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Relationship of satellite-derived fire severity to archaeological fire severity and fire effects in the Jemez Mountains, New Mexico, USA

Rachel A. Loehman^{1*} , Megan M. Friggens² , Connie I. Constan³ and Anastasia Steffen^{4^}

Abstract

Background Archaeological attributes important for determining cultural affiliation, site age, or artifact origin can be damaged or destroyed by wildfires. Satellite-derived fire severity products are used in post-fire rapid response to prioritize and guide stabilization and preservation activities, but their ability to predict archaeological fire effects has not yet been tested. We compared the severity of fire from Burned Area Reflectance Classification (BARC) maps with ground-based observations of fire severity ("archaeological fire severity") and fire-induced changes to architecture, features, or artifacts ("archaeological fire effects") for 904 archaeological sites within three wildfires in the Jemez Mountains of north-central New Mexico, U.S. Results from this unique study inform archaeological preservation in the context of wildfires and fire management.

Results We found a statistically significant, moderately strong association between BARC and archaeological fire severity and a high likelihood that sites with a low BARC fire severity also had a low archaeological fire severity designation. Sites burned at moderate or high BARC severity were less likely to have a matching severity classification in post-fire assessments, and BARC maps tended to identify as unburned areas where archaeologists determined that sites were burned at low severity. Archaeological fire effects were associated with all BARC fire severity classes, with an increasing proportion of effects observed for moderate versus low severity. Archaeological fire effects were also observed at sites classified by BARC as unburned.

Conclusions Generally, BARC maps provide good assessment of the severity of fire and its effects on archaeological resources, particularly for areas burned at low severity. In areas of moderate or high fire severity, BARC maps may not consistently identify sites with a high need for assessment, and archaeological fire effects can also be present at sites classified by BARC as unburned. Adoption of standardized post-fire archaeological assessments across wildfires and regions, exploration of alternative fire mapping products, and continued research on the fire environments that produce archaeological fire effects can enhance archaeological preservation and post-fire response.

Resumen

Antecedentes Los atributos arqueológicos importantes para determinar la afiliación, la edad del sitio arqueológico, u origen de los artefactos, pueden ser dañados o destruidos por los incendios. Los productos derivados de imágenes

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satelitales que determinan severidad de los incendios, son usados para dar una respuesta rápida post fuego y priorizar y guiar la estabilización y las actividades de preservación; sin embargo, su habilidad para predecir los efectos del fuego en sitios arqueológicos, no fueron probados aún. En este trabajo, comparamos la severidad del fuego mediante mapas basados en la clasificación de la reflectancia del área quemada (*Burned Area Reflectance Classification*, BARC), en conjunto con observaciones a campo de la severidad el fuego (severidad en sitios arqueológicos), y los cambios producidos por el fuego en la arquitectura, las características, o en los artefactos arqueológicos, en 904 sitios dentro del contexto de tres incendios ocurridos en las Montañas de Jemez, en el centro-norte de Nuevo México, EEUU. Los resultados de este estudio único informan sobre la preservación de sitios arqueológicos en el contexto de incendios de vegetación y su manejo.

Resultados Encontramos asociaciones moderadamente altas y estadísticamente significativas entre BARC y la severidad del fuego en sitios arqueológicos, y una alta probabilidad de que los sitios BARC quemados a baja severidad tuviesen también una designación como de baja severidad en las observaciones de campo. Los sitios quemados a severidad media o alta tuvieron una menor probabilidad de ajustar con la severidad observada a campo en las determinaciones post fuego, y los mapas BARC tendieron a identificar áreas como no quemadas mientras que los arqueólogos determinaron que esos sitios se habían quemado a baja severidad. Los efectos de los fuegos arqueológicos fueron asociados con todas las clases de severidad determinadas con BARC, con una proporción incremental de efectos observados en los casos de severidad moderada en comparación con los de baja severidad. Los efectos de los incendios en los sitios arqueológicos fueron también observados en sitios clasificados por la clasificación BARC como no quemados.

Conclusiones En general, los mapas BARC proveen de una determinación de la severidad del fuego y sus efectos sobre los recursos arqueológicos, particularmente en áreas quemadas a baja severidad. En áreas quemadas a moderada o alta severidad, los mapas BARC pueden no identificar consistentemente sitios con una alta necesidad de detección, y los efectos del fuego en sitios arqueológicos pueden también estar presentes en sitios clasificados por BARC como no quemados. La adopción de determinaciones estandarizadas en el post fuego entre distintos incendios y regiones, la exploración de alternativas a mapas de incendios, y la investigación continua sobre ambientes de incendios que produzcan efectos sobre sitios arqueológicos, pueden aumentar la preservación y la respuesta post incendio.

Keywords Archaeology, Cultural resources, Fire severity, Fire effects, BARC, BAER, Southwestern US, Jemez Mountains

Background

Archaeological landscapes of the southwestern United States (U.S.) have been exposed to frequent, low-severity wildfires for millennia (Swetnam et al. 2016; Roos et al. 2021). Combined changes in climate, land use, and fuel patterns over the last century (e.g., Littell et al. 2016; Parks and Abatzoglou 2020; Hagmann et al. 2021) have increased wildfire activity and amplified ecological and social impacts of fire relative to historical fire regimes (McWethy et al. 2019; Singleton et al. 2019; Mueller et al. 2020). Wildfires can affect the archaeological record through physical or chemical changes that obscure or destroy attributes important for determining site origin, age, or cultural affiliation, or technology of artifact production (Buenger 2003; Deal 2012; Loehman et al. 2016). Landscape features that inform past human-environment interactions (e.g., evidence of pre-European Indigenous influence on fire regimes and flora) or that have cultural significance for contemporary Indigenous peoples (e.g., medicinal or subsistence plants) may be altered or destroyed by uncharacteristic wildfires (Carter et al. 2021; Roos et al. 2021; Oeggerli and Grenz 2025).

The type and severity of archaeological fire effects have been linked to fire intensity and heating duration, fuel characteristics, seasonal weather, topographic setting, combustion process, and artifact material (Ryan and Koerner 2012; Loehman et al. 2016; Pozo-Antonio et al. 2020; Friggs et al. 2021). Here, we use the term fire severity to represent immediate post-fire changes that are the direct result of combustion processes (e.g., fuel consumption, charcoal production, and soil alteration) and stem from interactions of fire intensity and residence time (Jain 2004; Morgan et al. 2014).

Fire severity indices have been widely applied to quantify the degree of fire-induced ecological change within a fire perimeter via comparison of pre- and post-fire satellite imagery (e.g., Eidenshink et al. 2007; Robichaud et al. 2014; Pelletier et al. 2021). Most commonly, these include the delta or differenced Normalized Burn Ratio (dNBR) or relativized dNBR (RdNBR) (Parks et al. 2014), both of which capture changes in aboveground vegetation, presence of soil char and ash, and exposure of mineral soil (Miller and Thode 2007). Immediately following major wildfires, federal Burned Area Emergency Response (BAER) teams produce

field-calibrated dNBR-based Burned Area Reflectance Classification (BARC) maps, used to prioritize initial post-fire reconnaissance and to guide emergency stabilization activities (Safford et al. 2008; Parsons et al. 2010). The BARC maps identify areas where immediate (within days) post-fire hazards such as erosion, debris flows, and flooding may occur (Parsons et al. 2010, Robichaud and Ashmun 2013). For archaeological resources within wildfires, BARC maps guide implementation of emergency treatments that minimize or prevent degradation (Napper 2006), with priority given to those areas classified at higher fire severity (Haines and Schofer 2008).

