Journal of Soils and Sediments (2025) 25:3281–3296
https://doi.org/10.1007/s11368-025-04136-1

25TH ANNIVERSARY SPECIAL ISSUE - IMPACTS OF WILDFIRES ON SOIL AND SEDIMENT SYSTEMS

Contrasting burn legacies in Eucalypt forest soils of different textures in Southwest Australia

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Received: 23 March 2025 / Accepted: 6 September 2025 / Published online: 9 October 2025
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Abstract

Purpose We sought to understand potential legacy impacts of wildfire on loamy soils from karri (*Eucalyptus diversicolor*) forest compared to sandy soils from jarrah (*Eucalyptus marginata*) forests in southwest Australia.

Methods We sampled soils (0–5 and 5–10 cm) from forest burned five years previously at high and low severity as well as unburnt forest. Replicate plots for each forest type and burn severity were analysed for particle size analysis (PSA), total carbon (%C), total nitrogen (%N), organic and inorganic phosphorus, nitrate, ammonium, pH, and stable isotope composition ($\delta^{13}C$, $\delta^{15}N$).

Results Loamy soils showed clear evidence of effects of fire on soil properties regardless of fire severity after five years, but these effects were less pronounced in sandy soils. In loamy soils, clay content, % C and %N were significantly lower in burnt sites compared to unburnt sites. Conversely, sandy soils only recorded an increase in inorganic nitrogen and a higher pH in burnt sites. Both loamy and sandy soils burned at high severity had more enriched $\delta^{13}C$ signatures compared to other sites. Additionally, loamy soils burned at high severity also had more enriched $\delta^{15}N$ signatures.

Conclusion Different legacy effects of fire on the two soil types are likely associated with dissimilarities in soil texture. A higher percentage of clay in unburnt loamy soils contributes to greater retention of soil C and N in burnt soils. This study emphasises the importance of soil texture in carbon and nutrient retention, suggesting that soils in karri forests, while fire-prone, may be more "carbon-sensitive to fire" than previously believed.

Keywords Fire severity · Soil texture · Carbon · $\delta^{13}C$ · $\delta^{15}N$ · Eucalyptus

1 Introduction

Globally, wildfires have become more frequent, widespread and intense, with extreme fire events increasingly common (Abatzoglou et al. 2019; Jones et al. 2022). Consequently, the structure and functioning of forest ecosystems, including key biogeochemical processes in soils, is also increasingly impacted by changing fire regimes (Francos et al. 2024; Lucas-Borja et al. 2021; Xu et al. 2022). The 2019–2020 'Black Summer' fires of south-eastern Australia burned more than 8 million hectares (Godfree et al. 2021), resulting in loss of an estimated 54 to 85 Mg C ha^{-1} of aboveground carbon, depending on burn severity (Nolan et al. 2022). The unprecedented number of large fires in California during 2020, included a massive 418,000 hectares fire that comprised 38 separate fires (Keeley and Syphard 2021), with still largely unquantified impacts on soil processes over both shorter and longer term. The consequences and legacies of more frequent and extensive fires, often of high severity, for

Responsible editor: Zhihong Xu

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the functioning of many forest systems remains unknown (but see Gibson and Hislop (2022) and Volkova et al. (2022) from studies of the Black Summer fires). In particular, the specific impacts of variable fire severity on soils properties and how long these impacts may persist is fundamental to understanding the recovery and possible restoration of forests post-fire.

Fire is the most significant disturbance to forest ecosystems, influencing carbon and nutrient cycling processes, inducing the release and transformation of nutrients, and driving changes in biological, chemical and physical properties of soil (Bravo-Escobar et al. 2024; Certini 2005; Lasslop et al. 2019; Roshan and Biswas 2023). For instance, it has long been known that a pulse of increased availability of key plant nutrients such as inorganic N occurs immediately after fire (Bui and Henderson 2013; Granged et al. 2011). Elevated soil ammonium (NH_4^+) levels can result directly from the combustion of organic matter, whereas nitrification to nitrate (NO_3^-) may take several weeks or months to occur. This delay is primarily due to the gradual recovery of microbial communities (Hanan et al. 2016). By contrast, soil organic matter (SOM) content can be reduced and the composition of SOM transformed through the combustion of carbon and the creation of recalcitrant pyrogenic organic matter (Bento-Gonçalves et al. 2012). However, these shifts in nutrient forms and availability as well as persistence in patterns are highly variable and will depend on fire severity and post-fire climatic conditions (Francos et al. 2018; Hobley et al. 2019) as well as soil textures (Sawyer et al. 2018).

Fire severity is generally quantified as the amount of above- and belowground organic matter consumed (Keeley 2009). Nevertheless, most studies of forest fire or burn severity are primarily characterised by loss of aboveground carbon (e.g. (Nolan et al. 2022). At the soil surface, high severity fires can reach 700 °C at 2.5 cm soil depth, resulting in volatilisation of both carbon and nitrogen, and more enriched carbon and nitrogen isotope signatures (Caon et al. 2014; Tahmasbian et al. 2019). By contrast, after low severity fires, carbon contents of soil often increase because of the incorporation of burnt or partially burnt fragments of litter and roots into the soil (Alcañiz et al. 2018). However, changes in soil carbon and nutrient contents post-fire are also highly variable even immediately after fire owing to interactions and feedbacks with different vegetation and soil types (Francos et al. 2018; Hobley et al. 2019). Soil texture, in particular, strongly influences nutrient retention, soil aeration and water penetration (Angst et al. 2021), as well as key processes such as nitrogen mineralisation (Meng et al. 2023). High severity fires can result in significant changes in soil aggregation and more likely to be evident in clay and loamy soils compared to sandy soil textures (Mataix-Solera et al. 2011). However, field-based observations show clayey soils may not show a significant increase in soil aggregate stability that is observed under high temperatures in laboratory conditions (Thomaz 2021). High severity fires can also have long-lasting effects on P biogeochemistry of soils high in clays by altering adsorption characteristics (Deng et al. 2024). Consequently, the impacts of fire on forest ecosystems and their subsequent resilience and recovery processes will reflect at least in part differences in underlying soil textures (Claridge et al. 2009; Lucas-Borja et al. 2022; Moya et al. 2018).

The forests of southwest Australia are recognised as some of the world's most fire prone forests (Burrows and Abbott 2003), although the frequency of catastrophic fires is considerably less than the temperate forests of southeast Australia (Davey and Sarre 2020; Levin et al. 2021). Karri (*Eucalyptus diversicolor* F. Muell) and jarrah (*Eucalyptus marginata* Donn ex. Smith) dominate across the region and frequently occur in a mosaic across the landscape, where karri forest tends to occur on more fertile loamy soils while jarrah forest occurs on poor sandy or lateritic soils that are generally low in nutrients (O'Connell and Grove 1996). We might thus expect variability in the persistence of wildfire impacts on forest soils not only due to fire severity and vegetation type, but also to differences in underlying soil attributes. Here, we investigated whether impacts on soil nutrients, pH and texture are evident five years post fire across a fire severity gradient. We tested the following hypotheses: (i) High-severity fire would lead to lower soil carbon (C) and nitrogen (N) concentrations compared to areas affected by low-severity fire or that remained unburnt, due to greater combustion and nutrient loss. (ii) Burnt soils would exhibit more enriched isotopic signatures (e.g., $\delta^{13}C$, $\delta^{15}N$), as a result of the preferential volatilisation of lighter isotopes and post-fire transformation processes. (iii) Fire impacts on soil properties would be more pronounced in loamy soils, given their higher clay content and greater capacity to retain organic matter and nutrients, making changes more detectable.

