fire

Article

Quantitative Assessment of the Effect of Agency-Led Prescribed Burns and Cultural Burns on Soil Properties in Southeastern Australia

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Abstract: Fire management techniques play a critical role in mitigating the impact of bushfires on communities and ecosystems. In Australia, government agencies implement hazard reduction burn programs, while Indigenous communities have used fire for ecosystem management for thousands of years. The positive effect of prescribed burning goes beyond bushfire risk mitigation, with impacts also on soil and ecosystem health. This study evaluates the effects of prescribed burning on soil properties, with implications for soil and ecosystem health. Two fire management techniques were evaluated: agency-led prescribed burning and cultural burning. Both fire treatments resulted in an increase in soil moisture, showing that they positively affect the soil water balance (the greater effect seen following the agency-led burn). Both fire treatments also resulted in a decrease in soil bulk density and an increase in organic matter content, with the greater effect seen for soils affected by the Indigenous-led burn. These results show that both fire management techniques positively affect soil health, with important consequences for aboveground ecosystem health. Cultural burning is the most efficient to promote reduced soil bulk density (important for nutrient availability and microbial activity) and increase carbon and nitrogen stores.

Keywords: cultural burning; soil properties; prescribed burning

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1. Introduction

Bushfires have long been recognized as major drivers of ecosystem dynamics in fire-prone regions worldwide, including southeastern Australia [1]. In response to the risks posed by bushfires, fire management techniques have emerged as important strategies to mitigate their impacts on both communities and ecosystems. Government agencies have implemented techniques such as prescribed burning to reduce fire risks. Indigenous communities in Australia have also employed fire as a traditional ecosystem management technique for thousands of years [2]. While many of Australia's ecosystems benefit from the reoccurrence of fire, under certain conditions soil health can be significantly impacted. The term "soil health" refers to the various physical, chemical, and biological properties that contribute to the continued functionality of the surrounding environment [3]. Although fire generally constitutes a disturbance to these properties, the extent of the influence highly depends on fire severity and the soil's pre-existing characteristics [4]. While changes in soil properties have been documented for prescribed burns and wildfires across differing temporal and spatial scales [5,6], previous studies have focused on northern hemisphere ecosystems, with a few exceptions [7–10]. Furthermore, little is known in Western scientific literature about the effect of cultural burns. As soil functionality is the primary agent responsible for supporting aboveground biota, there is a need to quantitatively understand the effects of fire management techniques on soil properties.

This study investigates and compares the soil properties of three different plot groups in a coastal ecosystem in southeastern Australia: (i) plots that have recently undergone a cultural burn, (ii) plots that have recently undergone a prescribed burn, and (iii) plots that have not experienced any recent burns. To quantitatively assess the impacts of these fire management techniques on soil properties, various parameters were measured at each plot, including soil water content; bulk density; water repellency; soil texture; color; carbon, nitrogen, and total organic matter contents; pH; and carbon dioxide fluxes. By comparing these measurements across the different plot groups, we can begin to understand how different fire management techniques influence soil properties.

2. Material and Methods

2.1. Study Area

The study area is located in Murramarang Country, Narrawallee, on the Mid South Coast of New South Wales (NSW), Australia. It encompasses a diverse landscape, including suburban infrastructure, agricultural farmland, and a nature reserve. The site is of ecological and cultural significance, with the presence of endangered ecological communities and Aboriginal artifacts dating back thousands of years. The study site, managed by the Ulladulla Local Aboriginal Land Council (ULALC), covers 12 hectares and borders Narrawallee Creek (Figure 1). It predominantly features a vegetation cover with minimal access tracks and a relatively flat terrain without distinct gradients. The study area is classified as a dry sclerophyll forest, characterized by eucalypt forest, sclerophyll shrubs, grasses, and ferns. Dominant tree species here include Old Man Banksia, Coast Banksia, Bangalay, and Blackbutt. The site also exhibits a mix of shrubs, groundcovers, and climbers, both endemic and non-endemic species. The area experiences a peak fire season in summer, and hazard reduction burns are conducted to mitigate fire risks. The site holds a rich history, with evidence of Aboriginal utilization spanning over 20,000 years. British invasion led to extensive clearing for grazing and logging of hardwood trees, predominantly Turpentine (*Syncarpia glomulifera*), Blackbutt (*Eucalyptus pilularis*) and Red Bloodwood (*Corymbia gummifera*). The area is actively managed by the ULALC to protect its ecological and cultural values. Control sites were selected to serve as reference points for comparison. These areas were left unburnt and represented the natural state of the landscape. They exhibited a diverse range of vegetation, including eucalypt forests, shrubs, and groundcovers, providing a valuable habitat for various plant and animal species. Indigenous-led burn sites were another noteworthy feature of the study area. These sites were carefully managed by the ULALC in accordance with traditional Indigenous practices. The controlled burns carried out by Indigenous custodians aimed to promote ecological health, encourage plant regeneration, and maintain cultural connections to the land. The burn patterns and intensity varied, resulting in a mosaic of burnt and unburnt patches across the landscape. The agency-led burn sites were managed by government agencies responsible for land and fire management. These burns were conducted with the objective of reducing fuel loads and mitigating the risk of severe wildfires. The agency-led burns typically followed a more systematic approach, with larger areas targeted for controlled burns. This approach aimed to create buffer zones and protect surrounding communities from potential fire hazards.