A growing global body of work identifies vulnerabilities of archaeological resources to sea level rise, storm events, and glacial retreat (e.g., Daly 2014; Friesen 2018; Hollesen 2022), but less attention has been paid to wildfire. Although drivers of ecological and archaeological fire effects are generally consistent (e.g., climate, weather, topography, and fuels characteristics; Holden et al. 2009; Parks et al. 2018; Friggens et al. 2021), the ability of satellite-derived fire severity products to accurately represent the severity of fire and its effects on archaeological resources has not yet been evaluated. Previous studies have found that remotely sensed indices reliably (Holden et al. 2009; Parks et al. 2014) or inconsistently (Hudak et al. 2007; Miller et al. 2009) capture ecologically significant fire effects when compared to ground-based measures of fire severity, with low accuracy attributed to mismatches between satellite pixel resolution and the finer scale and heterogeneity of fire effects. Whether these indices represent the physical mechanisms within wildfires that cause effects is an open question, yet remotely sensed fire severity measures are frequently used to represent the severity of fire across a range of resources.

In this study we relate BARC fire severity to post-fire assessments of fire severity and archaeological fire effects for three wildfires in the Jemez Mountains of north-central New Mexico, U.S. Our objectives were to (1) evaluate the ability of BARC maps to represent observed fire severity at archaeological sites, (2) quantify the risk of archaeological fire effects within burned areas, and (3) identify fire-induced changes to archaeological architecture, features, or artifacts across a fire severity gradient. Within the context of the archaeological and ecological landscapes represented within this study, our results provide information on the applicability of existing post-fire assessment products for guiding emergency stabilization and preservation actions, and for identifying the fire environments that damage or alter archaeological sites and materials.

Methods

Study area

Our study area comprises the footprints of three wildfires that burned in the Jemez Mountains of northern New Mexico, U.S.: Virgin Canyon, ignited 09 October 2010, 688 ha; Las Conchas, ignited 26 June 2011, 61,058 ha; and Thompson Ridge, ignited 31 May 2011, 8531 ha (Short 2022) (Fig. 1). The Jemez Mountains are a mainly forested landscape of mesas and canyons ranging in elevation from 1500 to 3500 m above sea level (Muldavin et al. 2011). Plant communities along this gradient include lower elevation piñon pine (*Pinus edulis* Engelm.) and juniper (*Juniperus monosperma* (Engelm.) Sarg.) woodlands, mid-elevation ponderosa pine (*Pinus ponderosa* Douglas ex. P. Lawson & C. Lawson) forests, and upper-elevation mixed conifer forests of ponderosa pine, white fir (*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.), Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mayr) Franco), southwestern white pine (*Pinus strobiformis* Engelm.), limber pine (*Pinus flexilis* E. James), and quaking aspen (*Populus tremuloides* Michx.) (Muldavin et al. 2011). Climate is continental and semi-arid, with a bimodal precipitation regime dominated by convective summer monsoonal storms (Touchan et al. 1996). Winter precipitation is annually highly variable due to Pacific Ocean teleconnections including El Niño–Southern Oscillation (ENSO) (Sheppard et al. 2002), and wildfire occurrence at millennial time scales has been linked to alternating patterns of moisture and drought in winter seasons (Swetnam and Baisan 2003). Local tree fire scar chronologies describe historical fire regimes that were generally dominated by frequent (6- to 15-year mean interval), widespread, low-severity surface fires in dry forests (Touchan et al. 1996; Swetnam et al. 2016), and longer-interval (20 to 42 years) fires with small patches of high severity in more mesic forests (Margolis et al. 2017). Anthropogenic influences on fire regimes in the Jemez Mountains include (1) pre-1680 CE reduced widespread fire occurrence and increased number of small-extent fires resulting from Indigenous land and fire stewardship practices (Swetnam et al. 2016; Roos et al. 2021), (2) late nineteenth century reduction in surface fires, after intensive livestock grazing disrupted fuel continuity (Allen et al. 2002), and (3) twentieth century decreased fire frequency and increased high severity fire extent, driven by fuel accumulation and fuel aridity associated with mechanized fire suppression and anthropogenic climate changes, respectively (Singleton et al. 2019; McClure et al. 2024).

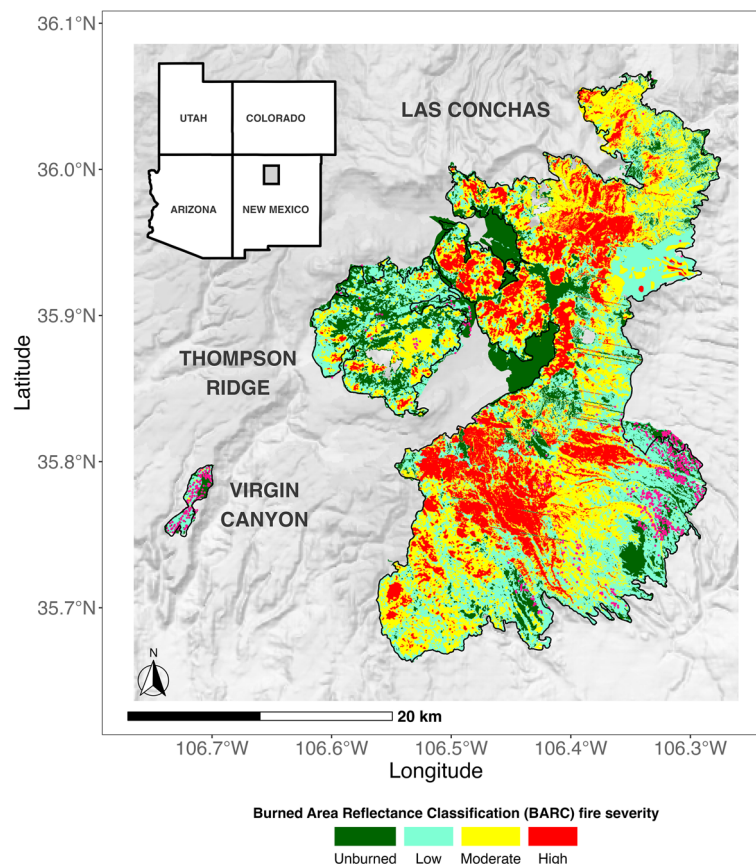


Fig. 1 Study region in the Jemez Mountains, New Mexico, U.S. We assessed the relationship of archaeological fire severity and fire effects to fire severity derived from Burned Area Reflectance Characterization (BARC) maps for three wildfires: Virgin Canyon (2010), Las Conchas (2011), and Thompson Ridge (2013). The BARC maps assess fire severity in four categories: unburned, low, moderate, or high severity, and are a rapid-response product used to prioritize initial post-fire reconnaissance and to guide emergency stabilization activities. Final fire perimeters, derived about a year post-fire, are shown as black outlines. Post-fire assessments for 904 archaeological sites within fire perimeters (shown as fuchsia dots) provided field observations of archaeological fire severity and fire-induced changes to archaeological architecture, features, and artifacts

