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Soil nutrient release and microbial changes after burning of masticated fuels

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Abstract

Soil temperature extremes are not uncommon when woody fuels are ignited in prescribed burns or wildfires. Whether this leads to substantial loss of soil organic matter or microbial life is unclear. We created a soil heat gradient by burning four levels of masticated woody fuels (0, 34, 101, and 169 Mg ha^{-1}) to determine if heat thresholds produce abrupt changes in soil C, N, microbial biomass, or fungal hyphae. Twenty-four burns were conducted with masticated fuels overlaying a clay loam soil equilibrated at either 4 or 25% volumetric soil water content. Maximum temperatures ranged from 40 to 450 ˚C depending on fuel load and soil moisture content, with heat duration (>60 ˚C) as great as 22 h. Moist soil quenched temperatures two- to threefold compared with dry soil at comparable fuel loads. A slight, gradual decline in total C and N was found with increasing temperature and heat duration, reaching a maximum loss of 14–18% of the total at the highest heat load. Available NH_4 increased linearly starting at 150–175 ˚C and reached a maximum 15-fold increase relative to unburned soil by 450 ˚C. Nitrification (30 d post-fire) was low regardless of treatment and was essentially eliminated at the highest temperatures. Microbial biomass declined curvilinearly with increased heating, approaching 65% loss compared with unburned soil, and was most rapid in moist soil once temperatures exceeded 60–70 ˚C. Ultimately, we found no evidence of abrupt heat thresholds for these common soil properties. Instead, property changes followed a slightly declining trajectory (soil C, N, NO_3, fungal hyphae) or a steady incremental increase (NH_4) or decrease (microbial biomass).

1 | INTRODUCTION

Concern for wildfire risk near urban settings in California wildlands is absolute, as recent wildfires have caused devastating loss of lives, homes, livelihoods, and infrastructure (http://www.fire.ca.gov/incidents/2021). Providing fire-safe conditions is of utmost priority to public and federal, state, tribal, and local agencies. Fuel-reduction practices—particularly prescribed fire and mechanical thinning—are a key component in this effort as they help eliminate ladder fuels, thin dense forest stands, consume excess surface fuels, and, consequently, lower fire hazard (Agee & Skinner, 2005). Mechanical chopping (mastication) of woody shrubs and small-diameter trees is an additional option that offers land managers an effective tool to convert these ladder fuels into fragmented surface organics (Kane et al., 2009), thus modifying fire behavior and lowering the risk of crown fire

Abbreviations: MBC, microbial biomass carbon; SOC, soil organic carbon.

(Kreye et al., 2014). However, masticated fuels burned by design or wildfire can generate extreme soil temperatures (Busse et al., 2005) with potential consequences to soil physical, chemical, and biological health.

Fire effects on soils have been well studied and basic concepts identified (see Certini, 2005; Certini et al., 2021). Included among these: soil is a poor conductor of heat and, consequently, most severe fire effects are restricted to the upper 5-to-10-cm soil profile; loss of mineral soil C and N begins around 200–250 ˚C and is complete above 450–490 ˚C (Fernández et al., 1997; Hungerford et al., 1991); release of inorganic N by moderate severity burning often stimulates post-fire plant growth (Wan et al., 2001); intense heating is thought to "sterilize" the soil microbial community; hydrophobic layers capable of restricting water percolation result when soil temperatures approaches 295 ˚C; and soil water substantially reduces downward heat penetration because of the added energy required to evaporate water. Because many of these concepts were derived from artificial heating experiments (e.g., muffle furnaces) or field studies where soil heating was not accurately quantified, their applicability across soil types, fuel types, and climates has not been fully established (Neary et al., 1999). This holds particular relevance for burning of masticated fuels given their variable mass, size classes, and arrangement within treatment areas (Kane et al., 2009).

Masticated fuels may (or may not) produce intense soil heating and, consequently, a variety of changes to soil properties when burned. Busse et al. (2005) found that fuel-bed depth was a primary driver of soil heating: burning masticate fuel layers 7.5 cm thick and greater led to soil temperatures often exceeding 700 ˚C on the soil surface and 300 ˚C at a depth of 5 cm. Knapp et al. (2011) refined this observation by showing that thick fuel beds only produced minor soil heating when the underlying duff layer was moist. Similarly, Busse et al. (2010) found that mineral soil moisture content was a more important factor determining the extent and duration of soil heating than either soil texture or structure. Clearly, within-site variability in fuel loading and soil moisture content exert a large and perhaps unpredictable effect on the soil heat pulse.

Identifying heat thresholds (i.e., maximum temperatures and heat duration), where any added energy input causes a marked system response (Groffman et al., 2006), is an ongoing challenge in fire-effects research. Such knowledge would assist resource managers when developing fire prescriptions and predicting post-fire soil damage. Common threshold values from Neary et al. (1999) include 60 ˚C for root mortality, 95 ˚C for soil water evaporation, and 295 ˚C for formation of hydrophobic soil. However, whether precise thresholds exist for other soil properties and, if so, whether they might be universal across soil and fuel types is less clear. In fact, Pingree & Kobziar (2019) provided convincing evidence that threshold values for soil organism and root mortality are not universal in natural systems and, instead, require consideration on a case-by-case basis, which questions the practicality and validity of heating thresholds for common soil properties.