2 Materials and methods

2.1 Study area and sampling design

The study was conducted near the town of Northcliffe in the Warren Bioregion, 350 km south of Perth, southwest Western Australia (Fig. 1). Climate of the area is Mediterranean, with warm, dry summers and mild, wet winters. The mean annual precipitation is ~1168 mm and the mean temperatures range from 26 °C in summer to 15 °C in winter. However, during extreme hot summers, maximum temperatures can reach 40 °C (Australian bureau of meteorology 2021). Regional forest soils are predominantly gravelly soils

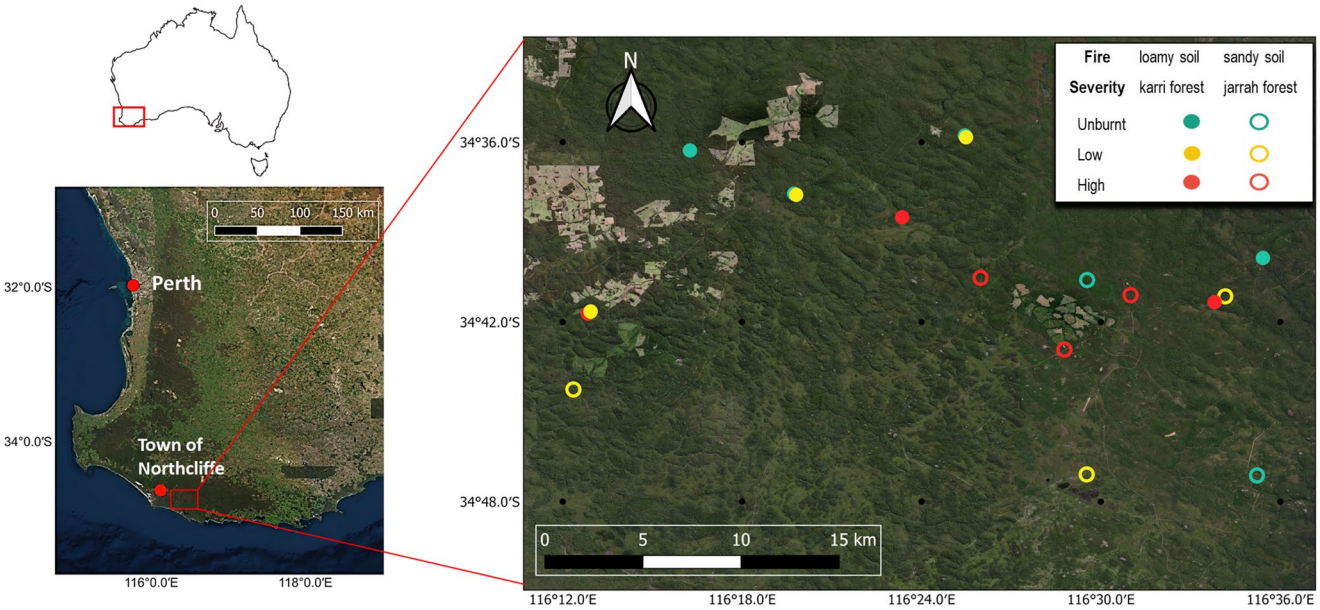


Fig. 1 Location of the 17 study sites from the "Northcliffe fire" in the Warren bioregion, south-west Western Australia and their repartition among fire severities categories and forest types: loamy soils - karri forest (filled circles) and sandy soils - jarrah forest (open circles)

ranging in texture from loamy earths and loamy gravels to sandy gravels, often with a clayey subsoil (Isbell 2016). Karri forests is mostly confined to more loamy soils and red earths while jarrah forest occurs mostly on sandier and more gravelly sites.

In January 2015, a wildfire, referred to here as "The Northcliffe fire" (Etchells et al. 2020) burnt nearly 1000 km^2 of the Warren bioregion, including significant areas of both karri and jarrah forests. The wildfire occurred during an extreme dry and hot summer. These dry weather conditions plus a high incidence of lightning favoured the ignition and spread of the fire, which lasted for two weeks and burnt heterogeneously across different vegetation types, creating a mosaic of burn severity, leaving some patches with high tree mortality, and others unburnt or with only light to moderate understorey scorch (Etchells et al. 2020). Five years after the fire, there was still evidence of the impacts of the fire in the forest structure of both forest types, especially in the canopy cover and quantity of litter, which were significantly reduced after the fire (Fig. 2).

The plots utilised in this study were previously established and classified according to fire severity one year after the fire in March 2016, as described in Etchells et al. (2020). Etchells et al. (2020) used a remotely-sensed spectral index from Landsat satellite images (difference Normalised Burn Ratio, dNBR) accompanied by on-ground confirmation based on estimates of crown scorch and epicormic resprouting height (Lacey and Johnston 1990; McCaw and Middleton 2015) to classify karri sites into three fire severity classes – unburnt, low severity and high severity. The same approach was subsequently extended for Etchells, et al. (unpublished) to encompass jarrah forest sites. A total of 17 plots (30 × 30 m; 900 m^2) were established across the two forest types (Fig. 1), comprised of nine plots in karri forest on loamy soils (three unburnt, three burnt at low severity and three burnt at high severity) and eight plots in jarrah forest on sandy soils (two unburnt plots - a third unburnt plot was prescribed burnt during the winter of 2019 and subsequently removed from the study - three burnt at low severity and three burnt at high severity). We collected soil samples from each of the plots in September 2019 (~five years post fire). Three soil samples were taken at two depths (0–5 cm and 5–10 cm) from random locations within in each plot after scraping away surface litter (Fig. 2).

After collection, soils were sieved (<2-mm diameter) and kept at field moisture at 4 °C in the dark until analyses within 15 days of sampling.

2.2 Soil analyses

Concentration of C and N (%) and stable isotope signatures ($\delta^{13}C$ and $\delta^{15}N$, ‰) of soils were obtained on soil dried at 50 °C using a continuous flow system consisting of a Delta V Plus mass spectrometer connected to a Thermo Flush 1112 via Conflo IV (Thermo-Finnigan/Germany) at the West Australian Biogeochemistry Centre at The University of Western Australia (https://www.wabc.uwa.edu.au/). All stable isotope analyses are reported in per mil (‰) after multi-point normalisation to international scales (Skrzypek 2013).