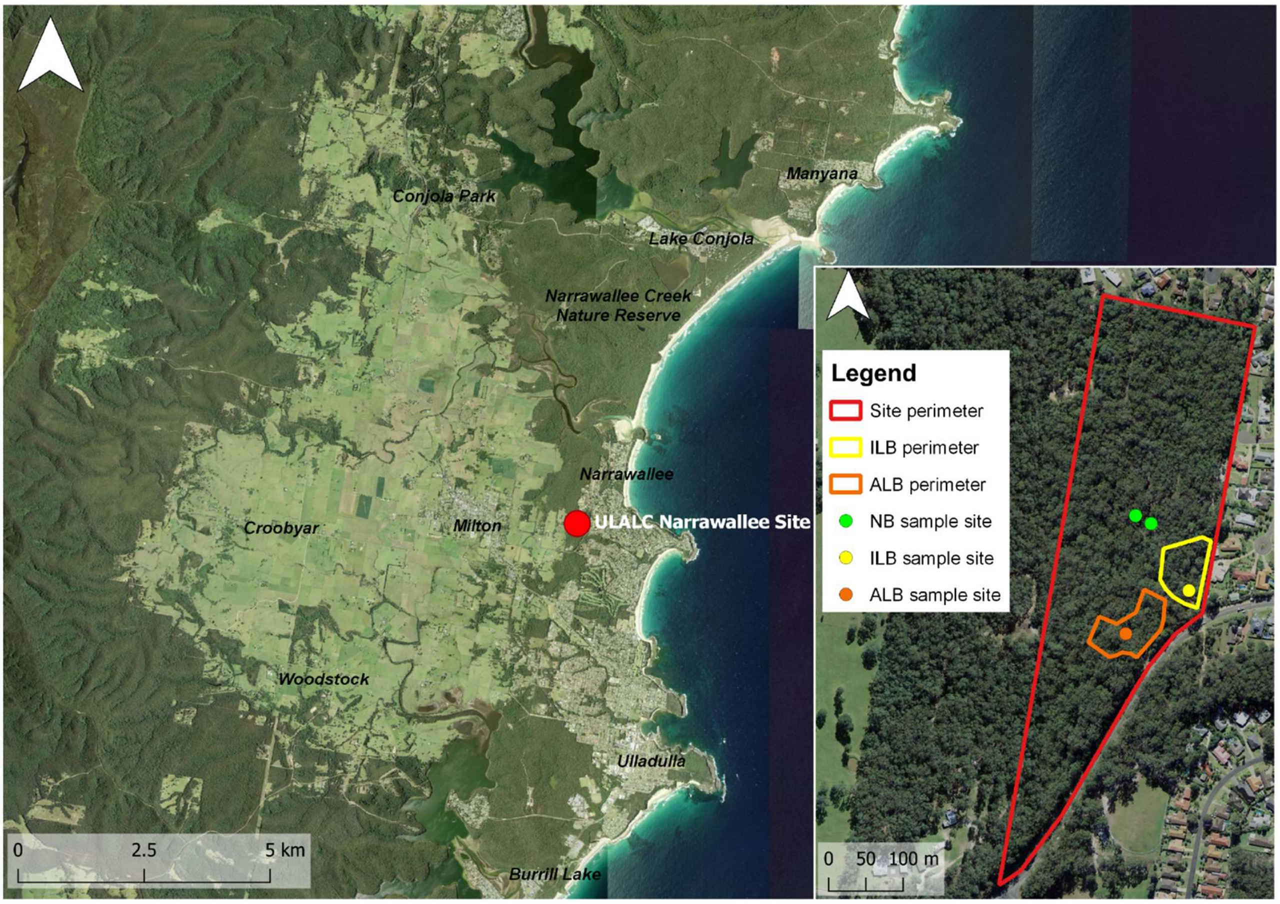


Figure 1. Map of the study area located on the southeast coast of NSW. The inset map shows the perimeter of ULALC's Narrawallee site (35.321560° S, 150.462690° E; WGS84) with locations of burn history and sample sites. NB: no burn/control, ILB: Indigenous-led burn, and ALB: agency-led burn (see text for details) (satellite imagery: Google Earth Pro).

2.2. Experimental Design and Soil Sampling

Field work was conducted between July and August 2022, within the boundary of ULALC's Narrawallee site. Three locations were selected for sampling based on previous burn activity (Supplementary Figure S1). Site one was split across two locations in proximity, providing a control with no recent burn history, which is referred to as NB ("No Burn"). Site two had undergone an Indigenous-led burn (ILB) conducted by ULALC in May 2021. Site three had undergone an agency-led burn (ALB) in September 2020, managed by the NSW Rural Fire Service (RFS), to simulate a cool burn. Five 5 × 5 m quadrats were established at each site, resulting in a total of 20 quadrats. For soil CO_2 efflux measurements, 3 × 80 mm length soil collars constructed from 225 mm diameter PVC were inserted ~30 mm into the soil surface in each quadrat at least one week prior to taking measurements, allowing for minimal disturbances to microbial activity. Five soil samples were collected per quadrat, by first removing the litter from the surface and then inserting a 60 mm diameter soil core ~50 mm into the soil surface.

2.3. Field Measurements

Soil profiles were manually excavated using a shovel to reveal the horizons of depths up to 15 cm (Supplementary Figure S2). Color was determined for the top 5 cm of the soil profile using a Munsell color chart, similar to the process defined by Malacara [11]. Soil electrical conductivity (EC) and temperature were measured on-site using a Direct Soil Electrical Conductivity and Temperature Tester. This method measures the EC of the dynamic soil matrix to incorporate the combined solid, liquid, and air, also known as bulk

EC. Measurements were taken in the field to avoid mechanic alteration of the samples during transport. This also allowed us to determine soil temperature at the time of CO_2 measurements. The instrument was calibrated in a 1413 μS/cm solution prior to each sampling campaign. Soil EC and temperature measurements were conducted by inserting the probe ~30 mm into the soil surface, in the vicinity of each soil CO_2 collar, at the time of the CO_2 efflux measurement.

Soil CO_2 efflux was measured using three low-cost Non-Dispersive Infrared (NDIR) sensors with a range of up to 2000 $\pm$ 40 ppm, with a sensitivity of $\pm$1 ppm. This gave a sensitivity to fluxes better than 0.05 mmol/m^2/s for a 20 min measurement. This technology uses an LED infrared source and offers a cost-effective alternative for closed-chamber environments measuring CO_2 close to the source of the output [12]. To measure the build-up of CO_2, the chambers were sealed to the fitted soil collars and closed to the surrounding environment. A small fan placed in the chamber ensured homogeneity of the CO_2 expelled from the soil surface. The portable sensors recorded humidity and CO_2 voltage every second. Each measurement was taken over a 30 min period, allowing time for the CO_2 to reach capacity and plateau. Measurements were taken from two minutes after the chamber was sealed to two minutes before the chamber was opened. CO_2 flux was calculated using the exponential method of Phillips [13].

2.4. Laboratory Analysis of Soil Physical and Chemical Properties

Moisture content and bulk density were determined for ~40 g of wet soil from the bulk core samples and after oven drying at 40 °C for three days. Moisture content was determined by weighing samples before and after drying, while bulk density was calculated using the dry sample mass and the core volume. Soil water repellency was determined by the water drop penetration time test [9,14]. Soil texture was measured by laser diffraction using a particle-size analyzer. Soil pH was measured on air-dried, <2 mm size fractions using an Orion 720A ion selective pH bench meter in a 1:5 *w*/*v* ratio of soil:water suspension, shaken at 15 rpm for 1 h followed by centrifugation [15]. Calibration in buffer solutions at pH 4.0, 7.0, and 10.0, respectively, was completed prior to each measurement session.

Organic matter content was determined for ~10 g of oven-dried soil placed in a muffle furnace for four hours at 550 °C, following the loss-on-ignition (LOI) method [16,17]. Total carbon (C) and nitrogen (N) concentrations were measured using a Vario MACRO cube organic elemental analyzer. ~40–60 mg of sample were weighed for analysis. Blanks and phenylalanine standards with known C and N concentrations were analyzed in each session.

2.5. Statistical Analysis

Statistical analysis was performed on soil properties to determine any significant differences between the mean values of each fire treatment (NB, ILB, ALB) and observed associations between properties. Parameters were tested for assumptions of normality and homogeneity of variance using the Shapiro–Wilk and Levene's tests ($p < 0.05$). Significant differences ($p < 0.05$) between means were determined using a one-way analysis of variance (ANOVA) (Ha: $\mu NB \neq \mu ILB \neq \mu ALB$; H0: $\mu NB = \mu ILB = \mu ALB$). Where the ANOVA null hypothesis (H_0) was rejected, a post hoc pairwise comparison was performed by way of Tukey's honestly significant difference (HSD) test for datasets with equal fire treatment sample sizes. A Tukey–Kramer test was performed for fire treatments with differing sample sizes. Variables were log transformed where normality was rejected to meet the assumptions for the ANOVA (presented data are non-transformed except where specified). Where the assumption of homogenous variances was not met, a non-parametric Welch's one-way ANOVA was conducted, which performs under the same null and alternative hypotheses as the standard ANOVA. If statistical significance was returned ($p < 0.05$), a post hoc Games–Howell test, based on Tukey's studentized range distribution, was used to compare fire treatments ($p < 0.05$). Pearson's correlations tested the relationships between selected properties and were considered significant if $p < 0.05$. All statistical analyses were performed using RStudio v. 2022.02 statistical software [18], using packages *RVaideMemoire*, *car*, and *rstatix*; figures were drafted using packages *ggplot2*, *scales*, *ggpmisc*, and *ggpubr*.

