-access FIRM earth data from NASA (https://earthdata.nasa.gov/firms) and maps were created using QGIS. Admin boundary of Chile used from DIVA-GIS.

Campana), the fire resulted in burning most of the vegetation. In contrast, in the humid temperate ecosystem (Nahuelbuta), the fire consumed only the understory, shrubs, and small trees, leaving the crowns of taller trees unscathed. Chronosequences were selected based on fire history, with La Campana sites up to 14.43 years post-fire and Nahuelbuta sites up to 11.83 years post-fire.

2.3. **Soil** sampling

In each control site (un-burnt for several decades) and fire-affected areas, four replicate plots were selected. Using 200 cm^3 steel cylinders, volumetric soil samples of 0–5 and 5–10 cm depth were collected for the bulk density. Destructive soil sampling of 0–2, 2–5 and 5–10 cm depth was done using shovel and spatula and samples were air-dried rapidly after the sampling.

2.4. Analysis of physical soil parameters

Soil bulk density was determined gravimetrically by drying volumetric samples (200 cm^3) at 105 °C to constant weight. Coarse fragments (>2 mm) were not removed for bulk density calculations, i.e. all grain sizes were considered.

All particle size measurements were made in distilled water at room temperature (refractive index of the liquid phase −1.33). The aqueous suspension of each soil sample was subjected to ultrasonic dispersion utilizing the horn-type ultrasonic disruptor Sonifier S-250D (Branson, USA) equipped with a ½" solid step horn with the threaded body. The calibration of the output ultrasonic energy was carried out according to the calorimetry method (North, 1976). For removing organic matter, the soil samples were pre-oxidised in a solution of H_2O_2 (20 %) for seven days at a temperature of 50 °C (until CO_2 emission has stopped). Then, the soil suspension was then dispersed by ultrasound with a total energy equal of 450 J·ml^{-1} (PP cup d = 3.4 cm, h = 5 cm, 15 ml of solvent) (Amelung and Zech, 1999; Graf-Rosenfellner et al., 2018).

Particle size distributions (PSD) were quantified using the laser diffraction method on the express analyzer Microtrac Bluewave (York, USA). The processing of the diffraction pattern was performed using the analyzer software Microtrac Flex 11.0.0.1 with the following parameters of the soil solid phase: absorption coefficient = 1 and particle shape = irregular (Ryżak and Bieganowski, 2011). The solvent circulation speed in the system was 50 % of the maximum speed (corresponds to 33 ml·sec^{-1}). Texture class was determined according to USDA classification.

2.5. Analysis of chemical soil parameters

To determine soil pH, the soil was mixed with deionized water at a ratio of 1:2.5, the mixture was vigorously shaken for 2 h, and thereafter left to equilibrate for 24 h at room temperature. The soil suspension was then filtered and the pH was measured using a glass electrode-based pH meter. The soil organic carbon (C), total nitrogen (N) contents, and stable isotopes (δ^{13}C and δ^{15}N values) were determined after drying the soils at 40 °C followed by fine grinding. The samples were weighed into tin capsules and measured on an isotope ratio mass spectrometer (Delta V Advantage with Conflo III interface, Thermo Electron, Bremen, Germany) coupled to an element analyzer (Flash 2000, Thermo Fisher Scientific, Cambridge UK) at the Center for Stable Isotope Research and Analysis (KOSI) of Georg-August-University of Göttingen, Germany.

To quantify the nutritional elements (besides N), pressure digestion of soils was done by adding around 90–100 mg of dried and grounded soil samples and 2 ml of 65 % nitric acid (HNO_3) into clean teflon cups with lids. A standard sample and a blank were prepared for every batch (24 samples). Closed teflon cups were placed into the metal extraction block and kept for extraction in a drying oven at 160 °C for 12 h. Once the samples were cooled down, bi-distilled water (H_2O) was added and the suspension was filtered through a filter paper prewashed with 0.065 % HNO_3. The flask was thereafter filled to a target volume of 50 ml. Finally, the samples were measured by inductively coupled plasma-optical emission spectroscopy (iCAP 7000 Series ICP-OES, Thermo Fischer Scientific, Dreieich, Germany) to gain the following element contents: calcium (Ca), magnesium (Mg), potassium (K), phosphorous (P), sulphur (S), iron (Fe), manganese (Mn), and aluminium (Al). Elements stocks were calculated using element contents and bulk density.

2.6. Statistical analysis

Logarithmic regression models were used to characterize changes in soil physical properties, reflecting an expected strong initial disturbance by fire followed by rapid changes during early post-fire recovery. In contrast, linear regression was applied to model soil chemical properties, as their recovery is generally more gradual and consistent over time, without a clearly defined peak within the recovery phase. Diagnostic plots and Shapiro-Wilk tests were performed to check regression assumptions. Regressions were visualized using the GGplot (Wickham, 2011) package. Soil particle size distribution was plotted using the ggtern package (Hamilton and Ferry 2018). To analyze the relationship between bulk density and carbon content across different study sites and soil depths we used the 'cor.test' function in R. Statistical analyses were performed using the software R (R Core Team, 2022). Supplementary data (Mallikarjun et al., 2025) is published on PANGAEA (Felden et al., 2023).

3. Results

3.1. Soil physical properties

Bulk density increased during post-fire recovery and exceeded the level of the unburned control site in both ecosystems and in all soil depths (Fig. 2). In the humid temperate ecosystem (Nahuelbuta), soil bulk density increased by 0.05 g cm^{-3} per year in the top 10 cm, and by 0.04 g cm^{-3} per year in the mediterranean ecosystem (La Campana) (see Supplementary Table 1.1). Thus, ongoing soil compaction persisted in both ecosystems during the ~14 years of vegetation recovery.