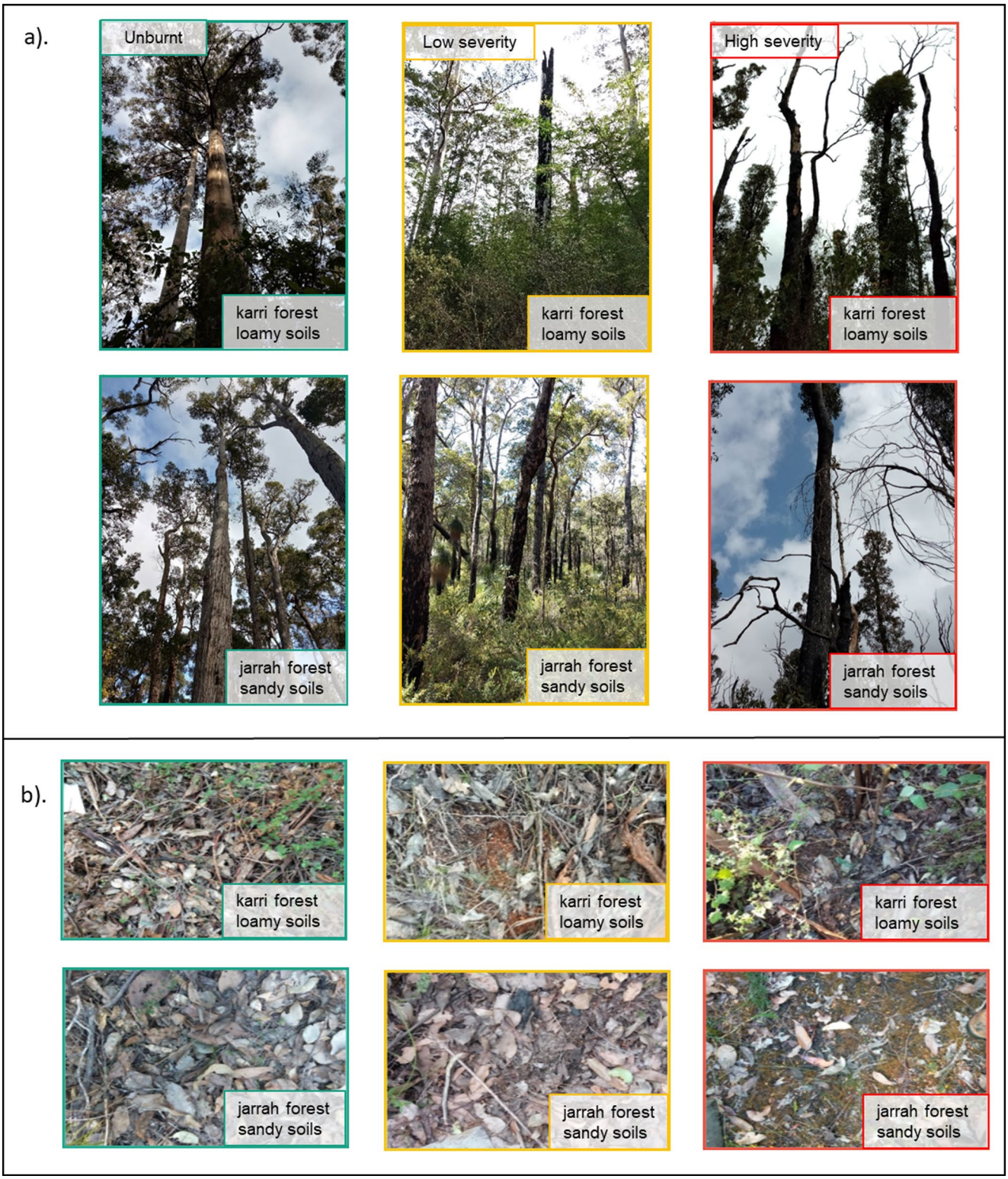


Fig. 2 Site photos taken in September 2019, five years after the Northcliffe fire. **a**. Unburnt stands and stands burnt a low to high severity for loamy soils (karri forest) and sandy soils (jarrah forest) (**b**) Soil surface and leaf litter from unburnt forest and forest burnt at low and high severity for loamy soils (karri forest) and sandy soils (jarrah forest)

Soil pH was measured on fresh soil in Milli-Q water (1:1 w/v). Ammonium (NH_4^+-N) and nitrate (NO_3^--N) were extracted using 1 M KCl on an end over shaker for 1 h, then filtered and stored at 4°C prior to analysis using automated colorimetric methods. Soil phosphorus (P) fractions were measured as described by Grierson and Adams (2000), modified from (Bowman and Cole 1978). Briefly, labile soil P was extracted in 0.1 M NaOH on an end-over shaker for 16 h. Total P (OH-P_t) was extracted by digesting filtered soil extracts using concentrated H_2SO_4 on a heat block followed by addition of H_2O_2 (30%). Inorganic P (OH-P_i) was extracted by acidifying soil extracts with concentrated HCl and filtering (Whatman 40). OH-P_t and OH-P_i. Phosphorus was analysed using a modified ascorbic acid method (Kuo and Sparks 1996). Labile organic P (OH-P_o) was determined as the difference between P_t and P_i.

Surface soils (0–5 cm depth) were analysed for particle size (PSA; 51samples in total) as these soils are most likely to have experienced higher temperatures and for longer duration compared to 5–10 cm soils (Brady et al. 2022). Samples were pre-treated to remove organic matter using 20 mL of H_2O_2 (30%) plus deionised water and heating for ~1 h. Charcoal particles were manually removed from soil samples. Particle size was then measured through fractionation of sand, silt and clay particles, using 10 mL of dispersing agent (Na-hexametaphosphate + NaOH) and then mixing for 10 min. Settling times for the clay and silt fractions were determined according to room temperature (Bowman and Hutka 2012).

2.3 Data analyses

We performed all statistical analyses using R (R Core Team 2021). A two-way ANOVA was used to evaluate the effect of fire severity on soil properties and to investigate whether the effects are similar between loamy soils (karri forest) and sandy soils (jarrah forest). Significant differences among severity classes and soil types were determined by performing a Tukey's test at $p<0.05$ significance level. All data were tested for normality using Shapiro-Wilkes test and for equality of variance using Levene's test. In cases where the assumption of normality was not met, a log-transformation was applied on the raw data and the log-transformed data analysed. Pearson's correlation matrix was used to test for significant correlations ($p<0.05$) between soil C, N, $\delta^{13}C$, $\delta^{15}N$ and clay content. Nonmetric multidimensional scaling (NMDS) was used to visualise the clustering of different fire severity classes for each soil-forest type, using Euclidean distance among the analysed soil properties. Before NMDS analysis, all data were $\log_{10}(x+1)$ transformed to standardise the data. NMDS was carried out using the vegan package in R (Oksanen et al. 2007).

3 Results

3.1 Effects of fire severity on carbon, nutrients, and other soil properties

The response of soil nutrients, pH and particle size distributions to fire differs between loamy and sandy soils (at 0–5 cm depth), regardless of burn severity. Long-term changes were reflected in an increase in C, N, pH and nitrate being most evident in loamy soils compared to sandy soils (Table 1). Most fire legacy effects were confined to the surface 0–5 cm of soil (Table 1).

Total C of 0–5 cm of loamy soils decline with fire severity. Total C of unburnt sites was almost twice that of sites burned at low ($p<0.05$) and high severity ($p<0.01$) (Table 1a). Total N was significantly higher ($p<0.05$) in unburnt loamy soils compared with low severity sites; however, low and high severity sites were not significantly different (Table 1a). C/N ratio of loamy soils was highly variable and while not significantly different ranged from 42 in unburnt sites to 67 in low severity sites (Table 1a).

Soil pH in loamy soils at 0–5 cm was significantly lower in unburnt sites ($p<0.01$), compared with sites burnt at low and high severity sites (Table 1a). Nitrate (NO_3^--N) in loamy soils was significantly lower in low severity sites compared with unburnt and high severity sites ($p<0.05$) (Table 1a). Ammonium (NH_4^+-N) did not significantly differ among fire severity classes within loamy soils (Table 1a). Also, inorganic and total phosphorus did not differ among burnt and unburnt sites (Table 1a).

Carbon and nitrogen concentrations in sandy soils (0–5 cm), did not differ significantly between unburnt and burnt sites (Table 1b). For C concentration the values ranged between 8.3% in unburnt sites and 10.3% in low severity sites ($p>0.05$), whereas N concentration values ranged between 0.1% in sites burnt at high severity and 0.17% in sites burnt at low severity ($p>0.05$). Also, C/N did not record differences ($p>0.05$) (Table 1b).

Soil pH (0–5 cm) was significant different between unburnt and burnt sites of sandy soils. Unburnt sites had lower pH, than sites burnt at high severity ($p<0.05$) (Table 1b). Nitrate was significantly higher in unburnt sandy soils sites ($p<0.01$) compared to sandy soil sites burnt at low and high severity (Table 1b). Ammonium also recorded statistical differences, and it was nearly two-fold higher in unburnt sites ($p<0.05$) than low and high severity sites (Table 1b). Inorganic and total phosphorus did not differ among burnt and burnt sandy soil sites (Table 1b).