Core Ideas

- Multiple burns and fuel loadings led to a wide range of critical soil temperatures.
- Soil C and N were generally unaffected at temperatures ranging from 40 to 450 ˚C.
- A large incremental increase in plant-available NH_4–N was found as temperatures surpassed 200 ˚C.
- Microorganisms declined steadily with increasing temperature.
- Changes in soil properties were mostly gradual and limited to the thin surface layer.

Our objective was to determine if heating thresholds exist for common soil chemical and microbial properties during burning of masticated fuels, including (a) total soil C and N loss, (b) NH_4 mineralization and nitrate production, (c) microbial biomass C (MBC) and respiration change, and (d) fungal hyphae loss. A wide range of soil temperatures and heat durations was established using a gradient of woody fuel loads in controlled-setting burns. Further, we compared heating responses in dry vs. moist soil and hypothesized that heating thresholds would be more easily exceeded in dry soil because of its greater heat transfer capacity compared with moist soil.

2 | MATERIALS AND METHODS

2.1 | Study design and experimental burns

Twenty-four controlled burns were conducted that compared four fuel loads (0, 34, 101, 169 Mg ha^{-1}) and two soil moisture contents (4 and 25% on a volumetric basis) in a factorial design, with three replications of each treatment. To measure the downward heat pulse during burning, constant-recording thermocouples were placed at depths of 0, 2.5, 5, and 10 cm below the mineral soil surface within 0.9-m × 0.9-m × 0.15-m burn plots.

Mineral soil and woody fuels were collected from a young ponderosa pine (*Pinus ponderosa* P. & C. Lawson) forest near the northern California town of Whitmore (40°37′46″ N, 121°55′0″ W). Soil was sampled from the A horizon of an Aiken pedon (fine, parasesquic, mesic Xeric Haplohumult) with 39% clay (clay loam texture) and 39.1 g kg^{-1} organic matter. Woody fuels were from masticated whiteleaf manzanita (*Arctostaphylos viscida* C. Parry) (46% C; 0.3% N) and ranged from 0.5 to 4 cm in diameter and 3 to 20 cm long, having cured on site for 2 yr. Approximately one-half of the mineral soil and woody fuel was kept containerized to maintain field-moist conditions. The remaining material was air dried for 3 wk under shade cover. Soil and fuel moisture contents were determined within 48 h of burning.

Soil was added to the burn plots in 2.5-cm layers. This allowed for placement of thermocouple wires at the plot center and for gentle packing of the soil to match the field bulk density of 1.0 Mg m^{-3}. Large roots and rocks were removed by hand prior to packing. Moist soil was packed within 30 min of ignition to limit evaporative losses, whereas the dry soil was packed no more than 12 h before burning.

Masticated fuels were placed on the mineral soil surface and packed to a bulk density of 0.13 Mg m^{-3} to approximate field conditions. Fuel moisture content at the time of ignition was 2% for the dry treatment and 16% for the moist treatment. The control treatment (no woody fuel) received a 2.0-cm layer of pine litter from the forested site.

Sixteen thermocouple wires were connected to one CR10X data logger (Campbell Scientific), allowing for temperature measurements on four burn plots at four soil depths simultaneously. Thermocouples with a range from −100 to 1,370 ˚C were constructed of 30-gauge chromel-alumel silica insulated wire (Omega Engineering). Soil temperatures were recorded every 30 s. Fuel layers were ignited at a single point in the upwind corner of each plot and soil heating was recorded until temperatures dropped below 40 ˚C at all soil depths. Immediately after burning, all ash and unconsumed organics were collected, oven dried at 60 ˚C for 48 h, and weighed to determine fuel consumption.

2.2 | Soil analyses

Soils were collected for nutrient and microbial analyses once temperatures dropped below 40 ˚C, typically less than 24 h after each burn. Four 10-cm-diam. cores were collected at each soil depth (0–2, 2–4, and 4–8 cm). One core was used to determine moisture content; the other three cores were composited to determine total C and N (dry combustion), NH_4 concentration (indophenol formation; Forster, 1995), NO_3 concentration (vanadium reduction; Doane & Horwath, 2003), microbial biomass (substrate-induced respiration), C mineralization (respiration using an infra-red gas analyzer), and fungal hyphal length (see below). After the initial sampling (Day 1 measurements), the remaining soils were wetted to 60% water holding capacity and incubated at 20 ˚C in the dark before repeated measures of NH_4 and NO_3 (Day 30), microbial biomass (Day 60), and C mineralization (Day 4, 7, 14, and 21).

Fungal hyphae were measured by epifluorescent microscopy (filter set 01, Carl Zeiss). Soil (5 g dry weight equivalent) was diluted with 67.5 ml 0.15 M saline in an Erlenmeyer flask containing 12.5 g of 3-mm glass beads and allowed to sit for 30 min before shaking for 15 min on a wrist-action shaker. Extracts were diluted 20-fold (10 ml extract in 190 ml 0.15 M saline), then 0.5-ml aliquots were incubated for 30 min with 2 ml of fluorescent brightener 28 (2.3 g ml^{-1} dH_2O; Sigma-Aldrich) and vacuum filtered onto 0.4-μm blackened polycarbonate filters. Filters were mounted on microscope slides with a drop of immersion oil (Type A, R. P. Cargille Laboratories) placed above and below each filter. Hyphal lengths were measured on 30 randomly selected fields per filter.

