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Reexamining the relationship between post-fire twig diameter and fire intensity in California's chaparral to better assess fire severity

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Abstract

Background Chaparral, including maritime chaparral, burns at high severity, but also has unique fire intensities within sites due to weather, topography, and fuels. These differences cause unique fire effects, including fuel consumption and floral biodiversity. A highly instrumented prescribed headfire within a steep canyon (California Canyon Fire Experiment, Salinas, CA) provided an opportunity to investigate the relationship between thermal image measurements, taken from both helicopter and ground stations, and vegetation burn severity. We used remote sensing to describe thermal exposure as a proxy for fire intensity, including maximum temperature and duration at high temperatures, across a range of fire intensities. Then, we compared methods of measuring post-fire remaining twig diameter for two species: *Adenostoma fasciculatum* (chamise) and *Salvia mellifera* (black sage).

Results Our results show that some post-fire twig diameter sampling methods do not relate well to thermal imagery-based thermal exposure. Duration of heating is a better indicator of fire effects than maximum temperature. For duration of heating, twig diameter is influenced most by how long the shrubs burn above lower temperatures rather than time at higher temperatures. While black sage and chamise have significantly distinct fire effects in terms of remaining twig diameter, the magnitude of difference was small and likely not ecologically important. Lastly, because the relationship between severity and twig diameter may diminish as twig tips weather, the timing of measurements is an important consideration for post-fire assessments.

Conclusions More wildfires and prescribed fires are occurring in chaparral, and both researchers and managers want to assess their fire effects. For prescribed fires, managers and researchers concerned about the desired heterogeneity of fire effects may benefit from using twig measurements as a fire severity proxy. More understanding of chaparral fire effects is needed to grasp the implications on biodiversity. Future refinement of estimating fire severity may help researchers and managers in this goal.

Keywords Fire effects, Shrubland, Shrub, Wildfire, Prescribed fire, Mediterranean, California Canyon Fire Experiment

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Resumen

Antecedentes El chaparral, incluyendo el chaparral costero, se quema a alta severidad, pero tiene también intensidades de fuego únicas dentro de los diferentes sitios debido al tiempo meteorológico, la topografía y los combustibles. Esas diferencias causan efectos del fuego únicos incluyendo el consumo de combustible y la diversidad floral. Una quema prescrita frontal altamente instrumentada dentro de un cañón con mucha pendiente (California Canyon Fire Experiment, Salinas, CA), proveyó de una oportunidad única para investigar las relaciones entre mediciones realizadas con imágenes térmicas, tomadas tanto desde un helicóptero como de estaciones terrestres, y la severidad de la quema sobre la vegetación. Usamos sensores remotos para describir la exposición térmica como un proxy de la intensidad del fuego, incluyendo temperaturas máximas y su duración a altas temperaturas, a través de un rango de intensidades del fuego. Luego, comparamos los métodos para medir el diámetro de los tallos remanentes en el post fuego de dos especies: *Adenostoma fasciculatum* (manzanita) y *Salvia mellifera* (salvia negra).

Resultados Nuestros resultados muestran que el método de medir el diámetro post fuego de los tallos no se relaciona bien con las obtenidas mediante la exposición de las imágenes térmicas. La duración del calentamiento es un mejor indicador de los efectos del fuego que las temperaturas máximas. En la duración del calentamiento, el diámetro de los tallos resulta más influenciado por cuánto tiempo los tallos se queman por encima de temperaturas más bajas que el tiempo que lo hacen a altas temperaturas. Mientras que la manzanita y la salvia negra tienen efectos del fuego significativamente diferentes en relación al tallo remanente post fuego, la magnitud de la diferencia fue muy pequeña y probablemente no importante desde el punto de vista ecológico. Finalmente, dado que la relación entre severidad y el diámetro del tallo disminuye con el tiempo, el tiempo que requiere la medición es una consideración importante a tener en cuenta para la determinación de efectos en el post fuego.

Conclusiones Más incendios y quemas prescritas ocurren en el chaparral, y tanto investigadores como gestores de recursos quieren determinar los efectos de los diferentes fuegos. Para las quemas prescritas, tanto los investigadores como los gestores están preocupados por saber si la heterogeneidad deseada con los efectos de los fuegos pueden beneficiarse del uso de medidas de los tallos remanentes en el post fuego como un proxy para determinar la severidad del fuego. Un mayor conocimiento de los efectos del fuego en el chaparral es necesario para entender sus implicancias sobre la biodiversidad. El refinamiento a futuro sobre la estimación de la severidad del fuego puede ayudar a los investigadores y a los gestores a alcanzar esta meta.

Background

Wildfires are getting bigger, more severe, and more frequent in the western United States (Dennison et al. 2014). These pressures are acutely affecting California's shrublands (Syphard et al. 2007; Moritz et al. 2014; Safford and Van De Water 2014) where effects from frequent, severe, and large fires increase with aridity (Syphard et al. 2018; Pratt 2022). Changes can alter habitat, shift species dominance, shift vegetation structure (Vegetation Type Conversion (VTC)), and threaten endemic and native species (Dunne et al. 1991; Syphard et al. 2018; Calhoun et al. 2021; Grunpenhoff and Safford 2024).

Prescribed fire use is increasing to reduce fires that are catastrophic for people and ecosystems (York et al. 2021; Wilkin et al. 2024). Despite Indigenous peoples' burns to enhance chaparral values at many scales for the past 12k years (Cooper 1922; Anderson and Keeley 2018), modern prescribed fires may have positive to negative impacts on ecological factors (Wilkin et al. 2017; Florence 1986; Kalies and Yocom Kent 2016; Amacher et al. 2008; Collins et al. 2007; Leck et al. 1989; Calhoun et al. 2021). In chaparral specifically, some managers prescribe fire to reduce fuel loading despite concerns about VTC and

biodiversity loss, to decrease the potential for explosive, high-intensity crown wildfires that threaten lives and structures (Riggan et al. 1986; Barro and Conard 1991; Downing 2017; Rundel 2018; California Department of Forestry and Fire Protection 2025a, b; Pratt 2022). While these prescribed fires reduce fuels in the short term, shrub cover may return quickly in 3 to 10 years (Dunne et al. 1991; Wilkin et al. 2017), and wind-driven wildfires may still occur soon after treatment (Dunn 1989; Moritz et al. 2004). Though fall fuel reduction treatments reduce chaparral fuels for longer (Wilkin et al. 2017), they do not align well with common winter and spring prescribed burn permits (York et al. 2020). Managers may be able to overcome the narrow burn windows by adjusting ignition patterns to increase fire intensity and severity. However, many chaparral fire season studies lack fire severity measurements (Dunne et al. 1991; Potts et al. 2010) that would help compare prescribed fire effects within and between fires (Rundel et al. 1987).

Ultimately, chaparral prescribed fires and wildfires are complex, and many factors need to be considered. To understand patterns of chaparral fire, we need to measure its intensity across a landscape, which Moreno and

Oechel (1989) pioneered by proposing “a simple method for estimating fire intensity” by relating it to in situ post-fire twig diameter. Since fire intensity is useful for describing variation within chaparral fires, we can use variation in thermal exposure as a proxy for fire intensity (Kennard et al. 2005; Shannon and Butler 2003) to validate in situ observations of differing fire severity, which we define as the magnitude of change in vegetation and soils after a fire (Keeley 2009). Following this, large shrub skeletons that retain small twigs can be considered to have experienced a relatively low-severity fire, and conversely, skeletons where small twigs were fully consumed, leaving only large twigs, experienced high-severity fire (Keeley 2009). Patterns in post-fire twig diameter also align with pre-burn shrub canopy presence, water evaporation from cans during fire, maximum fire temperature, and depth of litter consumed, as well as fire effects like seed mortality and seedling recruitment (Odion and Davis 2000). There appear to be obvious twig diameter patterns that relate fire behavior and severity across landscapes; however, methods that measure these patterns are not consistent or transparent (Rundel et al. 1987; Rice 1993; Safford and Harrison 2004; Keeley et al. 2008; Grunehoff and Safford 2024). While managers and researchers both use twig diameter to assess severity, methods used by managers for post-wildfire assessments categorize observed shrubs into severity bins (USDI National Park Service 2003), whereas researchers typically sample continuous data to improve statistical inference (Grunehoff and Safford 2024). Research methods also vary by measurement location in relationship to the twig tip and twig selection, e.g., by selecting the smallest twigs (Keeley et al. 2008), haphazardly selecting a subset of outer branches (Safford and Harrison 2004), or thorough sampling of outer branches (Moreno and Oechel 1989).