Archaeological record

The Indigenous occupational history of the Jemez Mountains spans 12,000 years, with a material archaeological record that reflects shifting land and resource use (Elliott 1986). Lithic artifact scatters and obsidian quarries present at high elevations (>2500 m) derive from the Archaic period (ca. 8000 years ago) hunting, gathering, and resource procurement (LeTourneau and Shackley 2009; Steffen 2016). Obsidians from the Jemez Mountains—and particularly from three source areas within the Valles Caldera National Preserve—are found at archaeological sites throughout the southwestern U.S. and southern Great Plains (Kilby and Cunningham 2002), hold cultural importance for descendent communities within the region (Liebmann 2017), and can be used to date or age archaeological sites via geochemical analysis (Friedman et al. 1997).

Lower elevation (<2500 m) archaeological sites mainly date to between 1200 and 1600 CE, when the Jemez

region was a center of settlement for late ancestral and early Pueblo peoples (Crown et al. 1996). The majority of sites are small, one to four room masonry structures (field houses) that were likely associated with agricultural activities (Orcutt 1993; Kulisheck 2003). Fewer in number are apartment-style villages (pueblos) of more than 50 rooms, some of which include multiple plazas and great kivas (Kulisheck 2003). Ceramic artifacts (sherds) present within sites include plain, slipped, and glazed wares (Elliott 1986), many of which are diagnostic for determining settlement history based on variation in decoration, source materials, formation methods, and vessel shape (Ramenofsky and Feathers 2002). Lithic artifacts—including formal and informal tools, flakes, and debitage—derive from chert, basalt, and obsidian (Kilby and Cunningham 2002). Other archaeological features include pithouses, rock shelters, kivas (ritual structures), shrines, rock art, reservoirs, agricultural terraces, grid gardens, check dams, and hearths (Elliott

1986, Anschuetz 2006). Collectively, this record (hereafter, “prehistoric”) preserves evidence of a long-term and complex history of migration, aggregation, agricultural intensification, fire and forest management, colonial-era population collapse, and adaptation to periods of unfavorable regional climate (Liebmann et al. 2016; Roos et al. 2021, Auivalasit and Jorgeson 2024). Post-dating this record are sites, artifacts, and features that record the history of European contact, colonization, and land use (hereafter, “historic”), including roads and trails, railroad grades, camps, townsites, graves, sawmills, mines, corals, wooden structures, and trash scatters (Anschuetz and Merlan 2007; Norris and Elliott 2022).

Data

Archaeological data

Data on fire severity and fire effects at archaeological sites were derived from post-fire assessments generated by the USDA Forest Service (USFS, Santa Fe National Forest) or National Park Service (NPS, Bandelier National Monument and Valles Caldera National Preserve) within the perimeters of three large wildfires: Virgin Canyon (2010), Las Conchas (2011), or Thompson Ridge (2013) (Fig. 1). Assessments are typically conducted by BAER teams soon after a wildfire incident and provide observations of site condition, fire severity, and fire effects, recommendations for preservation treatments, and other information relevant to identifying follow-up actions to reduce potential negative after-effects of fire (Haines and Schofer 2008; Parsons et al. 2010). Post-fire assessment activities

target archaeological sites recorded in pre-fire inventories, although wildfires can expose previously unrecorded sites (Davis 2018). In assessments included in this study, fire severity observations identified fire-induced changes to soils, duff, litter, and vegetation, whereas fire effects observations related to fire-induced changes to prehistoric or historic architecture, features, and artifacts at archaeological sites (Fig. 2).

Terminology and assessment rubrics varied between NPS and USFS assessment forms, requiring us to standardize fire severity observations at archaeological sites to one of four potential classifications (hereafter, “archaeological fire severity”) to match BARC fire severity classes: unburned, low (scorched or lightly burned), moderate, or high (severely or heavily burned) (Appendix A.1). Generally, unburned sites were locations that fire did not cross; sites burned at low severity had partially blackened to partially consumed litter, partially burned or scorched woody debris, and partially to completely consumed foliage and smaller twigs but mainly intact branches; sites burned at moderate severity had mostly to entirely consumed litter with residual coarse light ash, deeply charred duff and unaltered underlying soils, mainly consumed woody debris and deeply charred logs, and completely consumed foliage and smaller twigs but mainly intact branches; and sites burned at high severity had entirely consumed litter and duff with residual fine white ash, visibly altered mineral soil, deeply charred logs, and total consumption of all plants including most major stems and trunks.

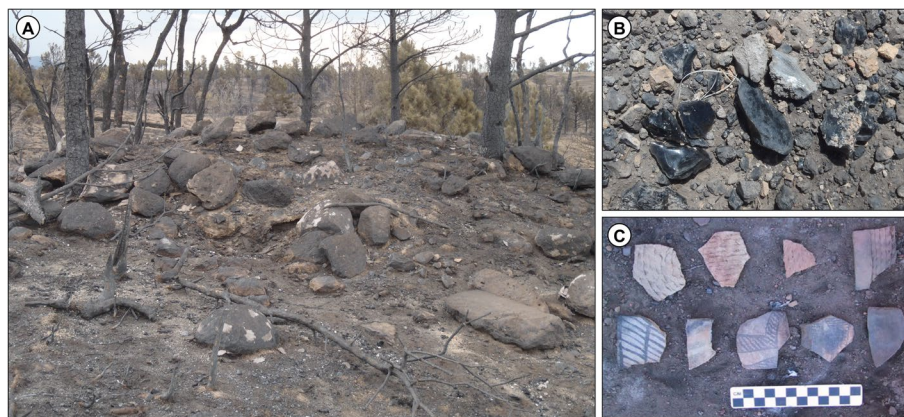


Fig. 2 **A** Prehistoric archaeological site in the Jemez Mountains, New Mexico, U.S., burned at a moderate archaeological fire severity during the 2011 Las Conchas wildfire. Note the presence of fire severity indicators including consumption of duff and litter layers, presence of white ash, and charred wood. Visible archaeological fire effects include spalling (lighter patches on architectural stones, resulting from exfoliation of portions of the original surface due to differential heating and pressure release), sooting, color changes, and scorching. **B** Fire effects to obsidian artifacts, including vesiculation (bubbling in response to heat exposure, creating a frothy, grey appearance), sheen (surface alteration that is silvery and reflective in appearance), and crazing (shallow cracking on object surfaces). **C** Fire effects to ceramic artifacts, including sooting, color changes, and oxidation. (reaction to oxygen and heat that can cause a change in pigmentation color (e.g., black to red) or combustion of the pigment entirely). See Ryan et al. 2012 for expanded definitions of archaeological fire effects. Photo credits: National Park Service (**A**), U.S. Geological Survey (**B**), U.S. Forest Service (**C**)

From an initial data set of 930 assessments, we excluded 10 assessments that contained no fire severity observations or represented archaeological sites that could not be relocated post-fire and 16 assessments representing archaeological site types that could not be definitively identified as prehistoric or historic (e.g., dumps, trails, trash, roads, or recent sites). Our final archaeological fire severity data set included 904 sites, most from NPS lands within the Las Conchas wildfire perimeter (Table 1). Fifteen sites were previously unrecorded, all from within the Las Conchas fire. Archaeological sites were predominantly prehistoric, including field houses and other small masonry structures, artifact scatters, and multi-roomed pueblo villages. A smaller proportion of the data set was comprised of historic sites or multi-component sites that included evidence of both prehistoric and historic use (Appendix A.2).