2.3 | Data analysis

The effects of fuel load, soil moisture, soil depth, and their interactions on individual response variables (i.e., maximum temperature, heat duration, C, N, NH_4, NO_3, microbial biomass, fungal biomass, and cumulative respiration) was tested by ANOVA (SAS version 9.4). Repeated measurements (Day 1, 30, or 60) were analyzed in separate ANOVA runs. Data were log transformed, if needed, to stabilize the error variance.

Evidence of heat thresholds was assessed qualitatively in linear regression analysis. Each soil response variable (C, N, NH_4, NO_3, microbial biomass, and fungal hyphae) was plotted separately against either maximum temperature or heat duration, and abrupt changes were noted visually. Data from the three soil depths were included in each regression to yield 72 observations per variable (four fuel loads × two moisture levels × three depths × three replications). Because soil temperatures were taken at discrete depths (0, 2.5, 5, and 10 cm) and soil samples were collected in layers (0–2, 2–4, and 4–8 cm), we estimated the mean temperature values (maximum temperature, heat duration) for each sample layer using regression equations that predicted heat pulse output along 0.5-cm depth increments as a function of the discrete thermocouple data (Supplemental Figure S1).

3 | RESULTS

3.1 | Soil heating

Soil heating varied considerably across the 24 experimental burns. Maximum temperature and heat duration increased markedly with increasing fuel load and, conversely, were moderated by soil moisture and soil depth (see Figure 1). In dry soil, the average maximum temperature at 0–2 cm

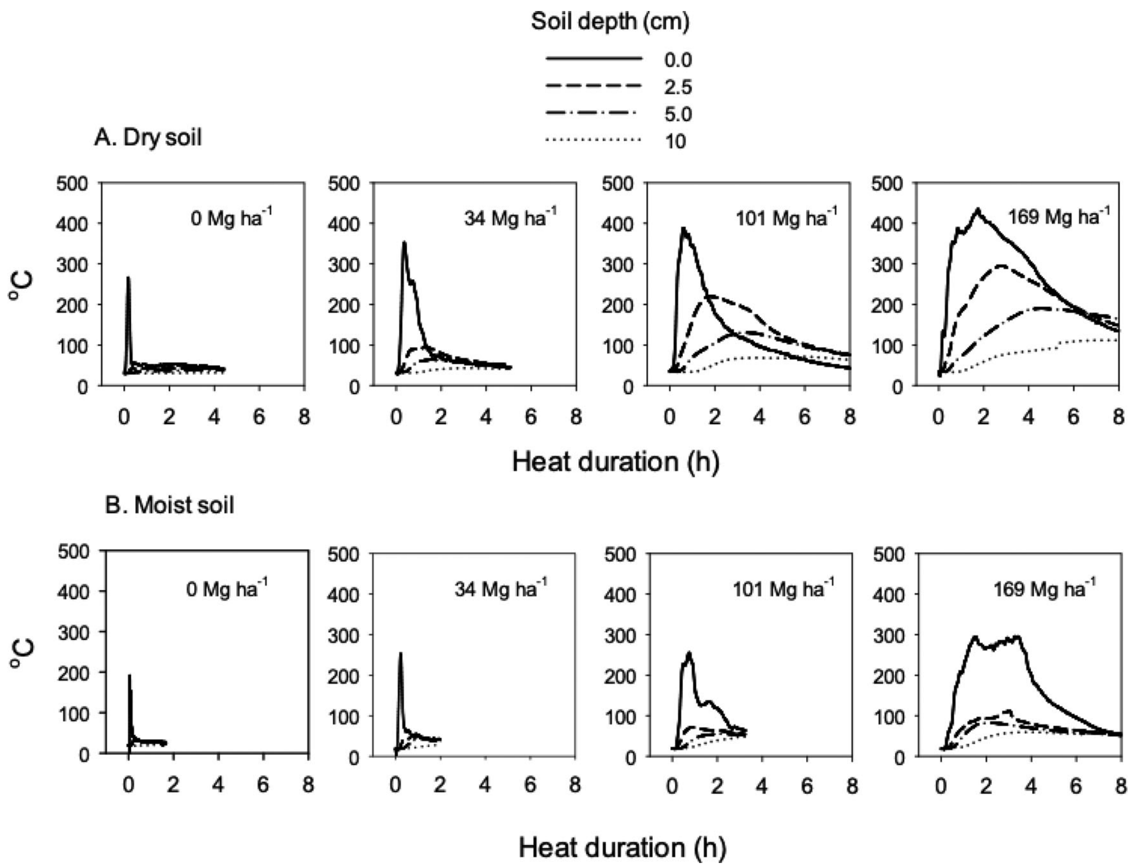

FIGURE 1 Examples of soil heat profiles associated with burning of masticated fuels. Note the strong influence of fuel load, soil depth, and soil moisture on soil heating. The control treatment (0 Mg ha^{-1} woody fuel) was burned with a thin layer of pine litter on the soil surface

increased from 115 ˚C for the control to 425 ˚C for the heaviest fuel load (Figure 2). Moisture effectively quenched soil temperatures two- to threefold across fuel loads and soil depths. Similarly, lethal heat duration averaged 15 h in dry soil and only 5 h in moist soil at the highest fuel load. A progressive decline in maximum temperature (but not heat duration) was found with increasing soil depth. Additionally, fuel consumption was 76–94% on all burns regardless of pre-burn fuel load.

