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ORIGINAL RESEARCH

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Evaluating slash piles as habitat for a threatened salamander

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Abstract

Background Amplified wildfire activity in forests of the western United States threatens biodiversity. Fuel treatments can reduce fire severity, modify fire behavior, and restore forest structure and composition, yet impacts of some treatments, including slash piling and burning, on wildlife have received little attention. Piling of residual woody material may create habitable microenvironments for species that require cool, moist microclimates for all biological and ecological functions. One such species, the Sacramento Mountain salamander (*Aneides hardii* Taylor), a relictual, endemic salamander narrowly distributed in the mountains of south-central New Mexico, USA, has been found below constructed slash piles within its range, but the characteristics of occupied slash piles and the extent of their occupancy has not yet been quantified. We surveyed for Sacramento Mountain salamanders in slash piles and under logs (cover objects) adjacent to piles and within a surrounding survey plot, and related salamander occupancy to slash pile and cover object characteristics, soil moisture and temperature, and environmental setting.

Results We found Sacramento Mountain salamanders in 50% of surveyed slash piles. About 90% of salamanders were found in piles that contained black plastic sheeting, which held accumulations of moist leaf litter and other forest debris. We found no differences in pile characteristics, soil variables, or environmental setting between piles occupied by salamanders and piles in which no salamanders were detected. Salamander density was highest in slash piles, ~ 10% lower under cover objects in the survey area, and ~ 23% lower under cover objects adjacent to slash piles.

Conclusions Slash piles serve as habitat for Sacramento Mountain salamanders. Our results suggest that within our study area or similar environments within the species range, any comparable slash pile has the potential to be occupied by salamanders. Species and habitat conservation measures indicated by this study and the timing of historical detections into mid-October include constructing smaller, pyramidal piles that minimize log-on-log or log-ground contact, avoiding the inclusion of black plastic in piles, limiting residence time of piles on the landscape, and initiating pile burning in late October or early November, when most salamanders are likely to have retreated below the ground surface.

Keywords *Aneides hardii*, Fuel treatments, New Mexico, Prescribed fire, Sacramento Mountain salamander, Slash pile, Soil moisture, Wildfire, Wildlife

Resumen

Antecedentes La amplificación en la actividad de incendios de vegetación en bosques del oeste de los EEUU amenaza la biodiversidad. Los tratamientos de combustibles pueden reducir la severidad de los incendios, modificar su comportamiento, y restaurar la estructura y composición forestal, aunque los impactos de algunos tratamientos,

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incluyendo el apilado y quema de residuos de poda sobre la fauna silvestre han recibido poca atención. El apilado de residuos forestales leñosos puede crear microambientes habitables para especies que requieren microclimas fríos y húmedos para todas sus funciones biológicas y ecológicas. Una de esas especies, la salamandra de las montañas de Sacramento (*Aneides hardii* Taylor), una especie de salamandra relicto, endémica y distribuida de manera reducida en las montañas del centro sur de Nuevo México, EEUU, ha sido encontrada debajo de pilas de residuos forestales en ese rango de distribución, aunque las características de esas pilas y el tiempo de ocupación en las mismas no ha sido determinado. Relevamos las salamandras de las montañas de Sacramento en las pilas y debajo de troncos (objetos cobertores) adyacentes a las pilas y dentro de una parcela a su alrededor, y relacionamos la ocupación de las salamandras con las características de las pilas, las coberturas de troncos, las temperaturas y humedad del suelo, y otros factores ambientales.

Resultados Encontramos salamandras de las montañas de Sacramento en el 50% de las pilas relevadas. Alrededor del 90% de las salamandras fueron encontradas en pilas que contenían láminas de plástico negro, las cuales tenían hojas y otras partículas leñosas que conservaban humedad. No encontramos diferencias en las características de las pilas, en las variables del suelo, o en otras variables ambientales en pilas ocupadas y no ocupadas por salamandras. La densidad de las salamandras fue más alta en las pilas de residuos forestales, ~ 10% más baja debajo de troncos cobertores, y un ~ 23% más baja en cobertores adyacentes a las pilas de residuos.

Conclusiones Las pilas de residuos forestales sirven como hábitat para las salamandras de las montañas de Sacramento. Nuestros estudios sugieren que dentro de nuestra área de estudio o en ambientes similares dentro del área de distribución de la especie, cualquier pila de residuos tiene el potencial de ser ocupado por estas salamandras. Las medidas de conservación de la especie y de su hábitat indicadas por este estudio y el tiempo de detecciones históricas a mediados de octubre incluye la construcción de pilas piramidales más pequeñas, que minimicen el contacto entre troncos entre sí o entre troncos y el suelo evitando la inclusión de láminas plásticas negras en las pilas, limitando la residencia de las pilas en el paisaje e iniciando la quema de las mismas en octubre o principios de noviembre, cuando la mayoría de las salamandras probablemente se hayan ya retirado a lugares por debajo de la superficie del suelo.

Background

Wildfires of uncharacteristic intensity, high severity extent, duration, or frequency are considered major threats to many wildlife species around the world (Kelly et al. 2020; Santos et al. 2022; Ayars et al. 2023). Wildlife can be vulnerable to direct mortality from wildfire smoke and heat and may be negatively impacted by post-fire habitat loss or fragmentation (Kennedy and Fontaine 2009, Driscoll et al. 2021). Conversely, wildfire in its characteristic role in ecosystems is an important driver of spatial heterogeneity, promotes biodiversity, and maintains fire-adapted habitat elements (Jager et al. 2021). In the southwestern United States, fire regime disruptions include increased fire intensity and size of high severity burned areas (Singleton et al. 2019; Parks and Abatzoglou 2020), attributed to impacts of anthropogenic climate change, land use, and fire suppression on fuel flammability, continuity, and density (Abatzoglou and Williams 2016; Hagmann et al. 2021; Hanan et al. 2021).

Forest-dwelling, terrestrial salamanders in the family Plethodontidae may be particularly vulnerable to changing climate and wildfire regimes (reviewed in Hossack and Pilliod 2011; Gade et al. 2019) because of their limited dispersal abilities and reliance on cool, moist conditions for cutaneous respiration and regulation of body temperature (Iannella et al. 2025). Endemic to south-central New Mexico and living within mesic mixed-conifer forests at elevations above 2400 m (Ramotnik 1997), populations of Sacramento Mountain salamanders (*Aneides hardii* Taylor) may be adversely impacted by habitat alteration associated with historic timber harvesting, recent changes in forest structure, warmer, drier weather patterns, and large, high-severity wildfires (Ramotnik and Scott 1988; Haan et al. 2007). Although abundances of Sacramento Mountain salamanders have not been quantified since the early 2000s (Haan et al. 2007), limited surveys of historically occupied sites by the authors and others (Osborne et al. 2019) in recent years suggest that significant population declines have occurred.

Fuel treatments can reduce the likelihood of high-severity fire (Strom and Fulé 2007, Lyderson et al. 2017, Parks et al. 2018) but can also alter critical microhabitat characteristics for wildlife (Bigelow and North 2012; Otto et al. 2013; Frey et al. 2016). Species most likely to be negatively influenced are those that depend on the structural features of removed fuels (Pilliod et al. 2006). For terrestrial salamanders, forest management can result in loss of primary constituent habitat elements including moderate to high tree canopy, large fallen trees, and other structural features such as moss mats,

rocks, woody debris, and bark (Degenhardt et al. 1996; Cummer and Painter 2007). Forest disturbance that alters thermal and moisture regimes can limit the window of time during which salamanders can be active above ground, beneath rocks, or beneath or within logs on the forest floor (hereafter, "cover objects"), where it is believed that most feeding and reproduction occurs (Karraker and Welsh 2006). However, restricting fuel treatments or suppressing wildfires in salamander habitat incurs risk of subsequent high severity wildfire (Coop et al. 2016; Parks et al. 2018) and potential loss of salamander habitats and populations.