At 5–10 cm soil depth, differences among fire severity classes within loamy soils were only found in pH where low and high severity sites showed higher values than unburnt sites ($p<0.05$) (Table 1c). Regarding sandy soils at 5–10 cm

Table 1 Effect of fire severity on carbon, soil nutrient concentrations and pH for loamy soils (karri forest) and sandy soils (jarrah forest) at two soil depths (0–5 and 5–10 cm). Values represent mean ± SE. Lowercase letters indicate significant differences among fire severity classes ($p<0.05$). $n=9$ per group, except for unburnt jarrah, where $n=6$ and *= not measured

a).	**Loamy soils - Karri (Eucalyptus diversicolor)**																	
0–5 cm	Carbon [wt %]		Nitrogen [wt %]		C/*N*		pH		$NO3^-$-*N* [µg/g soil]		NH4+-*N* [µg/g soil]		OH Pi [µg/g soil]		OH Pt [µg/g soil]		$\delta^{15}N$ ‰		$\delta^{13}C$ ‰	
Unburnt	14.1^{a}	±2.1	0.37^{a}	±0.06	42^{b}	±4.3	6.4^{bc}	±0.2	1.0^{a}	±0.3	19.8^{a}	±3.0	8.9^{a}	±1.2	33.2^{a}	±2.5	0.1^{c}	±0.2	−29.7ab	±0.2
Low	7.7^{b}	±1.2	0.15^{b}	±0.03	67^{ab}	±12.9	7.2^{a}	±0.1	0.3^{b}	±0.03	13.8^{a}	±1.7	7.2^{a}	±1.5	31.1^{a}	±3.1	2.2^{ab}	±0.3	-29.2^{bc}	±0.1
High	6.2^{b}	±0.8	0.18^{ab}	±0.04	44^{b}	±6.5	7.1^{a}	±0.1	1.2^{a}	±0.4	13.3^{a}	±1.9	7.1^{a}	±1.2	29.5^{a}	±1.1	2.7^{a}	±0.2	-29.2^{c}	±0.2
b).	**Sandy soils - Jarrah (*Eucalyptus marginata*)**																	
Unburnt	8.3^{b}	±2.0	0.14^{b}	±0.06	85^{ab}	±26.7	5.8^{c}	±0.2	0.3^{b}	±0.01	12.7^{a}	±1.7	5.3^{b}	±0.8	25.3^{b}	±2.5	0.6^{c}	±0.3	-30.0^{a}	±0.2
Low	10.3^{ab}	±2.1	0.17^{ab}	±0.03	55^{ab}	±6.5	6.4^{bc}	±0.1	0.1^{c}	±0.02	6.8^{b}	±1.3	6.1^{ab}	±0.1	27.9^{ab}	±2.1	1.2^{bc}	±0.3	-29.5^{abc}	±0.2
High	9.1^{b}	±1.1	0.11^{b}	±0.04	108^{a}	±21.1	6.6^{ab}	±0.2	0.1^{c}	±0.01	6.3^{b}	±1.3	5.7^{b}	±0.5	26.2^{ab}	±1.5	1.4^{bc}	±0.2	-29.4^{bc}	±0.1
c).	**Loamy soils - Karri (*Eucalyptus diversicolor*)**																	
5–10 cm	**Carbon [wt %]**		**Nitrogen [wt %]**		**C/N**		**pH**		**$NO3^-$-N [µg/g soil]**		**NH4+-N [µg/g soil]**		**OH Pi [µg/g soil]**		**OH Pt [µg/g soil]**		**$\delta^{15}N$ ‰**		**$\delta^{13}C$ ‰**	
Unburnt	6.6	±0.5	0.16	±0.02	56^{a}	±12	6.6^{b}	±0.2	1.2^{ab}	±0.4	10.3^{a}	±1.3	3.6	±0.8	21.2	±1.1	3.7^{ab}	±0.3	-28.9^{ab}	±0.2
Low	5.8	±0.5	0.15	±0.02	44^{a}	±5.2	7.1^{a}	±0.2	1.1^{ab}	±0.3	7.1^{ab}	±1.1	3.5	±1	22.7	±2.2	4.2^{a}	±0.4	-28.6^{a}	±0.1
High	5.6	±0.4	0.15	±0.02	42^{a}	±4.8	6.9^{a}	±0.1	1.6^{a}	±0.3	7.1^{ab}	±1.3	2.6	±0.7	19.9	±1.9	3.9^{ab}	±0.2	-28.7^{a}	±0.1
d).	**Sandy soils - Jarrah (*Eucalyptus marginata*)**																	
Unburnt	5.5	±1.7	0.11	±0.03	109^{b}	±33.0	6.1^{b}	±0.2	0.2^{b}	±0.01	10.1^{a}	±0.6	*		*		2.7^{b}	±0.3	-29.5^{b}	±0.2
Low	5.3	±1.0	0.12	±0.03	126^{b}	±51.4	6.2^{b}	±0.2	0.1^{b}	±0.02	4.4^{b}	±0.9	*		*		3.4^{ab}	±0.4	-28.8^{a}	±0.2
High	5.1	±0.7	0.09	±0.03	93^{ab}	±19.2	6.3^{b}	±0.1	0.1^{b}	±0.01	3.9^{b}	±0.5	*		*		3.1^{ab}	±0.4	-28.9^{ab}	±0.2

soil depth, the only significant difference observed was for ammonium. The results for ammonium obtained at 0–5 cm were replicated at 5–10 cm with two times more ammonium in unburnt samples than in burnt samples of sandy soils ($p<0.05$) (Table 1d).

3.2 Isotopic signature of carbon and nitrogen as fire legacy indicators in forest soils

Fire legacy effects were more evident for soil $\delta^{13}C$ signatures compared to $\delta^{15}N$ signatures at 0–5 cm depth (Table 1a-b). In loamy soils, the carbon isotopic signature ($\delta^{13}C$) also showed enrichment in sites burnt at high severity compared with unburnt sites ($p<0.01$). Differences in C isotopic composition were also observed in sandy soils, where unburnt sites were more depleted compared with sites burnt at high severity ($p<0.05$) (Table 1a-b). For loamy soils, low and high severity sites were enriched in $\delta^{15}N$ compared to unburnt sites ($p<0.05$) (Table 1a). However, there was no significant difference in $\delta^{15}N$ signatures between unburnt and burnt sites of sandy soils (Table 1b). For samples taken at 5–10 cm depth, only sandy soils showed a significant enrichment of $\delta^{13}C$ in sites burnt at low severity compared with unburnt sites (Table 1d).

A significant negative correlation between $\delta^{13}C$ and the percentage of C was observed across all loamy soil sites ($r=-0.66$; $p<0.001$), but not for sandy soil sites (Fig. 3a). The $\delta^{15}N$ signature was significantly and negatively correlated with concentration of N for loamy soils sites ($r=-0.57$; $p<0.001$), but not sandy soils sites (Fig. 3b).

3.3 Differences in soil texture influences concentration of C and N

The percentage of clay was significantly higher in unburnt sites of loamy soils than all other sites ($p<0.05$). Percentage of silt was higher in burnt and unburnt sites of loamy soils compared with sites of sandy soils burnt at high severity ($p<0.05$). Percentage of sand was lower in unburnt and low severity sites of loamy soils compared with burnt sites of sandy soils ($p<0.05$) (Table 2). Two-way ANOVA revealed significant effects of soil type ($p<0.001$), fire severity ($p<0.01$) and their interactions ($p<0.05$) on the percentage of clay. For silt and sand, only the effect of soil type ($p<0.001$) was significant - the sand fraction is where soil type explained most of the variance (Table 2).