In order to understand how fire severity in chaparral affects ecological factors such as recruitment and botanical diversity, we need clarity on how to effectively monitor this severity within and between fires, either with remote sensing or in situ sampling. Some remote-sensing indices do not detect differences in chaparral fire severity well (Keeley et al. 2008; Mohammad 2009) and typically map chaparral fires as high severity (Keeley 2009), though these fires vary in shrub fuel consumption. In situ twig diameter fire severity data could complement or improve on fire severity assessments that use space-borne or aerial remote sensing or binned in situ data. Fire severity sampling techniques may be validated by observations where fire intensity is measured. For example, thermal remote sensing of active fires captures apparent temperatures (Hudak et al. 2018). However, even apparent values, which may not be true temperatures, are informative as a proxy for change in temperature or relative temperature

differences across comparable imagery and may be helpful to determine relationships between thermal exposure and severity (Kennard et al. 2005).

Broadly, we are interested in how to improve accuracy and standardize fire severity measurements in chaparral. Our specific questions are:

- (1) What methods are used to assess fire severity via twig diameter in chaparral?
- (2) Is maximum temperature or duration of heating a better representation of fire intensity?
- (3) What is the best method and statistical model to accurately measure twig diameter to assess fire severity in chaparral?
- (4) What methods do we recommend for future research and management?

Methods

Study site

The study area was in maritime chaparral portions of a 58-hectare burn unit in the Gabilan Mountain Range, near Salinas, CA (Fig. 1). Dominant maritime chaparral species included chamise (*Adenostoma fasciculatum*) and black sage (*Salvia mellifera*); all plant nomenclature follows Baldwin and Goldman (2012). The region has a Mediterranean climate with similar temperatures throughout the year, with lows 5–13 °C and highs 17–22 °C, and it has 32 cm annual precipitation (Arguez et al. 2021). Previous management history included grazing and fire, indicated by charred stumps present at the site. Within the burn unit, maritime chaparral dominated on steeper or more south-facing slopes, oak scrub was present on the northernmost-facing slopes, oak woodlands occurred on the gentle slopes in lower elevation, and grasslands occurred near the mountain base. Slopes generally ranged from 10 to > 100%, and elevation ranged from approximately 145 to 407 m.

The San José State University (SJSU) Wildfire Interdisciplinary Research Center (WIRC), a National Science Foundation Industry-University Interdisciplinary Research Center, collaborated with the California Department of Forestry and Fire Protection (CAL FIRE) to conduct the California Canyon Fire Experiment (Clements et al. 2023). The experiment included canyon fire behavior, meteorology, and fire effects research (Arreola Amaya 2024; Ren et al. 2025), and also reduced fire hazards (CAL FIRE 2022).

On October 24, 2022, CAL FIRE lit a prescribed fire in a west-facing canyon. It was planned to mimic wildfire that might erupt in the canyon on an extreme wildfire day, and it did erupt. Before the fire, the area surrounding the main burn unit was burned to create a “catcher’s mitt” to contain the fire. The fire was ignited in grasses and shrubs adjacent to the bottom of the main canyon

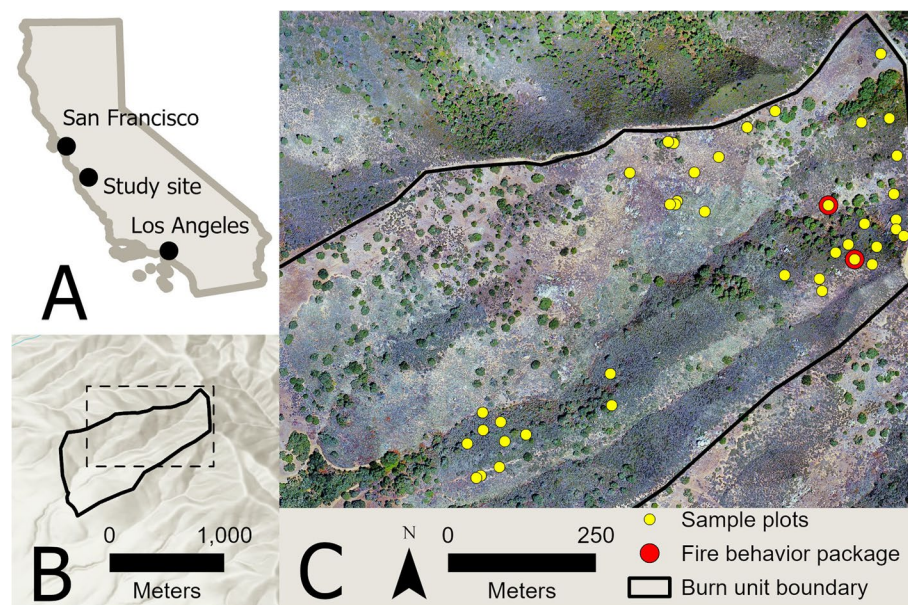


Fig. 1 Site map. **A** The California Canyon Fire Experiment occurred near Salinas, CA. **B** Burn unit boundary outlined in black with hillshade map. Dashed black lines indicate extent of **C**. **C** Plot layout on a background of high-resolution visible-color orthomosaic generated from uncrewed aerial vehicle (UAV) mounted images taken before the prescribed fire. Burn unit boundary in black. Sample plots indicated with yellow dots. Fire behavior packages indicated with red dots

between 11:55 AM and 12:28 PM. The burn conditions were 27% relative humidity, 55% live fuel moisture, 8–10% 10-h fuel moisture content, and an ambient wind of 2 to 3 m/s.

Fire intensity measurements and imagery

Remote sensing observations

We used thermal exposure as a proxy for fire intensity (Kennard et al. 2005; Shannon and Butler 2003). The SJSU Wildfire Imaging System (SWIS) measured apparent fire temperature from a helicopter in a fixed position using a Telops M150 camera at an oblique angle to the canyon, capturing 30 frames per second for approximately 12 min as the fire made a run up the canyon. The Telops camera uses radiometric temperature, which may be lower than the true temperature (Telops 2019), and temperature values could be inaccurate by up to 10 °C due to atmospheric effects like water vapor in the air. Mid-wavelength infrared brightness temperature was filtered ≥ 249 °C. We stabilized the video and georeferenced the keyframes by tracking individual bushes that were burning. We interpolated the data down to square meter spatial resolution using the Lanczos interpolation scheme, then used the result to create a maximum temperature raster. Georeferencing/orthoprojection error could be 4–20 m. We then created a Python script to extract temperature for every frame (30 frames per second for approximately 12 min)

(Python Software Foundation 2024) (Fig. 2), which allowed us to obtain the temperature time series for the pixel representing each sample plot. Plot location was taken with ~ 0.5 m accuracy with a Trimble R1 Global Navigation Satellite System (GNSS) Receiver (Trimble Navigation Limited 2016). Additionally, a DJI Phantom 4 Pro V2.0 drone/UAV equipped with a 1-inch 20MP CMOS sensor captured Red–Green–Blue (RGB) pre-fire imagery of the site on July 27, 2022, under clear conditions. The imagery, collected at ~ 80 m altitude with 80% forward and 70% side overlap, was processed in Drone2Map for ArcGIS (Esri 2023) to produce a high-resolution orthomosaic and Digital Surface Model (DSM) using Structure-from-Motion (SfM) photogrammetry. The orthomosaic (~ 2.5 cm Ground Sampling Distance (GSD)) was georeferenced with onboard GPS data and refined using Trimble R1 GNSS ground control points (≤ 0.5 m accuracy).