Slash pile burns (controlled burning of residual, piled debris) are often used to eliminate unmerchantable fuels remaining after fuel treatments (Evans et al. 2011; Creech et al. 2012). Pile burning is relatively cost-effective as compared with other prescribed fire treatments and can be easier to implement (Korb et al. 2004; Page-Dumroese et al. 2017). Slash pile burning has been associated with localized, adverse ecological impacts including changes in soil physical and chemical properties, loss of soil biota, altered nutrient cycling and microbial processes, and establishment of non-native plant species (Korb et al. 2004; Creech et al. 2012; Busse et al. 2013; Esquilín et al. 2007). Ecological impacts are related to characteristics of soil texture, soil moisture, and weather conditions during burning (Frandsen and Ryan 1986, Page-Dumroese et al. 2017), the distribution and density of piles within an activity area (Busse et al. 2013), fuel amount and type within piles (Hubbert et al. 2015), and pile age and the season in which piles are burned (Wright et al. 2019).

Impacts of slash piles on microenvironments prior to combustion are less well characterized than combustion dynamics. In forests of Sweden, low evapotranspiration rates beneath slash piles led to elevated soil moisture content during the growing season as compared with exposed, vegetated soil surfaces, despite low precipitation infiltration through the piles (Rosén and Lundmark-Thelin 1987). In the boreal forest of Newfoundland, Canada, slash piling resulted in cooler soil conditions during the growing season and created warmer soil temperatures during winter as compared with slash-free sites but had little impact on soil moisture (Moroni et al. 2009). In south central New Mexico, USA, soil moisture content and infiltration rates following simulated rainfall events were not different among untreated mixed conifer forested stands, thinned forest with piled slash, and thinned forest with scattered slash, although these metrics were not assessed for the soils directly under slash piles (Madrid et al. 2006). An important ecological consideration that remains largely unaddressed concerns the potential use of slash piles as habitat following fuel treatments that alter microclimate and habitat structure.

In June 2019, U.S. Fish and Wildlife Service biologists in New Mexico raised the concern that slash piles constructed after forest thinning treatments might create favorable microhabitats for salamanders, which could lead to their occurrence within slash piles at the time of burning. This concern stemmed in part from limited observations of Sacramento Mountain salamanders within slash piles (Cordova and Rawlinson 2015). As a New Mexico Threatened Species (New Mexico Department of Game and Fish, 2018), New Mexico Species of Greatest Conservation Need (New Mexico Department of Game and Fish, 2016), and a USDA Forest Service Region 3 Sensitive Species (USDA Forest Service 2013), lack of information on fuel treatment effects on Sacramento Mountain salamander populations and habitats limits potential for species conservation in the context of other management objectives (Schultz et al. 2013; Steinhoff 2018).

Our study objectives were to (1) evaluate whether slash piles are occupied by and provide habitat for Sacramento Mountain salamanders during their period of surface activity (when they are above ground), (2) quantify salamander occupancy across the study area, including within piles and under other non-pile log cover objects, and (3) compare characteristics of occupied piles and piles in which salamanders were not detected with those of log cover objects in the surrounding area. Our study was conducted in the Lincoln National Forest, New Mexico, USA, where Sacramento Mountain salamanders have been detected and where concern over risk of high severity wildfire has resulted in increased thinning treatments and planned pile burning in recent years. This study was designed to aid biologists, fire management officers, and land managers by providing guidance on the management of slash piles within the habitats of vulnerable salamander species, including *A. hardii* and other terrestrial salamanders. Importantly, information gained from this study may also inform recovery planning efforts for Jemez Mountains salamanders (*Plethodon neomexicanus* Stebbins and Riemer; Endangered, U.S. Fish and Wildlife Service 2013), a related and ecologically similar species that occurs in north-central New Mexico.

Methods

Study area

Our study site encompassed about 1.4 ha within a forested stand in the Sacramento Mountains on the Lincoln National Forest in south-central New Mexico, USA (Fig. 1A, B). Within this stand we surveyed 16 hand-constructed slash piles (Fig. 2A), in the vicinity of historical detections for Sacramento Mountain salamanders (Fig. 2B) and within suitable habitat for the species (Ramotnik and Scott 1988). Slash piles, comprised

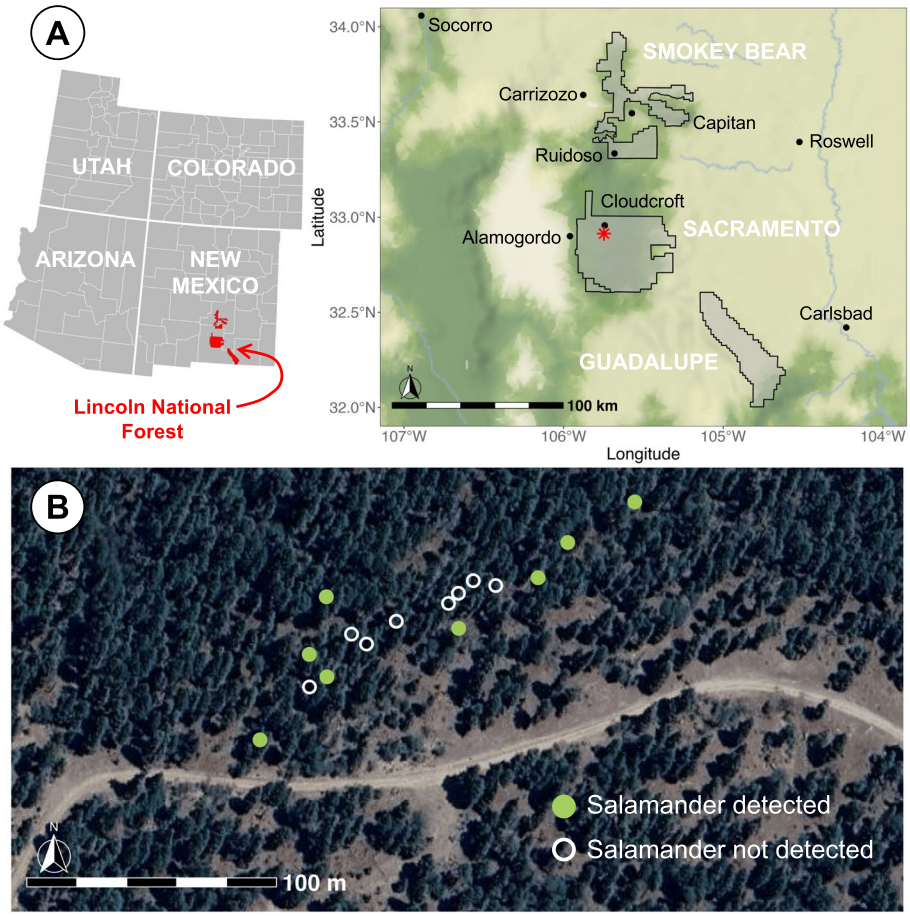


Fig. 1 **A** Study region in the Lincoln National Forest of south-central New Mexico, USA. Measured slash piles were located in a 1.4 ha study area (red starburst) within a mountainous, forested landscape (indicated as green shading) in the Sacramento Ranger District of the Lincoln National Forest. **B** Distribution of sixteen measured slash piles within the 1.4 ha study area. Filled, green circles indicate slash piles where salamanders were detected during the study, and open white circles indicate piles with no detected salamanders. Basemaps sourced from Stadia Maps, stadiamaps.com; Stamen Design, stamen.com (**A**) and Google Maps (**B**) using the ggmap package (v.4.0.1, Kahle and Wickham 2013), R Statistical Software (v4.1.1; R Core Team 2024)

of coniferous thinning debris including logs and small diameter branches, were constructed ca. 2002 following a precommercial thinning treatment (removal of all conifer trees < 9″ DBH), implemented to reduce high conifer stocking levels, remove ladder fuels, and move treated stands to a less dense, historical reference condition (USDA Forest Service 2002). Some of the slash piles included a layer of black plastic sheeting interior to the pile (Fig. 2A), intended as a moisture barrier to promote drying and expedite ignition upon burning.

The study site is flat to gently sloped (elevation 2794–2801 masl) with a moderately dense forest canopy of primarily mature Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mayr) Franco) and white fir (*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.). Midstory vegetation included smaller diameter Douglas-fir, white fir, blue spruce (*Picea pungens* Engelm.), and Rocky Mountain maple (*Acer glabrum* Torr.), and surface layers were litter, wood, moss, and rock with an herbaceous sedge, grass, and forb component. Downed logs were present throughout the study site, potentially serving as salamander cover objects (Fig. 2C). Historical fire intervals within the region's mixed conifer forests ranged from 4 to 14 years (Brown et al. 2001). Other forest-altering disturbances occurring in the region after Euro-American settlement in the mid-1800s include logging, grazing, agriculture, and fire suppression (Kauffman et al. 1998). Average precipitation (1987–2016) near the study site (Cloudcroft, Station ID 291931, 2640 m elevation) is 75 cm/year (Western Regional Climate Center 2025), with 60–70% of precipitation coming as rainfall during summer (July–September) monsoons, and the remainder falling from October to March as rain or snow (Brown et al. 2001).