3. Results

Soil bulk density was significantly lower at the ILB sites, compared to those at the ALB and NB sites ($p < 0.01$ in both cases, Tukey–Kramer HSD Test; Figure 2A). Soil moisture was significantly different between each group ($p \leq 0.001$) and increased in the following order: NB < ILB < ALB soils (Figure 2B). All the soils were dominated by sand-sized particles (~60% of the soil particles) and the different groups (NB, ILB, and ALB) also showed similar sand and silt contents (Table 1). Conversely, the clay content decreased from NB to ILB to ALB soils, with a significant difference ($p < 0.001$) between each group (Figure 2C).

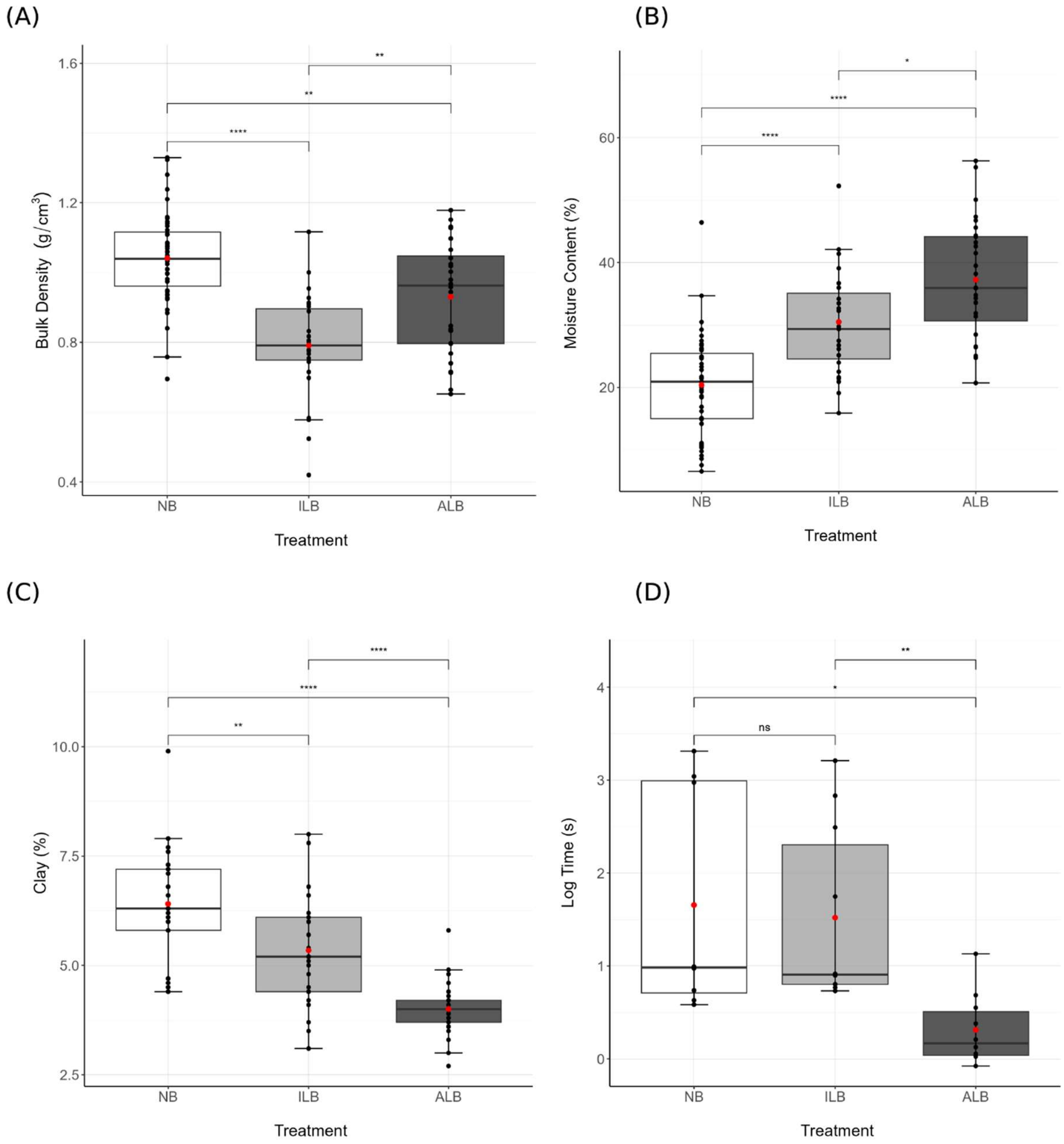


Figure 2. (**A**) Soil bulk density (g/cm^3), (**B**) moisture content (%), (**C**) clay-sized particle content (%), and (**D**) base 10 logarithm of water drop penetration time (s) for each fire treatment. NB = no burn; ILB = Indigenous-led burn; ALB = agency-led burn. Red circles represent mean values. Asterisks (*) indicate statistical significance: * $p < 0.05$, ** $p < 0.01$, **** $p < 0.001$. ns: not significant.

Table 1. Soil physical, chemical, and biological properties of control (NB), Indigenous-led burn (ILB), and Agency-led burn (ALB) soils.

	NB	ILB	ALB	Sample Size	F Value	*p*-Value
Moisture content (%)	20.4 ± 1.1 [a]	30.5 ± 1.7 [b]	37.3 ± 1.8 [c]	n = 100	34.895	3.39×10^{-12}
Bulk density ($g.cm^{-3}$)	1.04 ± 0.02 [c]	0.79 ± 0.03 [a]	0.93 ± 0.03 [b]	n = 100	26.214	7.308×10^{-10}
Sand (%)	62.3 ± 1.0 [a]	62.0 ± 1.0 [a]	63.5 ± 1.6 [a]	n = 73	0.5735	0.5661
Silt (%)	31.3 ± 0.8 [a]	32.7 ± 0.8 [a]	32.5 ± 1.1 [a]	n = 73	0.665	0.5174
Clay (%)	6.4 ± 0.3 [a]	5.3 ± 0.2 [b]	4.0 ± 0.1 [c]	n = 73	29.849	3.623×10^{-10}
WDPT (s)	516 ± 255 [b]	270 ± 156 [b]	3 ± 1 [a]	n = 26	6.4589	0.005479
pH	5.1 ± 0.1 [a]	5.5 ± 0.1 [b]	6.0 ± 0.1 [c]	n = 20	36.715	2.971×10^{-7}
EC ($\mu S.cm^{-1}$)	50 ± 3 [b]	21 ± 5 [a]	66 ± 7 [b]	n = 68	25.863	4.744×10^{-9}
Organic matter (wt%)	8.6 ± 0.4 [a]	12.9 ± 0.6 [b]	12.0 ± 0.5 [b]	n = 100	23.797	3.768×10^{-9}
C (wt%)	3.8 ± 0.4 [a]	6.5 ± 0.4 [b]	4.3 ± 0.4 [a]	n = 91	21.489	2.349×10^{-8}
N (wt%)	0.13 ± 0.01 [a]	0.21 ± 0.02 [b]	0.13 ± 0.01 [a]	n = 91	18.701	1.614×10^{-7}
CO_2 respiration rate ($mol.cm^{-2}.s^{-1}$)	1.23 ± 0.17 [a]	1.97 ± 0.30 [a]	1.85 ± 0.26 [a]	n = 47	2.236	0.1189

Values shown are the mean and standard error of all data for a given fire treatment. Different letters indicate significant differences between fire treatments for each parameter, where for instance, results with "a" and "b" are significantly different, while results with "a" and "a" are not significantly different (ANOVA test, $p < 0.05$). WDPT: water drop penetration time; EC: electrical conductivity. F value and *p*-value refer to values from the ANOVA test.