Clay content of soils was positively correlated with the concentration of both carbon and nitrogen in loamy soil sites ($r=0.7$, $p<0.001$ and $r=0.66$, $p<0.001$, respectively), but not in sandy soil sites ($r=0.13$; $r=0.27$; $p>0.05$, respectively; Fig. 4a and b).

3.4 Ordination of soil properties

An NMDS ordination was used to represent dissimilarities between fire severities in loamy soils (Fig. 5a) and sandy soils (Fig. 5b). Loamy soil sites clearly grouped according to fire severities, which were mainly distinguished by differences in $\delta^{15}N$, N, C and NO_3. By contrast, soil properties of sandy soils did not clearly differentiate between fire severities. More details for the NMDS outputs are given in supplementary material (Table S2 and S3). Figure 5c clearly shows two clusters according to soil-forest type, the differences between soil types were driven mostly by TC, TN, $\delta^{15}N$, NH_4 and C/N. More details for the NMDS outputs are given in Table S4.

4 Discussion

Fire legacy effects on soils, i.e. the persistence of a "fingerprint" of wildfire, are variable among forest types, likely reflecting the underlying soil types on which these forests grow and interactions with fire severity. However, the legacy was more evident between unburnt and burnt samples than between fire severity categories. Here, we found that the impacts of the Northcliffe wildfire were evident in the physical and chemical properties of loamy soils five years after fire, with burnt sites containing only half of the total C and N, a lower clay content and higher pH compared to unburnt sites. However, the legacy of fire is more variable/less evident in sandy soils; we found that inorganic fractions of N and pH were the only soil properties affected by fire in this soil type. All these differences were recorded at 0–5 cm soil depth. At 5–10 cm only pH, $\delta^{13}C$ and inorganic forms of N in sandy soils recorded differences. These findings are discussed in more detail below.

4.1 Loamy soils exhibit stronger fire legacy on carbon, nitrogen, but not on other soil properties

In loamy soils, carbon and nitrogen concentration of surface soils (0–5 cm) were approximately 1.5 times higher in unburnt sites compared to burnt sites (low and high severity), indicating that fire resulted in losses of C and N that are still evident five years later. Losses of carbon and nitrogen in the short term after fire are mainly due to volatilisation, erosion, leaching, and denitrification (Carrà et al. 2022; Ojima et al. 1994; Raison et al. 2009). However, in the long term, reduced C and N concentration after fire have been attributed to the lack of inputs and decomposition process that are sustained by litter fall such as leaf, wood, and other debris that falls to the forest floor (Pellegrini and Jackson 2020). Long term effects of forest fires on soil C and N are

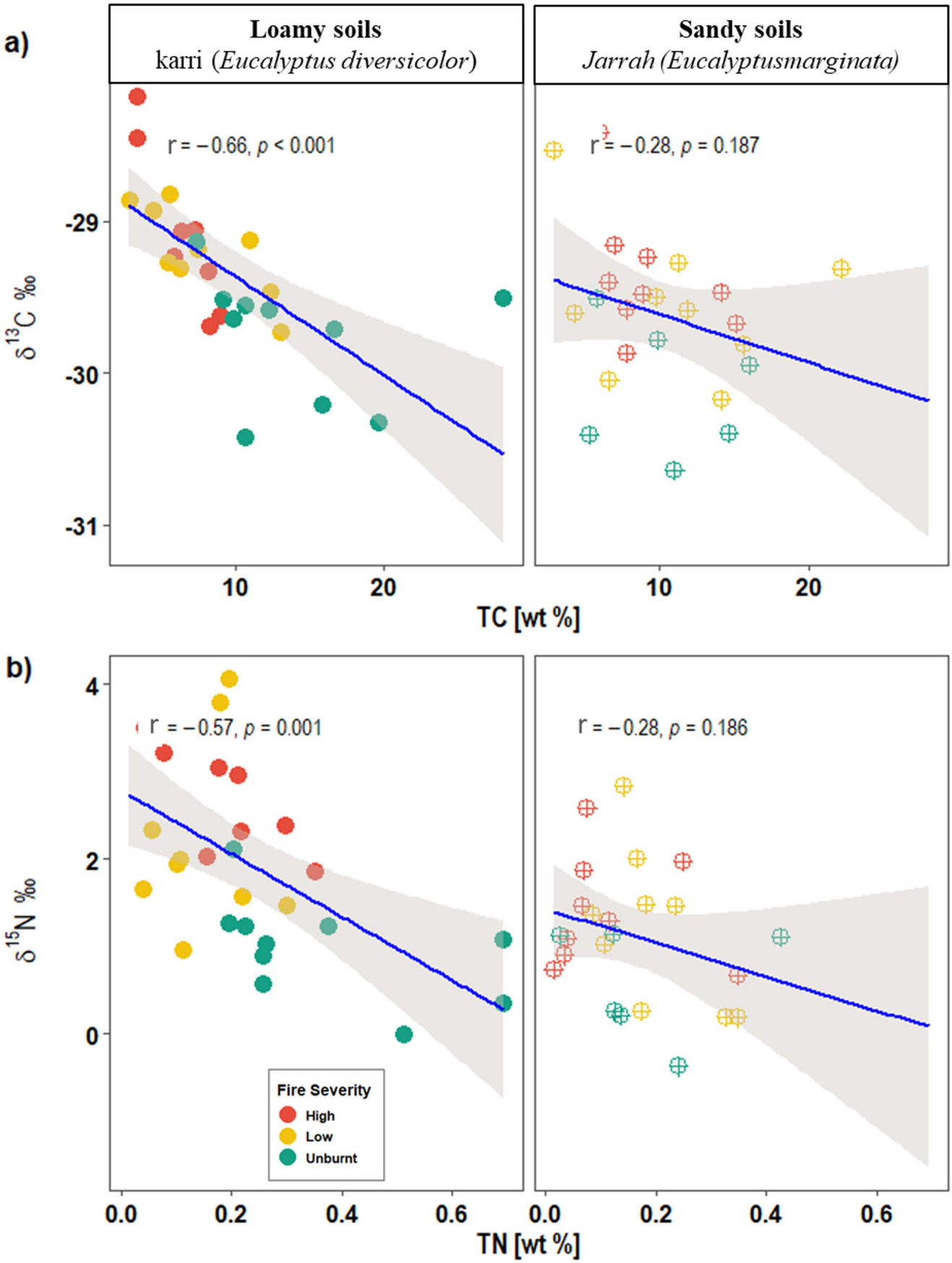

a)
Loamy soils
karri (Eucalyptus diversicolor)
Sandy soils
Jarrah (Eucalyptusmarginata)
r = −0.66, p < 0.001
r = −0.28, p = 0.187
δ13C ‰
-29
-30
-31
10
20
TC [wt %]
b)
r = −0.57, p = 0.001
r = −0.28, p = 0.186
δ15N ‰
4
2
0
Fire Severity
High
Low
Unburnt
0.0
0.2
0.4
0.6
TN [wt %]

Fig. 3 Relationships (Pearson correlation, r) between (**a**) Carbon (wt %) versus and $\delta^{13}C$ (‰) and (**b**) Nitrogen (wt %) versus and $\delta^{15}N$ (‰) and their Pearson coefficient correlation (r). Samples collected at 0–5 cm, five years after fire. Each point represents one sampling site from two forest types; karri forest (filled circles) and jarrah forest (empty circles)

not unusual and have been described for different ecosystems and under different fire severities (Dove et al. 2020; Rovira et al. 2012). For example, 18 years after fire in Mediterranean forests of Spain, soil C content had not recovered to pre-burn levels, which was associated with insufficient organic matter inputs from vegetation, which had not fully recovered either (Francos et al. 2018). In our study site, only high severity sites of loamy soils (karri forest), were subject to crown loss, while low severity sites had significant reductions in understorey cover (Etchells et al. 2020). Both processes would result in reduced litter inputs, possibly higher soil temperatures, increased vulnerability to soil leaching that together would result in less carbon returned to the soil. In addition, the lower levels of N in burnt soils could be due to the uptake by recovering understorey plant species and the regeneration of the fast-growing overstorey dominant species such as *Acacia pentadenia* and *Trymalium odoritissimum*, which have seen to dominate karri forest after fire (Etchells et al. 2020; O'Connell 1988; Robinson and Bougher 2003).