3.2 | Soil C and N

Soil C concentration was mostly unaltered across the experimental range of temperatures and heat durations (Figure 3A). This was corroborated by the lack of a statistically significant effect of fuel load treatment on soil C (Supplemental Table S1). Regression analysis showed a weak yet significant relationship between soil C and maximum temperature in dry soil ($r^2 = .17$, $p = .013$) that predicted an 18% decline in total C at a soil temperature of 450 ˚C compared with ambient. A similar response was found for the effect of heat duration on soil C ($r^2 = .12$, $p = .041$), or a 14% decline in C when lethal heating exceeded 20 h. Predictive equations of soil C loss were not significant for moist soil ($p > .05$).

Soil N concentration also showed little response to soil heating (Figure 3B). The relationship between soil N and maximum temperature was significant in moist soil only ($r^2 = .15$, $p = .018$), as a loss of 14% N was predicted when the temperature reached 250 ˚C.

Ammonium concentration increased 10- to 15-fold immediately after burning in the surface 0–4 cm of dry soil (Figure 4A). In comparison, NH_4 concentrations were substantially lower in moist soil than in dry soil (Figure 4B), leading to a significant fuel load × soil moisture × soil depth interaction ($p < .001$). Unlike NH_4, NO_3 concentrations did not increase immediately after burning compared with the control and remained below 1.5 mg kg^{-1} for all treatments (Supplemental Figure S2).

A curvilinear increase in NH_4 concentration with increasing soil temperature was found for Day 1 samples in dry soil (Figure 5A; $r^2 = .87$, $p < .0001$). This was particularly evident as temperatures surpassed 150–175 ˚C. The response was considerably lower in moist soil, as maximum temperatures were mostly below 200 ˚C. Nitrate concentrations showed a slight decline with increasing temperature on Day 1 ($r^2 = .26$, $p = .001$). By Day 30, NO_3 production was noted in dry soil at low soil temperatures and declined as temperatures increased above 150 ˚C (Figure 5B; $r^2 = .47$, $p < .001$),

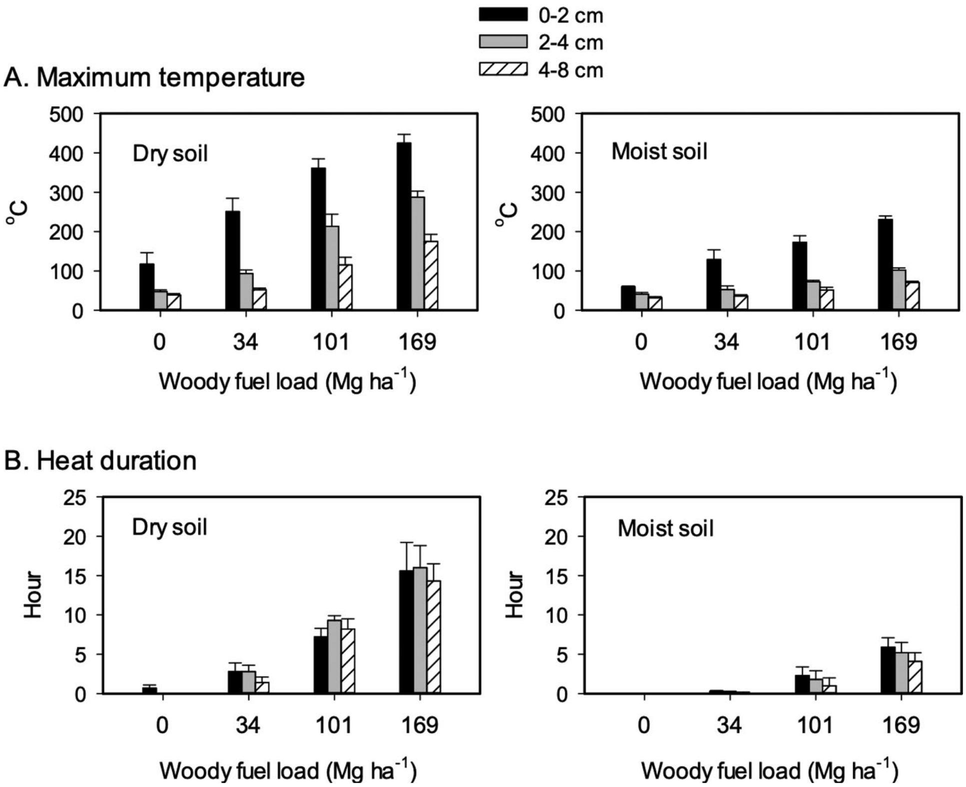

FIGURE 2 Effects of fuel load, soil depth, and soil moisture on (A) maximum temperature and (B) heat duration above 60 ˚C. Bars are means plus SE ($n = 3$)

suggesting a detrimental effect of high temperature on nitrifier populations.