Soil texture in the mediterranean ecosystem varied more strongly over the sites of the chronosequence than in the humid-temperate system (Fig. 3). The fractions of clay (<0.002 mm) and silt (0.002–0.05 mm) increased above the level of the control sample, in contrast reduction in the sand fraction (>0.05 mm) in all three soil depths. Thereafter, it remained at same level without further changes (Supplementary Table 1.1). At the humid temperate site, the clay fraction decreased (annual loss of 0.93 %) in all three soil depths post-fire, resulting in a reduction of 10–12 % in 12 years post-fire compared to the unburned control site. The silt remained at the level of this fraction in the control soil at the humid temperate site, except 0–2 cm depth which reduced. The sand fractions also increased over the control level, with rapid increases occurring in the earlier years, followed by a slower rate of change as time progressed. Overall, the sand fraction increased by 0.75 %, 0.73 %, and 0.32 % per year in the 0–2 cm, 2–5 cm, and 5–10 cm soil depths, respectively (Supplementary Table 1.1).

3.2. Soil chemical properties

3.2.1. pH-value

The pH-value increased in humid temperate soil after fire above that of the unburned control site in all depths during the vegetation recovery period of ~12 years (Supplementary Table 1.1 and Fig. S 1.2a). The pH value in 0–2 cm soil depth of mediterranean site was stable ($p > 0.05$) during the recovery phase. In lower depth, pH values were lower post-fire than that of the control site, but then increased ($p < 0.05$) successively during the recovery phase, eventually reaching pre-fire conditions after 14 years.

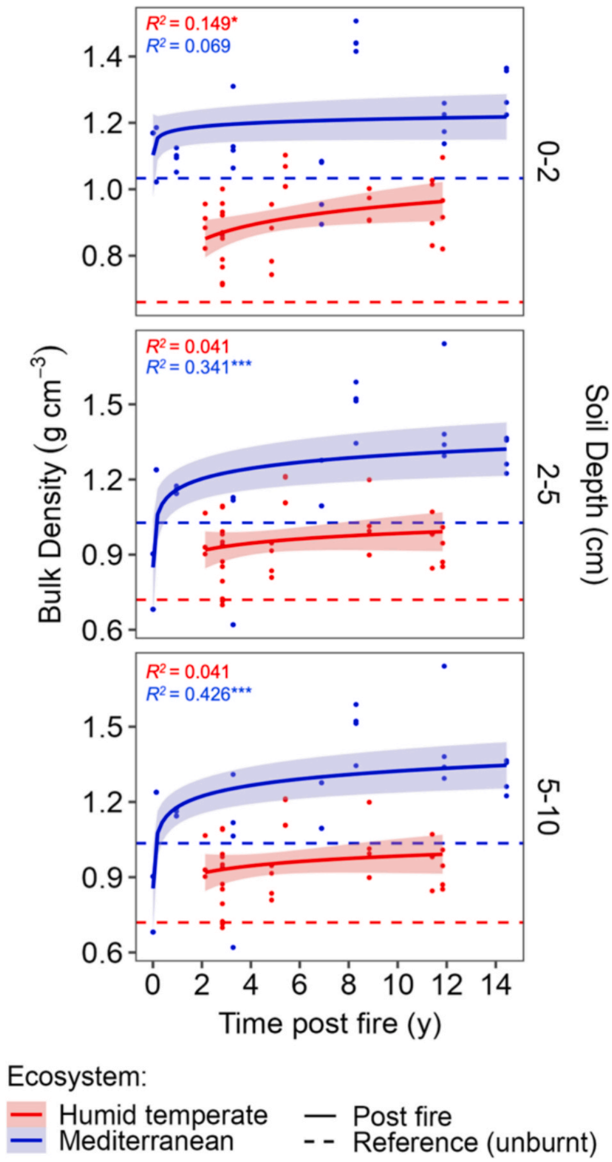

Fig. 2. Logarithmic regressions of post-fire soils bulk density (g cm^3) of Nahuelbuta (red) and La Campana (blue). The dotted lines represent the respective control soil of the > 39 years unburnt national parks. Three rows represent three depth of topsoil horizon (0–10 cm). Shaded areas around the regression lines indicate 95 % confidence intervals. R^2 with significance * $p < 0.05$, ** $p < 0{,}01$ and *** $p < 0{,}001$ are indicated.

3.2.2. Carbon and nitrogen stocks and stable isotope signatures

Post-fire reduction of total carbon (C) compared to the control site was marginal in all soil depths of the humid temperate site. In contrast, C losses were higher (~40 %) in all soil depths of the mediterranean ecosystem after the fire and recovery of this stock occurred only in the lower depth but not in 0–2 cm depth during the ~14 years (Fig. 4). In the litter horizon, it was exactly opposite: the fire-induced decrease of the C stock was higher in the humid temperate systems than in the mediterranean ones. Similarly, nitrogen (N) losses of the litter horizon were higher in the humid temperate compared to the mediterranean sites after the fire (Supplementary Table 1.1 and Fig. S 1.2b). N stocks in all three soil depths of the humid temperate ecosystems accumulated successively, even exceeding the level of the control site. In contrast, N stocks at the mediterranean site were not affected by fire or the recovery processes in the top 0–2 cm of the soil, but fire-induced N losses in 2–10 cm depth recovered fully during the ~14 years of recovery of our chronosequence (Fig. 4; Supplementary Table 1.1).

Post-fire $\delta^{13}C$ values of litter and soil horizons in both ecosystems were lower than that of the unburned control site except in the litter horizon of the mediterranean site (Fig. 5; Supplementary Table 1.4). $\delta^{13}C$ values did not recover to pre-fire levels during the 12–14 years, but instead, post-fire $\delta^{13}C$ of the humid temperate site decreased further than that of the mediterranean one.

$\delta^{15}N$ values of litter and soil horizons in both ecosystems were higher than that of the control site in the humid temperate and the mediterranean system post-fire and most of them did not change throughout the 14 years post fire recovery. An exception was a decreasing $\delta^{15}N$ value in the litter horizon of the mediterranean site reaching the pre-fire (control) level during the observed vegetation recovery period (Fig. 5).