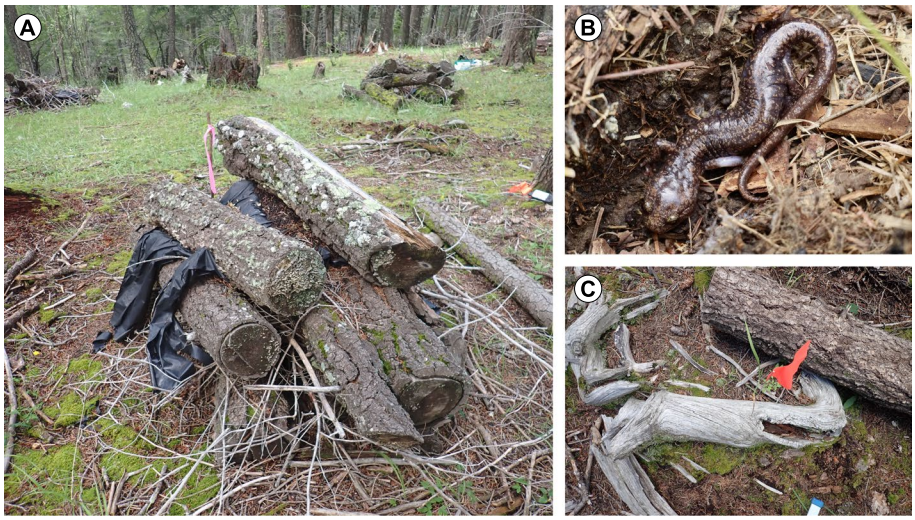


Fig. 2 **A** Slash piles (foreground and background), paraboloid in shape and consisting of coniferous logs and other residual materials from a forest thinning treatment approximately 20 years prior to our study. Note black plastic remnants, present in 11 of 16 measured piles, intended as a moisture barrier to promote drying and expedite ignition upon burning. **B** Mature Sacramento Mountain salamander (*Aneides hardii*), a New Mexico State Threatened species and Species of Greatest Conservation Need, and USDA Forest Service Region 3 Sensitive Species, detected in a slash pile during the study. **C** Log cover objects in contact with the ground surface or other logs can serve as habitat for Sacramento Mountain salamanders and other fossorial amphibians. These may include naturally recruiting logs or activity fuels associated with forest management activities. Photo credits: R. Loehman and N. Karraker, 2021

Data collection

We collected field data over a 3-day period (0800–1700 h each day) in late August 2021, during the salamander surface-active season, which is historically mid-May (Ramotnik 1997) through mid-October (University of Texas at El Paso Biodiversity Collections 2025), and when weather conditions were suitable for salamander surveys (Haan et al. 2007). During field data collection, mean air temperature was 20.9 °C (SD = 4.2) and relative humidity was 50.6% (SD = 11.2), measured at a 1-m height directly above each slash pile using a Kestral 3000 weather meter (Kestrel Weather Meters, Boothwyn, Pennsylvania).

For each slash pile, we recorded pile geometric characteristics (length, width, and height in m). We then deconstructed piles to collect data related to their constituent log characteristics and belowground environment, and to systematically survey for salamanders. For each constituent log with at least one end diameter larger than 7.62 cm (3 in.; assessed from ongoing studies to be a lower threshold for use by salamanders for woody cover objects), we measured log structural characteristics (end diameters, total length, and contact length). Contact length—the linear portion of a log in contact with the ground surface or an adjacent log—is an important variable because it represents the log microhabitat where salamanders can be detected using non-invasive survey methods. Because we did not pry bark from logs or pull apart cracks in wood, suspended portions of logs could not be evaluated for the interior presence of salamanders. We also assessed the condition or decay class of each log in the field using a stage-based classification system that identifies the range of decomposition in larger-diameter woody fuels, ranging from Class 1 (all wood sound, needles and branches present) to Class 5 (logs lacking structural integrity, with decomposed heartwood) (Maser et al. 1979; Sollins 1982; Waddell 2002). We used field measurements to calculate the volume of individual logs within piles (Smalian's formula for parabolic frustra; Freese 1974), total log volume within piles, geometric pile volume (product of pile widths [two measured sides] and height, for piles of irregular shape with straight but uneven sides; Hardy 1996), pile surface area (product of pile widths [two measured sides]) and the proportion of a pile comprised of unsound (decay class 4 or 5) logs. We recorded the presence of black plastic when it occurred within slash piles.

To determine near-surface soil moisture associated with slash piles and the adjacent soils, we measured soil volumetric water content (VWC, the ratio of water volume to soil volume) at four cardinal points (north, east, south, west) immediately below logs that were visible at the outermost pile edges and in full contact with the ground surface, and below bare ground at four cardinal points 25 cm from the outermost pile edges (i.e., not under logs or other surface objects) using a Hydrosense II TDR probe with a 12-cm-long rod inserted at an angle

to a depth of approximately 6 cm below soil surface (Campbell Scientific, Logan, Utah) (Kim et al. 2020). We measured soil temperature (T, °C) adjacent to soil VWC samples using a GroLine Soil Test Direct Soil EC Tester penetration probe (Hanna Instruments, Smithfield, Rhode Island), inserted approximately 6 cm below soil surface. Slash piles were reconstructed after measurements were completed.

To characterize environmental setting, we estimated the percent cover of surface vegetation (shrubs, grasses, forbs, moss) and other ground cover (litter, down/dead wood, rock, bare ground) in 25% cover classes within circular plots of 2-m radius surrounding each slash pile, and captured canopy cover in upward looking photographs from a reference point at the approximate center of each slash pile.

We measured structural characteristics of log cover objects located adjacent to but not associated with slash piles and surveyed for salamanders under these objects. For each slash pile, we identified the nearest log cover object with minimum end diameter >7.62 cm in each of four cardinal directions (north, east, south, or west). When the nearest log was visibly associated with a different slash pile (i.e., had once been a part of another pile), we selected other logs even when they were further from our reference slash pile. For each log cover object, we recorded distance from pile edge (m), end diameters, length in contact with the ground surface, and decay class, and measured soil VWC and temperature below the contact surface at depths of approximately 6 cm below soil surface.

We documented salamander occupancy and abundance within slash piles, beneath nearby log cover objects, and beneath downed wood within a surrounding 1.4 ha forested area. We searched for salamanders beneath and among individual pile logs and within leaf litter and debris accumulations on top of and beneath black plastic sheeting (when present) during slash pile deconstruction. As we measured nearby log cover objects we searched for salamanders beneath them, by carefully lifting or turning each object. On the final day of the study, we conducted a single survey of a 165 m × 85 m (1.4 ha) plot encompassing all slash piles but not including logs in slash piles or the logs nearby slash piles that were searched previously. To do this, five surveyors (authors plus three USDA Forest Service wildlife biologists) lined up, each approximately 10 m apart, along the westerly edge of the plot, and moved from west to east in a zigzag pattern searching beneath downed wood for salamanders. All downed logs with some portion of their length in contact with the ground surface were carefully lifted or turned; after searching beneath each object, large end diameter and small end diameter of the contact portion of the log, and contact length, were measured using a meter tape and reported to a data recorder. In all cases, when a salamander was observed it was captured, placed in a pre-moistened plastic bag, stored in a cooler until the end of the survey period, and subsequently measured and released as described below.

Because no survey protocol currently exists for the Sacramento Mountain salamander and because survey procedures are identical for the Jemez Mountains salamander, for all searches we observed U.S. Fish and Wildlife survey protocols for Jemez Mountains salamanders (U.S. Fish and Wildlife Service 2022). We disinfected our boots before and after each day using a solution that is safe for animal use, and disinfected our hands with an alcohol solution before and after handling salamanders. We placed numbered pin flags at locations of capture and the pin flag number was written on the corresponding salamander bag to ensure that each salamander was released at its precise location of capture. To protect salamander microhabitats, we did not strip bark from logs or pry apart crevices in logs during our searches, and we carefully replaced cover objects in their original locations. Measurements of slash piles, nearby log cover objects, and associated searches for and measurements of salamanders were conducted solely by the authors or trained biologists, and efforts were made to limit movements throughout and disturbance of the broader study area.