Field observations of fire-induced changes to archaeological architecture, features, or artifacts (hereafter, “archaeological fire effect”) included a subset of the archaeological site data described above ($n=622$ sites) within the perimeters of the Las Conchas or Thompson Ridge fires, on lands administered by the NPS. We excluded USFS assessments because information on archaeological fire effects was not comparable with the larger NPS data set. We focused on direct effects (resulting from exposure to heat and flame during a fire, versus indirect effects that occur in the days, weeks, or years after wildfire has burned; Ryan et al. 2012) and grouped observations into categories reflecting mechanism of effect: sooting or other combustible residue (additive mechanism); color change or oxidation (chemical mechanism); fire fracture, including cracking, crazing, spalling, or shattering (physical mechanism); scorching (additive and chemical mechanisms); and obsidian effects (additive, chemical, or physical mechanism). We created two types of archaeological effect variables: the first coded an effect as

“present” when one or more direct fire effects to architecture, features, or artifacts were recorded on a site assessment form, and as “not present” when no effect was recorded. The second variable indicated which of the direct fire effect categories were observed at each site. Sites could have more than one type of fire effect; this could occur if a site contained multiple artifact or feature types with varying sensitivities or responses to fire (Steffen et al. 2024).

Satellite-derived fire severity

Fire severity data in the form of 30-m resolution BARC maps were provided by the USFS, Santa Fe National Forest for the three fires included in the study. Standard to BARC processing, severity was assessed using comparisons of pre- and post-fire satellite imagery (dNBR) to quantify the degree of fire-induced ecological change, which was then thresholded into categories of severity (unburned, low, moderate, and high) (Hudak et al. 2007). Initial severity thresholds were adjusted via field validation of soil (e.g., ash color and depth, soil structure, soil water repellency) and vegetation (e.g., aboveground vegetation consumption, mortality and scorch) properties that are indicators of the degree of severity (Parsons et al. 2010; Robichaud et al. 2014).

In post-fire assessments, a central point (datum) identified the geographic location of each archaeological site (i.e., assessments did not include site dimensions). To produce an area-based fire severity for each site (hereafter, “BARC fire severity”), we buffered each central site location (datum) by 10 m and used the resulting polygons to extract BARC fire severity pixels using ArcMap 10.2.2 (Esri, Inc. 2016). The 314 m² polygons were assumed to encompass the central features of the predominant archaeological site types in our study—small masonry structures and artifact scatters—based on site dimensions reported in the literature for the Jemez Mountains (Traylor et al. 1990; Lentz et al. 1996; Nisengard et al. 2002). A single BARC severity classification was assigned to each polygon, and where polygons encompassed more than one BARC classification (five sites), we assigned the BARC severity that comprised the majority of the polygon area. We then created a variable representing fire exposure, where sites were considered “fire exposed” if a BARC fire severity of low, moderate, or high was assigned to that site and were coded as “unexposed” if BARC maps indicated a fire severity of unburned. These variables allowed us to compare archaeological and BARC fire severities and to relate archaeological fire effects to fire exposure along a fire severity gradient.

Table 1 Number of analyzed archaeological sites ($n=904$) by land managing agency (National Park Service or U.S. Forest Service) within the Virgin Canyon (2010), Las Conchas (2011), and Thompson Ridge (2013) wildfires in New Mexico, U.S.

	Overall $n=904$	Wildfire		
		Virgin Canyon $n=155$	Las Conchas $n=696$	Thompson Ridge $n=53$
National Park Service	622	0	569	53
U.S. Forest Service	282	155	127	0

Analysis

Comparison of BARC and archaeological fire severity

All analyses were performed using R Statistical Software (v4.1.1; R Core Team 2025). To evaluate the relationship between BARC fire severity and observed fire severity at archaeological sites we first created four-way contingency tables with BARC fire severity as the independent variable and archaeological fire severity as the dependent variable. We used the Pearson chi-square test of independence (Franke et al. 2012) to test whether fire severity observations from these two data sources were associated, where a statistically significant response indicates that variables are related to, rather than independent of, one another. We then assessed the strength of that relationship using Cramér's *V*, an effect size test for nominal data (McHugh 2013), in package *vcd* (Meyer et al. 2024). We calculated standardized Pearson residuals and Bonferroni adjusted *p*-values (Beasley and Schumacker 1995) for each cell in the contingency table to identify the pairwise fire severity classes that contributed most to the overall chi-square statistic. We used conditional probabilities to determine the likelihood of observing an archaeological fire severity class given an obtained BARC fire severity class; for example, the likelihood of observing a low archaeological fire severity for sites with a low BARC fire severity designation. We applied the “margin=1” option in the *prop.table* function to convert our contingency table into a cell-wise conditional probability table conditioned on BARC fire severity, using the formula $P(B|A)=P(A \text{ and } B)/P(A)$ where the conditional probability (*P*) of an archaeological fire severity event (*B*) given a BARC fire severity event (*A*) is equal to the joint probability of both events' occurrence (*A* and *B*) divided by the probability of the BARC fire severity event (*A*). Fire severity analyses were performed on the full set of 904 observations.

Archaeological fire effects

As above, we tested the significance and strength of the relationship between BARC severity and archaeological fire effects using the Pearson chi-square test of independence followed by Cramér's *V*. We then calculated the likelihood that fire exposure results in an archaeological fire effect using absolute risk and risk ratio with unconditional maximum likelihood estimation (Wald) (package *epitools*, Aragon et al. 2017). Both metrics are common epidemiologic approaches for comparing the outcome of an event (typically, a disease) in an exposed group versus an unexposed group (Cipriani et al. 2007). In our analysis, the outcome is an observation of a fire effect and exposure is the presence of wildfire of any severity at that site (as indicated by BARC maps). Absolute risk is the likelihood of occurrence of an archaeological fire effect in a fire-exposed site (or, conversely, the risk of a fire effect occurring at a site classified as unburned), and risk ratio represents the increased likelihood (risk) of a fire effect occurring at a fire-exposed site versus at a site classified by BARC as unburned (unexposed). We compared proportional occurrence of direct fire effects (e.g., sooting or other combustive residue, fire fracture, scorching) within and across BARC fire severity classes to identify patterns of fire alteration across the gradient of fire severity. Analyses were performed on the subset of 622 observations from NPS post-fire assessments.