Ground stations

Fire behavior packages (FBP) were positioned near the top of the canyon to record local gas temperature, using type-K thermocouples, which have an accuracy of 0.75% ($N=11$). Thermocouples were 0.5 m, 1.0 m, and 1.5 m above ground at the site of the FBP pole, over the hole (Fig. 5 in Appendix B). We were able to sample shrubs at two ground station locations (Fig. 1).

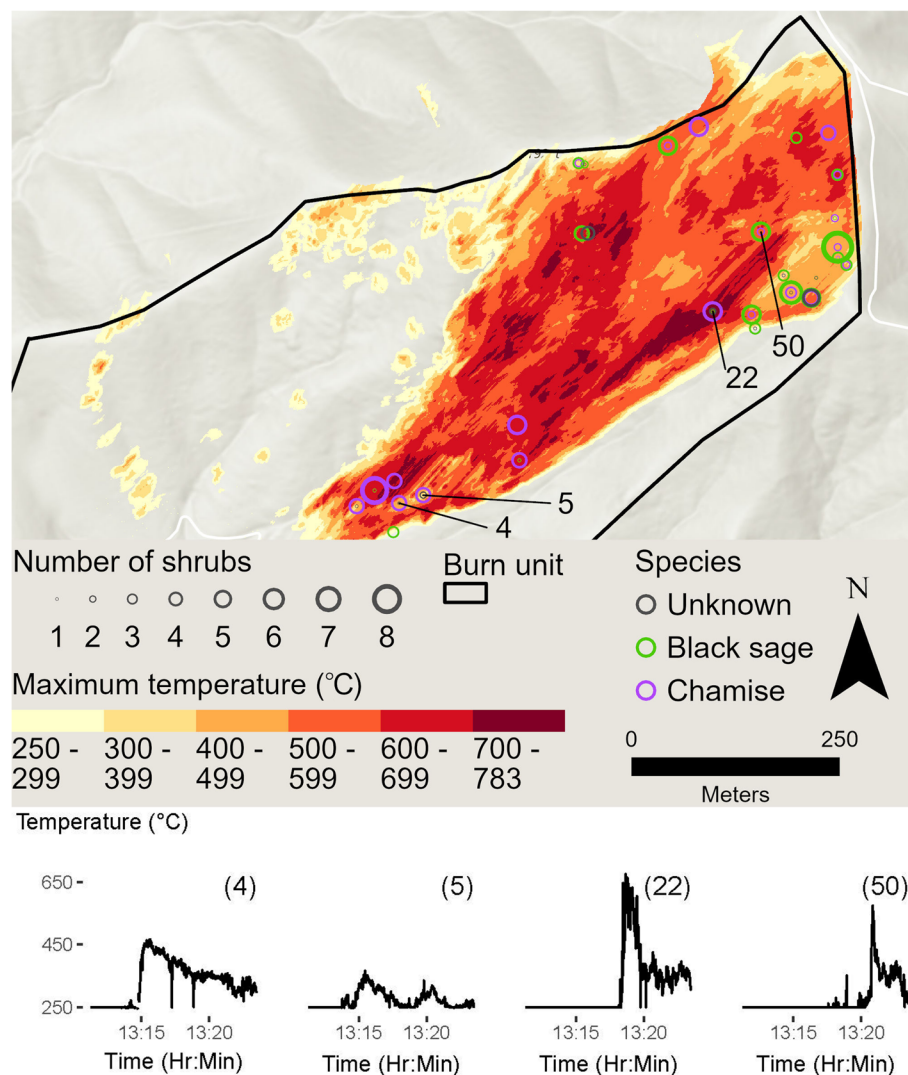


Fig. 2 Fire mid-wavelength infrared brightness temperature. (Top) Experimental design was based on the fire intensity and safe access to sites. Within the burn unit (indicated in black), helicopter-based maximum brightness temperatures (°C) are shown from light yellow to deep red during a 12-min flight, and areas without maximum temperature burned before or after the flight. The number of shrubs sampled per plot is an example from Methods 2, 4, and 6, represented by the size of the circle ranging from one to 8 shrubs. The species is represented by the circle color (*Salvia mellifera* (black sage) is green, *Adenostoma fasciculatum* (chamise) is purple, and unknown species is dark gray). (Bottom) Time series brightness temperature (°C) at one frame per second for selected plots (4, 5, 22, and 50) for the duration of the helicopter flight, e.g., 12:12 (minutes:seconds), during the timeframe 13:11:15–13:23:28 (hour:minute:second)

Fire effects: post-fire shrub measurements

We sampled twig diameters to estimate fire severity and created a sampling method matrix based on past research (Moritz et al. 2022). Our matrix included how to select twigs, where on the twig to measure, and other relevant sampling protocols (Table 1, Fig. 3). Shrubs within the burn unit experienced varying levels of woody fuel consumption. Most experienced topkill, leaving many skeletons and stumps. Burnt shrubs' species were identified based on foliage if they had resprouted at their bases, or

their stems' density and texture if not. For example, black sage had a much smoother, less dense, and chalkier feeling stem than chamise. In some cases, it was difficult to distinguish between species, especially when all that remained was a stump. These individuals were classified as unknowns.

Sampling for Method 1

We sampled twig diameter on chamise and black sage 1 year post-fire (October 2023) across the range of

Table 1 Comparison of literature using post-fire twig measurements in chaparral. Summary of similar, but distinct methods past researchers have used to measure post-fire twigs. We mainly used research from Moritz et al. (2022) and more recent papers that related post-fire twig measurements to fire intensity or severity. Location indicates where the twig diameter was measured

Citation	Species	Twig selection	Location	Tool	Fire intensity
Keeley et al. 2008	Chamise and others	Smallest-diameter twig remaining on the 2 chamise closest to each quadrat	Unspecified	Unspecified	Not measured
Moreno and Oechel 1989	Chamise	Outer twigs of stems originating in plot. Twigs extend ≥ 1 cm long from node (or lead to other significant branches)	Beyond carboniferous tip	Vernier calipers	Heat release measured using cans of water Temperature measured using Tempil [®] temperature pellets
Odion and Davis 2000	Chamise	All remaining branches within 1×1 m plot around each thermocouple. All branches directly over each transect plot	Unspecified	Unspecified	Thermocouples Tempilac pyrometers (paint) Metal cans with water
Rice 1993	Chamise	5 smallest twigs within quadrat	2 cm from tip	Unspecified	Not measured
Rundel et al. 1987	Chamise	Unspecified	Unspecified	Unspecified	Not measured
Safford and Harrison 2004 and Grunehoff 2024	Chamise and other	4 stem termini on each randomly chosen individual that was rooted in or adjacent to the quadrat or belt transect	1 cm from tip	Unspecified (2004); 300-mm digital caliper (Arbor Scientific, Saline, MI) (2024)	Not measured

maximum temperatures, with at least ten shrub individuals in each of six temperature bins (250–299 °C, 300–399 °C, 400–499 °C, 500–599 °C, 600–699 °C, 700–783 °C). Our goal was to get an even mix of the two species and an approximately even number of shrubs across the six temperature bins. Target sample plots were pre-selected based on the maximum temperature raster, and additional plots were selected while in the field as needed to ensure an even sampling effort across species and temperature bins. We navigated to the pre-selected points with the GNSS receiver and were careful to distance ourselves by at least twice the horizontal accuracy of the receiver from the borders between temperature bins. GSD at the sample plots was typically less than 2 m for this and following plots. Selected shrubs were within an approximately 2-m radius of each plot's center point.

For each shrub, we used rulers to measure the diameter at the tip of the smallest-diameter twig at least 1 cm long on each of the plant's stems, for up to ten stems per plant. Stems were considered separate if they split within 6 cm above ground. Zero to ten shrubs of each species were sampled at each plot, depending on how many shrubs were in that location. We also recorded whether each individual had resprouted or not. We used

digital calipers (Louisware ROHS NORM 2011/65/EU) to sample additional shrubs the following spring to better include stumps, which were rare in the original data (Table 4 in Appendix A).