3.2.3. Litter and soil nutrient stocks

Phosphorous (P) and sulfur (S) stocks of the litter horizon of both ecosystems reduced after a fire compared to the unburnt control sites (Fig. 4). While S stocks in the litter horizon show a similar trend as N stocks, the litter P stocks in the humid temperate site but not of the mediterranean one recovered within ~12 years. The P and S stocks of the humid temperate soils were unaffected by fire and the post-fire recovery processes (Fig. 4). Conversely, at the mediterranean site, P stocks accumulated higher than the stock of the control soil in lower soil depth (2–10 cm) (rate: ~0.013 Mg ha^{-1} y^{-1}), whereas S stocks slightly decrease (−0.003 Mg ha^{-} y^{-1}) in 0–2 cm soil depth during the ~14 years recovery period but did not change in lower soil depths (2–10 cm) (Supplementary Table 1.1).

Ca stocks in the litter horizon decreased in the mediterranean site post-fire with no subsequent recovery, while recovered during ~14 years in the humid temperate site. In contrast to Ca, Mg stocks of the litter layer were unaffected by fire in the humid temperate ecosystem but decreased post-fire at the mediterranean site, with recovery within a period of ~14 years (Supplementary Fig. S 1.2b). In contrast to Ca and Mg, the K stocks of the litter layer decreased in both ecosystems as a result of fire. These losses nearly completely recovered at the mediterranean site (rate: 0.002 Mg K ha^{-1} y^{-1}), but remained low without any change during the ~12 years in the humid temperate site (Supplementary Fig. S 1.2b).

Calcium (Ca) stocks in the soils of both ecosystems decreased after the fire, with higher losses in humid temperate soils than at the mediterranean site (Fig. 6). In contrast to Ca, the fire-induce loss of Mg and K was only significant any more for the mediterranean ecosystem. The high losses of the basic cations from the humid temperate ecosystems topsoil layers could recover during the 12-year recovery period for Ca and K, but not yet for Mg (Fig. 6). Annual recovery rates were 0.087, 0.12 and 0.13 Mg Ca ha^{-1} in 0–2, 2–5 and 5–10 cm soil depths, respectively and ranged from 0.013 to 0.022 Mg K ha−1 y^{-1} during the ~12 years recovery period (Supplementary Table 1.1). Irrespective of an initial stock decrease post-fire, all basic cations accumulated during the observed vegetation recovery period (~ 14 years) to levels exceeding that of the unburnt control site in mediterranean ecosystem. Annual increases for Ca were 0.10, 0.23 and 0.41 Mg ha^{-1}, for Mg 0.036, 0.081 and 0.184 Mg ha^{-1} y^{-1} and K −0.06, 0.05 and 0.12 Mg ha^{-1} in soil depths of 0–2, 2–5 and 5–10 cm, respectively,

The stocks of the trace nutrients iron (Fe) and manganese (Mn), but also of aluminium (Al) remained at the same level post-fire and during the vegetation recovery period (~12 years) in all horizons (soil and litter) of the humid temperate ecosystem (Supplementary Fig. 1.2c). In contrast, in the mediterranean site, Fe increased as a consequence of the fire event, exceeding that of the unburnt control litter and soil. Mn and Al had trends like Fe, except that Mn levels remained unaffected by fire in the litter horizon of the mediterranean site (see Supplementary Table 1.1 and Fig. 1.2c).