The difference in the response of C and N in sandy soils (jarrah forest) compared to loamy soils (karri forest) could reflect differences shifts in plant community composition, annual litterfall inputs and/or nutrient concentrations between forest types. First, it has been seen that differences in species composition were still evident between unburnt and burnt sites of karri forest (loamy soils) two years after fire, with a higher species richness found in burnt sites of karri forest (Etchells et al. 2020). On the other hand, it has been observed that jarrah forest (sandy soils) species have a rapid re-establishment because the majority of these species are able to regenerate from either epicormic buds or basal sprouts or both, and no differences in species richness have been seen in the short term (Bell et al. 1989). Therefore, it can be inferred that even five years after the fire, the differences in plant community composition between unburnt and burnt sites of the karri forest (loamy soils) are still likely to be significant. In contrast, it is probable that there were no significant differences in plant composition between unburnt and burnt sites of jarrah forest (sandy soils). This similarity in plant composition likely contributes to the stabilisation of soil carbon and nutrients within the forest soil. Second, it is worth noting that litterfall in karri forest is 3–4 times greater than in jarrah forest (O'Connell and Menage 1982). Moreover, the nutrient concentrations in the jarrah leaf litter are lower when compared to those in the karri leaf litter. For instance, it has been found that jarrah forest litters have five-fold less nitrogen (N), three-fold less phosphorus (P) and potassium (K) compared to the karri forest (O'Connell and Grove 1996; O'Connell et al. 1978). These differences in litter inputs and nutrients concentration could explain why C and N in unburnt reference soils of karri forest were twice compared to unburnt jarrah forest but could also be driving differences in fire legacy between soil properties of both forest types.

Our results show that C/N contributed to differences between both soil types (Fig. 5c). Generally, a reduction in C/N immediately after fire is due to higher proportions of carbon lost relative to nitrogen but also due to the formation and accumulation of new forms of recalcitrant nitrogen (Aaltonen et al. 2019; Rodríguez et al. 2017). However, despite recording differences in the levels of C and N in loamy soils, there were no statistical differences in C/N ratios between unburnt and burnt sites of both soil types. Nevertheless, sandy soils sites burnt at high severity had a higher C/N ratio compared to sites of loamy soils. The higher C/N ratio registered by sandy soils is typical of poor soils and reflects N limited conditions, whereas ratios of loamy soils indicates a more rich nutrient soil (Zhang et al. 2020).

Regarding inorganic nitrogen, specific observations in eucalypt forests have indicated a relatively fast recovery time, compared with other ecosystems (Wang et al. 2012). In eucalypt ecosystems, ammonium levels typically return to pre-fire levels in less than five months, while nitrate levels recover within approximately 18 months (Attiwill 1994; Attiwill and Adams 1993). Hence, our initial expectation was that there would be no significant differences in the inorganic forms of N five years after fire, between the fire severity classes. However, it was unexpected to discover a higher concentration of inorganic N fractions in the unburnt sites of sandy soils compared to the burnt sites. While this finding has been described less frequently in the literature, it is not entirely uncommon, and it can be possibly explained by the reduction in the quality of soil organic matter inputs that likely lead to the decrease in mineralisation rates in the burnt sites of sandy soils (jarrah forest). Our results agree with those found by Durán et al. (2009) who reported a lower amount of nitrate and ammonium in burnt soils of pine compared to unburnt soils, after more than ten years of fire in Canary island, Spain. They attributed this to reduced canopy recovery and poorer litter quality, which slowed mineralisation. In contrast, loamy soils in our study showed no change in inorganic nitrogen, likely due to higher-quality organic inputs and lower C/N ratios in burnt sites, which may have promoted mineralisation compared to sandy soils.

A fire legacy was also evident in the higher pH of burnt sites compared to unburnt sites of loamy and sandy soils. This increase in pH after fire has been well documented

Table 2 Mean values with standard error in parentheses for particle size distribution of topsoil profile (0–5 cm) by soil type and fire severity. Values are means +/- standard errors and F ratios from ANOVA outputs of these parameters and their interaction. Within rows, means followed by different superscript letters indicate that mean parameter values are significantly different ($p<0.05$). $n=9$ for each group, except for unburnt sandy soil, where $n=6$

Soil Type	loamy soils karri (Eucalyptus diversicolor)						sandy soils jarrah (Eucalyptus marginata)						Two-way ANOVA		
Fire Severity	Unburnt		Low		High		Unburnt		Low		High		Soil Type	Severity	S. Type *Severity
Classification	Loam		Loam		Loam		Sandy loam		Sandy loam		Sandy loam				
% clay	16.2^{a}	±1.7	12.8^{b}	±0.8	11.7^{b}	±0.4	10.5^{b}	±0.8	11.8^{b}	±1.2	9.3^{b}	±0.8	16.1***	7.5**	5.7*
% silt	12.0^{ab}	±1.6	12.5^{ab}	±2.7	10.8^{ab}	±1.8	8.1^{bc}	±0.9	7.9^{bc}	±1.2	5.5^{c}	±0.6	14.1***	1.0	0.7
% sand	71.3^{c}	±2.3	75.8^{bc}	±3.0	77.6^{abc}	±3.1	81.4^{ab}	±2.2	80.2^{a}	±2.1	85.2^{a}	±1.5	18.3***	3.1	0.9

and is a response to the inputs of base cations (K^+, Ca^{2+}, and Mg^{2+}) by burnt vegetation, wood charcoal and ashes. Generally, an increase in pH after wildfires has been considered short-lived (< 1 year) (Granged et al. 2011; Rodríguez et al. 2017). However, our findings are consistent with a few other studies. For instance, Longo et al. (2011) found that six years after a fire of a *Nothofagus* forest in Argentina, burnt soil sites still had a higher pH compared with unburnt sites. Úbeda et al. (2005) also found that seven years after fire in Mediterranean forest of Spain, soils burnt at low and high fire severity had a higher pH compared with unburnt soil sites. The persistence of higher pH several years post-fire has been attributable to the amount of ash released, original soil pH, chemical composition of the ash, and wetness of the climate (Alcañiz et al. 2016). In the sandy soils of jarrah forest, and to a lesser extent loamy soils of karri forest, soil pH is acidic and thus has a low buffering capacity and may experience more pronounced and longer-lasting shifts in pH following a fire (Certini 2005).

Finally, phosphorus did not record differences for either forest type. In the case of total P, this may be because volatilisation temperatures for P are considerably higher than those ones for C and N, therefore loss of P during fires is rare (Certini 2005). However, an increase in the inorganic form of P after thermal conversion of organic P has been widely described. These increases are generally short-lived as inorganic P is rapidly taken up by plants after fire (Cade-Menun et al. 2000; Chen and Shrestha 2012; Turrion et al. 2010). This is particularly the case in Australian soils where P deficiency is a major factor limiting growth of eucalyptus species (Bougher et al. 1990). Thus, our results are consistent with the literature, showing no fire legacy effects in any forms of P for either loamy (karri forest) or sandy soils (jarrah forest).