Sampling for Methods 2–6

We conducted further sampling with other methods the following spring, March–June 2024 (Fig. 3, Table 4 in Appendix A). We used digital calipers to measure chamise and black sage twig diameters at both the tip and 1 cm from tip. Up to ten outer twigs that were at least 1 cm long were selected on up to five stems per plant, prioritizing outer branches. As before, we recorded shrub species and whether each individual had resprouted. We also tried to estimate the shrubs' pre-fire size and/or age by measuring the total diameter across all stems at base with a ruler (both the widest span and perpendicular to that, measured 1 cm above ground), similar to measurements Moreno and Oechel (1993) used to estimate lignotuber area.

Data preparation and analysis

Data preparation and selection

All R coding was done using version 4.3.0 (R Core Team 2023) in R Studio (Posit Team 2023). We subsetting the

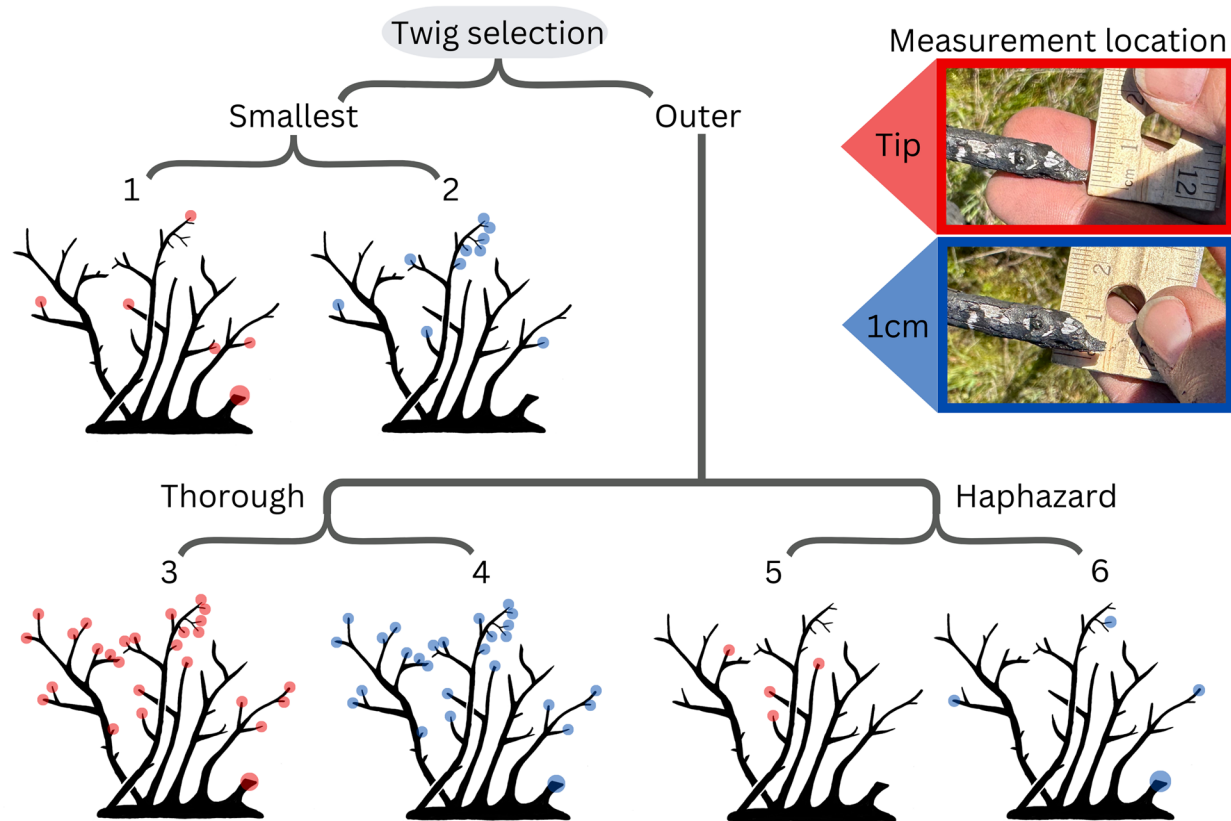


Fig. 3 Post-fire remaining twig diameter sampling methods. Twig sampling methods were based on where twigs were selected (smallest versus outer), sampling effort (thorough versus haphazard), and where the measurements were taken (tip versus 1 cm from tip). Method 1: the smallest twig ≥ 1 cm long on each stem was measured at the tip. Method 2: within the outer twigs, the ten smallest-diameter twigs were selected and measured 1 cm from the tip. Method 3: within the outer twigs, up to ten twigs per stem on up to five stems were measured at the tip. Method 4: within the outer twigs, up to ten twigs per stem on up to five stems were measured 1 cm from the tip. This method was similar to Moreno and Oechel (1989). Method 5: within the outer twigs, four haphazardly chosen twigs were measured at the tip. Method 6: within the outer twigs, four haphazardly chosen twigs were measured 1 cm from the tip. This method was similar to Safford and Harrison (2004) and Grunehoff and Safford (2024). Drawing and schematic by Pauline Allen and Jannike Allen. Photographs by Kate Wilkin

data to select six twig diameter datasets, each representing a different method of sampling (Table 6 in Appendix A, Fig. 3). Tip measurements were selected for Methods 1, 3, and 5, and measurements taken 1 cm from the tip were selected for Methods 2, 4, and 6. For Method 1, we selected twigs that were at least 1 cm long (from the node) from the first round of sampling, and included additional data sampled the second year. For Method 2, we selected the ten smallest twig diameter values for each shrub that had measurements taken 1 cm from the tip from Method 4 field data, since we had not originally measured 1 cm from the tip when sampling the smallest twig on each stem. For Methods 3 and 4, we included all twigs measured in the second round of sampling and considered these methods to be “thorough.” For each “haphazard” method, i.e., Methods 5 and 6, we

subsampling with “slice_sample” to select four twigs from each shrub, from Methods 3 and 4 field data respectively (Wickham et al. 2023).

Heat duration

We used Visual Studio Code and Python to extract 30 remote-sensed temperature values per second at each sampling plot, based on the pixel each plot’s center point fell in (30 frames per second for approximately 12 min) (Microsoft 2024; Python Software Foundation 2024). In R Studio, we selected the first temperature each second for each sampling plot (Posit Team 2023; R Core Team 2023). Then, we counted the number of seconds each plot was over multiple temperature thresholds at and above 250 °C (thresholds: 250, 300, 350, 400, 450, 500, 550, 600 °C).

Statistical models

We statistically modeled our six twig sampling methods with Generalized Linear Mixed-Effects Models (GLMER) (Bates et al. 2015) (Eq. 1).

Random effects included shrub base area (calculated as an oval from measured base diameters) and twigs found on the same stem, individual shrub, or in the same plot (Table 2). Before each model, we assessed predictive

$$\gamma \sim \text{fire temperature variable} + \text{species} + \text{random effects of base area} + \text{nested random effects of plot, shrub, and stem}$$

(1)

where γ is twig diameter (mm); fire temperature variable is either maximum temperature (°C) or time above a temperature threshold (seconds); species includes chamise, black sage, and unknown; random effects of base area (cm²) account for pre-fire size or age; and the nested random effect of plot, shrub, and stem are added where appropriate. For example, a stem is only included if there are multiple measurements on one stem, e.g., Methods 2, 3, and 4.

The dependent variable was the remaining twig diameter (mm). Fixed effect explanatory variables included species and temperature, including maximum temperature (°C) or duration of heating above temperature thresholds (250, 300, 350, 400, 450, 500, 550, or 600 °C).

power scores to confirm it was appropriate to include both species and that model’s temperature metric (van der Laken 2024). We also tested to see if maximum temperature and duration of heating could be modeled together. When modeled together, the Variance Inflation Factor (VIF) indicated low multicollinearity (VIF < 1). Although they were not correlated, we only used one per model due to convergence issues. After modeling, we assessed VIF for each model (VIF < 1.2 for all models) (Fox and Weisberg 2019). We started analysis with the simplest models (gamma family), and if they did not converge, we used more complex models (gamma family with link log), scaled explanatory variables, and added optimizers when issues arose. Model fit was assessed for overdispersion.