The water repellency was very variable in the NB and ILB soils, with water drop penetration times (WDPTs) ranging from 4 to 2050 s for NB soils, and from 5 to 1618 s for ILB soils (Figure 2D). The ALB soils showed much lower WDPT values compared to the NB ($p = 0.011$) and ILB ($p = 0.016$) soils, and a narrower range of values (between 0.84 and 13.5 s). As the WDPT for the ALB soils was mostly <5 s, these soils were classified as "wettable" [19]. The NB and ILB soils were classified as "strongly water repellent", since most WDPT values exceeded 60 s in both cases. No significant difference in water repellency was observed between the NB and ILB sites.

Soil colors varied between each fire treatment site. At the NB sites, the color at depths of 10–13 cm was dark gray (10YR 4/1). At depths of 13–18 cm, the value and chroma increased to very pale brown (10YR 8/3). At the ILB sites, the topsoil layer was considerably darker due to the presence of charcoal from the burn. At depths of 1.5–6 cm, the dominant color was a very dark gray (5YR 3/1). Below 6 cm, the hue did not change, and the value and chroma increased to a reddish yellow (5YR 6/8). No distinct color changes could be seen at the ALB sites, although evidence of charcoal discoloration was observed. The ALB soils showed the same hue as the ILB soils; however, they were predominantly gray (5YR 5/1).

Soil pH significantly increased from the NB to ILB to ALB soils (Figure 3A). The NB and ILB soils were classified as strongly acidic (5.1 ± 0.1 and 5.5 ± 0.1, respectively), with the ALB soils being moderately acidic (6.0 ± 0.2). The electric conductivity at the ILB sites (21 ± 5 $\mu S.cm^{-1}$) was significantly lower than that at the NB (50 ± 3 $\mu S.cm^{-1}$) and ALB sites (66 ± 7 $\mu S.cm^{-1}$) (Figure 3B), with no significant difference observed between the NB and ALB sites. The EC was 58% higher for the NB sites compared to that for the ILB sites, and 66% higher for the ALB sites compared to that for the ILB sites.

The soil organic matter was significantly higher for the sites that experienced either the agency-led or the Indigenous-led burns, compared to the "non-burnt" sites (Figure 3C). The ILB soils had 33% more organic matter than the NB soils had, and the ALB soils had 28% more organic matter than the NB soils had. There was no significant difference between the soil organic matter contents in the ILB and ALB sites ($p = 0.678$).

The C and N concentrations were considerably higher at the Indigenous-led burn sites compared to those at the unburnt and agency-led burn sites (Figure 3D,E), similar to what was observed for the soil organic matter content (see above), but with a more pronounced difference between the ILB and ALB sites for C and N concentrations. At the ILB sites, the mean C concentration was 6.5 ± 0.4%, nearly twice the value as that at the NB sites (3.8 ± 0.4%) and about 1.5 times greater than that at the ALB sites (4.3 ± 0.4%). While at the ALB sites, the C concentration was higher than that at the NB sites, this difference was not found to be significant. At the ILB sites, the mean N concentration (0.21 ± 0.02%) was 1.6 times greater than that at both the NB (0.13 ± 0.01%) and ALB sites (0.13 ± 0.01%) (Figure 3E). No difference was found between the N concentration at the NB and ALB sites. Finally, no significant difference was observed between the C/N ratios of the different sites (Figure 3F).

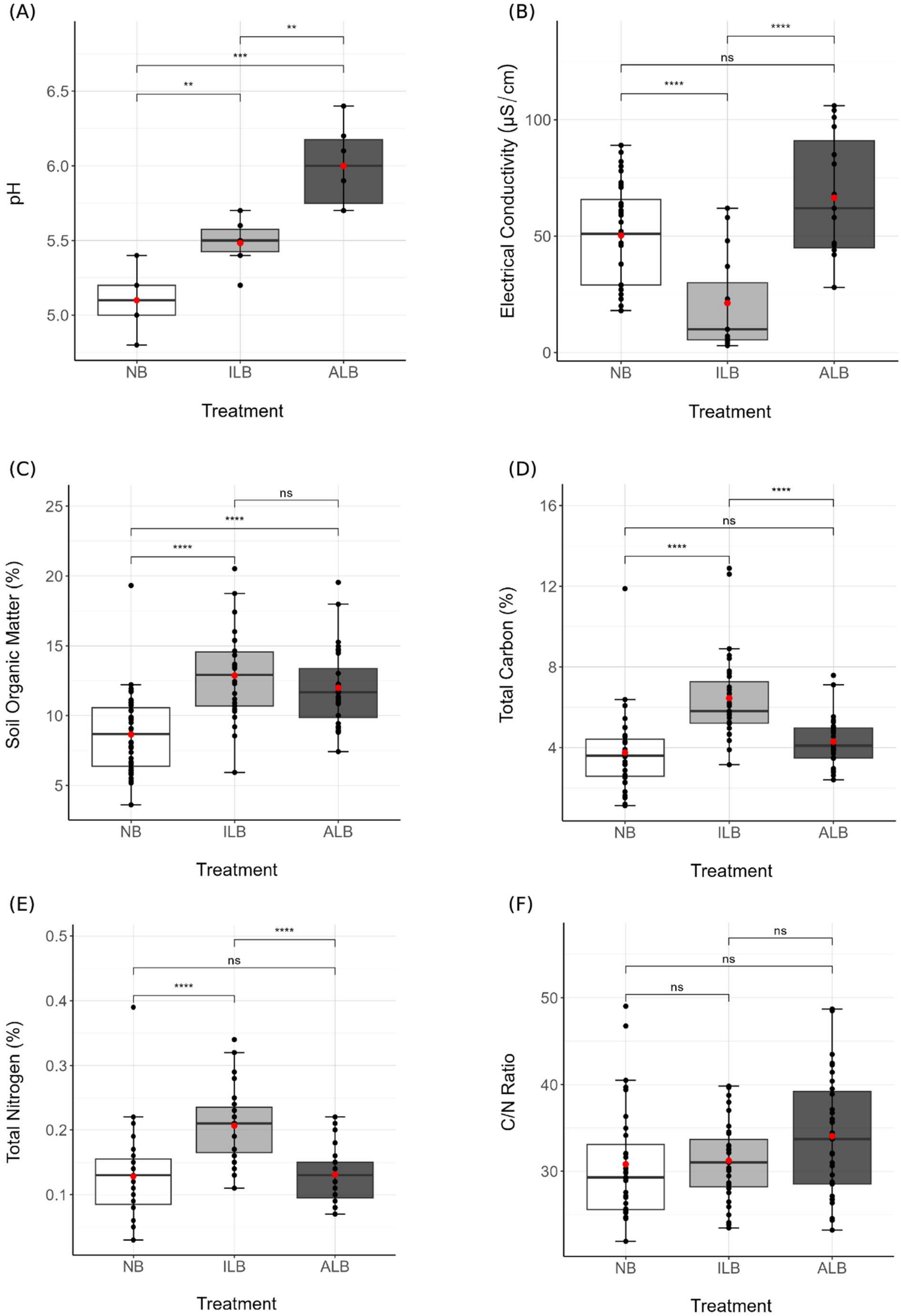
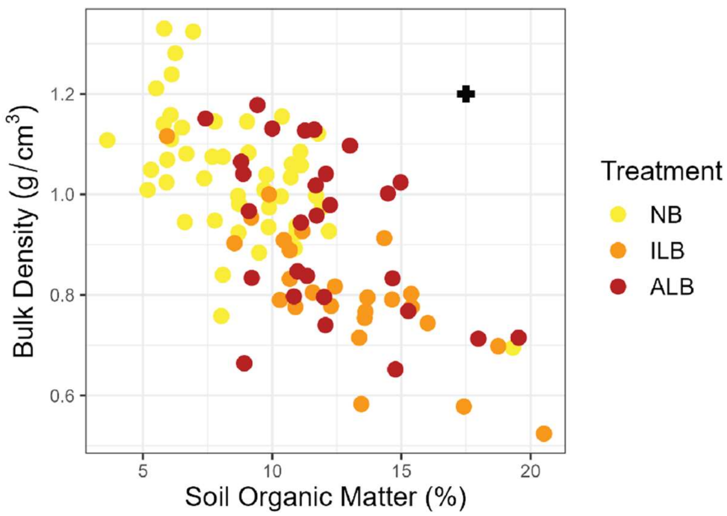


Figure 3. Soil (**A**) pH, (**B**) electric conductivity, (**C**) organic matter content, (**D**) carbon and (**E**) nitrogen concentrations, and (**F**) C/N ratios for different fire treatments. Red circles represent mean values. Asterisks (*) indicate statistical significance: ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$. ns: not significant.