3.3 | Microbial responses to fire

Microbial biomass C declined with increasing fuel load in both dry and moist soil (Figure 6; $p < .001$; Supplemental Table S2). Interestingly, a near complete loss of MBC was noted at the highest fuel load in moist soil on Day 1 (but not dry soil), with partial recovery by Day 60. Curvilinear declines in MBC were identified in regression analysis with increasing temperature and heat duration, reaching a minimum MBC between 200 and 400 mg kg^{-1} by Day 60 (Figure 7A). Soil temperature was significantly related to MBC in dry soil ($r^2 = .64$, $p < .001$) and moist soil ($r^2 = .27$, $p = .006$). Similarly, the relationship between heat duration and MBC was significant in dry soil ($r^2 = .80$, $p < .001$) and moist soil ($r^2 = .69$, $p < .001$). Fungal hyphal length also declined with increasing maximum temperature and heat duration (Figure 7B; Supplemental Figure S3), although the relationship was not as strong as noted for MBC and was only significant for dry soil ($p < .001$).

Soil respiration was measured for 3 wk after burning. An initial flush in CO_2 production lasted for 7 d for all treatments, after which no differences in respiration were detected among treatments (Supplemental Figure S4).

4 | DISCUSSION

We selected the fuel load and soil moisture treatments to generate a broad array of heat profiles and, thus, help identify temperature thresholds for common soil properties. Across 24 burns, maximum temperatures ranged from 40 to 450 ˚C, and lethal heating above 60 ˚C ranged from 0 to 22 h. In addition, the fuel loads were chosen to approximate field conditions in young conifer forests of northern California where masticated residues averaged 15–63 Mg ha^{-1} (Kane et al., 2009) with extremes of 175 Mg ha^{-1} (Busse et al., 2005). The results support the well-established concept that soil heating varies broadly depending on fuel mass, soil moisture content, and soil depth, among other factors (Neary et al., 1999). With respect to our study objectives, we found no evidence of abrupt changes or thresholds in soil properties across the heating gradient. Instead, soil responses were incremental. They ranged from a slight decline in total soil C and N to a strong, progressive increase in inorganic N and comparable decrease in microbial biomass.

Soil C studies have reported a variety of responses to fire, including in the most severe case the complete loss of soil organic C (SOC) in coarse-textured soils heated to 490–500 ˚C in a muffle furnace (Badía & Martí, 2003; Fernández et al., 1997). Field studies, in comparison, have reported less drastic changes that range from 25 to 60% SOC loss as temperatures reach 300–350 ˚C in the surface layer (Armas-Herrera

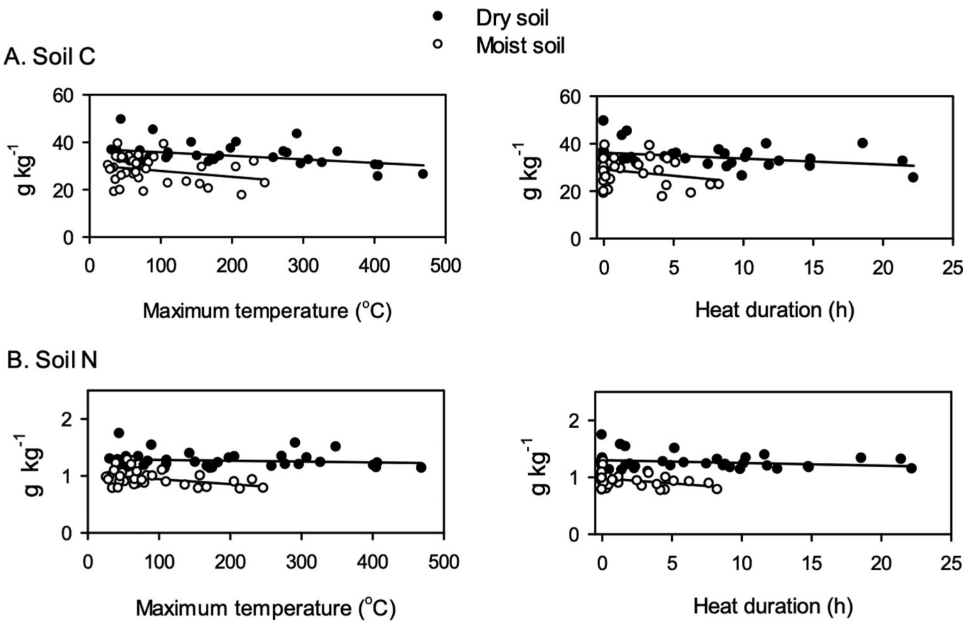

FIGURE 3 Assessment of soil heat thresholds for soil C and N. Regression plots show minimal change in soil C and N with increasing temperature or heat duration in both dry and moist soil