Table 2 Random effects varied between methods for both the maximum temperature and heat duration models. Shading indicates presence of the random effect in the model, e.g., gray indicates presence while white indicates absence. Some of the random effects were nested, including stems on shrubs within plots. Letters indicate paired twig selection methods, where odd-numbered methods used measurements at the tip and even-numbered methods used measurements 1 cm from the tip (Fig. 3)

Model		shrub base area	Nested		
			plot	shrub	stem
Maximum temperature	Method 1 ^A				
	Method 2 ^A				
	Method 3 ^B				
	Method 4 ^B				
	Method 5 ^C				
	Method 6 ^C				
Heat duration	Method 1 ^A				
	Method 2 ^A				
	Method 3 ^B				
	Method 4 ^B				
	Method 5 ^C				
	Method 6 ^C				

For each method's model using duration of heating, we selected the threshold with the best Akaike information criterion (AIC). We considered the best models to be those with the lowest AIC values, because these models would explain future data better (Mazerolle 2023). Models with high R^2 values were also considered to best explain the variation in our observed data (Kahane 2008), where the marginal R^2 (R^2_M) enumerates variation due to the fixed effect and the conditional R^2 (R^2_C) enumerates the variation due to both the fixed and random effects combined.

Results

Maximum temperature

Maximum temperature models explained some variation in the observed data (Fig. 4, Table 3, $0.01 < \text{marginal } R^2 < 0.18$). Overall, Method 1 had the lowest AIC value (-114) and the highest marginal R^2 (0.18). When comparing methods with paired twig selection protocols, measuring at the tip was better than measuring 1 cm from the tip (Table 3). Interestingly, AICs were lower for “haphazard”/lesser sampling efforts (Methods 5 and 6) than for “thorough” sampling efforts (Methods 3 and 4).

Duration of heating

Broadly, models with duration of heating over the threshold of 250 °C were better than models with duration of heating at higher temperatures (300, 350, 400, 450, 500, 550, or 600 °C). For most methods, the model using time over the threshold of 250 °C had the lowest AIC, except for Method 1, where 300 °C had the lowest AIC (Fig. 4, Table 3).

Duration of heating models were better than maximum temperature models; they explained more of the observed data variation than maximum temperature models (Fig. 4, Table 3, $0.03 < \text{marginal } R^2 < 0.39$) and also had lower AIC values. Overall, Method 1 modeled with time over the threshold 300 °C had the lowest AIC (-129). However, its R^2 was only 0.16. At the 300 °C threshold for Method 1 and chamise: when time over 300 °C was 100 s, modeled twigs were 0.27 mm in diameter ($SE: -0.03$), and when time over 300 °C was 500 s, modeled twigs were 0.63 mm in diameter ($SE: 0.12$). For black sage, when time over 300 °C was 100 s, modeled twigs were 0.48 mm in diameter ($SE: 0.05$), and when time over 300 °C was 500 s, modeled twigs were 1.12 mm in diameter ($SE: 0.27$). For unknown species, when time over 300 °C was 100 s, modeled twigs were 1.16 mm in diameter ($SE: 0.32$), and when time over 300 °C was 500 s, modeled twigs were 2.68 mm in diameter ($SE: 0.86$).

Again, measuring at the tip was better than measuring 1 cm from the tip when comparing twig measurement location between methods with paired twig selection protocols, and AICs were lower for “haphazard”/lesser sampling efforts (Methods 5 and 6) than for “thorough” level sampling efforts (Methods 3 and 4) (Table 3).

Species

While each species had statistically distinct remaining twig diameters for all methods and for both models using maximum temperature and duration of heating, the trends were not the same, and the effect size was generally not large ($P < 0.05$, Table 5 in Appendix A, Fig. 4). Black sage retained smaller twigs than chamise in maximum temperature models ($P < 0.05$; Table 5 in Appendix A); chamise model twig diameter estimates were 1.2 to 1.5 times larger than black sage models. Chamise retained smaller twigs than black sage in duration of heating models ($P < 0.0035$; Table 5); black sage model estimates were 1.3 to 1.8 times larger than chamise model estimates. Across all methods, unknown species twigs were larger than black sage and chamise ($P < 0.024$; Table 5 in Appendix A) and unknown species model estimates could be over twice as large as for the smallest species (black sage for maximum temperature models and chamise for duration of heating models).

All species had similar twig tip diameters (Methods 1, 3, and 5) and differences may not be ecologically relevant (Table 6 in Appendix A). The average black sage twig diameter ranged from 0.7 to 4.4 mm with a standard deviation up to 3.1 mm (average Method 1: 0.7 mm; Method 3: 3.7 mm; Method 5: 4.4 mm). The average chamise twig diameter ranged from 0.4 to 3.6 mm with a standard deviation up to 2.7 mm (average Method 1: 0.4 mm; Method 3: 2.9 mm; Method 5: 3.6 mm). The average unknown twig diameters were larger, ranging from 1.7 to 8.9 mm with a standard deviation up to 7.4 mm (average Method 1: 1.7 mm; Method 3: 8.9 mm; Method 5: 8.9 mm).

Average twig diameters 1 cm from the tip (Methods 2, 4, and 6) varied more among species (Table 6 in Appendix A). The average black sage twig diameter ranged from 5.7 to 7.3 mm with a standard deviation up to 8.5 mm (average Method 1: 5.7 mm; Method 3: 5.8 mm; Method 5: 7.3 mm). The average chamise twig diameter ranged from 4.6 to 6.0 mm with a standard deviation up to 4.8 mm (average Method 1: 4.6 mm; Method 3: 4.8 mm; Method 5: 6.0 mm). The average unknown twig diameters were larger, at 14.4 mm with a standard deviation of 8.5 mm (average Method 1: 14.4 mm; Method 3: 14.4 mm; Method 5: 14.4 mm).