For all captured salamanders, we measured snout-vent length (from the tip of the snout to the posterior edge of the vent) and total length (from the tip of the snout to the tip of the tail) and noted salamanders with missing portions of tails. We weighed each salamander using a 10-g spring scale (Pesola AG, Switzerland). Salamanders were released immediately after measurement beneath the object under which they were found.

Analysis

All analyses were performed using R Statistical Software (v4.1.1; R Core Team 2024). Prior to analysis, we used the coveR package (v.1.0.0, Chianucci et al. 2022) to extract canopy cover (%) from upward looking photographs above each slash pile. We used Welch's two sample *t*-tests (Derrick et al. 2017) to test for differences in pile geometry and log characteristics, the belowground soil environment immediately below and immediately adjacent to piles, and environmental setting, for piles in which we detected salamanders versus piles with no detections. We used one-way analysis of variance (ANOVA) (Underwood 1997) to test for significant differences in soil VWC and T below piles, immediately adjacent to piles, and below nearby cover objects, and body size (snout-vent length and total length) of salamanders found within

slash piles or under nearby log cover objects or logs searched within the surveyed plot. Where ANOVA indicated significant differences ($P < 0.05$), we performed adjusted post hoc multiple comparisons using Tukey's honestly significant difference (HSD) tests to identify significant pairwise differences (adjusted $P < 0.05$) by measurement location. Tukey's HSD test evaluates all pairwise differences while controlling the probability of making one or more Type I errors (Adbi and Williams 2010).

We compared proportional occupancy of slash piles, nearby log cover objects, and logs searched within the surveyed plot by calculating salamander density per cubic meter of log for each location, where density = total number of salamanders detected in each location/total contact-length log volume (m^3) for each location. For slash piles, we used log end diameters and measured contact length (usually, a smaller linear distance than the total log length) to calculate contact-length log volume. For all other cover objects, length measurements and end diameters represented only portions in contact with the ground surface.

We evaluated potential interacting effects of slash pile and environmental characteristics on presence of salamanders within piles via non-metric multidimensional scaling (NMDS) using the "metaMDS" function (Dixon 2003) in the "vegan" package (v2.6.6.1, Oksanen et al. 2018). Ordination allowed us to collapse pile and environment measures into fewer dimensions to assess which characteristics are most important for differentiating piles with and without salamander detections. We used the Bray–Curtis dissimilarity index (Ricotta and Podani 2017) as the distance measure and restricted the number of ordination dimensions to the minimum necessary to achieve stress values < 0.2. We then tested for differences among piles with and without detected salamanders by overlaying 95th percentile confidence-interval ellipses around centroids within the ordination space. We used the envfit function (v2.6.6.1, Oksanen et al. 2018) to fit biplot vectors for plot-level means of pile and environment variables within the ordination, in which arrows representing the most significant variables ($P < 0.05$, corresponding to R^2 values better than expected with random data permutations) extend in the direction of increasing values for that variable.

Results

Salamander detections within slash piles and beneath other cover objects

We found a total of 38 Sacramento Mountain salamanders during this study: 18 salamanders within and below slash piles, eight salamanders under nearby log cover objects, and 12 salamanders beneath logs searched within the 1.4 ha survey plot. Salamanders occupied 50% (8/16) of surveyed slash piles (Table 1), in locations throughout the piles including beneath the lowermost logs that were in direct contact with the ground surface, between

Table 1 Characteristics of measured slash piles ($n = 16$) on the Lincoln National Forest, New Mexico, USA, 2021. Slash piles are ordered from greatest to fewest number of salamanders detected; data for individual piles include geometric properties and characteristics of constituent logs

Pile ID	Number of salamanders detected	Plastic present?	Number of logs	Pile surface area (m^2)	Pile geometric volume (m^3)	Total log volume (m^3)	Total log contact length (m)	Proportion unsound
P11	6	y	14	2.730	1.092	0.239	10.700	0.500
P10	4	y	17	4.400	3.080	0.343	12.900	0.412
P12	3	y	13	2.520	1.260	0.234	11.200	0.846
P2	1	y	16	4.200	1.638	0.249	10.200	0.125
P4	1	n	17	3.220	1.063	0.341	17.500	0.000
P9	1	y	10	3.150	1.103	0.219	11.000	0.500
P14	1	n	12	2.200	1.100	0.251	7.500	0.500
P15	1	y	14	2.850	1.425	0.168	9.000	0.571
P1	0	n	12	9.920	2.282	0.352	14.600	0.417
P3	0	n	18	7.280	2.548	0.364	14.300	0.611
P5	0	y	10	2.280	1.368	0.342	7.000	0.000
P6	0	y	5	2.470	0.864	0.137	3.900	0.800
P7	0	n	6	2.700	0.810	0.312	6.800	1.000
P8	0	y	7	1.710	0.598	0.115	6.800	0.000
P13	0	y	11	3.150	2.205	0.233	8.400	0.091
P16	0	y	13	3.300	1.980	0.414	10.400	0.231

logs within the pile on log-to-log contact surfaces, and on black plastic that contained accumulated leaf litter, bark, and other debris. Eleven (69%) of the 16 surveyed piles contained black plastic (Fig. 2A). Of those, 55% ($n=6$) contained salamanders, representing 89% of the total detections across all piles (Table 1).

We searched beneath 64 cover objects near slash piles (mean distance of 4.5 m, SD = 3.2 m, range = 0.01–11.8 m) and found salamanders beneath 11% (7/64) of these (in one case, two salamanders were found under a single cover object). During our survey of the 1.4 ha area surrounding the slash piles, we turned 115 log cover objects and found salamanders beneath 10% (12/115) of all measured logs.

Collectively, the 16 slash piles in our study contained 195 logs, with a total of 2.79 m^3 of contact length log volume. Adjacent log cover objects represented 1.60 m^3 total contact-length log volume, and logs in the 1.4 ha surveyed area represented 2.06 m^3 contact-length log volume. Salamander density was highest in slash piles (6.45 salamanders/m^3 contact-length log volume), nearly 10% lower (5.84 salamanders/m^3 contact-length log volume) under logs in the surveyed area surrounding the piles, and nearly 23% lower (4.99 salamanders/m^3 contact-length log volume) beneath logs near piles (Table 2). We found no significant differences in snout-vent length (SVL) or total length (TL) of salamanders found in slash piles (mean SVL = 33.61 mm, SD = 8.58; mean TL = 55.89 mm, SD = 12.95), below logs near piles (mean SVL = 30.75 mm, SD = 4.40; mean TL = 52.88 mm, SD = 10.33), or below logs searched within the surveyed plot (mean SVL = 33.92 mm, SD = 10.05; mean TL = 56.0 mm, SD = 15.53) (Loehman and Karraker 2025).

Pile characteristics (number of logs, surface area, geometric volume, total log volume, total contact length, proportion of unsound logs) were not significantly different between piles in which we detected salamanders versus piles with no detections (Table 1, Fig. 3). We found no significant differences in groundcover, the belowground soil environment (soil VWC and temperature), or canopy cover between occupied and unoccupied piles (Tables 3 and 4, Fig. 4).

Two NMDS ordination dimensions were sufficient to meet the stress threshold (stress scores < 0.2). The ordination plot (Fig. 5) showed likely correlations among most variables (e.g., pile geometry and log characteristics) where biplot vectors were co-located in multidimensional space. Ordination points, representing individual slash piles, were not clustered within the plot by salamander occupancy, and confidence-interval ellipses overlapped, indicating no clear separation of pile characteristics and environmental setting between piles in which we detected salamanders versus piles within which no salamanders were detected.

Characteristics of slash piles and other log cover objects

All slash piles were irregularly solid in shape, with straight but unequal dimensions for opposing sides (Hardy 1996). Piles were constructed with horizontal log orientation (long axis parallel to the ground surface), maximizing log-ground and log–log contact below and within each pile. Pile mean height was 0.45 m (SD = 0.14), mean surface area was 3.63 m^2 (SD = 2.11) and mean geometric volume was 1.53 m^3 (SD = 0.70) (Table 1). Across all measured piles, individual log length ranged from 0.5 to 2.8 m (mean = 1.42, SD = 0.36) and mean log diameter (average of two ends for each log) ranged from 6.15 to 26.65 cm (mean = 13.45, SD = 4.51) (Loehman and Karraker 2025).