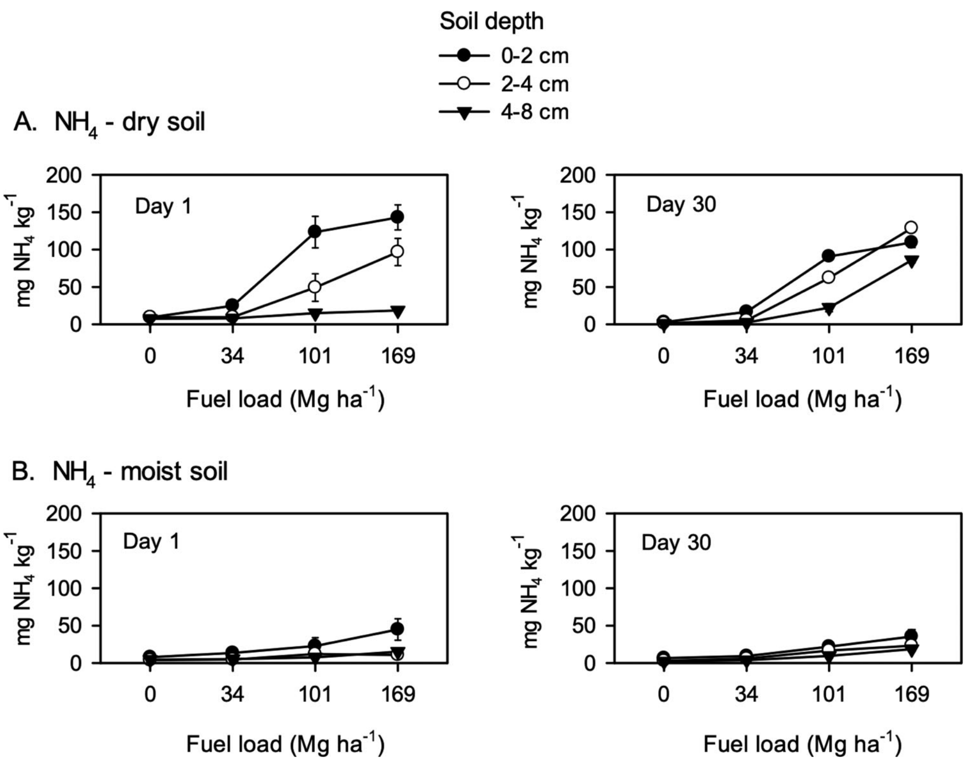

FIGURE 4 Effects of fuel load and soil depth on NH_4 concentration in (A) dry and (B) moist soil, 1 and 30 d after burning. Symbols are means plus SE ($n = 3$)

et al., 2016; Cowan et al., 2016; Granged et al., 2011; Jiménez Esquilín et al., 2007; Santorufo et al., 2021). Increases in SOC after fire have also been noted if charcoal from incomplete combustion is leached into the mineral soil (Larroulet et al., 2016). Our findings differed from these examples in that SOC showed limited change at high temperatures. Increasing fuel loads from 0 to 169 Mg ha^{-1} and temperatures from 40 to 450 ˚C had nominal effect on SOC concentrations, as the

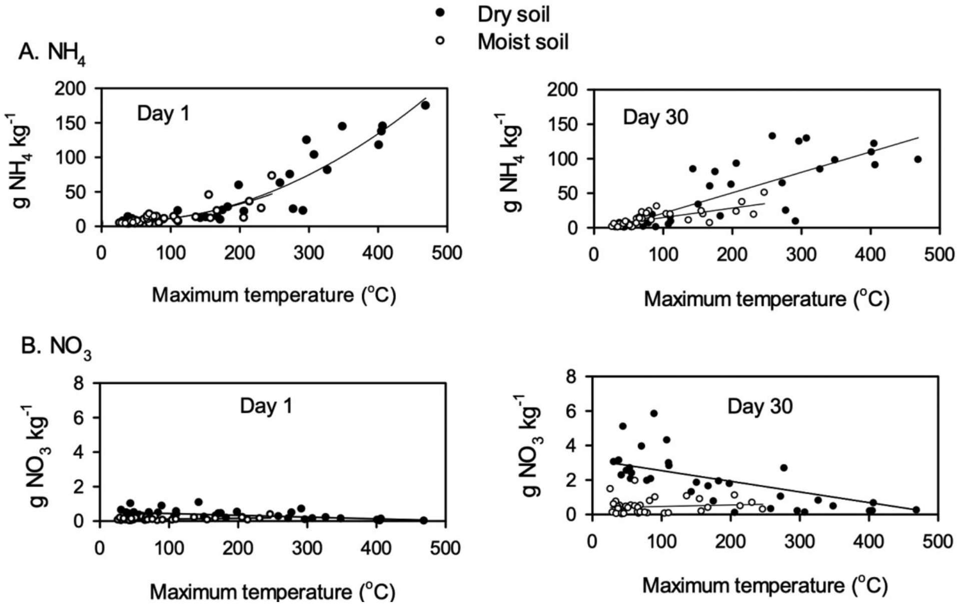

FIGURE 5 Assessment of soil heat thresholds for (A) NH_4 and (B) NO_3 concentration, 1 and 30 d after burning. Regression plots show the effect of maximum temperature on NH_4 and NO_3 separately for dry and moist soil