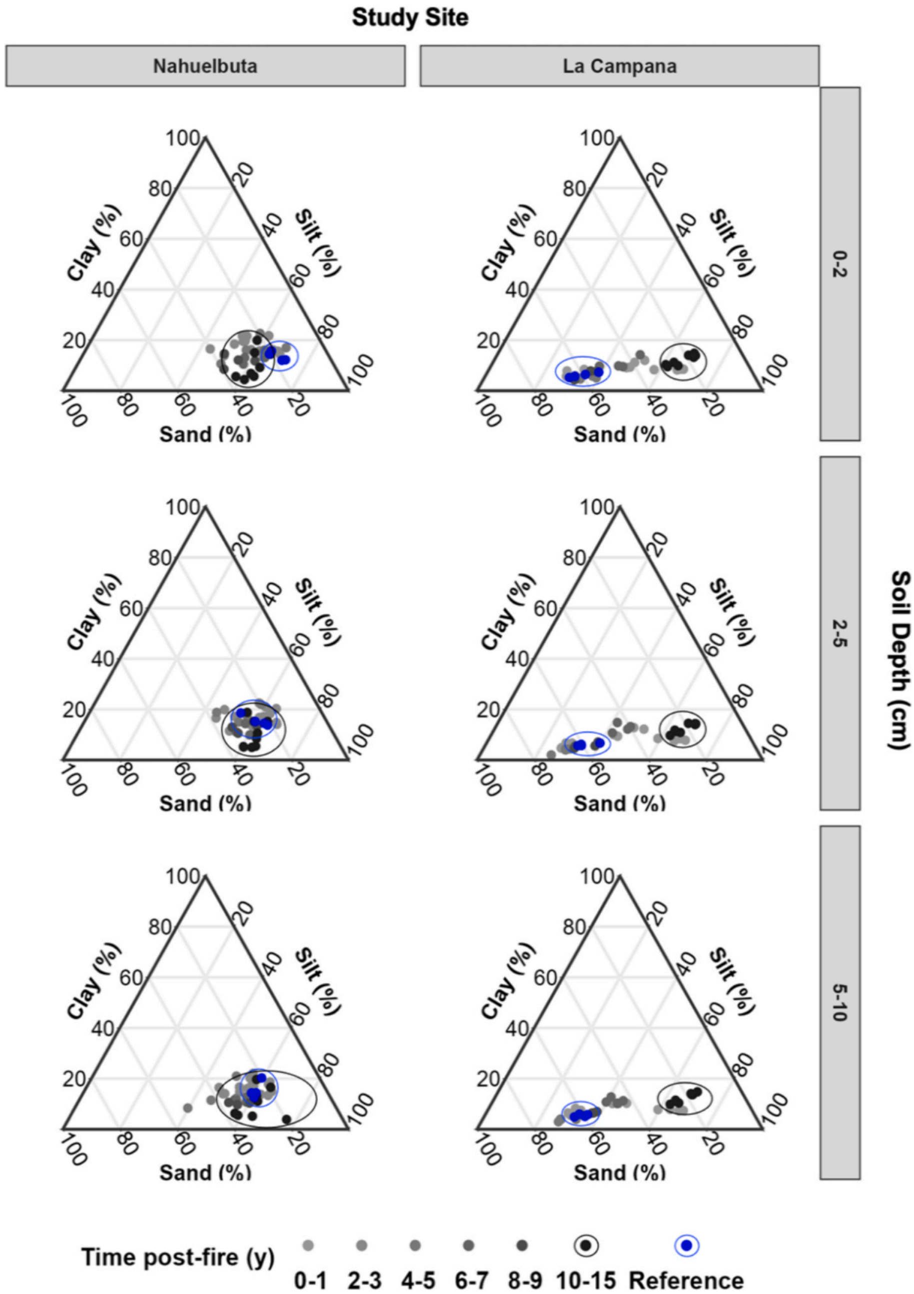

Fig. 3. Post-fire changes in particle size fraction (% of fine soil) distribution for each soil depth at humid temperate and mediterranean ecosystem. Particle fraction of <0.002 mm classified as clay, 0.002–0.05 mm as silt and >0.05 as sand. Blue colour encircled represents the respective control soil of the >3 decades unburnt national parks. Black colour encircled data represents soil texture of 10–15 years post fire. The three rows represent three depth increment of the 0–10 cm is the soil depth (cm).

4. Discussion

4.1. Ash effects on post-fire soil properties

The bulk density of soils in both ecosystems and at all depths (0–10 cm) increased after the wildfire, and did not shift back towards pre-fire levels during the vegetation recovery of 14-years. A decline in organic matter due to fire-induced combustion can weaken soil aggregate structure and increase compaction (Alcañiz et al., 2018; Heydari et al., 2017). An negative correlation between soil carbon (C) content and bulk density in the 2–10 cm depth of humid temperate, and in the top 0–2 cm of mediterranean ecosystems (refer to Supplementary Table 1.3) supports this explanation. However, there are further processes which may contribute to at least in decadal times irreversible compaction: (i) the temperature-induced loss in biota (e.g. fungal hyphae or biofilms) may destabilize aggregates (Agbeshie et al., 2022), (ii) bulk density is inversely proportional to soil porosity, and a reduction in porosity due to ash clogging can impact soil hydrological properties (Wieting et al., 2017; Lucas-Borja et al., 2020), (iii) accelerated post-fire erosion can result in the loss of topsoil, revealing denser subsoil with higher bulk density at the surface (Kim et al., 2005; Guillaume et al., 2015).

The increase in bulk density after fire was higher in the mediterranean ecosystem than in the humid temperate ecosystem during the recovery period. Thus, it is very likely that the recovery of vegetation, i.e. also root biomass, was not sufficient to restore the original soil structure and density, but this was strongly pronounced in the water-restricted mediterranean ecosystems, where longer periods are required to reach the pre-fire state of the vegetation (Blanco-Rodríguez et al., 2023). In

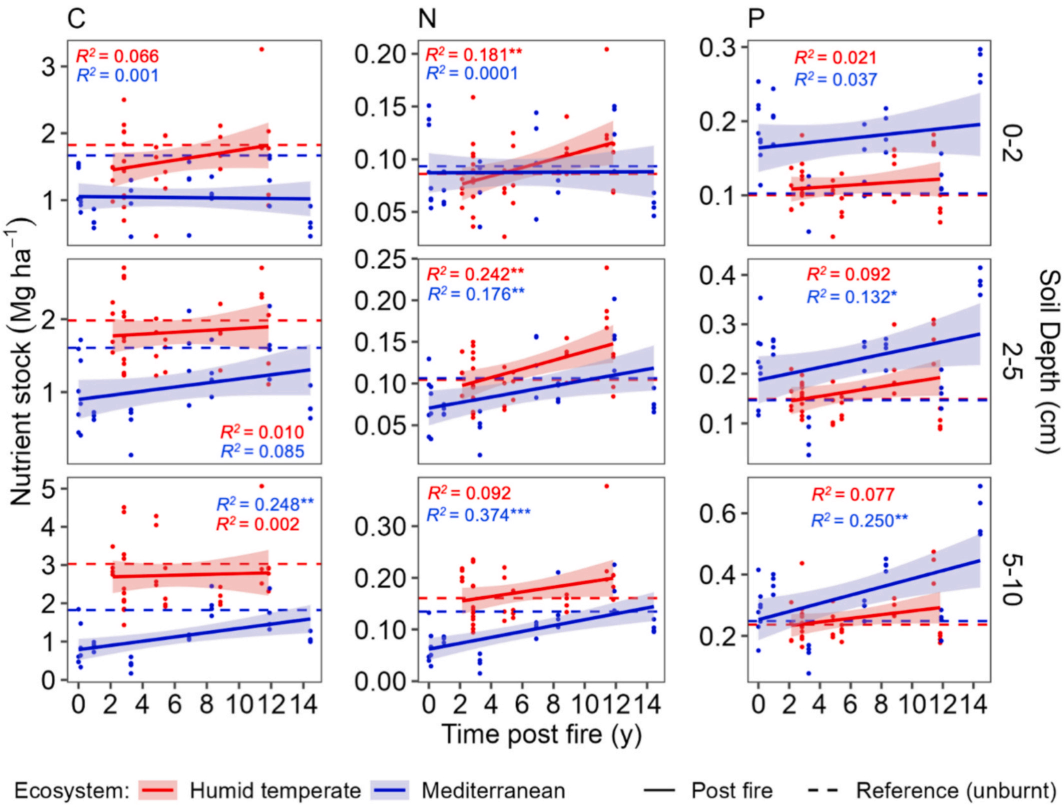

Fig. 4. Linear regressions of post-fire soils Carbon (C), Nitrogen (N), Phosphorus (P) stocks of Nahuelbuta (red) and La Campana (blue). The dotted lines represent the respective control soil of the >39 years unburnt national parks. Three rows represent three depth of topsoil horizon (0–10 cm). Shaded areas around the regression lines indicate 95 % confidence intervals. R^2 with significance * $p < 0.05$, ** $p < 0,01$ and *** $p < 0,001$ are indicated.