After combining the data for all the fire treatments, the soil bulk density showed a significant negative correlation with the soil organic matter (r(99) = −0.70, $p < 0.001$) (Figure 4). Similarly, C concentrations showed a significant positive correlation with soil organic matter (r(72) = 0.59, $p < 0.001$), as did N concentrations to a lesser extent (r(72) = 0.47, $p < 0.001$) (not shown).

(A)



(B)

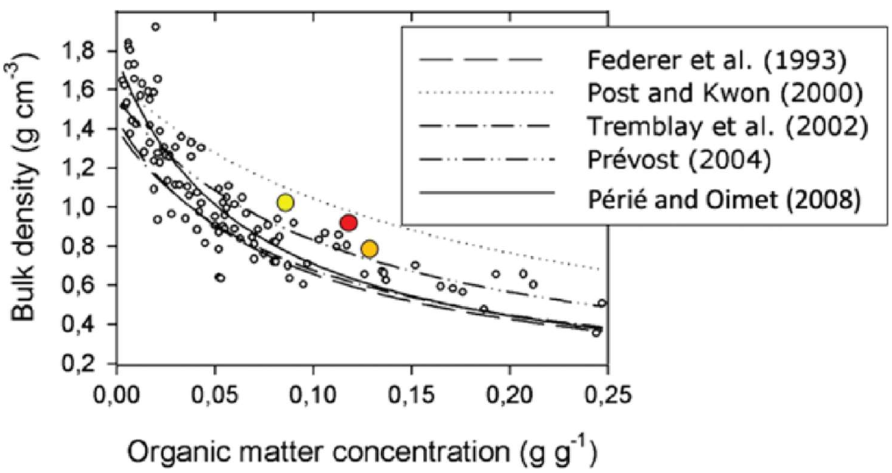


Figure 4. (**A**) Soil bulk density as a function of organic matter content for all samples. The cross in the upper right shows the uncertainty for each parameter. (**B**) Non-linear relationship between soil bulk density and organic matter from previous studies (modified from [20]) with the mean values of each group from this study: yellow = NB, orange = ILB, and red = ALB.

The mean soil CO_2 respiration rates (mol/m^2/s) at the ILB and ALB sites were 37.5% and 33.7% higher than that at the NB site (Figure 5), respectively. However, due to the large spread observed for both burn sites, these differences were not found to be significant. During the sampling period at each fire treatment location, the temperature remained consistent at the soil surface, with the largest increase being 1.3 °C at both the NB and ILB sites (NB = 11.2–12.5 °C; ILB = 11.5–12.8 °C; and ALB = 13.6–14.6 °C).

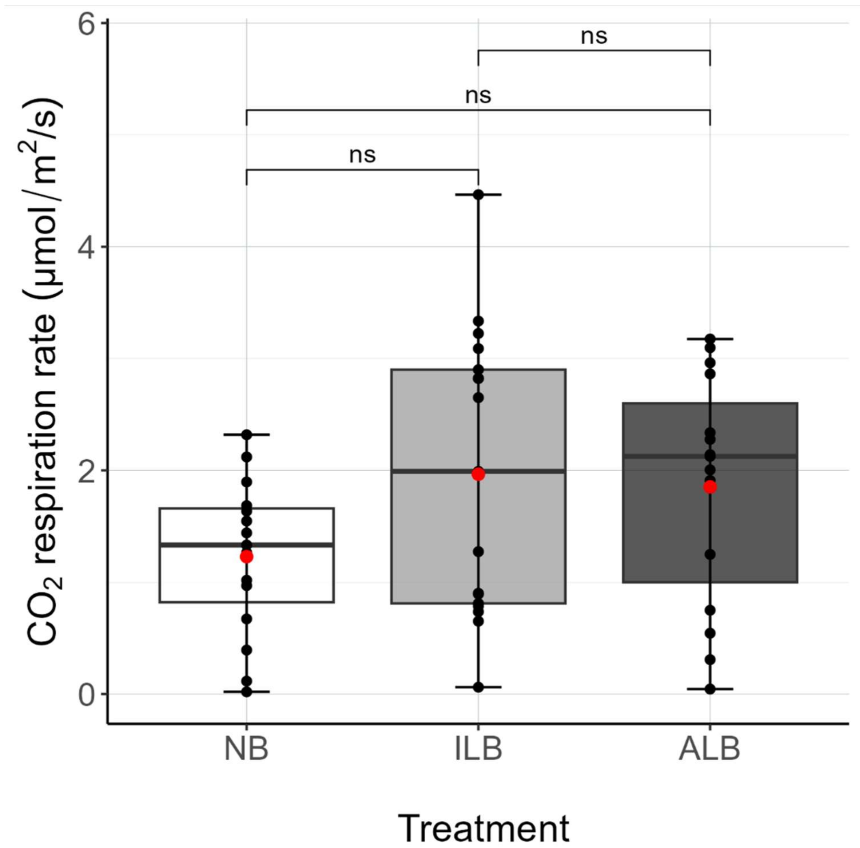


Figure 5. Soil CO_2 flux for different fire treatments. Red circles represent mean values. ns: not significant.

4. Discussion

Most soil properties were significantly affected by either fire treatment. For instance, the soil bulk density decreased, and the organic matter increased following both Indigenous- and agency-led burns. Previous studies have shown variable changes in soil bulk density following prescribed burning [5]. Here, both fire treatment methods showed a clear decrease (Figure 2A). A decrease in bulk density is generally associated with a gain in organic matter [20,21], which was also observed here (Figure 5). Indigenous-led burning seemed to better facilitate the input of organic matter into the soil, compared to agency-led burning, resulting in a greater decrease in bulk density. This is important as a lower soil density promotes water infiltration and reduces erosion risk [22]. It also enhances the ability for plant nutrients to be transported through the soil matrix, with greater aeration allowing for the improved efficiency of gas exchanges [22]. Finally, a lower soil density also promotes microbial activity [5]. Thus, fire treatment (either agency- or Indigenous-led) not only reduces bushfire risk but also promotes the input of organic matter and a reduction in soil density (Indigenous-led burning having the greater effect).

As indicated above, burnt soils have significantly greater amounts of organic matter compared to soils that were not burnt (Figure 3C). Soil organic matter is often found to decrease following a fire, due to the partial or complete combustion of organic matter [5], even at relatively low temperatures (~100 °C) [23]. However, increases in soil organic matter have also been reported following low- to moderate-severity fires, as a result of two processes: (i) the reintroduction of vegetation due to high net primary productivity following an influx of nutrients in ash deposits [6,21]. This hypothesis is supported by the ALB sites, with the dense colonization of *D. triquetra* following the burn. (ii) The incorporation of partially burnt material into the soil [24]. This could explain the higher soil organic matter content at the ILB sites. Such incorporation could have been particularly significant, since at the ILB sites, the ground and shrub cover was lower than that at the other sites, suggesting a lower primary productivity.