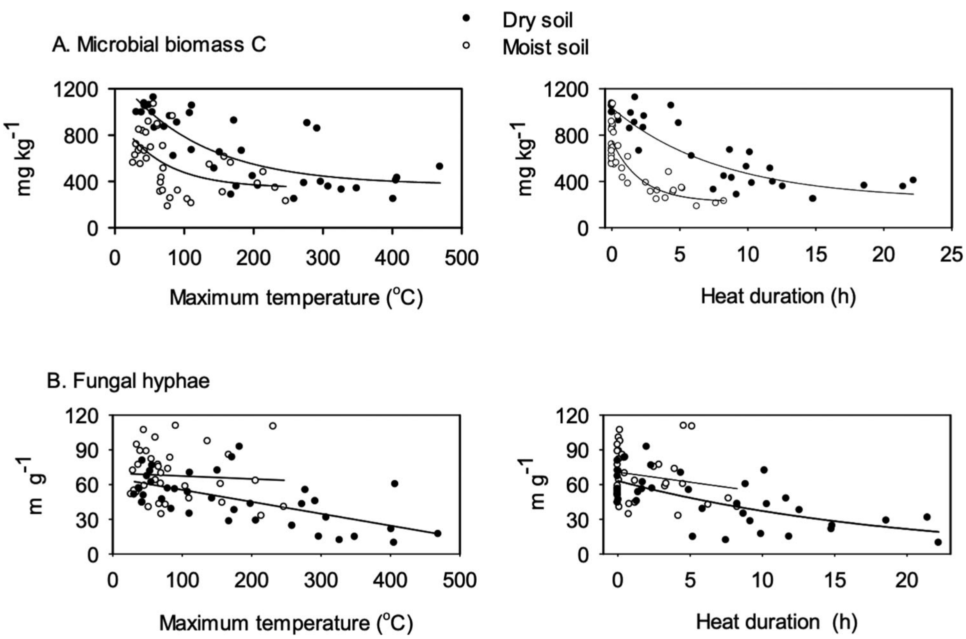

FIGURE 6 Effects of fuel load and soil depth on microbial biomass in (A) dry and (B) moist soil. Symbols are means plus SE (n = 3)

relationship between maximum temperature and SOC was either weak ($r^2 = .17$ for dry soil) or insignificant (moist soil). Two related factors are important to consider here. First, measurements of total SOC do not address proportional changes in C fractions known to occur during fire. Typically, labile organic matter is preferentially mineralized, whereas stable C fractions are resistant to fire (Prendergast-Miller et al., 2017). Thus, only knowing the total SOC response, as in our study, may oversimplify or fail to detect important changes in the relative distribution of soil C fractions during fire. Relatedly, most studies have examined soils with higher total soil organic matter content than ours and, presumably, higher concentrations of fire-sensitive, labile C. Second, clay particles are known to conserve soil organic matter by providing protected microsites and forming strong organic matter–Fe(III)–clay complexes that resist change (Giannetta et al., 2019). The

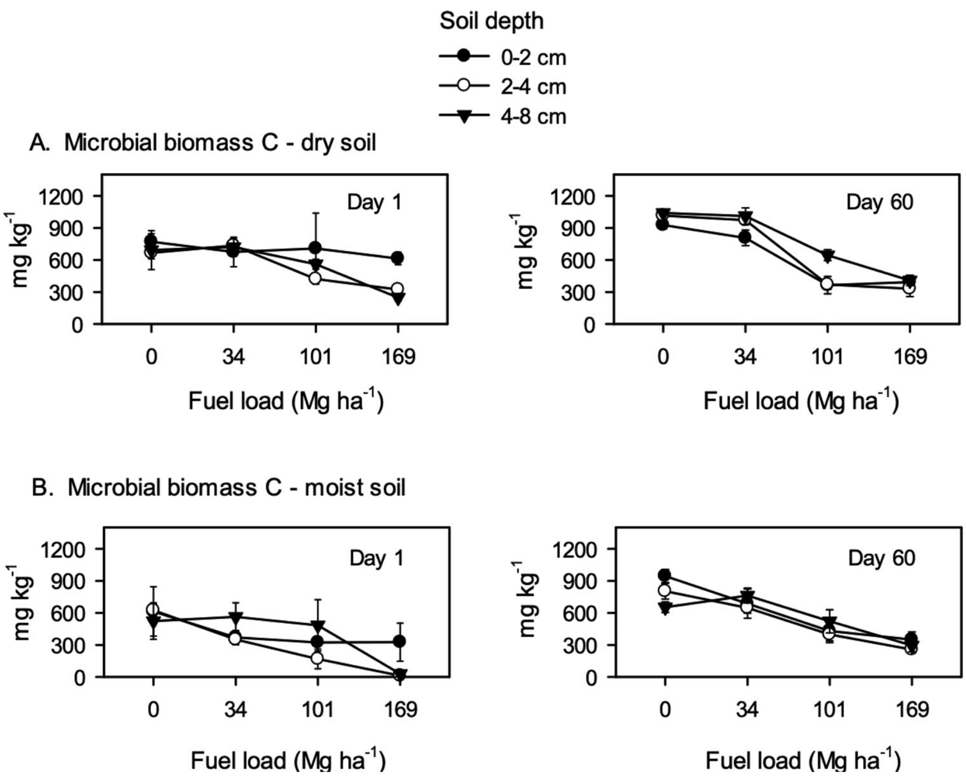

FIGURE 7 Assessment of soil heat thresholds for (A) microbial biomass and (B) fungal hyphae 60 d after burning. Regression plots show the relationship between maximum temperature and microbial properties separately for dry and moist soil