Of the 195 logs measured in piles, most were decay class 3 (57.4%, $n=112$) or 4 (38.5%, $n=75$), corresponding to logs with sloughing, detached or absent bark, absent or nearly absent sapwood, mostly sound to rotten heartwood, with some remaining branches or branch stubs (Sollins 1982). Less than 5% of logs were of decay class 2 (bark mostly intact, sapwood and heartwood sound, large twigs and branches present) or 5 (bark detached or absent, no intact woody structures or branches). Ground cover surrounding slash piles, measured as percent of horizontal cover, was comprised mainly of litter (mean = 65.94%, SD = 23.04), woody debris (mean = 27.19%, SD = 13.16), grass (mean = 24.38%, SD = 12.76%), forbs (mean = 22.81%, SD = 10.80), and moss (mean = 19.38%, SD = 20.07), with lesser amounts of shrub cover (mean

Table 2 Proportional occupancy of slash piles ($n=16$), nearby log cover objects ($n=64$), and logs searched within the surveyed plot ($n=155$) on the Lincoln National Forest, New Mexico, USA, 2021. Salamander density is calculated as total number of salamanders detected in each location per total contact-length log volume (m^3) for each location

Location	Number of salamanders detected	Total contact-length log volume (m^3)	Salamander density per m^3 contact length
Slash pile	18	2.79	6.45
Logs adjacent to slash piles	8	1.60	4.99
Logs within the 1.4 ha survey plot	12	2.06	5.84

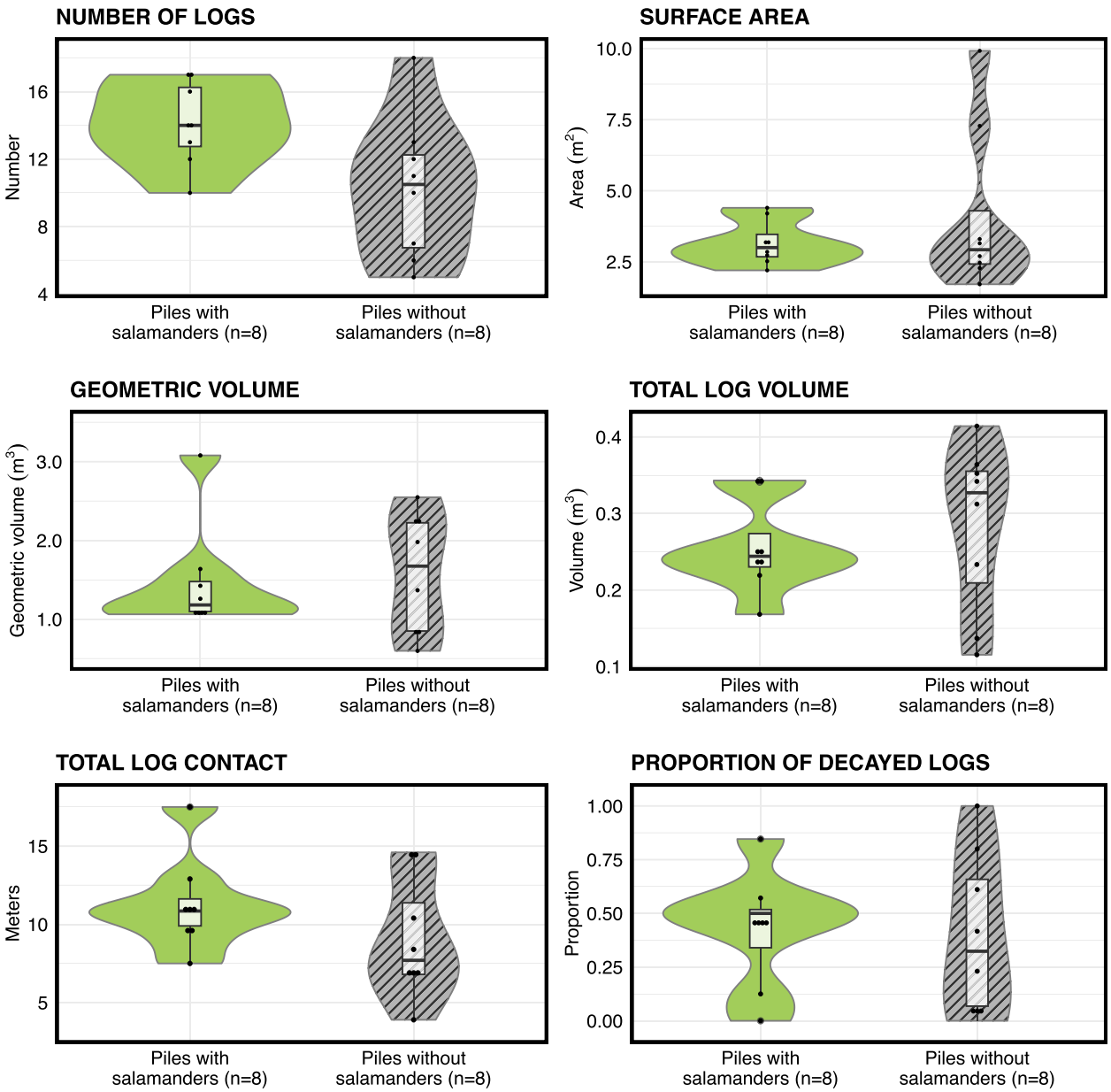


Fig. 3 Number of logs, surface area (m^2), geometric volume (m^3), total log volume (m^3), total log contact (m), and proportion of decayed logs for slash piles where salamanders were detected ($n = 8$) (green fill) versus piles where salamanders were not detected ($n = 8$) (grey fill) during our study in late August 2021, in the Lincoln National Forest of south-central New Mexico, USA. Boxplots bound the interquartile range (IQR) divided by the median, whiskers extend to a maximum of 1.5 times the IQR, and circles are individual data points. Encompassing violin plots indicate kernel probability density, such that the width of the shaded area represents the proportion of the data located there. We found no significant differences (Welch's two sample *t*-tests, $P < 0.05$) in variables between slash piles where salamanders were detected versus piles where salamanders were not detected. Mean values are provided in Table 1

=6.25%, SD =5.0%), rock (mean =5.94%, SD =5.23), and bare ground (mean =5.63%, SD =5.44). Canopy cover above slash piles ranged from 42 to 84% (mean =62.87%, SD =11.92%) (Table 3).

Within piles, the number of logs per pile ranged from five to 18 (mean =12.19, SD =3.92). Mean log contact length ranged from 0.63 to 1.22 m (mean =0.85, SD =0.19). Total log contact length per pile (summed contact portion for all logs within a pile) ranged from 3.9 to 17.5 m (mean =10.14, SD =3.50), and total log volume (the summed volume of all individual logs within a pile) ranged from 0.12 to 0.41 m^3 (mean =0.27, SD =0.087).

Table 3 Percent cover of surface vegetation and other ground cover (estimated in 25% cover classes) within circular plots of 2-m radius surrounding each slash pile ($n = 16$), and overstory canopy percent cover (calculated via interpretation of upward-looking photographs), Lincoln National Forest, New Mexico, USA, 2021

Pile ID	Number of salamanders detected	Grass	Forbs	Shrubs	Litter	Rock	Bare ground	Wood	Moss	Canopy cover
P11	6	25.00	50.00	5.00	75.00	5.00	5.00	25.00	25.00	76.86
P10	4	5.00	25.00	5.00	50.00	25.00	5.00	25.00	25.00	56.79
P12	3	25.00	25.00	5.00	75.00	5.00	5.00	50.00	25.00	76.06
P2	1	25.00	25.00	5.00	50.00	5.00	5.00	25.00	5.00	56.21
P4	1	25.00	25.00	5.00	100.00	5.00	5.00	25.00	25.00	60.45
P9	1	25.00	25.00	5.00	75.00	0.00	5.00	25.00	25.00	55.80
P14	1	25.00	25.00	5.00	75.00	5.00	5.00	25.00	50.00	45.73
P15	1	25.00	5.00	5.00	75.00	5.00	5.00	5.00	5.00	53.55
P1	0	50.00	25.00	5.00	5.00	5.00	25.00	25.00	5.00	42.35
P3	0	25.00	25.00	25.00	75.00	5.00	5.00	50.00	5.00	73.06
P5	0	25.00	25.00	5.00	75.00	5.00	5.00	25.00	25.00	65.74
P6	0	25.00	25.00	5.00	75.00	5.00	5.00	25.00	0.00	63.03
P7	0	25.00	25.00	5.00	75.00	5.00	5.00	25.00	5.00	66.18
P8	0	5.00	5.00	5.00	75.00	5.00	0.00	50.00	5.00	84.13
P13	0	5.00	5.00	5.00	75.00	5.00	5.00	25.00	5.00	75.88
P16	0	50.00	25.00	5.00	25.00	5.00	0.00	5.00	75.00	54.07