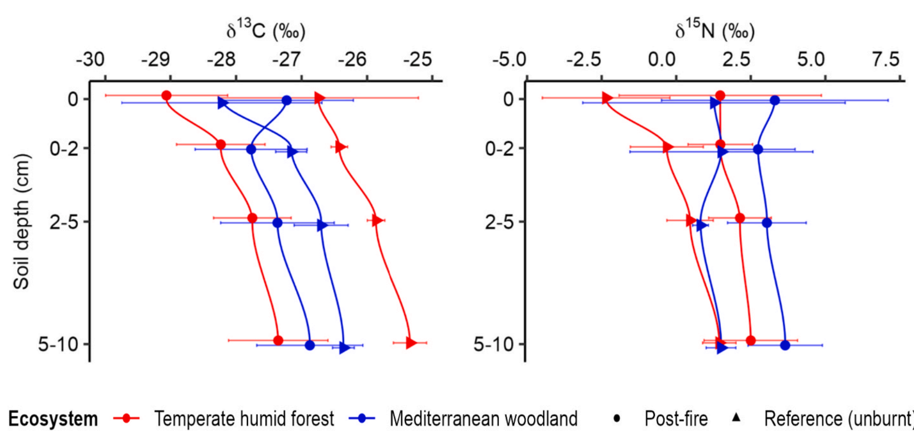

Fig. 5. Mean +- SD soil δ ^{13}C and δ ^{15}N of control site (filled triangles) and post-fire (filled circles) of Nahuelbuta (temperate humid forest; in red) and La Campana (mediterranean woodland; in blue).

addition, high rainfall intensity in humid temperate climates may lead to particulate transport of the ash particles, while low precipitation intensity under mediterranean climate could favor ash clogging and, by that, further increasing bulk density (Pereira et al., 2019).

Besides its physical role as a particle, post-fire ash accumulation increases soil pH due to its high content of base cations (Akburak et al., 2018; Francos et al., 2019; Hinojosa et al., 2021, Alcañiz et al., 2018). While we observed such an increase for the humid temperate ecosystem across all depths, the soil pH in the mediterranean ecosystem remained stable within the top 2 cm of soil, while it initially even decreased for deeper horizons. However, during the recovery phase, this changed and the pH value increased in these soil layers, suggesting slow ash transport downwards in the soil profile. This is supported by the observation that the pH recovery in the mediterranean ecosystem goes along with a net accumulation of nearly all base cations at these soil depths (Fig. 5 and Supplementary Fig. S 1.2a). Overall, the increase in soil pH due to fire-derived ash is expected to be higher in soils with initially low pH, such as the humid temperate region of Nahuelbuta (pH = 4.8 to 5.8), compared to the higher pH of the mediterranean region of La Campana (pH = 6 to 7) (Neary et al., 2005).

Correspondingly to the increase in soil pH, ash accumulation also results in an increase in base cations, which were observed in both of ecosystems. Although ash accumulates primarily at the soil surface, nutrients leached from the ash post fire can be adsorbed in the mineral horizons throughout the soil profile, which can retain 89 to 98 % of the allocated nutrients, depending on soil properties (Neary et al., 2005;

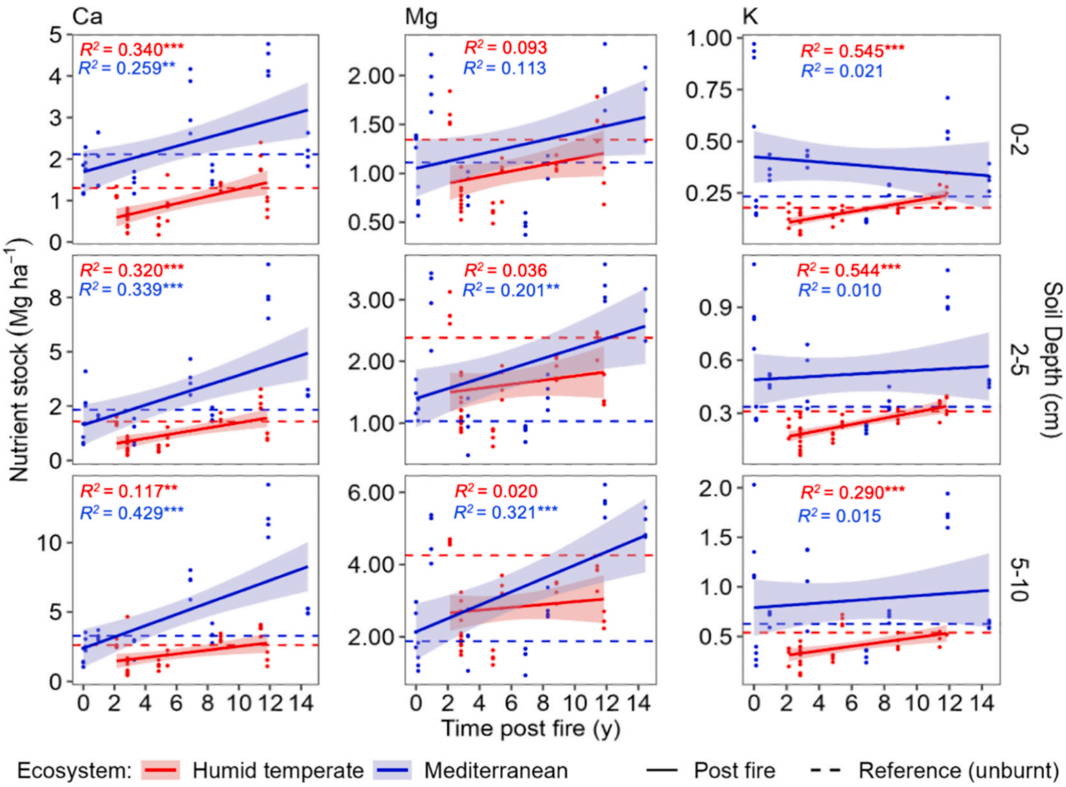

Fig. 6. Linear regressions of post-fire soils calcium (Ca), magnesium (Mg), potassium (K) stocks of Nahuelbuta (red) and La Campana (blue). The dotted lines represent the respective control soil of the >39 years unburnt national parks. Three rows represent three depth of topsoil horizon (0–10 cm). Shaded areas around the regression lines indicate 95 % confidence intervals. R^2 with significance * $p < 0.05$, ** $p < 0,01$ and *** $p < 0,001$ are indicated.