Results

Relationship of BARC and archaeological fire severity

Archaeological post-fire assessments from three wildfires identified 19% of sites as unburned, 63% as burned at low severity, 12% as burned at moderate severity, and 6% as burned at high severity (Table 2). Relative to archaeological assessments, BARC maps identified more unburned sites (37%), fewer sites burned at low (49%) or high (1%)

Table 2 Frequency of observed archaeological fire severity and Burned Area Reflectance Classification (BARC) fire severity by class (unburned, low, moderate, or high severity) for 904 archaeological sites within the Virgin Canyon (2010), Las Conchas (2011), and Thompson Ridge (2013) wildfires in New Mexico, U.S. Each cell reports the combined class frequency (contingency; i.e., the number of observations for which post-fire assessments and BARC maps reported the same fire severity class). Values in parentheses are Pearson standardized residuals. Bold values indicate where BARC and archaeological severity classes were observed more (positive numbers) or less (negative numbers) frequently than expected under a null hypothesis of random association, with significance at the $P < 0.05$ level. Residuals in plain text were less than the threshold (± 2) for determining deviation from the expected frequency and/or were non-significant

Archaeological fire severity	BARC fire severity			
	Unburned <i>n</i> = 338	Low <i>n</i> = 445	Moderate <i>n</i> = 113	High <i>n</i> = 8
Unburned (<i>n</i> = 175)	105 (6.88)	68 (– 3.06)	2 (– 5.06)	0 (– 1.39)
Low (<i>n</i> = 567)	202 (– 1.42)	322 (5.90)	42 (– 6.01)	1 (– 2.95)
Moderate (<i>n</i> = 107)	29 (– 2.34)	34 (– 3.85)	39 (7.98)	5 (4.46)
High (<i>n</i> = 55)	2 (– 5.34)	21 (– 1.69)	30 (9.73)	2 (2.25)

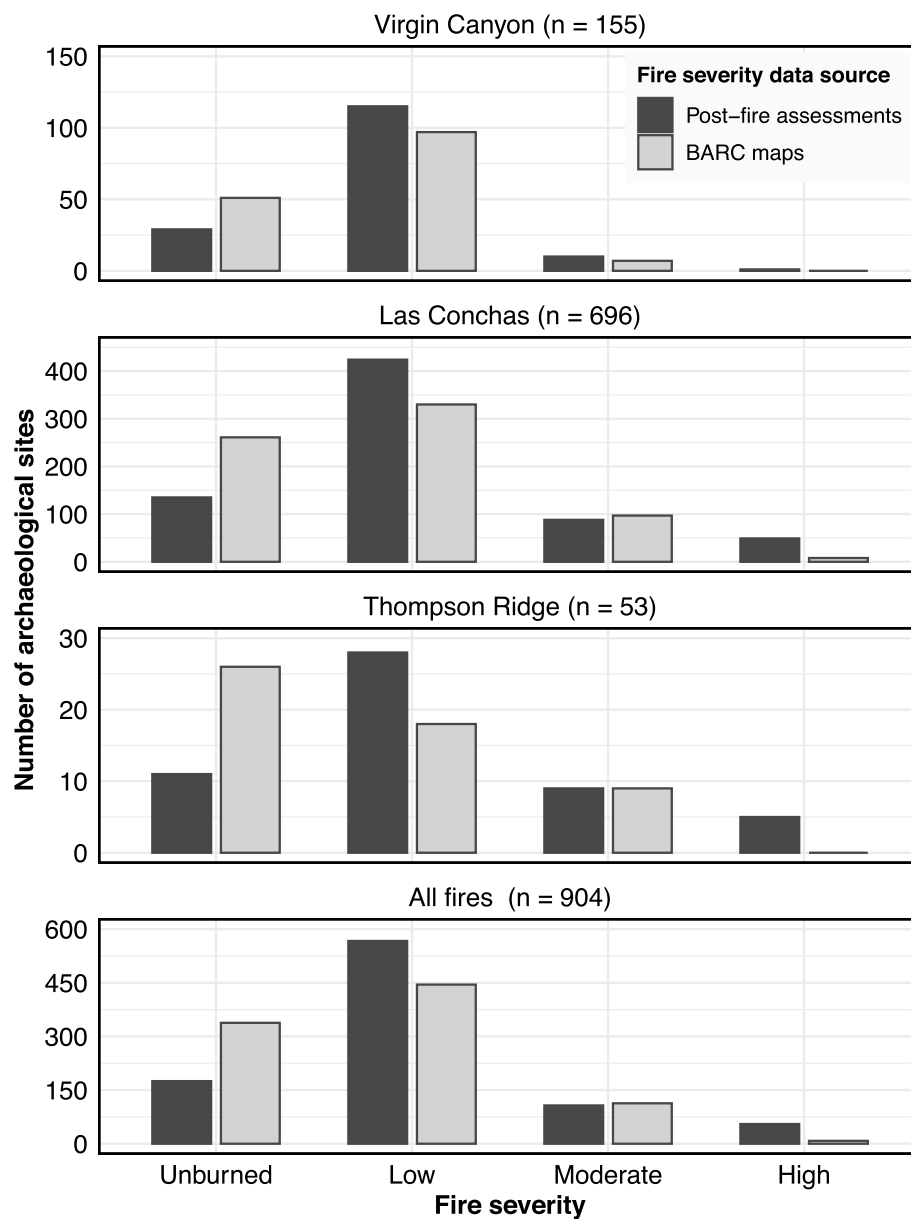


Fig. 3 Archaeological sites classified as unburned or burned at low, moderate, or high severity in post-fire archaeological assessments (black bars) and Burned Area Reflectance Characterization (BARC) maps (gray bars). Fire severity observations are reported for individual fires in the study (Virgin Canyon, 2010, $n = 155$; Las Conchas, 2011, $n = 696$; and Thompson Ridge, 2013, $n = 53$) and for all fires combined ($n = 904$), for all archaeological sites in the study. Note different scales for y-axes for each fire, to account for large differences in the number of archaeological sites assessed across fires

severity, and approximately the same number of moderately burned sites (13%) (Table 2). This pattern was consistent for each fire in the study (Fig. 3). We found a statistically significant, moderately strong association between archaeological fire severity and BARC fire severity ($X^2 = 246.1$, $df = 9$, $P < 0.001$, $V = 0.301$). Large ($> \pm 2$) and significant ($P < 0.05$) residuals identified the contingent severity classes that contributed most to the overall chi-square statistic. Matching observations of unburned,

low, or moderate severity (sites with the same BARC and archaeological fire severity class) occurred more frequently than expected due to chance. Some mismatched fire severity combinations also occurred more frequently than due to chance (e.g., moderate BARC fire severity but high archaeological fire severity; high BARC fire severity but moderate archaeological fire severity) (Table 2). We found a high likelihood ($\sim 72\%$ probability) that sites with a low BARC fire severity also had a low archaeological

fire severity designation, but a lower likelihood (<35% probability in all cases) of a match between BARC and archaeological fire severity for unburned, moderate, or high severity classes. Sites with an unburned BARC designation were more likely to have low archaeological fire severity (~60%) than unburned (~32%). Sites classified as moderate BARC fire severity were nearly equally likely to have been assessed as low (~37%) or moderate (~35%) archaeological fire severity. Among sites classified as high BARC fire severity, a moderate archaeological fire severity designation was more likely (~63%) than a high fire severity designation (25%) (Fig. 4).