Table 4 Mean soil volumetric water content (VWC, %) and temperature (°C) of individual slash piles ($n = 16$) on the Lincoln National Forest, New Mexico, USA, 2021. Soil moisture and temperature were measured at depths of approximately 6 cm below soil surface, at each of four cardinal points (north, east, south, west) immediately below logs that were visible at the outermost pile edges and in full contact with the ground surface. Values in ellipses are one standard deviation around the mean measurement value of four locations per pile

Pile ID	Number of salamanders detected	Mean (SD) soil VWC (%)	Mean (SD) soil temperature (°C)
P11	6	24.73 (3.55)	14.6 (0.392)
P10	4	25.93 (5.71)	13.83 (0.263)
P12	3	23.33 (4.87)	12.43 (0.403)
P2	1	21.85 (3.35)	13.93 (0.206)
P4	1	22.08 (4.77)	13.6 (0.294)
P9	1	24.48 (4.40)	14.13 (0.386)
P14	1	21.85 (3.66)	13.05 (0.289)
P15	1	23.43 (4.04)	13.5 (0.408)
P1	0	24.38 (5.94)	14.45 (0.208)
P3	0	21.93 (4.16)	13.75 (0.451)
P5	0	21.88 (3.27)	13.35 (0.412)
P6	0	20.78 (4.31)	14.68 (0.55)
P7	0	19.55 (2.26)	15.25 (0.208)
P8	0	18.38 (1.78)	14.58 (0.532)
P13	0	19.83 (2.80)	13.28 (0.512)
P16	0	23.63 (2.78)	12.925 (0.15)

The proportion of logs of decay class 4 or 5 (hereafter, "unsound") in piles, assessed to be important constituents of salamander habitat and cover because progressive decay increases access to the undersides and interiors and colonization by invertebrate prey (Maser et al. 1979), ranged from 0 to 100 (mean = 41.27, SD = 31.63) (Table 1).

We measured 64 log cover objects adjacent to but disconnected from measured piles. Logs were a combination of naturally recruiting woody material and activity fuels, with mean log length of 1.68 m (SD = 1.82), mean log end diameter of 13.68 cm (SD = 6.69), and mean log volume of 0.025 m^3 (SD = 0.026). Most (68.8%, $n = 44$) logs were of decay class 4, with fewer decay class 3 (17.2%, $n = 11$) or decay class 5 (14.1%, $n = 9$) members. In the 1.4 ha survey area, we measured 115 log cover objects that were comprised of naturally recruiting woody material and activity fuels, with mean log contact length of 1.09 m (SD = 0.70), mean log end diameter of 13.42 cm (SD = 4.74) and mean log volume of 0.018 m^3 (SD = 0.017) (Loehman and Karraker 2025).

We found significant differences in soil VWC (*ANOVA*, $F_2 = 13.56$, $P \leq 0.001$) and soil temperature (*ANOVA*, $F_2 = 3.54$, $P \leq 0.05$) by measurement location (Fig. 5). Soils were ~15% wetter beneath bare ground immediately adjacent to piles (mean = 26.28%, SD = 6.97; Tukey's adjusted $P \leq 0.001$) than beneath pile logs (mean = 22.37%, SD = 4.04), and ~18% wetter than beneath

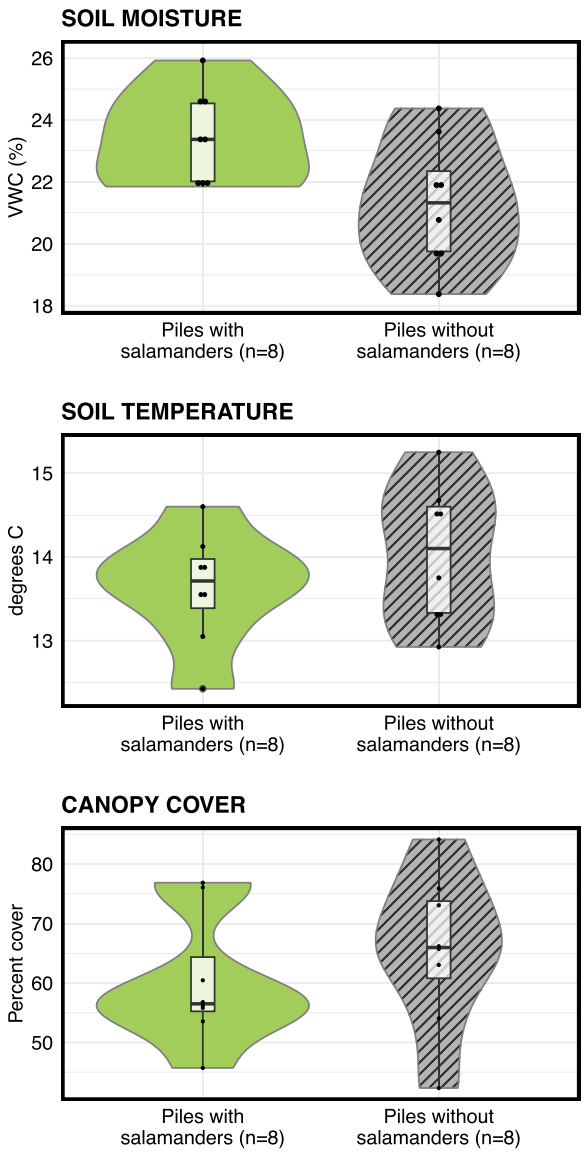


Fig. 4 Soil volumetric water content (VWC, %), soil temperature (ºC), and canopy cover (%) for slash piles where salamanders were detected ($n = 8$) (green fill) versus piles where salamanders were not detected ($n = 8$) (grey fill) during our study in late August 2021, in the Lincoln National Forest of south-central New Mexico, USA. Boxplots bound the interquartile range (IQR) divided by the median, whiskers extend to a maximum of 1.5 times the IQR, and circles are individual data points. Encompassing violin plots indicate kernel probability density, such that the width of the shaded area represents the proportion of the data located there. We found no significant differences (Welch's two sample *t*-tests, $P < 0.05$) in variables between slash piles where salamanders were detected versus piles where salamanders were not detected. Mean values are provided in Table 4

nearby log cover objects (mean = 21.63%, SD = 4.86; Tukey's adjusted $P \leq 0.001$) (Table 5). Soil VWC was not significantly different beneath piles or nearby cover objects. Soils were ~3% warmer beneath cover objects near piles (mean = 14.30, SD = 1.05; Tukey's adjusted $P \leq 0.05$ than beneath piles (mean = 13.83, $SD = 0.80$; Tukey's adjusted $P \leq 0.05$); we found no significant differences in soil temperature below piles versus adjacent bare ground (Table 5, Fig. 6).

Discussion

We determined that slash piles can serve as habitat for Sacramento Mountain salamanders. In our study, 50% of surveyed piles were occupied by one or more salamanders. We found no significant differences in the physical characteristics, environmental setting, or the belowground soil environment between occupied and unoccupied piles, suggesting that any slash pile in the study area exhibiting characteristics within the measured ranges could be occupied by salamanders during the salamander surface-active season of mid-May through mid-October. Nearly 90% of all salamanders documented in our study were found in slash piles that contained black plastic. Plastic sheeting can be incorporated into hand constructed slash piles in wetter environments to promote drying, allowing for more rapid and complete combustion of piles when they are burned (Barker et al. 2025). We found that black plastic accumulated leaf litter, bark, and other detritus, creating a moist organic layer. Presence of this layer may have *amplified* the amount of microhabitat available within slash piles that included plastic sheeting.