Soto and Diaz-Fierros, 1993). Post-fire nutrient leaching is stronger in coarser textured soils (Raison et al., 2009) and higher with higher precipitation. In the humid temperate ecosystem, higher annual precipitation leads to the loss of base cations Ca, Mg, K, and Na, which have a high mobility in the low pH soil solution, resulting in the highest degree of topsoil depletion by leaching compared to the unburnt humid temperate site (Oeser et al., 2018). This leaching is lower under mediterranean climate due to a limited period of high soil moisture, which restricts the depletion of the base cations Ca, Mg, K, and Na (Oeser et al., 2018).

Differences in the two chronosequences include the survival of taller trees in the humid temperate ecosystem after fire. These trees, through their deep roots and immediate post-fire nutrient consumption, not only support rapid vegetation recovery, but also influence post-fire effects (Mills and Fey 2004). For example, reduced accumulation in the shallow depth horizons may indicate uptake by recovering vegetation. However, in the humid temperate ecosystem, post-fire losses of base cations occur at all soil depths, maybe related to a combination of the higher precipitation and a textural shift toward a higher sand fraction (Fig. 2; Fig. 4; Supplementary Fig. S 1.2b). We observed a longer period of recovery of base cation content (or only partial recovery for Mg) than in the mediterranean systems, which suggests, that it is more difficult to refill the nutrient stocks by uplift considering the deeply weathered profile and base-cation depleted saprolite of this site (Stock et al., 2022). In these acidic soils, the exchange positions are filled with hydrogen and hydroxy aluminium ions, limiting the close association of potassium ions and reducing its recovery under low pH.

4.2. Wildfire impacts on soil texture

While clay and silt fractions continuously increased in the mediterranean ecosystem post-fire, soils of the humid temperate ecosystems displayed a much less pronounced effect, and if rather an increase in silt and sand fractions. (Fig. 2). Such inconsistent results are similarly reported in the literature, where often even no direct fire impact on soil texture was reported (DeBano et al. 1998; Green et al., 1998). However, Stoof et al. (2010) experimentally confirmed that temperatures above 300 °C, potentially due to differential thermal expansion, can weaken the cohesion forces in larger particles, leading to the disintegration or at least strongly accelerated weathering of sand-sized particles under the formation of clay-sized once (Badía and Martí, 2019). However, coarser soil textures have also been observed as a post-fire consequence (Terefe et al., 2008; Inbar et al., 2014; Brook and Wittenberg, 2016). High temperatures can induce the collapse of the crystalline structure of clay lattices (e.g., through the loss of hydroxyl ions or dehydration), resulting in the cementation of clay particles and the formation of either silt or sand-sized new particles (Heydari et al., 2017). Furthermore, the heat-induced transformation of iron and aluminum oxides in soils may form new binding agents to bind clay into silt-sized particles (Badía and Martí, 2019). As specifically, the high amount of Fe and Al in soils is a profound difference between our two sites, this may explain the contrasting effects observed for the humid-temperate versus the mediterranean ecosystem. The rapid recovery of pre-fire soil texture is supported by high biological productivity and soil faunal activity, with the recovery of biological functions (bioturbation, biological weathering, organic matter accumulation) mainly drive soil structure and texture (Mataix-Solera et al., 2011), and is thus more rapid in the humid temperate than in the mediterranean ecosystem.

4.3. Post-fire soil carbon recovery

Fire has a direct impact on ecosystem C stocks due to the combustion of plant biomass, litter and even soil organic C. C stocks in the litter horizon of the mediterranean ecosystem are very low, and the net stock was hardly affected by wildfire. However, the shift in $\delta^{13}C$ values from ~-27 ‰ to −28.5 ‰ suggests that the newly accumulated litter is of different quality and likely also from other (understory) plants. In contrast, the temperate humid rainforest of Nahuelbuta is characterized by a massive litter horizon that was strongly reduced by burning and did not recover within a decade post-fire, suggesting that vegetation recovery is not yet complete. However, soil organic carbon stocks were remained largely unaffected by the fire. Besides the input of long-term stable, charred C from the partially "charred" litter layer (Hobley et al., 2017), this can only be explained by a rapid recovery of the belowground input e.g. by rhizodeposition (Scharenbroch et al., 2012; Francos et al., 2018a), attributed to the large proportion of fire-prone trees (*Araucaria araucana*, *Nothofagus antarctica* and *Nothofagus pumilio*) in these forest types (Burns, 1993; González et al., 2005).

While soil C stocks were largely unaffected in humid-temperate ecosystems, they decreased strongly in fire-affected soils of the mediterranean system, indicating severe effects of complete vegetation removal in this ecosystem. Recovery of belowground C requires more than a decade in these systems and occurs only at depths below 2 cm, suggesting that plant investment in deeper roots or a shift to deeper-rooted plants may be an essential process during post-fire recovery. Stock et al., (2021) even attributed this C investment in lower soil layers even to mycorrhizal fungi as an essential nutrient strategy in these stressed mediterranean systems. Similarly slow recovery as in our top 2 cm has been noted across various mediterranean ecosystems, in some cases even partially ongoing decline in soil C up to 2 decades post-fire with no signs of recovery (Francos et al., 2018b), suggesting ongoing insufficient organic matter inputs from vegetation.