Archaeological fire effects

After testing for independence via Pearson chi-square tests, we found a statistically significant but weak association between BARC fire exposure and archaeological fire effects ($\chi^2=41.209$, $df=1$, $P<0.001$, $V=0.26$). The absolute risk of fire effects at fire exposed sites (i.e., sites with a low, moderate, or high BARC fire severity) was 64%; conversely, the risk of fire effects at sites classified by BARC as unburned was 36% (Table 3). As identified via risk ratio, fire exposure was associated with a 1.7-fold (170%) increase in the risk of archaeological fire effects, relative to the risk of effects at BARC-classified unburned sites (95% CI 1.45, 2.07, $P<0.001$).

Archaeological fire effects were observed at 51% of the 622 archaeological sites represented in NPS post-fire assessments (Table 4). Sooting or combustive

Table 3 Frequency and absolute risk (%) of archaeological fire effects for 622 archaeological sites within the Las Conchas (2011) and Thompson Ridge (2013) fires in New Mexico, U.S. Fire exposed archaeological sites have a Burned Area Reflectance Classification (BARC) fire severity of low, moderate, or high severity and unexposed sites have an associated unburned BARC classification. Archaeological fire effects include one or more of the following: sooting or combustive residue, color change or oxidation, fire fracture (cracking, crazing, spalling, or shattering), scorching, or obsidian effects (see Fig. 2)

Archaeological fire effect	All sites $n=622$	Fire exposed sites $n=352$	Unexposed sites $n=270$
No effects observed	306 (49%)	133 (38%)	173 (64%)
One or more effects observed	316 (51%)	219 (62%)	97 (36%)

residue was the most frequently noted effect, occurring at almost half of all sites (46%), regardless of BARC fire severity class, followed by color changes or oxidation (31% of sites), fire fracture (26% of sites), scorching (21% of sites), and obsidian effects (9% of sites) (Table 4). All categories of archaeological fire effects occurred more frequently at sites with moderate versus low BARC fire severity (Fig. 5). Archaeological sites with an associated high BARC fire severity were underrepresented in our data set, making it difficult to discern a relationship with fire effects. One or more archaeological fire effects were present at 36% of

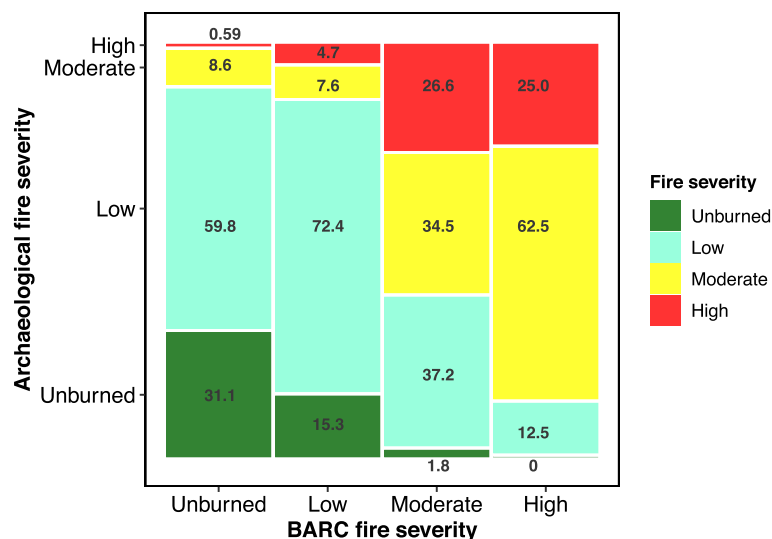


Fig. 4 Conditional probability of observing an archaeological fire severity class (unburned, low, moderate, or high) for a given Burned Area Reflectance Characterization (BARC) fire severity class, for 904 archaeological sites within the Virgin Canyon (2010), Las Conchas (2011), or Thompson Ridge (2013) fires in New Mexico, U.S. Larger cells indicate a higher conditional probability; for example, the conditional probability of obtaining a “low” archaeological fire severity for sites mapped by BARC as low severity is ~72%. All pairwise conditional probabilities are shown as numbers within corresponding cells

Table 4 Frequency and proportional occurrence of archaeological fire effects for all archaeological sites and sites within unburned, low, moderate, and high severity Burned Area Reflectance Classification (BARC) fire severity classes, for 622 archaeological sites within the Las Conchas (2011) and Thompson Ridge (2013) fires in New Mexico, U.S. Values in parentheses represent the proportion of sites within a BARC fire severity class for which an archaeological fire effect was observed. It is important to note that fire effects are not exclusive: more than one effect may be present at a single archaeological site

Archaeological fire effect	BARC fire severity				
	All sites <i>n</i> = 622	Unburned <i>n</i> = 270	Low <i>n</i> = 291	Moderate <i>n</i> = 57	High <i>n</i> = 4
Sooting, combustive residue	286 (46%)	86 (32%)	150 (52%)	48 (84%)	2 (50%)
Color change, oxidation	193 (31%)	60 (22%)	99 (34%)	33 (58%)	1 (25%)
Fire fracture	161 (26%)	49 (18%)	75 (26%)	35 (61%)	2 (50%)
Scorching	129 (21%)	33 (12%)	66 (23%)	30 (53%)	0 (0%)
Obsidian effects	55 (9%)	9 (3.3%)	27 (9.3%)	17 (30%)	2 (50%)
Any effect	316 (51%)	97 (36%)	164 (56%)	52 (91%)	3 (75%)