While both Indigenous- and agency-led burns resulted in higher soil organic matter contents than that where there was no burn, the total C content was only significantly elevated for soils that experienced the Indigenous-led burn. The higher C content at the ILB sites compared to that at the ALB sites could have been the result of lower fire temperatures during the Indigenous-led burn compared to those during the agency-led burn: a fire experiment conducted on soils in southeastern Australia showed that soils exposed to the lowest temperature (142 °C) had a ~14% gain in C compared to that in the control site, while soils that experienced temperatures of up to 525 °C showed a 50% loss in C [7]. Carbon gain was attributed to the incorporation of partially combusted ash and charred material to the soil matrix, while the loss of C reflected its volatilization during the fire [7]. It was possible that at the ALB sites, more C was lost through volatilization, then replenished to pre-fire levels from the input of root biomass. At the ILB sites, the greater C content could be explained by both the incorporation of root biomass and the incomplete combustion of forest floor litter.

As observed for C, ILB sites showed an enrichment in soil N compared to other sites (Figure 3E). Low fire temperatures often result in a minor volatilization of N, and ash containing N often incorporates into the soil after a fire event, which can be readily mobilized by plants [4]. An increase in soil N can also occur when the rate of mineralization from microbial activity is outweighed by the introduction of N [25]. Therefore, the addition of N from ash could have supplemented existing pools at the ILB sites. Since no differences in soil N were found between the NB and ALB sites, it is possible that N was volatilized and replenished by the subsequent root biomass (as hypothesized for C).

The ALB soils showed a reduced hydrophobicity compared to the ILB and NB soils. While fire tends to promote water repellency, higher temperatures can reduce or eliminate the hydrophobic wax layer on soil particles [7,26,27]. This is the case when surface temperatures exceed 260 °C for 40 min, or 310 °C for just 5 min [26]. Thus, the reduced water repellency properties in soils that experienced the agency-led burn could have been a consequence of higher fire temperatures compared to those for the Indigenous-led burn. The similarity of water repellency properties for the ILB and NB soils could suggest that either the Indigenous-led burn did not affect soil hydrophobicity due to its low temperatures and/or enough time elapsed between the burn and soil sample collection for the soils to recover their pre-fire water repellency properties. The first hypothesis alone is unlikely, as Doerr [26] found that even the lowest severity fire for as little as five minutes induces repellency in sandy loam soils under a eucalypt canopy. A recovery to pre-fire conditions is more likely, since soil water repellency properties were found to return to pre-fire values only five months after experiencing a low-intensity fire [7].

The soil moisture was greater at the ALB and ILB sites compared to that at the NB sites. Other studies have reported a decrease in soil moisture following fire [9,23,24]. A strong relationship exists between water repellency and soil water infiltration and retention [5]. The susceptibility of soils to surface runoff significantly increases with repellency, thereby reducing water infiltration and dispersal through the soil matrix [5]. The inverse is also true, with the water absorption rate of hydrophilic soils being much greater than that of hydrophobic soils, resulting in a higher moisture content. Soil organic matter and bulk density are also contributing factors, since elevated soil organic matter and low density/high porosity increase the ability for soil to hold water [28]. Increased infiltration rates caused by fire-induced wettability, in addition to improved soil organic matter and density, had likely contributed to a considerably higher moisture content in the ALB soils. This could have been a consequence of higher temperatures during the agency-led burn, reducing the soil water repellency (see above).

The clay content decreased from the NB to ILB to ALB soils (Figure 2C). The silt content slightly increased in the same order. These results contradicted the findings of Granged [7], who found that prescribed fire significantly increased the sand content in sandy loam soils due to the formation of unstable aggregates. This could have been the result of clay aggregation [29], which is supported by a negative correlation between clay and silt contents (not shown).

The increase in soil pH observed following fire treatment (with a greater increase in the ALB soils compared to that in the ILB soils) was consistent with previous studies on soils in Australia and elsewhere, which have shown that soil pH immediately increases post-fire and can remain high for up to three years after the fire [7,23,30]. Increases in the same order as the one observed here were measured following fires reaching temperatures between 142 and 317 °C [7] (Figure 6). Increases in soil pH following low- to moderate-severity fires have been mostly attributed to the ephemeral ash layer produced from combusted organic matter [6,7]. This causes the topsoil to neutralize as cations are released from ash, entering the exchange complex and expulsing protons [6,23,31]. As the presence of ash is temporary in topsoil, pH levels eventually recover to pre-fire levels, although the timeframes for this to occur are highly variable (from one month to several years) [9]. The extent of the change in pH is mostly related to both the amount and composition of the ash produced during a fire event [7]. Other factors that may control the recovery time include the abiotic removal of ash from environmental controls such as wind and rainfall [9]. Since this study was conducted more than a year after both fire events, it is difficult to establish a link between the immediate response of soil pH and the characteristics of the ash produced. However, these results further reflect the susceptibility of soil pH to low–moderate fire severities and the variability in recovery periods.

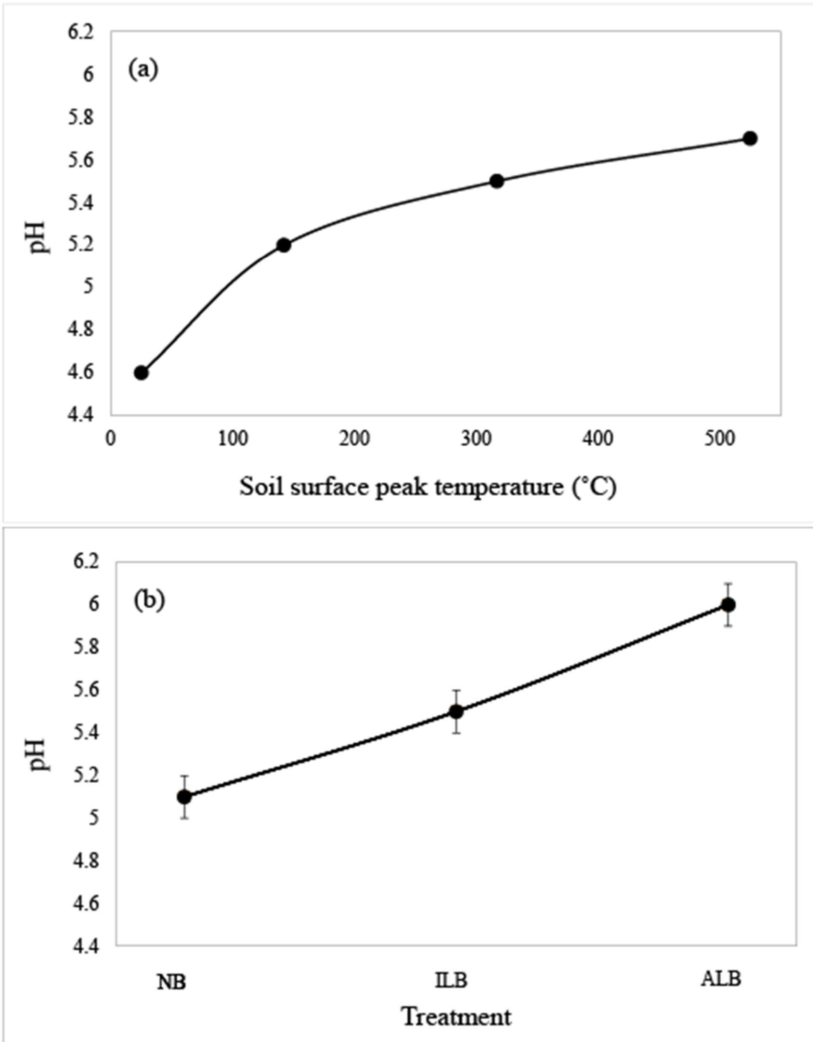


Figure 6. Comparable soil pH relationship with associated fire severity between two studies in south-eastern Australia. (**a**) Average soil pH over seven months following experimental fire temperatures in sandy loam soils under a eucalyptus forest [7]. (**b**) Differences in soil pH related to the treatment type of this study in sandy loam soils, Narrawallee, NSW (this study).