Limited research has examined the use of slash piles by amphibians. An experimental study (Rittenhouse et al. 2008) in Missouri, USA, evaluated water loss and survival of juveniles of three species of frogs in small enclosures established in forested drainages, forested ridgetops, and clearcuts with and without constructed brush piles (containing coarse woody debris >10 cm in diameter). Presence of brush piles reduced risk of desiccation mortality and increased survival as compared with forested ridgetops and open clearcuts and buffered the effects of low soil moisture on desiccation time. All three frog species exhibited lower water loss and higher survival in brush piles in clearcuts than in forested ridgetops and open clearcuts (Rittenhouse et al. 2008).

Another study (Romano et al. 2018) evaluated factors influencing occupancy by alpine salamanders (*Salamandra atra* Laurenti) in spruce, fir, and beech forested stands in Italy. Presence of brush piles containing fine woody debris (< 10 cm diameter) was positively associated with occupancy of forested stands, potentially because these structures may have mitigated the negative desiccation effects of timber harvest on habitat.

Woody debris deposits have been termed a "multifunctional resource" for amphibians (Indermauer et al. 2009)

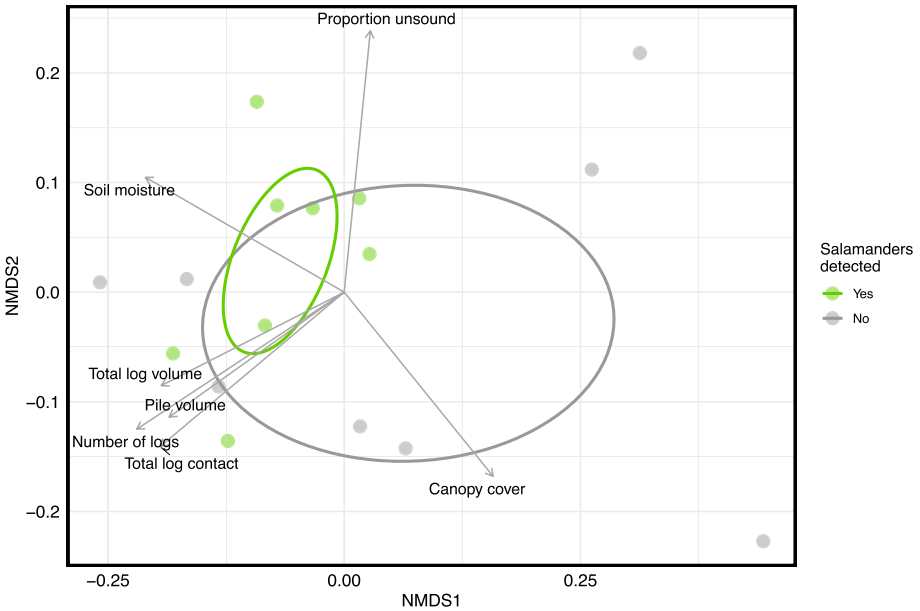


Fig. 5 Nonmetric multidimensional scaling (NMDS) ordination of environmental variables associated with 16 slash piles measured in late August 2021, in the Lincoln National Forest of south-central New Mexico, USA. Green (salamanders detected) or grey (no salamanders detected) dots represent the location of individual piles by occupancy in multidimensional space, defined by environmental measurements. Ellipses are 95th percentile confidence intervals (standard error) around centroid means by occupancy (green = salamanders detected; grey = no salamanders detected). Biplot arrows extend in the direction of increasing values for each significant ($P < 0.05$) environmental variable

Table 5 Mean, minimum, and maximum soil volumetric water content (VWC, %) and temperature (°C) below slash piles ($n = 64$), adjacent bare ground ($n = 64$), and nearby log cover objects ($n = 64$), measured at depths of approximately 6 cm below soil surface on the Lincoln National Forest, New Mexico, USA, 2021. Values in ellipses are one standard deviation around the mean measurement value of four locations per pile

Sample location	Mean (SD) soil VWC (%)	Minimum soil VWC (%)	Maximum soil VWC (%)
Slash pile	22.37 (4.04)	15.3	32.7
Bare ground	26.28 (6.97)	10.8	40.3
Cover object	21.63 (4.86)	11.7	32.8
Sample location	**Mean (SD) soil temperature (°C)**	**Minimum soil temperature (°C)**	**Maximum soil temperature (°C)**
Slash pile	13.83 (0.8)	12.1	15.5
Bare ground	14.05 (1.23)	12	18.3
Cover object	14.3 (1.05)	12.3	16.9

because they provide both shelter and food. Although the species and treatments in the two studies described above differ from those in our study, collectively the results indicate that slash (brush) piles containing either coarse (> 10 cm diameter) or fine (< 10 cm diameter) woody debris create microclimate and microhabitat conditions suitable for some species of amphibians. These microhabitats may be particularly important as buffers against increasingly warm and arid conditions associated with changing climate, increased forest disturbance, and forest management.

At our study site, salamanders occurred at a higher density in slash piles than beneath log cover objects near piles or under log cover objects in the surveyed area surrounding the slash piles. Soil VWC did not differ significantly between piles (mean = 22.37%, range = 15.30–32.70%) and nearby logs (mean = 21.63%, range = 11.70–30.80%). Soil moisture is critical to surface activity of this terrestrial species, and in a previous study Sacramento Mountain salamanders were detected at levels ranging from 22.65 to 77.15% (Haan et al. 2007). Although soil moisture levels documented in our study were lower than those reported by Haan et al. (2007), comparability in soil moisture between slash piles and nearby log cover objects suggests that this variable did not influence densities of salamanders we observed in the two cover types.

Although soil temperature was statistically lower beneath piles than nearby logs, likely due to the three-dimensional structure of slash piles providing additional shading to that contributed by overstory and understory canopy, we do not believe that an average difference of

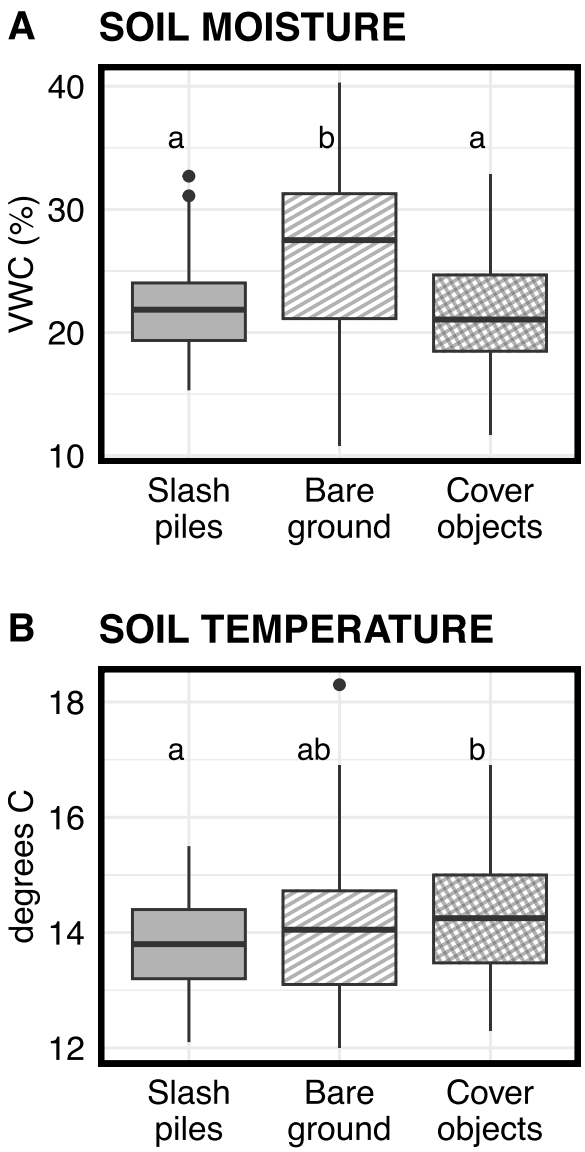


Fig. 6 **A** Soil volumetric water content (VWC, %) and **B** soil temperature (°C) measured approximately 6 cm below soil surface beneath exterior slash pile logs ($n = 64$) (solid fill), bare ground ($n = 64$) (diagonal fill), and adjacent single-log cover objects ($n = 64$) (hatched fill) in late August 2021, in the Lincoln National Forest of south-central New Mexico, USA. Boxplots bound the interquartile range (IQR) divided by the median, whiskers extend to a maximum of 1.5 times the IQR, and letters indicate significant groupings based on adjusted post hoc multiple comparisons (Tukey's HSD, adjusted $P < 0.05$). Mean values are provided in Table 5