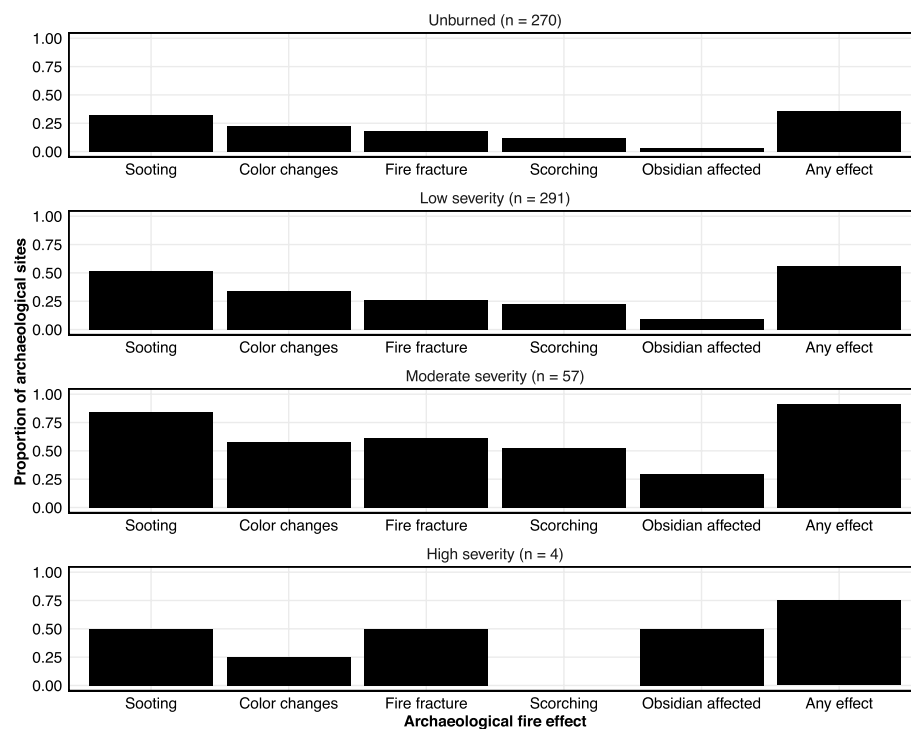


Fig. 5 Archaeological fire effects associated with Burned Area Reflectance Classification (BARC) fire severity classes, for 622 archaeological sites within the Las Conchas (2011) or Thompson Ridge (2013) fires in New Mexico, U.S. Black bars indicate proportion of sites within each Burned Area Reflectance Characterization (BARC) fire severity class (unburned, low, moderate, or high severity) for which an archaeological fire effect was recorded on a post-fire site assessment form. Fire effects are not exclusive; i.e., a single archaeological site may have multiple recorded effects

the 270 archaeological sites identified as unburned by BARC maps (Table 4).

Discussion

We found an overall significant and moderately strong association between BARC and archaeological fire severity, suggesting that BARC maps can serve as a general guide for prioritizing post-fire archaeological

reconnaissance and emergency stabilization measures. The BARC maps were reliable indicators of low archaeological fire severity (> 70% conditional probability) but were less reliable for higher fire severity classes (< 35% match between classes). In our study BARC maps tended to underestimate fire severity at archaeological sites relative to post-fire assessments (i.e., ~63% probability that a site with a high fire severity designation

in post-fire assessments was mapped as a moderate BARC fire severity) (Fig. 4). Archaeological sites burned at low severity had a ~60% probability of an unburned BARC fire severity classification, although Pearson residuals were less than the threshold (± 2) for determining deviation from the expected frequency and were non-significant (Table 2, Fig. 4). Our analysis suggests that archaeological sites within moderately burned areas of BARC maps may warrant prioritization in post-fire planning and reconnaissance, to identify imminent post-fire vulnerabilities to erosion, flooding, and other post-fire disturbances associated with severe fire. Reconnaissance efforts may also consider that fire activity could be present at archaeological sites within unburned regions of BARC maps—in our study, 338 archaeological sites were within areas classified by BARC as unburned, but only 175 of those received an unburned designation in post-fire assessments (Table 2).

Ecological studies have found improved BARC classification accuracy for high severity over lower severity classes, related to the heterogeneous nature of fire effects in low and moderate severity burned areas (Hudak et al. 2007; Lutz et al. 2011). Fire severity is a notoriously ambiguous measure and remains challenging to quantify and standardize using field-based or remote sensing methods (Lutz et al. 2011; Morgan et al. 2014). Remote sensing-based methods are subject to error due to (1) subjectivity in thresholds for categorizing continuous dNBR values into discrete severity classes (Kokaly et al. 2007; Spies et al. 2010); (2) rapid changes in post-fire effects (e.g., vegetation regrowth, redistribution of ash cover by wind or water) that may alter validation plot characteristics relative to post-fire imagery (Hudak et al. 2007); (3) spatial scaling inherent in patterns of fire, from heterogeneity within burned patches to landscape-scale variation (Turner et al. 1994); and (4) the potential scale mismatch between the area and shape of a field plot and the pixel resolution used to remotely assess the plot condition (Pelletier et al. 2021). Each of these sources of potential error may have been present in our study, affecting the ability of BARC maps to represent observations of archaeological fire severity. The fire severity classification rubric in post-fire assessment forms may also have introduced error, by imposing generalized severity categories on complex interactions of fire, fuels, biota, and the biophysical environment (Morgan et al. 2014), or because of observer bias or differences in terminology in NPS and USFS assessment forms. The 10-m buffer distance around site datums, intended to encompass but not overextend beyond the central features of the majority of sites in our study, could have led to differences between BARC and archaeological fire severity, particularly for

archaeological sites larger in area than the 314 m² buffer polygons.

We found a statistically significant but weak relationship (Cramér's $V < 0.30$, McHugh 2013) between fire exposure and archaeological fire effects. We quantified the risk of archaeological fire effects in two ways: first, with absolute risk, a metric that measures the probability of one or more effects occurring among fire-exposed sites, and second, with risk ratio, a comparison of the risk of effects in fire-exposed sites versus those classified by BARC as unburned. The risk of fire effects was higher at fire-exposed sites than unburned sites, but about a third of archaeological sites with one or more observed fire effects were within unburned areas of BARC maps (Table 3). Fire effects noted at sites mapped as unburned—and particularly combustion residues that are relatively transient on the surfaces of artifacts (Buenger 2003; Sturdevant et al. 2009); i.e., were not caused by a previous wildfire—suggests that localized fire activity at relatively small archaeological sites could be undetected at the resolution of BARC maps.

Our archaeological data set included five categories of fire effect: sooting or combustive residue, color changes or oxidation, fire fracture (cracking, crazing, spalling, or shattering), scorching, and obsidian effects. All effects occurred more frequently as fire severity increased (Table 4, Fig. 5). Archaeological sites with a moderate BARC fire severity classification had the highest proportion of observed fire effects (91% of sites) despite comprising just 9% of the data set, highlighting the importance of considering moderately burned sites in BAER reconnaissance. Few ($n=4$) archaeological sites were classified as having high BARC fire severity, but we suspect, based on archaeological assessments following other fires (Lissoway and Propper 1988; Lentz et al. 1996; Steffen 2005), that a larger sample size would have yielded a larger proportion of effects relative to lower severity classes.

Additive fire effects (sooting and combustive residue) occurred most frequently in post-fire assessments (Table 4, Fig. 5) and have been found to occur in a wide array of archaeological materials including ceramics (Rude and Jones 2012), flaked stone, ground stone, masonry, and rock art (Deal 2012; Kelly and McCarthy 2012), and bone, glass, and metal (Sturdevant et al. 2009). Combustion residues that are relatively transient on the surfaces of artifacts (Buenger 2003; Sturdevant et al. 2009) may not permanently alter attributes important for determining site origin, age, or cultural affiliation. Physical and chemical fire effects occurred less frequently in our data set, though they were present at >50% of sites burned at moderate severity, and are of greater preservation concern. For example, thermal fracturing of stone

artifacts can obscure evidence of prehistoric quarrying activity or tool making techniques (Lissoway and Propper 1998), spalling on rock art can destroy design elements indicating past land use and cultural relationships (Kelly and McCarthy 2012), and a change in surface pigments of ceramic artifacts can make their identification impossible (Rude and Jones 2012).