Electrical conductivity (EC) has been reported to immediately increase following a fire event as a result of the release of soluble ions from combusted organic matter [6,9,23,30]. Recovery periods to pre-fire levels vary from less than a year [23] to five years [10]. In this study, the soil EC following the agency-led burn was slightly higher than that at sites that were not burnt, while it was lower at sites that experienced the Indigenous-led burn. While it is uncommon to observe a decrease in soil EC post-fire, Mills and Fey [32] reported similar findings, suggesting that salt-bearing ash was removed by surface runoff due to the "crusting" or "sealing" of the burnt soils. Alternatively, differences in the soil EC at the ALB sites on the one hand, and ILB and NB sites on the other hand, could be explained by differences in vegetation structure. Denser foliage and shrub cover can trap atmospheric salts transported to the soil following rain events [32]. This is particularly relevant at our study site, considering its proximity to the ocean (~1 km). As the vegetation density at the ILB sites has been significantly reduced, atmospheric salts have less available plant surface to attach to, therefore reducing the load of soluble ions deposited into the soil, possibly explaining the lower soil EC values observed.

Fire was found to have no apparent impact on soil CO_2 respiration in either of the burnt sites (Figure 4). It was expected that improvements in the availability and quality of soil organic matter and C and N concentrations in the ILB soils would contribute to enhanced microbial activity; however, this was not observed. One study reported similar findings, suggesting that microbial activity and the plant root contribution of CO_2 respiration continue to recover and proceed regardless of disturbances to soil properties [33]. Another influence affecting respiration could be attributed to the climatic conditions at the time of measurement. Previous studies have shown that soil respiration decreased substantially during the first three months following a fire [34]. Afterwards, soil respiration showed a distinct fluctuation with seasonal temperatures. Considering this study was conducted over a year after each burn, it is possible that too much time has elapsed for the fire to still have an influence on soil respiration, which is then a function of seasonal climate. Furthermore, CO_2 measurements were taken during the Australian winter; as a result, microbial activity is expected to slow down, which could have further masked any differences in the soil respiration between sites. Further investigation would be required to determine the effect on Indigenous- and agency-led burns on soil respiration.

Soil salinity, moisture, temperature, and nutrient availability are expected to be the key drivers of microbial activity within the soil system [35]. It appears that the substantial differences found between parameters, particularly for salinity, moisture content, and N concentrations, had no effect on respiration rates. Soil salinity can be detrimental to microbial activity and plant growth as a direct result of osmotic stress and toxic ions [36]. However, the corelative results of this study showed that salinity was not a likely contributing factor to microbial activity. This information implies that temperature and/or nutrient availability may have been the primary influencers of the heterotrophic and autotrophic activity throughout the study site. Decomposition rates can be associated with C/N ratios rather than the individual concentrations, as this parameter indicates the amount of N available for microbial uptake [37]. A low C/N ratio typically leads to enhanced activity, as less N is tied up within the decaying plant residue [37]. This could further explain the homogeneity seen in the respiration values between each site, since no significant differences were found between the treatment C/N ratios (Figure 3F).

5. Conclusions

In this study, we compared the effects of Indigenous- and agency-led burns on soil properties in a coastal ecosystem in southeastern Australia. Overall, we found that both fire treatments led to a decrease in soil bulk density, an important outcome for soil health, as well as an increase in organic matter content. The greater effect was for soils affected by the Indigenous-led burn. This is possibly explained by the lower temperature of the fire compared to that of the agency-led burn. Furthermore, soils affected by the Indigenous-led burn showed greater C and N stocks compared to those unburnt or affected by the agency-led burn. This suggests that while both fire treatments promote a positive effect on the soil organic matter, the agency-led burn may have resulted in a greater volatilization of C and N during the fire, leading to a slower recovery of these key nutrients compared to that of the Indigenous-led burn, which induced an overall accumulation of these two nutrients.

Both fire treatments also resulted in an increase in soil moisture content, suggesting that they positively affect the soil water balance. Here, a greater effect was observed in soils affected by the agency-led burn. This could be explained by the fact that the hydrophobicity in the soils affected by the agency-led burn was lower than that in the soils affected by the Indigenous-led burn, possibly allowing greater water infiltration.

The soil pH increased following fire treatment, and the extent of the increase could be related to fire temperature, with a greater increase in soils affected by the agency-led burn, which could have reached higher temperatures than those of the Indigenous-led burn. For other properties, such as the soil respiration rate, the effect of the fire treatment was difficult to establish as the effect of fire on these properties could be shorter lived than the time elapsed between the burns and sample collection in this study.

Overall, both fire treatments have positive, quantifiable effects on soil and ecosystem health. While the agency-led burn could be more beneficial to soil water balance, the Indigenous-led burn has clear positive effects on the soil organic matter stock, in particular, on key nutrients such as carbon and nitrogen.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire7030075/s1, Figure S1: Quadrat design for each site: control–no burn (NB), agency-led burn (ALB), and Indigenous-led burn (ILB). In the top right, the sizing of each quadrat and approximate locations of where the soil cores were taken and CO_2 chambers were fitted are displayed; Figure S2: Soil profile at the control/no burn site. Yellow marker on the scale indicates the depth of the soil core taken for sampling; Figure S3: Soil profile of the Indigenous-led burn (ILB) site. Yellow marker on the scale indicates the depth of each soil core taken for sampling; Figure S4: Soil profile of the Agency-led burn (ALB) site. Yellow marker on the scale indicates the depth of each soil core taken.

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References

1. Bradstock, R.A. A biogeographic model of fire regimes in Australia: Current and future implications. *Glob. Ecol. Biogeogr.* **2010**, *19*, 145–158. [CrossRef]
2. Morgan, G.W.; Tolhurst, K.G.; Poynter, M.W.; Cooper, N.; McGuffog, T.; Ryan, R.; Wouters, M.A.; Stephens, N.; Black, P.; Sheehan, D.; et al. Prescribed burning in south-eastern Australia: History and future directions. *Aust. For.* **2020**, *83*, 28–32. [CrossRef]
3. Arias, M.E.; Gonzalez-Perez, J.A.; Gonzalez-Vila, F.J.; Ball, A.S. Soil health–A new challenge for microbiologists and chemists. *Int. Microbiol. Off. J. Span. Soc. Microbiol.* **2005**, *8*, 13–21.
4. Alcañiz, M.; Outeiro, L.; Francos, M.; Farguell, J.; Úbeda, X. Long-term dynamics of soil chemical properties after a prescribed fire in a Mediterranean forest (Montgrí Massif, Catalonia, Spain). *Sci. Total Environ.* **2016**, *572*, 1329–1335. [CrossRef] [PubMed]
5. Alcañiz, M.; Outeiro, L.; Francos, M.; Úbeda, X. Effects of prescribed fires on soil properties: A review. *Sci. Total Environ.* **2018**, *613–614*, 944–957. [CrossRef] [PubMed]
6. Certini, G. Effects of fire on properties of forest soils: A review. *Oecologia* **2005**, *143*, 1–10. [CrossRef] [PubMed]