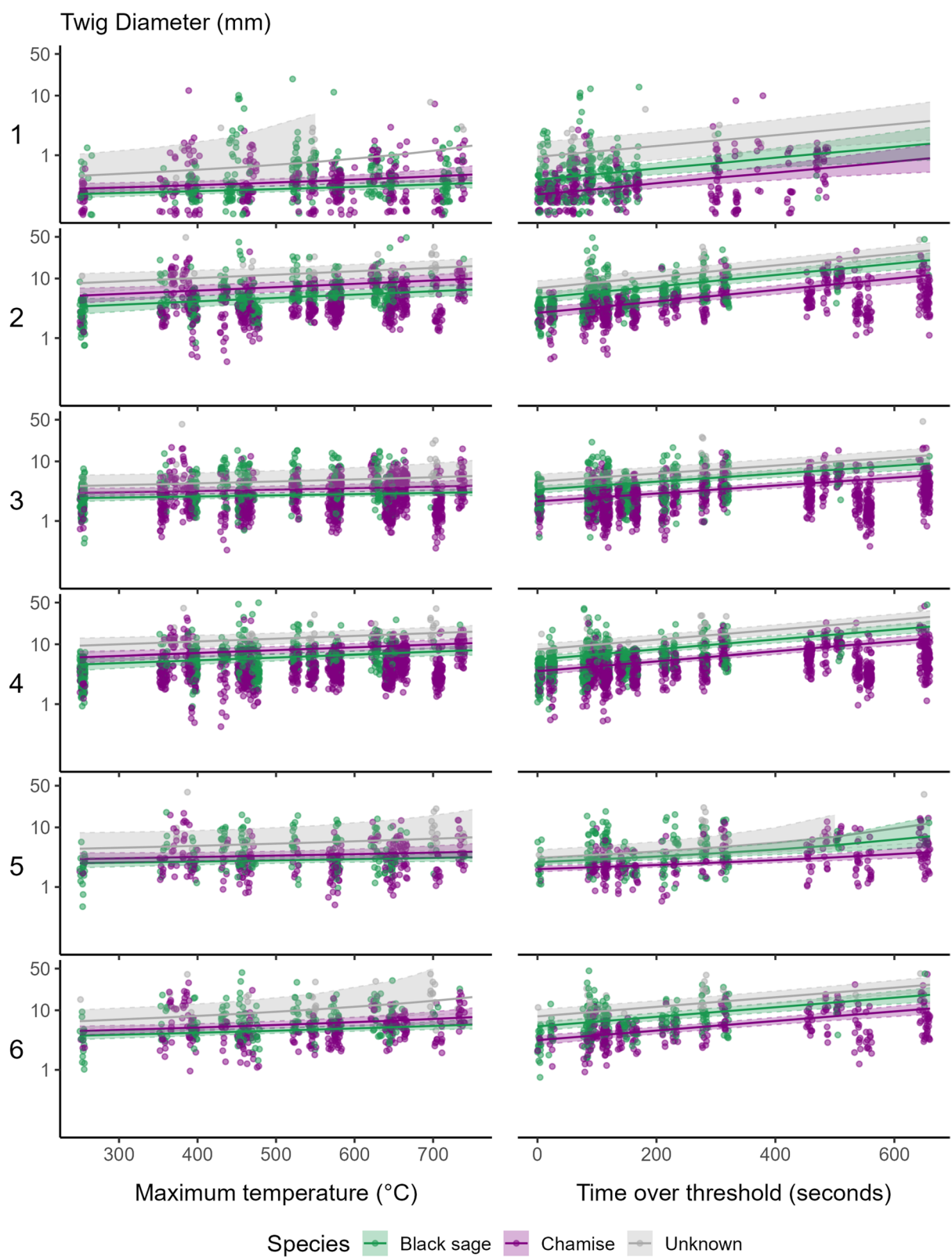


Fig. 4 Results. For each method, remaining twig diameter (mm) was related to (left) maximum temperature (°C), and (right) time over threshold (seconds) over the temperature threshold with the best model fit for that method (300 °C for Method 1, 250 °C for all others). Lines are model predictions, ribbons are 95% confidence intervals, and dots represent raw data with a small amount of jitter to aid in visualization of points. Green indicates black sage, purple indicates chamise, and gray indicates unknown species

Table 3 Model AIC and R^2 values for each twig sampling method. Marginal R^2 (R^2_M) values include species and temperature (maximum temperature or duration of heating) and conditional R^2 (R^2_C) values additionally include random effects (Table 2). Some models have fewer random effects: Method 1 does not have shrub base area (cm^2) and the specific stem sampled, Methods 5 and 6 do not have the specific stem sampled. Letters indicate paired twig selection methods where the odd number was measured at the tip and even number indicates it was measured 1 cm from the tip (Fig. 3)

Twig sampling method	Maximum temperature models			Duration of heating models			
	AIC	R^2_M	R^2_C	Threshold ($^{\circ}\text{C}$)	AIC	R^2_M	R^2_C
1 ^A	–114	0.18	0.85	300	–129	0.16	0.61
2 ^A	3862	0.18	0.73	250	3800	0.39	0.78
3 ^B	5708	0.01	0.06	250	5652	0.23	0.52
4 ^B	7042	0.12	0.58	250	6967	0.37	0.66
5 ^C	1906	0.01	0.05	250	1875	0.03	0.09
6 ^C	2469	0.01	0.03	250	2430	0.32	0.73

Discussion

Broadly, we sought to relate unique post-fire twig diameter measurement methods to fire severity in maritime chaparral. Our results showed that some sampling methods did not reflect our proxy for fire intensity well, while others did. As duration of heating was better related to twig diameter than maximum temperature was, our accuracy and recommendation comparisons refer to models that used duration of heating to represent fire intensity. Specifically, we found that twig diameter is influenced most by how long the shrubs burn above lower temperatures rather than time at higher temperatures. Of the six sampling methods we compared, Method 1 modeled with duration of heating over 300 $^{\circ}\text{C}$ had the lowest AIC and thus best predicted future data. Interestingly, all of the sampling methods with high R^2 values were measured 1 cm from the tip. These methods had high R^2 values (i.e., the models explained the observed data well), but they also had higher AIC scores than other methods (i.e., they do not predict future observations well).

Fire intensity limitations

Like most measurements of fire intensity, the spatial and temporal limitations of remotely sensed thermal data may have created some error (Shannon and Butler 2003; Kennard et al. 2005; Hudak et al. 2018; Moran et al. 2019; McGranahan 2020; Paugam et al. 2021). For example, our thermal spatial resolution was approximately 4 m, while similar research using temperature pellets had 1 m resolution (Moreno and Oechel 1989). GSD varied across the site due to the projection and steep terrain, which caused some sensor pixels to be mapped onto larger land areas than others. The limited timeframe our thermal imagery captured may have also caused some errors for areas near the fire unit boundary (Hudak et al. 2018). For instance, some areas near the top of the canyon may have burned hotter and longer than our records showed. Additionally,

the remotely sensed thermal data primarily represent the surface of the burning vegetation at or above plant height but cannot capture a complete characterization of the heating that the plants experienced. Thermal imagery may also not reflect true temperatures, but rather relative temperatures within the fire studied, due to atmospheric transmittance, sensors, their calibration and filters, and pixel area (Hudak et al. 2018). This is not unique to remote sensing and can occur with thermocouples as well (Iverson et al. 2004). Although too few ground stations remained after the fire for a finer spatial resolution statistical analysis (several FBPs failed, were located outside the spatial area recorded by the helicopter, or were not possible to relocate for subsequent shrub sampling), thermocouples on our remaining fire behavior packages show that sensors' vertical placement affects what temperature is recorded (Fig. 5 in Appendix B). The impact of thermocouple location and orientation on temperatures recorded has been noted by others as well (Odion and Davis 2000; Coates et al. 2018). In addition, some thermocouples also have their own innate error (Shannon and Butler 2003; Kennard et al. 2005), and they can also take more time to cool down than the fuels (McGranahan 2020).

Study design limitations

Limitations in our study design included shrub and plot selection bias, design of fire effects methods, different sampling times, lack of pre-fire data, and a limited fire intensity gradient. First, selection of specific shrubs to measure was biased toward shrubs that could be easily found and identified. This led us to record fewer shrubs that burned all the way to the ground, as shrubs that were completely consumed were likely to be covered with loose soil and difficult to detect. Our plot locations also favored safe terrain, as steep slopes, which often burned the hottest, were not always accessible. Second, we were unable to exactly replicate published methods of twig

measurement for fire effects monitoring. Many papers had limited detail on how to select twigs, what tools to use to measure the twigs, and where exactly to measure on each twig (e.g., at the tip or 1 cm from the tip). We sampled with both calipers and rulers, and we anecdotally found that digital calipers made sampling easier and more consistent. Third, weathering of shrub skeletons post-fire made sample timing a consideration. Burned twig tips are often carboniferous, so they can be broken easily. Swelling can occur due to moisture content in wood, which may also cause twig diameters to vary (Reeb 2009). These inconsistencies within and across multiple years may reduce their relevance as a proxy for fire severity. Sampling Method 1 was primarily used 1 year after the fire, after just one rain season. We planned additional sampling 6 months after preliminary results to capture more stumps for the Method 1 dataset and to test Methods 2–6. Due to this timeline, data for Methods 2–6 were collected after two rain seasons had occurred post-fire. This increased the likelihood of inconsistent data across this gap in time due to additional weathering of twig tips. Fourth, variation in pre-fire vegetation may have impacted fire behavior and effects. We tried to account for this by measuring shrub base diameters as a proxy for varying shrub sizes and ages and including species in our models. Lastly, our data represent one site, with one fire intensity gradient. While chaparral fires are known to reach over 1900 °C (Downing 2017), our helicopter-based thermal sensors recorded maximum apparent temperatures under 800 °C. Our experiment represents a medium-intensity chaparral fire, but does not describe the full potential range of chaparral fire behavior.