4.2 Soil isotopic composition as a sensitive indicator of fire severity legacy

As we hypothesised, burnt sites showed enrichment of $\delta^{15}N$ and $\delta^{13}C$. We attribute this enrichment to volatilisation of the lighter isotopes. This can be supported by the inverse correlation found between $\delta^{15}N$ versus total N and $\delta^{13}C$ versus total C, where the more severe the fire, the greater the losses of C and N (Fig. 3). However, Different mechanisms may have contributed to shift the isotopic signature in burnt sites of both eucalypt forests. High-severity fires can completely consume the upper litter layer or scorch the canopy, resulting in reduced litter input to forest soils post-fire (Collins 2020; Hammill and Bradstock 2006). As a result, the isotopic signature of surface soils is less influenced by litter, leading to carbon and nitrogen isotopic enrichment in soils

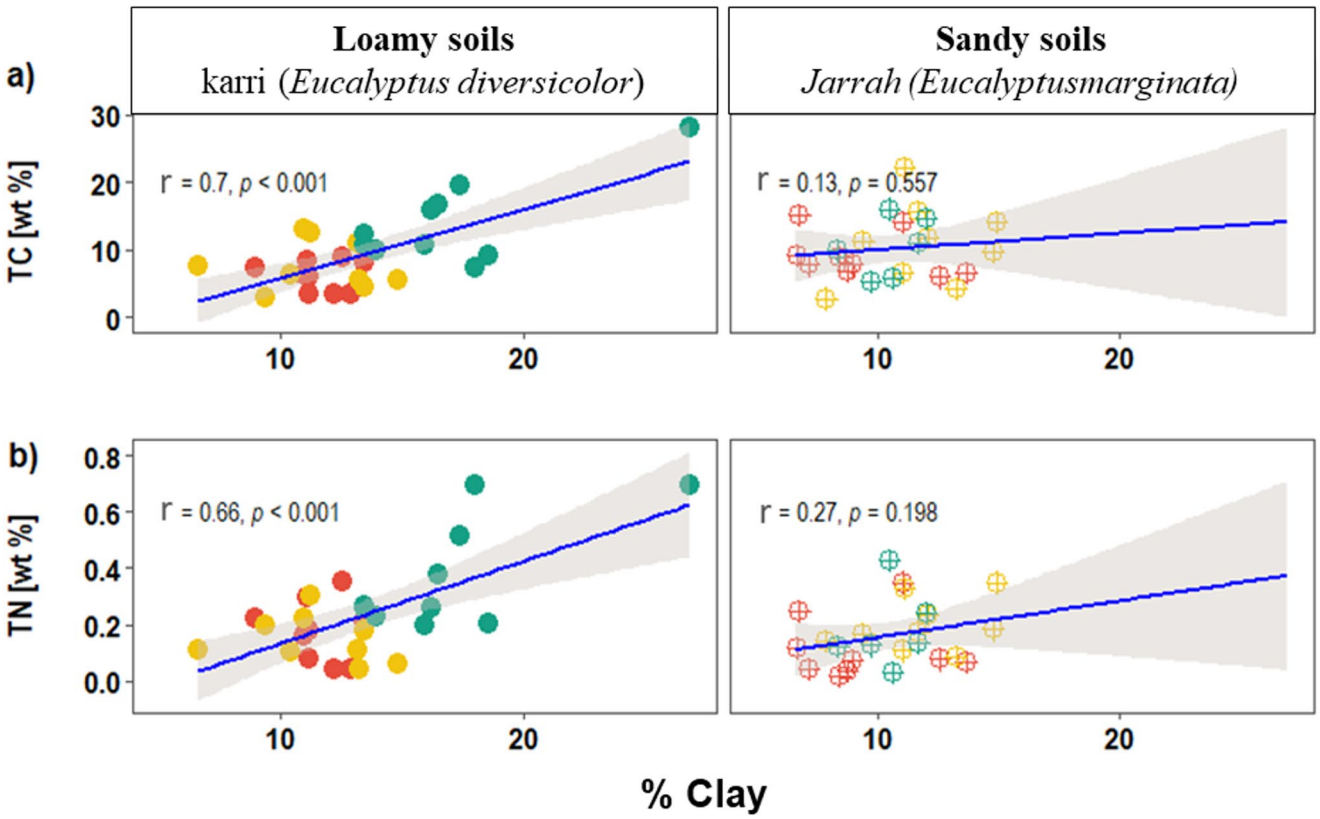


Fig. 4 Relationships (Pearson correlation, r) between percentage of clay and (**a**) Carbon (wt %) and (**b**). Nitrogen (wt%). Samples collected at 0–5 cm, five years after fire. Each point represents one sampling site from unburnt (green), low (yellow) and high (red) severity sites, from two soil-forest types: loamy soil-karri forest (filled circles) and sandy soil-jarrah forest (empty circles)

due to the absence of fresh litter input and the volatilisation of lighter isotopes during the fire.

Low $\delta^{15}N$ values in soils are often cited as evidence for N_2 fixation (Hobbie et al. 2000; Robinson 2001). The more depleted $\delta^{15}N$ signature of burnt sites of sandy soils (jarrah forest) compared to burnt sites of loamy soils (karri forest) could be explained due to large abundance in the understorey of the legume creeper *Kennedia coccinea* (personal observations), which could have partially depleted burnt soils incorporating $\delta^{15}N$ signatures close to zero, during the fixation.

4.3 Fire severity legacy implications for soil texture, C and N retention

Our results show that karri and jarrah forest soils differ in the percentage of clay, silt and sand, confirming that both forest types have different soil texture classes. However, fire severity and its interaction with forest type also showed significant effects on the percentage of clay, where unburnt sites of loamy soils (karri forest) showed a higher percentage of clay compared to the rest of the sites (Table 2). This pattern may be explained by fire intensity, which can modify soil texture, by aggregating clay particles into stable sand-sized particles, making the soil texture more coarse and erodible (Granged et al. 2011). Clay is the most sensitive fraction to fire, starting to change at 400° C when clay hydration and clay lattice structure begin to collapse (Neary et al. 2005). On the other hand, as sand and silt are primarily quartz particles, they have a higher melting point with temperatures over 1000° C (Neary et al. 2005). For instance, Kara and Bolat (2009) measured soil texture in a plantation of black pine in Turkey, two months after fire and found a significant decrease of 10% in the amount of clay in burnt soils compared to unburnt soils. Similar results were obtained by Ulery and Graham (1993) who found a significant decrease in clay content in conifer forests of California that had burnt between 22 days and three years prior to sampling. Reductions in the percentage of clay after fire have also been observed in non-forested ecosystems. For example, maize-rice systems in Thailand that are burnt by low severity fires after harvesting showed a reduction of 5% in clay content after fire (Arunrat et al. 2021). However, other studies have also reported a significant increase in the silt and sand fractions after laboratory heating of soils (Ketterings et al. 2000; Terefe et al. 2008). Additionally, it is important to consider other factors that can contribute to changes in soil texture following a fire, like the selective removal of the fine