7. Granged, A.J.; Jordán, A.; Zavala, L.M.; Muñoz-Rojas, M.; Mataix-Solera, J. Short-term effects of experimental fire for a soil under eucalyptus forest (SE Australia). *Geoderma* **2011**, *167–168*, 125–134. [CrossRef]
8. Muqaddas, B.; Zhou, X.; Lewis, T.; Wild, C.; Chen, C. Long-term frequent prescribed fire decreases surface soil carbon and nitrogen pools in a wet sclerophyll forest of Southeast Queensland, Australia. *Sci. Total Environ.* **2015**, *536*, 39–47. [CrossRef]
9. Muñoz-Rojas, M.; Erickson, T.E.; Martini, D.; Dixon, K.W.; Merritt, D.J. Soil physicochemical and microbiological indicators of short, medium and long term post-fire recovery in semi-arid ecosystems. *Ecol. Indic.* **2016**, *63*, 14–22. [CrossRef]
10. Muñoz-Rojas, M.; Lewandrowski, W.; Erickson, T.E.; Dixon, K.W.; Merritt, D.J. Soil respiration dynamics in fire affected semi-arid ecosystems: Effects of vegetation type and environmental factors. *Sci. Total Environ.* **2016**, *572*, 1385–1394. [CrossRef]
11. Malacara, D. *Color Vision and Colorimetry: Theory and Applications*; SPIE: Bellingham, WA, USA, 2011.
12. Walker, B. *Development of Low-Cost Sensors and Evaluation using High Precision Fourier Transform Infrared Spectroscopy*; University of Wollongong: Wollongong, Australia, 2021.
13. Phillips, R.; Griffith, D.W.; Dijkstra, F.; Lugg, G.; Lawrie, R.; Macdonald, B. Tracking Short-Term Effects of Nitrogen-15 Addition on Nitrous Oxide Fluxes Using Fourier-Transform Infrared Spectroscopy. *J. Environ. Qual.* **2013**, *42*, 1327–1340. [CrossRef] [PubMed]
14. Wessel, A. On using the effective contact angle and the water drop penetration time for classification of water repellency in dune soils. *Earth Surf. Process. Landf.* **1988**, *13*, 555–561. [CrossRef]
15. Rayment, G.; Higginson, F.R. *Australian Laboratory Handbook of Soil and Water Chemical Methods*; Inkata Press Pty Ltd.: Melbourne, Australia, 1992.
16. Heiri, O.; Lotter, A.; Lemcke, G. Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *J. Paleolimnol.* **2001**, *25*, 101–110. [CrossRef]
17. Donkin, M.J. Loss-on-ignition as an estimator of soil organic carbon in A-horizon forestry soils. *Commun. Soil Sci. Plant Anal.* **1991**, *22*, 233–241. [CrossRef]
18. Allaire, J. *RStudio: Integrated Development Environment for R*, version 0.96.122; RStudio: Boston, MA, USA, 2012; Volume 770, pp. 165–171.
19. Bisdom, E.B.A.; Dekker, L.W.; Schoute, J.F.T. Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. In *Soil Structure/Soil Biota Interrelationships*; Brussaard, L., Kooistra, M.J., Eds.; Elsevier: Amsterdam, The Netherlands, 1993; pp. 105–118.
20. Périé, C.; Ouimet, R. Organic carbon, organic matter and bulk density relationships in boreal forest soils. *Can. J. Soil Sci.* **2008**, *88*, 315–325. [CrossRef]
21. Brye, K.R. Soil physiochemical changes following 12 years of annual burning in a humid–subtropical tallgrass prairie: A hypothesis. *Acta Oecologica* **2006**, *30*, 407–413. [CrossRef]
22. Lal, R.; Kimble, J. Importance of soil bulk density and methods of its measurement. In *Assessment Methods for Soil Carbon*; CRC Press: Boca Raton, FL, USA, 2000; pp. 31–44.
23. Granged, A.J.; Zavala, L.M.; Jordán, A.; Bárcenas-Moreno, G. Post-fire evolution of soil properties and vegetation cover in a Mediterranean heathland after experimental burning: A 3-year study. *Geoderma* **2011**, *164*, 85–94. [CrossRef]
24. Kennard, D.K.; Gholz, H.L. Effects of high- and low-intensity fires on soil properties and plant growth in a Bolivian dry forest. *Plant Soil* **2001**, *234*, 119–129. [CrossRef]
25. Prieto-Fernández, A.; Acea, M.J.; Carballas, T. Soil microbial and extractable C and N after wildfire. *Biol. Fertil. Soils* **1998**, *27*, 132–142. [CrossRef]
26. Doerr, S.H.; Blake, W.H.; Shakesby, R.A.; Stagnitti, F.; Vuurens, S.H.; Humphreys, G.S.; Wallbrink, P. Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil temperatures. *Int. J. Wildland Fire* **2004**, *13*, 157–163. [CrossRef]
27. Doerr, S.; Shakesby, R.; Blake, W.; Chafer, C.; Humphreys, G.; Wallbrink, P. Effects of differing wildfire severities on soil wettability and implications for hydrological response. *J. Hydrol.* **2006**, *319*, 295–311. [CrossRef]
28. USDA-NRCS. *Soil Bulk Density/Moisture/Aeration–Soil Quality Kit*; USDA: Washington, DC, USA, 2008.
29. Hubbert, K.R.; Oriol, V. Temporal fluctuations in soil water repellency following wildfire in chaparral steeplands, southern California. *Int. J. Wildland Fire* **2005**, *14*, 439–447. [CrossRef]
30. Terefe, T.; Mariscal-Sancho, I.; Peregrina, F.; Espejo, R. Influence of heating on various properties of six Mediterranean soils. A laboratory study. *Geoderma* **2008**, *143*, 273–280. [CrossRef]
31. Jensen, M.; Michelsen, A.; Gashaw, M. Responses in plant, soil inorganic and microbial nutrient pools to experimental fire, ash and biomass addition in a woodland savanna. *Oecologia* **2001**, *128*, 85–93. [CrossRef]
32. Mills, A.J.; Fey, M.V. Frequent fires intensify soil crusting: Physicochemical feedback in the pedoderm of long-term burn experiments in South Africa. *Geoderma* **2004**, *121*, 45–64. [CrossRef]
33. Livesley, S.J.; Grover, S.; Hutley, L.B.; Jamali, H.; Butterbach-Bahl, K.; Fest, B.; Beringer, J.; Arndt, S.K. Seasonal variation and fire effects on CH_4, N_2O and CO_2 exchange in savanna soils of northern Australia. *Agric. For. Meteorol.* **2011**, *151*, 1440–1452. [CrossRef]
34. Hu, T.; Zhao, B.; Li, F.; Dou, X.; Hu, H.; Sun, L. Effects of fire on soil respiration and its components in a Dahurian larch (*Larix gmelinii*) forest in northeast China: Implications for forest ecosystem carbon cycling. *Geoderma* **2021**, *402*, 115273. [CrossRef]
35. Serna-Chavez, H.M.; Fierer, N.; van Bodegom, P.M. Global drivers and patterns of microbial abundance in soil. *Glob. Ecol. Biogeogr.* **2013**, *22*, 1162–1172. [CrossRef]

36. Yan, N.; Marschner, P.; Cao, W.; Zuo, C.; Qin, W. Influence of salinity and water content on soil microorganisms. *Int. Soil Water Conserv. Res.* **2015**, *3*, 316–323. [CrossRef]
37. Burton, J.; Chen, C.; Xu, Z.; Ghadiri, H. Soil microbial biomass, activity and community composition in adjacent native and plantation forests of subtropical Australia. *J. Soils Sediments* **2010**, *10*, 1267–1277. [CrossRef]