Researchers should continue to consider multiple sampling methods when selecting monitoring protocols. Using these methods across a larger gradient of chaparral ecosystems and further comparing tip versus 1-cm-from-the-tip measurements (using Methods 5 and 6) will help the community determine how widely and reliably each can be applied. Researchers should also sample under a wider range of fire conditions (e.g., including prescribed and wild-fire), consider using other forms of thermal data, assess whether UAV, aerial, or satellite imagery best represents fire severity patterns (Belikov et al. 2023), consider tagging and sampling shrubs pre-fire, and increase number of sites (e.g., including in northern California, where chaparral fire regime research has been minimal (Moritz et al. 2022)).

Insights about fire severity based on shrub twig measurements

Many researchers that used in situ twig diameter measurements found insights into chaparral fire effects. At Sequoia National Park, Rundel (1987) found that higher fire severity increased chamise mortality, while Rice

(1993) found that ash depth correlated with fire severity, and that some species established more frequently where fire severity was low. Odion and Davis (2000) found that fire severity and intensity can relate to pre-fire shrub canopy patterns, with lower fire severity and intensity in canopy gaps, at Vandenberg Air Force Base in California's central coast. Safford and Harrison (2004) saw varied relationships between fire severity and post-fire species diversity in Lake County's sandstone and serpentine chaparral. Keeley et al. (2008) found that higher fire severity can affect ecosystem responses, leading to less total plant cover and fewer both nonnative and total species in Los Angeles, San Bernardino, and San Diego counties. Mohammad (2009) validated a relationship between in situ twig-based categories and remotely sensed differenced Normalized Burn Ratio (dNBR) a common fire severity metric, at 30 m spatial resolution near Malibu, CA. Most recently, Grupenhoff and Safford (2024) found a strong relationship between wildfire reburns and fire severity, with higher fire severity in plots that only burned once in 30 years in northern California's Interior Coast Range.

Validated methods can help others effectively monitor burned chaparral sites, and prescribed fire practitioners need methods to assess whether burn objectives are met. Since chaparral can burn at varying intensities, and especially since prescribed fires are often ignited in ways and conditions that minimize fire behavior, we need to understand what types of fire are ecologically beneficial. Whether prescribed burn severity objectives are homogenous or heterogenous, twig diameters could serve as a short-term indicator of fire effects to help land managers assess treatment success and make adjustments if needed. For example, if they seek to treat multiple units with high-severity fire, but fine twigs are retained in their first burn unit, they could halt operations until there is a more favorable burn window or increase intensity of ignition operations. Further, these continuous fire severity data may be more appropriate than the binned fire severity categories some managers use (USDI National Park Service 2003), which may be more difficult than continuous data to statistically relate to some fire effect goals, such as floral diversity. Future research should evaluate how fires of different severities, frequencies, and locations affect ecosystem responses such as plant community changes and succession (Storey et al. 2021; Downing 2017; Florence 1986). More research is also needed to understand temperature and duration thresholds that lead to mortality of shrubs and soil biota, as well as other biotic ecosystem components like post-fire floral diversity (Pingree and Kobziar 2019). Validated fire severity categories may also be useful to help compare sites with different species, abiotic factors, and fire histories.

Twig diameter sampling method recommendations

Standardizing shrubland fire severity monitoring methods could help comparisons within and between studies and management programs. For future research and management, we recommend our Methods 1, 5, and or 6 to monitor the gradient of fire intensities within burned chaparral sites. Our sampling Method 1, which has a moderate sampling effort, is especially recommended for those able to sample soon after fire. Method 1 sampling likely encountered the least amount of twig degradation due to weathering since we sampled one rain season post-fire, compared to two rain seasons post-fire for other methods. Twig tips may have reliably represented fire effects, allowing this model to perform well and have a lower AIC than our other methods. Based on these results, we suspect that the timing of sampling may influence where on the twig land managers and researchers measure: if a lot of weathering has occurred, it might be better to measure 1 cm from the tip. Method 6 was particularly promising due to its relatively low AIC and higher R^2 values and may be appropriate when sampling is delayed post-fire.

Sampling effort is worth considering when selecting a sampling method. While thorough sampling efforts (Methods 3 and 4) described observed data well, surprisingly, they may not predict new data well (Table 3). Despite low sampling effort, Methods 5 and 6 predicted new data moderately well, and Method 6 described observed relationships well. However, we have reservations about Method 5 due to (1) low R^2 values and (2) concerns about tip loss if significant time passes before sampling. Our low R^2 values indicate that very little of the observed data were described by our Method 5 model, which may be due to weathering of twig tips during two rain seasons post-fire. Even so, we recommend others test how both Methods 5 and 6 perform with their own data.

While species were statistically distinct, the small magnitude differences between chamise and black sage twig diameters were not ecologically significant. Unknown species' remaining twigs were largest, likely because shrubs with greater consumption were harder to identify. However, most unknown shrubs were likely either chamise or black sage, and lumping the species together may simplify sampling methods without significant drawbacks. Based on these similarities, it may also be reasonable to lump together other species whose known species-specific wood densities are between those of chamise ($679.3 \pm 12.8 \text{ kg m}^3$) and black sage ($528.9 \pm 10.0 \text{ kg m}^3$) (Jacobsen et al. 2008), since wood density impacts stem loss during fire. Some potential species include, but are not restricted to, *Adenostoma sparsifolium*, *Arctostaphylos glandulosa*, *Ceanothus cuneatus*, *Ceanothus megacarpus*, *Ceanothus oliganthus*, *Ceanothus spinosus*,

Heteromeles arbutifolia, and *Quercus berberidifolia* (Jacobsen et al. 2008; Grupenhoff and Safford 2024). While some believe manzanitas (*Arctostaphylos* spp.) should be assessed separately, others have found them useful in predicting fire severity when chamise was not present (Keeley et al. 2008).

Conclusion

It is important to validate the relationship between twig diameter measurements and fire intensity. Our findings support twig diameter sampling as a useful tool to help researchers and land managers assess fire severity within burn sites. We quantified fire severity from twig measurements within a sample site with consistent stand age, but more research is needed to compare fire severity across sites that include different stand ages and species. As a community, it would be helpful to standardize methods to assess shrubland in situ fire severity using twig diameter measurements. While our research supports our Method 1 (the smallest twig ≥ 1 cm long on each stem, measured at the tip) as the best protocol for future research, Methods 5 and 6 (four haphazardly chosen twigs from outermost branches, measured at the tip (Method 5), or 1 cm from the tip (Method 6)) should not be discounted, especially since they were the best methods when 2 years of weathering had occurred. Further research could incorporate heat flux measurements, thermocouple ground stations, remotely sensed fire severity, other species and shrub sizes, and larger variations in fire behavior.

Appendix A

Table 4 Sampling effort (e.g., number of plots, shrubs, and twigs) varied by each species, method, and measurement locations. These measurements occurred during distinct times as well, e.g., years. Methods not described in this table were derived from subsampling these datasets: Method 5 data were subsampled from Method 3 data, and Method 2 and 6 data were subsampled from Method 4 to reduce the total number of twigs and mimic the reduced surveyor/sampling effort

Species	Year	Method	Measurement location	Plots	Shrubs	Twigs
Black sage	2023–2024	1	Tip	25	91	342
Chamise	2023–2024	1	Tip	25	88	371
Unknown	2023–2024	1	Tip	8	12	20
Black sage	2024	3	Tip	19	59	580
Chamise	2024	3	Tip	22	70	1103
Unknown	2024	3	Tip	11	16	28
Black sage	2024	4	1 cm	22	70	773
Chamise	2024	4	1 cm	25	77	1212
Unknown	2024	4	1 cm	12	21	40
Total				39	321	2758

Table 5 Species *P* values for species comparisons of black sage, chamise, and unknown plants. White around values indicate that the difference in post-fire remaining twig diameter between species is not statistically significant. Dark gray indicates it is statistically significant ($P < 0.05$). Letters indicate paired twig selection methods where the odd number was measured at the tip and even number indicates it was measured 1 cm from the tip (Fig. 3)