1 °C is biologically significant. Temperatures measured in association with 390 cover objects (logs and rocks) under which Sacramento Mountain salamanders were found in a previous study ranged from 8.0 to 18.0 °C (mean = 11.4 °C) (Williams 1978). In contrast, Haan et al. (2007) detected Sacramento Mountain salamanders under cover objects at soil temperatures up to 28.3 °C. Given that the maximum soil temperature we measured was 16.9 °C, differences in soil temperature are unlikely to explain higher salamander density in piles than nearby log cover objects. Importantly, our study was conducted over three consecutive days in the peak of the monsoonal rainy period in the region. Thus, our spatially and temporally discrete study conducted during a cooler, wetter period optimized condition for detecting salamanders but also limited variability in microclimate conditions. As with all fossorial salamanders that move above and below ground in response to changes in temperature and moisture (e.g., Spotila 1972), detection is imperfect and we may have failed to detect salamanders within the study area that were not active on the surface. It is not known if this species is nocturnal or diurnal, and the timing of surveys may also influence detection probability. However, given that surveys of slash piles, nearby logs, and logs within the surrounding 1.4 ha area all occurred during the day on three consecutive days and in similar weather conditions, we expect that salamander detection probability was likely comparable across the three groups.

Some species in the genus *Aneides* are territorial, and males and females display agonistic behavior toward conspecifics (Staub 1993). As such, individuals are generally found singly beneath or within a cover object, except during mating. Sacramento Mountain salamanders, however, are occasionally found clustered in groups of two to four individuals, and up to eight individuals, under a single cover object (N. Karraker, University of Rhode Island, Kingston, Rhode Island, USA, unpublished data, 2021). In one slash pile, we found six salamanders. As this species is known to share cover objects, it is unlikely that our finding of higher densities of salamanders in slash piles can be attributed to the limiting effects of increased structural complexity on agonistic interactions.

We conclude that the higher density of Sacramento Mountain salamanders calculated for slash piles versus individual log cover objects (nearby logs or those in the surrounding surveyed area) is most likely due to higher volume of coarse woody debris in piles as compared with the surrounding environment, equating to larger areas of suitable microhabitat and potentially increased prey abundance within structurally complex slash piles. Higher abundances of other species of terrestrial, lungless salamanders in the family Plethodontidae have been linked to increased amounts of coarse woody debris. In research on the red-backed salamander (*Plethodon cinereus* Green) in hardwood forests in Vermont, USA, density of coarse woody debris strongly influenced abundance of salamanders (McKenny et al. 2006). Similarly, abundance of Oregon slender salamanders (*Batrachoseps wrighti* Bishop) was positively associated with quantities

of coarse woody debris in conifer-dominated stands in Oregon, USA (Homyack and Kroll 2014).

In contrast to studies based on shorter (< 3 years) residence times (Busse et al. 2013; Wright et al. 2019), the slash piles we surveyed had been constructed about 20 years prior to our study and were comprised of decaying logs. Wood density, biomass, shape, compactness, and size decrease with increasing decay (Russell et al. 2014); for example, the projected mass loss for 10-year old hand-piled fuels in the Jemez Mountains of New Mexico was ~50% of original pile biomass (Wright et al. 2017). Pile age also affects combustion dynamics, including decreased peak flame height, increased duration of flaming, and decreased fuel consumption, as documented over a 2-year experiment in north-central New Mexico (Wright et al. 2019). Long residence time of slash piles in treated stands may increase their suitability as salamander habitat, while decreasing the efficiency of their combustion when they are burned.

Fuel treatments are an important management tool for reducing risk of high severity wildfire and increasing forest resilience to disturbances (Stephens et al. 2012; Lydersen et al. 2017; Coop et al. 2020). As demonstrated in this study, residual fuels can also be wildlife habitat, potentially serving as important microrefugia (locally favorable environment amidst an unfavorable regional environment) (Dobrowski 2011). In the southwestern United States, climate regimes over the past several decades have included the highest temperatures in the observed record (Williams et al. 2013), anomalously severe drought and hydrologic stress (Overpeck and Udall 2020), and soils of greater aridity than in any other period since the late 1500s megadrought (Williams et al. 2020). Given expectations of continuing aridification and amplification of wildfire activity across the western United States (Brown et al. 2021), fuel treatments can be seen as both challenges and opportunities for species conservation.

This study represents a critical step in planning efforts to support conservation of Sacramento Mountain salamander populations in the context of necessary, on-going land management activities. There are no consistent guidelines within land management agencies for construction and burning of slash piles (Seymour and Tecle 2004), and this raises concerns because of potential risks to threatened or endangered species, such as Sacramento Mountain salamanders. A wide range of variability within and between slash pile types exists because of differences among methods used to construct piles and the materials within a pile (Page-Dumroese et al. 2017). Further work is needed to relate salamander occupancy to variation in pile characteristics (e.g., size, geometry, log orientation, age) across species ranges.

Based on our understanding of the species' life history and best evidence from this and other studies, the following considerations could benefit salamander habitat:

(1) *Slash pile construction.* Slash piles oriented pyramidally limit log contact with soils at their bases and log-on-log contact along their height, potentially reducing the availability of suitable microhabitats within a pile. In contrast, slash piles with horizontal stacking of larger-diameter logs (such as those in this study) result in greater log-soil and log-on-log contact, creating large areas of suitable microhabitat for salamanders within the piles. When possible, avoid incorporating black plastic sheeting in slash piles to reduce the probability of amplifying microhabitat areas, particularly when burning of slash piles may be delayed for several years. Piles dominated by large diameter wood generally burn for longer periods of time at elevated, lethal temperatures, particularly at the soil surface and near-surface depths, as compared with piles consisting of smaller diameter slash (Busse et al. 2013; Hubbert et al. 2015).

(2) *Timing of slash pile burning.* Pile burning outside of the surface-active period for Sacramento Mountain salamanders (generally, the active period is May through October) reduces potential for pile occupancy, as salamanders are presumed to be belowground outside of this period (Ramotnik 1997). Pile burning when soils are moist (e.g., atop snow cover or after rain or snowfall) can limit heat pulse intensity through soils (Frandsen and Ryan 1986; Massman et al. 2003), moderating potential adverse impacts to soil properties and biota beneath piles (Rhoades et al. 2021).

(3) *Age of piles.* As constituent logs begin to decay, piles may become increasingly suitable as microhabitat for salamanders (Welsh and Lind 1988; Otto et al. 2013). As specified in fuel treatment guidelines for projects within the habitat of the endangered Jemez Mountains salamander, burning piles within 1.5 to 2 years of creation limits the potential for colonization by individual salamanders (USDA Forest Service 2023).

(4) *Retention of coarse woody debris following timber harvesting.* Retention of some piles or other downed woody material within managed forests may contribute to biodiversity conservation, including salamanders (Romano et al. 2018). Previous studies have documented positive relationships between salamander abundance and downed woody material quantity or volume, particularly when the mate-

rial is well-decayed (McKenny et al. 2006; Otto et al. 2013).

Conclusions

Our study represents one of the first efforts to evaluate the microenvironmental conditions within slash piles relative to their potential use as habitat by salamanders in the western United States. Forest management activities, including forest thinning and slash pile burning, are important tools for mitigating the risk of uncharacteristic high-severity wildfires in forests with historically frequent, low-severity fire regimes (Hood et al. 2024) and promoting forest resilience to future drought and fire (Stephens et al. 2020). These activities serve as a precursor to restoring wildland fire to ecosystems (Stevens et al. 2014). Embedding science central to wildlife conservation within a forest management context is important for equitable consideration of species and their habitats with other land management priorities. We encourage future research on the retention of limited slash piles as a conservation tool or habitat restoration approach for forest-dwelling salamanders, particularly across a diversity of forest habitats, inclusive of a range of fuel treatment characteristics.

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Authors' contributions
RL designed the study, collected data, conducted analyses, interpreted results, and drafted the manuscript; NK designed the study, collected data, interpreted results, and drafted the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are published (Loehman and Karraker 2025) and included in this published article and its supplementary information files.

Declarations

Ethics approval and consent to participate
This research was conducted under New Mexico Department of Game and Fish permit #3175, and University of Rhode Island Institutional Animal Care and Use Protocol AN1718-005.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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