soil used in our study was 39% clay, which is considerably greater than the clay content in the abovementioned studies. We assume these two factors contributed to the minimal effect of burning on SOC, although clearly more research is needed to compare SOC losses in soils differing in clay content and stable C fractions. Here again, it is worth noting that absolute changes in SOC after high-severity fire, whether small like in our study or large, are mostly surficial, occurring in the O horizon and top few centimeters of the mineral soil profile (Neary et al., 1999). Therefore, any effects on the total SOC pool are likely to be modest except in shallow soils. Finally, our results confirm that burning masticated fuels when soils are moist is a successful practice to limit heat penetration and protect against soil organic matter loss.

Unlike the small change in soil C and N, fire produced a 10- to 15-fold increase in NH_4 concentration as temperatures increased from 150 to 475 ˚C. Again, the response was incremental, with NH_4 increasing by about 40 g kg^{-1} for every 100 ˚C increase; thus, no dramatic shift in NH_4 was observed that would suggest an exacting heat threshold. Strong responses by NH_4 to fire were previously shown by Wan et al. (2001) in their meta-analysis study. Similar to our findings, they noted that NH_4 release was greatest the upper soil layer (0–4 cm) in slash burns and wildfires where temperatures were presumed high (although not measured). Also similar to our results, they noted that nitrification was slow to proceed after fire despite increased levels of available NH_4, taking as much as 1 yr to reach peak NO_3 levels, presumably due to the sensitivity of nitrifier populations to high heat (Dunn et al., 1985).

The observed decline in microbial biomass with increasing fire severity in our study is fairly typical of literature results (Certini et al., 2021; Pressler et al., 2019), but again, we found no critical heat threshold associated with the response, especially in dry soil. Instead, the decline was fairly consistent as maximum temperatures increased from 60 to 200 ˚C, above which microbial biomass appeared to stabilize at 40–50% of that in the control plots. Microbial biomass was more sensitive to burning in moist soil, declining rapidly above 60 ˚C, and perhaps suggesting a threshold at this relatively low level of heat. However, given the modest relationship between temperature and microbial biomass (r^2 = .27), we hesitate to suggest a possible threshold without further testing of other soil textures and moisture contents. Of concern, Pressler et al. (2019) suggested that post-fire recovery by microbial biomass is generally poor and can take more than a decade before pre-fire levels are restored. Whether this is a universal response across soil types is unproven, however, and would benefit from additional monitoring in fire-prone forests.

Like microbial biomass, no heating threshold was detected for fungal hyphae in dry soil. Somewhat surprisingly, there was not a strong temperature-dependent decline in hyphal lengths in moist soil (as there was for microbial biomass). We are at a loss to explain this finding, although we surmise that a portion of the total hyphae visualized by microscopy were either dead or rendered inactive by fire. Alternatively, fire-tolerant species capable of rapidly recolonizing burned soil via hyphal proliferation may have dominated the fungal community, although this runs counter to most studies that indicate greater fire sensitivity of soil fungi compared with bacteria (Certini et al., 2021; Dunn et al., 1985).

From a practical standpoint, fuel-reduction practices (including mastication of shrubs and small-diameter trees) are an important component of healthy forest practices in California. Unforeseen risks associated with burning masticated residues, such as the strong decline in microbial biomass we observed in surface soil, may therefore be an unavoidable trade-off when promoting fire-safe landscapes. Such a trade-off would be particularly tenable where fuel loading is variable across treatment units and mosaic burn patterns are planned, thus likely resulting in spatially variable effects on soil microorganisms. Nevertheless, careful consideration of prescription conditions (fuel load, fuel moisture, soil moisture, and burning pattern) can help limit any potential damage to soil resources. Here, we would also encourage future fire-effects studies to incorporate measurements of soil heating and soil moisture to help facilitate cross-study comparisons, as recommended by Certini et al. (2021).

5 | CONCLUSION

By creating a range of soil heating profiles, we were able to show that selected soil properties respond to fire incrementally, either increasing or decreasing in a near linear fashion with no apparent heat threshold responses. Temperatures as high as 450 ˚C had limited effect on total C or N in either dry or moist soil, whereas inorganic N (increase) and microbial biomass (decrease) were substantially affected by the extreme temperatures created at the highest fuel loads (101 and 169 Mg ha^{-1}). The caveat to our findings is that only one soil texture (clay loam) was tested, and thus the results are likely less applicable to coarse-textured soils that lack the degree of heat protection provided by high clay and oxide-containing soils.

AUTHOR CONTRIBUTIONS

Matt Busse: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Writing-original draft. Carol J. Shestak: Data curation; Investigation; Methodology; Writing-review & editing. Kenneth Hubbert: Conceptualization; Investigation; Methodology; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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