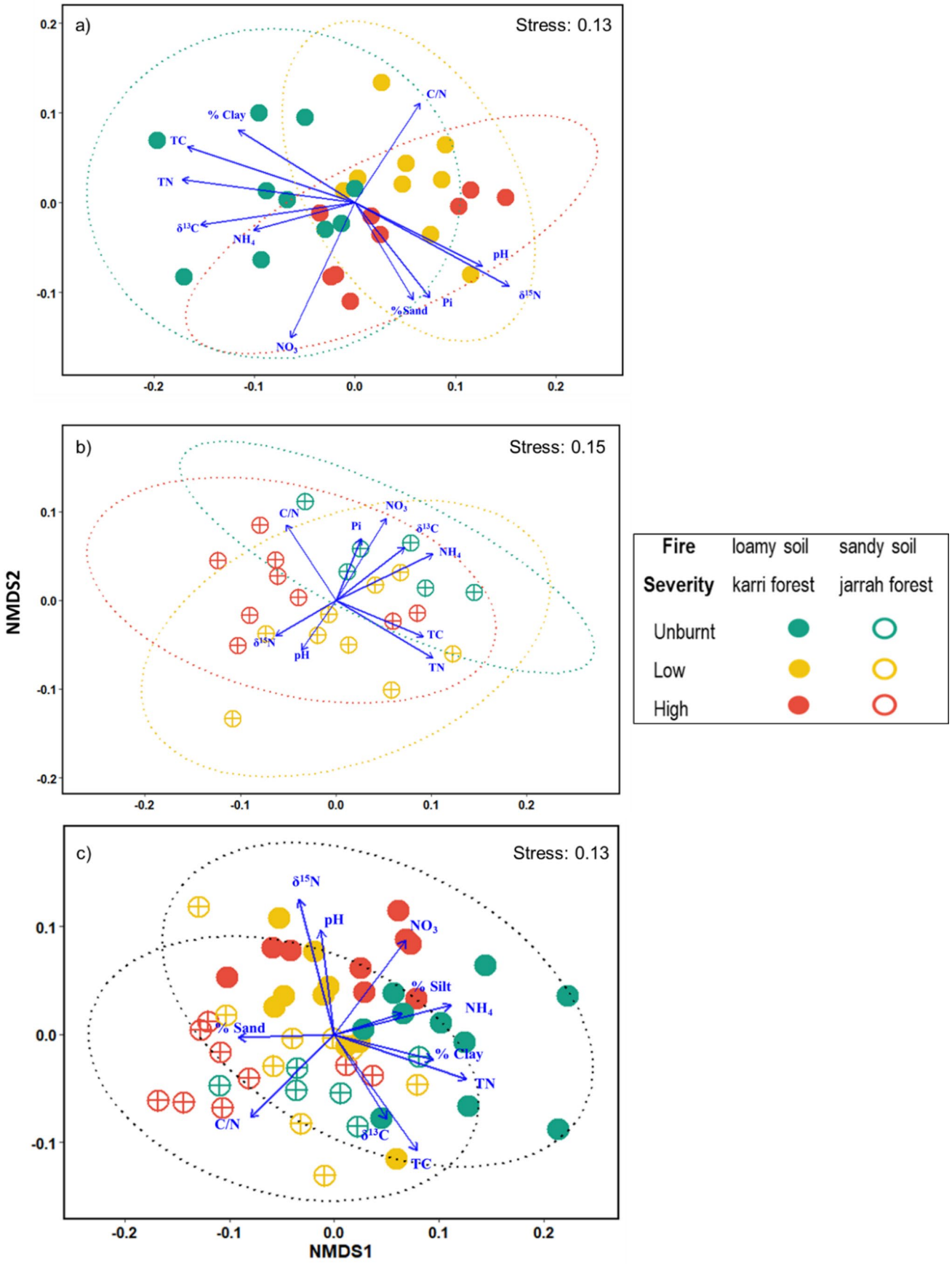

a)
Stress: 0.13
C/N
% Clay
TC
TN
δ13C
NH4
pH
δ15N
Pi
%Sand
NO3
b)
Stress: 0.15
C/N
NO3
Pi
δ13C
NH4
δ15N
pH
TC
TN
c)
Stress: 0.13
δ15N
pH
NO3
% Silt
NH4
% Sand
% Clay
TN
C/N
δ13C
TC
NMDS1
NMDS2
Fire
loamy soil
sandy soil
Severity
karri forest
jarrah forest
Unburnt
Low
High

Fig. 5 Non-metric dimensional scaling (NMDS) plot of soil properties (0–5 cm) from samples of unburnt forest (green), low severity burnt (yellow) and high severity burnt (red) for a). loamy soils-karri forest, b). sandy soils-jarrah forest and c). between loamy and sandy soils. Ellipses show 95% confidence intervals in multivariate space around group centroids. Vectors of each soil property represent the direction and strength of the gradients, only significant ($p < 0.05$) soil properties, were included in the figure

fraction of soil through erosion, this process, can also result in a shift towards a coarser soil texture (Certini 2005). However, it should be noted that in some cases, no significant differences in clay content have been observed, as reported in a study conducted after three years of fire on Andosols of pine forests in the SE region of the Iberian Peninsula (Moya et al. 2019).

Our results are in line with previous studies and strongly indicate a decrease in the fine fraction of loamy soils after fire. This pattern was not evident in sandy soils, although we can assume that given the higher percentage of sand in the jarrah forest soils, its texture was not greatly affected by fire. However, we suggest that with increasing time since fire, the clay fraction in burnt sites of loamy soils may increase, as has been reported elsewhere. For example, agricultural soils show an increase the coarse fraction of soils after burning, but recovery of the fine fraction to pre-fire levels during subsequent fallow periods (~7years; (Arunrat et al. 2022). The recovery of the clay fraction and C and nutrient content in fire-affected soils can be attributed to soil aggregation and the presence of organic matter. Longer fallow periods and increased vegetation coverage during secondary succession promote the formation of soil aggregates, improving soil structure (Laskar et al. 2021).

The amount of C and N were positively correlated with percentage of clay in loamy soils but not in sandy soils. This result is expected, given that a higher clay content typically reduces nutrient leaching by stabilising/protecting a greater proportion of soil organic matter in soils leading to higher retention of soil nutrients (Doetterl et al. 2015; Tahir and Marschner 2017). Thus, the higher amount of soils C and N found in the unburnt loamy soils can be lasting on the surface until degradation, sustained by the dense fine nature of the clay present in its soil (English et al. 2005). In contrast, the return to pre-fire levels by the burnt stands of loamy soils was likely hindered, primarily, as was explained in **Sect. 4.1**, due to total or partial surface litter consumption or crown scorch, plus a reduction in clay content by fire. Also fire could have reduced particles of C to a size that allowed them to readily enter the soil promoting its infiltration (Bird et al. 2000). Therefore, our results suggest that fire legacy in loamy soils may be more long lasting compared to sandy soils, due to soil texture and litterfall inputs acting together to shape the response of soils according to fire severity.

5 Conclusion

Karri (loamy soils) and jarrah (sandy soils) forests historically have experienced frequent fires of low to moderate severity, but increasing occurrence and frequency of high severity fires may interact with the soil ecosystem by altering forest composition and destabilising soil C and nutrient stocks. We found that soil C and N contents in loamy soils, in particular, were only half of those of unburnt sites, five years after fire. These results highlight that monitoring fire legacy of "sensitive" soil nutrients ecosystems such as karri forest is extremely important, particularly as forest fires are likely to have a key role in shifting the Western Australia forest soil carbon and nutrients balance under the future climate change scenarios.

In summary, the results shown in this study reinforce the idea that recovery trajectories of soils often vary in response to the complex relation of variables such as soil characteristics, fire severity, plant communities, among other variables.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11368-025-04136-1.

Acknowledgements We would like to thank Kate Bowler for her fieldwork and laboratory assistance, Hanna Etchells for her logistical support and for kindly sharing details of the Northcliffe fire, and finally, we acknowledge the Noongar people, the traditional custodians of the land where this study took place.

Authors contribution Andrea V. Bravo-Escobar: Conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, visualization, writing – original draft, writing–review and editing. Alison J. O'Donnell: Formal analysis, investigation, methodology, writing – review and editing. Pauline F. Grierson: Conceptualization, investigation, methodology, visualization, writing – original draft, writing – review and editing.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. The Chilean Scientific Council (ANID) through the doctoral scholarship Becas-Chile supported Andrea Bravo-Escobar.

Declarations

Competing interests The authors 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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