Maximum temperature			Duration of heating	
Method 1 ^A	Black sage	Chamise	Black sage	Chamise
Chamise	0.003595		0.0035	
Unknown	<2e-16	1.77E-04	0.0139	0.000112
Method 2 ^A	Black sage	Chamise	Black sage	Chamise
Chamise	3.90E-05		4.78E-10	
Unknown	0.000345	9.48E-10	0.0022	1.57E-12
Method 3 ^B	Black sage	Chamise	Black sage	Chamise
Chamise	0.000656		3.09E-09	
Unknown	0.003483	9.82E-05	0.0241	2.82E-08
Method 4 ^B	Black sage	Chamise	Black sage	Chamise
Chamise	0.000438		1.34E-10	
Unknown	0.000108	1.62E-09	0.000289	8.02E-15
Method 5 ^C	Black sage	Chamise	Black sage	Chamise
Chamise	0.0446		2.63E-06	
Unknown	0.0201	0.000337	0.172	2.82E-05*
Method 6 ^C	Black sage	Chamise	Black sage	Chamise
Chamise	0.00846		1.25E-08	
Unknown	0.00524	4.71E-06	0.00267	6.15E-12

Table 6 Twig diameter (mm) summaries (number of samples (*N*), mean, standard deviation (SD), standard error (SE)) for each sampling method and species. Letters indicate paired twig selection methods where the odd number was measured at the tip and even number indicates it was measured 1 cm from the tip (Fig. 3)

Method number	Species	<i>N</i>	Mean	SD	SE
1 ^A	Black sage	342	0.7	1.5	0.1
1 ^A	Chamise	371	0.4	0.8	0.0
1 ^A	Unknown	20	1.7	1.5	0.3
2 ^A	Black sage	502	5.7	4.7	0.2
2 ^A	Chamise	604	4.6	3.9	0.2
2 ^A	Unknown	40	14.4	8.5	1.3
3 ^B	Black sage	580	3.7	2.5	0.1
3 ^B	Chamise	1103	2.9	1.9	0.1
3 ^B	Unknown	28	8.9	7.4	1.4
4 ^B	Black sage	773	5.8	4.4	0.2
4 ^B	Chamise	1212	4.8	3.2	0.1
4 ^B	Unknown	40	14.4	8.5	1.3
5 ^C	Black sage	197	4.4	3.1	0.2
5 ^C	Chamise	248	3.6	2.7	0.2
5 ^C	Unknown	28	8.9	7.4	1.4
6 ^C	Black sage	240	7.3	6.0	0.4
6 ^C	Chamise	276	6.0	4.8	0.3
6 ^C	Unknown	40	14.4	8.5	1.3

Appendix B

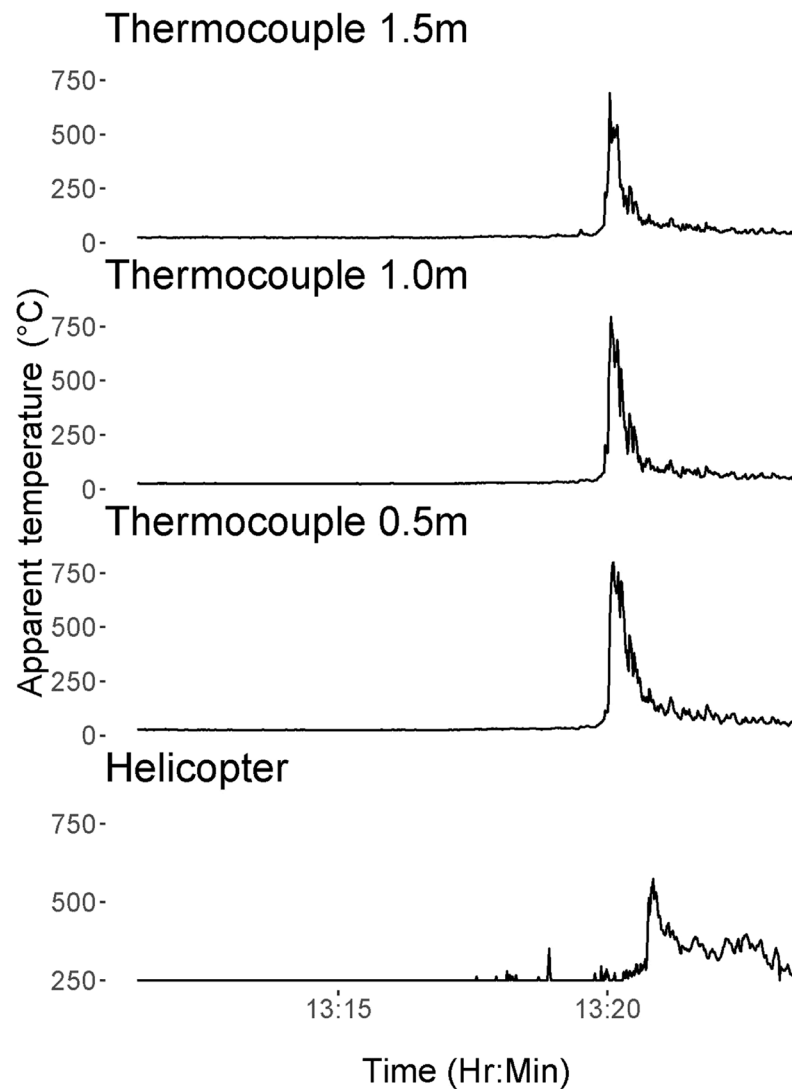


Fig. 5 Variation in apparent temperature values recorded by thermocouples and helicopter-based thermal sensors for plot 50 at the California Canyon Fire Experiment. The thermocouples were part of Worcester Polytechnic Institute (WPI) Fire Behavior Package 4 that was constructed in-house, and located 0.5, 1.0, and 1.5 m above the ground. The sensors were 1-mm bead diameter K-type thermocouples and the time constant was ~ 0.15 s. The thermocouples were connected to a U6 Labjack DAQ and read at 1 Hz, which limited the data acquisition rate. The data acquired from the DAQ were logged using a Raspberry Pi 4. The DAQ + Raspberry were powered by a lithium-ion battery pack and fitted inside a Pelican-like plastic case. Due to location accuracy issues, this fire behavior package location was estimated to be ~ 11 m from the recorded coordinates. Helicopter data (thermal imagery) was filtered to capture values ≥ 249 °C, and primarily represents the surface of the burning vegetation at plant height

Abbreviations

AIC	Akaike information criterion
°C	Degrees Celsius
CAL FIRE	California Department of Forestry and Fire Protection
cm	Centimeter
dNBR	Differenced Normalized Burn Ratio
DSM	Digital Surface Model
FBP	Fire behavior package
FRI	Fire return interval
GLMER	Generalized Linear Mixed-Effects Model
GNSS	Global Navigation Satellite System
GSD	Ground Sampling Distance
km	Kilometer
m	Meter
mm	Millimeter
NBR	Normalized Burn Ratio
NSF	National Science Foundation
R ² C	Conditional <i>R</i> squared
R ² M	Marginal <i>R</i> squared
RGB	Red-Green-Blue
s	Second
SE	Standard error
SJSU	San José State University
SWIS	San José State University Wildfire Imaging System
UAV	Uncrewed aerial vehicle
VIF	Variance Inflation Factor
VMP	Vegetation Management Program
VTC	Vegetation-type conversion
WIRC	Wildfire Interdisciplinary Research Center

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Authors' contributions

JA collaboratively designed the scope of the project; led data acquisition, analysis, and interpretation; and coordinated and wrote the work. DB assisted with data acquisition and some original methods text. HB assisted with data acquisition. KC assisted with data acquisition, graphical communication, and revised the work. AK assisted with data acquisition and interpretation. MV designed helicopter-based data acquisitions and assisted with interpretation. XR assisted with data acquisition and some original methods text. CC collaboratively conceived of the project and facilitated the prescribed fire experiment. AG collaboratively conceived of the project, assisted with data acquisition, analysis, and interpretation; and revised the work. BY collaboratively designed the work and assisted with some original methods text. KW collaboratively conceived of the project and designed the scope, assisted with data analysis and interpretation, and drafted and revised the work.

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Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to future manuscripts in preparation, but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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