An often underestimated factor affecting SOC loss during fires is the soil moisture. Dry soils can lose up to 50 % of their SOC, while moist soils lose only 25 % (Badía et al., 2017). Fires in mediterranean ecosystems, characterized by low precipitation and high summer temperatures, often occur in much drier soil conditions than burning in temperate rainforests where the soil remains moist under a thick litter layer and soil horizons. Thus, fires in mediterranean ecosystems result in higher SOC losses compared to those in humid temperate ecosystems.

The fire-induced decrease in $\delta^{13}C$ values in soils of both humid temperate and mediterranean ecosystem carbon stocks did not level out during ~14 years (Fig. 5). Thus, fire itself, or altered post-fire microbial activity leads to a loss of "light" soil C throughout the soil profiles, which is insufficiently gets replaced by fresh C3 input from new vegetation. The consistent shift across depths suggests that soil C decomposition by microbial processes is more likely to play a key role than direct fire-induced combustion.

4.4. Atmogenic and geogenic nutrient dynamics after fire

Nitrogen (N)

Losses of N stocks in the mediterranean ecosystem were larger than in the humid temperate ecosystem, resembling the behavior of the C stocks. Fire-induced combustion and volatilization of NH_4^+ (Muqaddas et al., 2015; Fraterrigo and Rembelski 2021; Pellegrini et al., 2021) can be accompanied by post-fire mineral N losses (Sánchez Meador et al., 2017; Franco et al., 2019; Hahn et al., 2021). They occur through leaching or denitrification of NO_3^- formed during the fire (Huddell et al., 2020, Cheng et al., 2021; Qiu et al., 2021) or wind and water erosion of topsoil or litter-derived ash, both fostered due to the lack of N_{min} adsorbing or soil protecting vegetation, respectively. As N losses in both systems (top 2 cm in the humid-temperate and lower soil layers in the mediterranean) were accompanied by increases in the $\delta^{15}N$ value, direct loss from the fire linked to a fractionation by burning itself is likely involved in the observed N losses (Saito et al., 2007, Choi et al., 2020).

While we observed such losses in the lower soil horizons of the mediterranean system, it was not obvious in the upmost 2 cm. A lack of fire impact on N stocks of the topmost soil horizons – or even an increase – has also frequently observed (Hosseini et al., 2017; Liu et al., 2018; Fernández-García et al., 2019a; Fernández-García et al., 2019b). It was explained by the absence of losses of N-rich ash, but its accumulation in the first soil cm, but can be further enhanced by high mineralization of non-burnt litter (Alcañiz et al., 2018; Ferrer et al., 2021; Wan et al., 2021). These processes likely explain the largely unaltered N stocks as observed in the humid temperate system (Fig. 4).

The contrasting N dynamics between the humid-temperate and mediterranean ecosystems post-fire can be explained by two key processes. First, fires in the temperate-humid forests were of lower severity than those in the mediterranean woodland, so the absolute amount of combusted organic matter (and therefore N) was smaller. Second, fire preferentially consumes the ^{15}N-depleted surface organic horizon (Soldatova et al., 2024), leaving behind a soil profile that is relatively enriched in ^{15}N and thus more similar to deeper mineral horizons (LeDuc et al., 2013). This mechanism explains why post-fire $\delta^{15}N$ values in upper horizons converge toward those at depth and why this ^{15}N enrichment persists for more than a decade (Fig. 5) (Soldatova et al., 2024). Elevated post-fire net nitrification further enriches the residual NH_4^+ pool in ^{15}N, supplying enriched inorganic N to regenerating vegetation and reinforcing this vertical convergence (LeDuc et al., 2013).

In both ecosystems, the recovery of N stocks goes along with that of C, suggesting an identical process, i.e. belowground C and N input by rhizodeposition of recovering vegetation that takes up leached N from deeper soil horizons. The net increase in N stocks in the humid-temperate systems, in addition to lower N losses, can also be attributed to the high capacity for N fixation in these temperate humid forests, as evidenced by natural abundance isotopic signatures and nifH abundance in their rhizosphere (Abdallah et al., 2022). Because $\delta^{15}N$ in the upper horizons remains enriched relative to the control soil (Fig. 5), deep-root uptake of leached ^{15}N-enriched nitrate (Stock et al., 2022), together with moderate asymbiotic N fixation (Abdallah et al., 2022), offers a probable explanation for the observed recovery of N stocks without a return of the isotopic signature to pre-fire values.

An altered soil N dynamics post fire, as observed for the mediterranean system, has ultimate feedback on vegetation recovery, as N is the most limiting macronutrient for net primary productivity (NPP) (Ojima et al., 1994; Pellegrini et al., 2022). Consequently, the N losses in the mediterranean system can affect vegetation succession, specifically in ecosystems, where decomposition rates are slow (Neary et al., 1999), e. g. during dry seasons, and thus may delay vegetation recovery in the mediterranean compared to the humid temperate ecosystem post-fire.

Phosphorus and sulfur

Both ecosystems lost large proportions of their P and S stocks due to litter burning, suggesting i) volatilization and combustion of S, which can be lost in gaseous form, and ii) losses of ash implying P losses, specifically in the mediterranean systems, where complete vegetation removal occurred at their very steep slopes (Schaller et al., 2018). The P and S litter stocks could not recover post-fire in the mediterranean systems due to a lack in vegetation recovery and litter input, whereas their litter stocks quickly recovered after 12 years in the humid temperate ecosystem (Supplementary Fig. S 1.2b).

Immediately after combustion, the upper few centimeters of soil received a brief but pronounced flush of labile, plant-available inorganic P (Souza-Alonso et al., 2024; Turrión et al., 2010; Resende et al., 2011). The net increase in P in the upper 10 cm of the mediterranean ecosystem soils is therefore explained that large amounts of the litter- and vegetation-derived ash, containing mineral P, which can be allocated throughout the upper 10 cm of the soil by particulate transport. While in the first year post-fire this P may be highly plant available (Souza-Alonso et al., 2024), ongoing recovery can make this ash-derived P more and more unavailable to plants (Neary et al., 2005). A co-accumulation of Fe, Al, Mn and Ca at the same depth increments post-fire suggests that polyvalent cations may immobilize P in unavailable forms. Consistent with this, long-term data from Cerrado woodland how that the orthophosphate peak observed in the first year after fire can further reduce, even with ongoing fire activity, and the pool of plant-available P can reduce below the level of the unburnt control (Resende et al., 2011;

Santín et al., 2018).

The available forms of P more likely have to be gained by P uptake from secondary P mineral weathering of the subsoil (Koester et al., 2021) or even from biological weathering in the saprolite layer (Oeser et al., 2018), or by subsequent uplift of these nutrients, as is similarly possible to explain the recovery of S stocks. However, S stocks may recover faster than P stocks due to atmospheric inputs from the sea (Tipping et al., 2014), while the recovery of the available P forms is limited to the slow weathering of primary, secondary or ash-bound P minerals.

Fe, Mn and Al stocks were largely unaffected by fire and post-fire recovery in the humid temperate forests of Nahuelbuta (Supplementary Fig. S1.2c), whereas, in the mediterranean ecosystem, they were largely lost from the litter horizon, but not from soils. As recovery progressed, their levels in both soils and litter often surpassed those in the unburnt control soils (Supplementary Table 1.1 and Fig. 1.2c). Similar to S and P, the accumulation of these elements is likely related to the deposition of mineral ash, which contains considerable amounts of Fe, Al, and Mn oxides with low mobility and availability that are distributed over the upper 10 cm of the soil profile by particulate transport of ash (Groeschl et al., 1993, Kutiel and Naveh 1987). Furthermore, any soil compaction also contributes to an increase in their stocks.

4.5. Ecosystem implications and limitations

The mediterranean chronosequence (La Campana) burned almost completely, whereas the humid-temperate sequence (Nahuelbuta) experienced only understory fires; thus, ecosystem type and fire severity are inseparable in our dataset, and the large C–N losses, pH shifts and cation accumulations may therefore also result from fire severity rather than solely from climate-vegetation interaction. Because the fires were historic and uncontrolled, we relied on a space-for-time approach: soil-physical variables were fitted with a logarithmic model to reflect the abrupt, rapidly decelerating compaction that follows heating, whereas soil-chemical variables were fitted linearly because nutrient stocks usually rebuild gradually and no distinct peak recovery period can be predicted a-priori. These empirical fits cannot capture the first weeks after burning—when ash leaching, erosion and gaseous N losses peak—because those very early stages were not available in the chronosequence. Sampling was also restricted to the litter horizon and the upper 0–10 cm of mineral soil, where heat effects are concentrated, so deeper weathering feedbacks and nutrient uplift were beyond the study scope. Consequently, the absolute loss-and-recovery rates presented here should be regarded as indicative and adjusted to local fire behaviour and soil depth when applied on larger scales or transferred to other ecosystems. Nevertheless, by analysing real, uncontrolled wildfires across a pronounced climatic gradient and tracking recovery over many years, our study provides rare, ecosystem-scale evidence that can help managers anticipate post-fire nutrient trajectories and refine restoration strategies.

5. Conclusions

This study assessed wildfire-induced changes in soil properties and nutrient dynamics post-fire and during vegetation recovery in mediterranean woodlands (La Campana) and humid temperate forests (Nahuelbuta). Wildfires altered soil physical properties, and caused compaction in both ecosystems, but differing in their impact on texture between the two ecosystems. Mediterranean soils showed heat-driven mineralogical transformations, ash dissolved and particulate transport, as well as strong erosion, while humid temperate systems experienced less pronounced physical changes.

Ash inputs increased pH in humid temperate forest soils, mitigating acidity and aluminium toxicity. Ash deposition can lead to accumulation of base cations in mediterranean soils when ash is transported to deeper horizons. As fire causes only an initial increase in inorganic P availability at the surface, the long-term replenishment of plant-available P depends on the slow weathering of sub-soil and saprolite minerals.

Mediterranean ecosystems displayed the highest C and substantial N depletion, particularly in the deeper mineral horizons, whereas the humid temperate forests, despite complete combustion of the litter layer, the N stock of the upper mineral soil rapidly replenishes through uplift of leached N by deep roots of surviving, fire-adapted trees. The survival of tall, fire-adapted trees in these humid forests also ensures rapid recovery of the litter horizon. In contrast, mediterranean soils, which are prone to further erosion after complete vegetation removal by fire, cannot rapidly recover their organic matter and nutrient stocks, but have increased availability of basic cation contents, and thus face strongly altered stoichiometric balances post-fire. Intensive feedbacks between the slow recovery of the macronutrient stocks (N and P) and the slow vegetation regrowth are evident, arising doubts that the pre-fire reference state can be easily reached in mediterranean systems.

In conclusion, our research elucidates the complex interplay between wildfires, soil properties, and nutrient recovery in mediterranean woodlands and humid temperate forests. The fire-induced reduction in nutrient stocks could have broad implications for plant nutrition. Vegetation cannot depend solely on the litter horizon as a nutrient reservoir for several decades after a fire. The research underscores the importance of considering the unique ecological and environmental factors that influence post-fire ecosystem resilience and recovery trajectories, paving the way for targeted restoration strategies under enhanced future fire abundance.

CRediT authorship contribution statement

Jhenkhar Mallikarjun: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anna Gorbushina:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Yakov Kuzyakov:** Writing – review & editing, Visualization, Methodology, Investigation, Conceptualization. **Moritz Koester:** Writing – review & editing, Resources, Investigation. **Rodrigo Castro:** Resources, Investigation. **Anna Yudina:** Methodology, Formal analysis, Data curation. **Khaled Abdallah:** Writing – review & editing, Project administration, Investigation. **Francisco J. Matus:** Writing – review & editing, Resources, Investigation, Funding acquisition, Conceptualization. **Michaela A. Dippold:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jhenkhar Mallikarjun reports financial support was provided by University of Göttingen. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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the collaborative work amongst the two projects.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2025.109431.

Data availability

Post-fire soil physical and chemical properties, temperate and mediterranean ecosystem of Chile [dataset] (Original data).

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