Section 106 of the National Historic Preservation Act and its amendments [54 USC, Pub. L. No. 89- 665, as amended by Pub. L. No. 96- 515] direct land managers to account for potential or actual wildfire damage as part of the inventory, evaluation, and preservation of historic properties (Rockman 2024). Decades of observational studies (e.g., Lissoway and Propper 1988; Lentz et al. 1996; Steffen 2005; Deal 2012) and experimental research (Buenger 2003; Sturdevant et al. 2009; Loehman et al. 2016) highlight the complex relationships among the pre-fire environment (e.g., fuel type, configuration, and condition), the behaviors of fire (e.g., fire intensity and duration), and resulting fire effects to archaeological sites, features, and artifacts. Predicting where and when archaeological fire effects may occur is difficult—over small spatial extents, heterogeneity in fuel patterns, fuel condition, and wind speeds creates fine-grained patterns of fire spread and combustion intensity (Falk et al. 2007; Hiers et al. 2009). In experimental fires, thermal alteration of subsurface deposits was constrained to areas directly under the heat source (fuel) (Aldeias et al. 2016), and other studies have linked archaeological fire impacts to direct flame contact (Lissoway and Propper 1988; Steffen et al. 2024). Not all fire exposure or types of fire cause measurable effects to archaeological materials—studies indicate variation in fire effects resulting from differences in archaeological material types and properties (e.g., wood, stone, ceramic, or metal artifacts; type of stone or ceramic ware type), context and location (e.g., surface or subsurface deposits and soil properties; proximity to burning fuel), and the fire behavior (e.g., duration of heat exposure and combustion intensity) (Lissoway and Propper 1988; Lentz et al. 1996; Buenger 2003; Aldeias et al. 2016; Loehman et al. 2016). Previous studies have found that BARC maps are more indicative of post-fire vegetation condition than soil condition (Hudak et al. 2007; Cansler and MacKenzie 2012); thus, fire environments that cause immediate changes to vegetation may not result in observable fire effects to archaeological materials on or below the ground surface.

Our study results indicate that BARC maps are reliable guides within areas burned at low severity but underestimate archaeological fire severity and fire effects at higher severities and in areas classified as

unburned. Based on these results and understanding of archaeological preservation in the context of wildfires and fire management, we present the following as potential next steps for enhancing fire response and resource protection:

- 1) Development of a standardized archaeological fire severity classification rubric to systematically and objectively document archaeological fire severity and fire effects, to be implemented widely in BAER and other post-fire programs. As suggested by Jain (2004), this would create evaluation metrics tailored to the specific, measurable targets of interest in a consistent and repeatable framework. A robust and intercomparable data set is essential for improving our ability to objectively relate ecological fire severity classifications to archaeological fire effects across a range of environments, site types, and wildfires.
- 2) Detection of archaeological fire severity and fire effects from alternative remote sensing instruments. For example, observations derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) or Visible Infrared Imaging Radiometer Suite (VIIRS) (Schroeder et al. 2014; Giglio et al. 2016) are available within minutes to hours after each satellite overpass and provide measures of fire rate of spread, fire persistence, and fire intensity (Orland et al. 2025) -fire-behavior metrics directly relatable to the physical and chemical impacts of fire on archaeological sites and materials (Ryan and Koerner 2012). Hyperspectral imagery provides a higher spatial resolution and an enhanced spectral signature over multispectral imagery and has been found to capture variable patterns of post-fire surface ash and scorched trees not evident in BARC maps (Kokaly et al. 2007). These approaches could improve mapping accuracy but require specialized data processing.
- 3) Expanded observational, experimental, and model-based evaluation of the relationships among the pre-fire environment, fire behavior, and archaeological fire effects. Friggens et al. (2021) identified topography and weather variables related to fuel dryness as predictors of archaeological fire severity in the Jemez Mountains of New Mexico but noted that model complexity constrained predictions to within the study region. Models based on larger archaeological data sets across diverse environments would lead to broader predictions of where and when fires might negatively impact the archaeological record and could provide programmatic guidance on fuel treatment prioritization and fire management planning.

Conclusions

The potential for negative impacts of wildfires on the archaeological record is a topic of major concern. Uncharacteristically severe wildfires expose archaeological materials to longer heating durations and higher fire intensities than typically occurred in the past (Roos et al. 2020), potentially compromising preservation and interpretation (Lissoway and Propper 1988; Lentz et al. 1996; Steffen 2005). Amplified wildfire activity is highly likely to continue with warming air temperatures and severe regional droughts (Richardson et al. 2022), putting archaeological sites at increasing risk of impacts from high-intensity, long-duration wildfires.

We found good agreement between BARC maps and archaeological post-fire assessments for sites burned at low severity (in either measure); however, BARC maps did not consistently identify sites impacted by higher severity of fire as indicated in post-fire assessments. The BARC maps also tended to identify as unburned areas where archaeologists determined that sites were burned at low severity. Wildfire of any severity resulted in measurable effects to archaeological architecture, features, or artifacts at some sites, but effects of fire were also observed at sites classified by BARC as unburned. These included additive, chemical, and physical changes to the archaeological material record, but our data set did not allow us to determine whether these effects compromised archaeological preservation or interpretation. Important next steps for archaeological preservation and protection in fire-prone environments include adoption of standardized post-fire archaeological assessment rubrics, evaluation of alternative products for mapping the severity of fire in archaeological contexts, and development of predictive models for anticipating archaeological fire impacts—and potential mitigation actions—before wildfires occur.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42408-026-00472-w>.

Supplementary Material 1: A.1 Archaeological fire severity classifications from National Park Service (NPS) and U.S. Forest Service (USFS) post-fire assessment forms, standardized to BARC fire severity classes. A.2. Number of analyzed archaeological sites (n = 904) by archaeological site type within the Virgin Canyon (2010), Las Conchas (2011), and Thompson Ridge (2013) wildfires in New Mexico, U.S.

Acknowledgements

We thank Jamie Civitello (National Park Service) for assistance with obtaining post-fire assessments, and two anonymous reviewers for their suggestions for improving the manuscript. We also gratefully acknowledge the fire archaeologists who protect sites as part of the BAER process and in doing so provided data for this research. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The findings and conclusions in this publication are those of the author(s) and should not be construed to represent any official USDA determination or

policy. No generative artificial intelligence (AI) was used in the development, analysis, or writing of this work.

Authors' contributions

RL and MF designed the study, conducted analyses, interpreted results, and drafted the manuscript; CC collected data, contributed important foundational concepts, and contributed to the manuscript; AS contributed important foundational concepts. All living authors read and approved the final manuscript.

Funding

This research was supported by the Joint Fire Science Program (JFSP 12-1-04-5, *ArcBurn: Linking field-based and experimental methods to quantify, predict, and manage fire effects on cultural resources*). Funding was also provided in part by the USDA Forest Service Rocky Mountain Research Station.

Data availability

The raw data associated with this research contain archaeological site locations. The sites are on federal land (USDA Forest Service and National Park Service lands). Disclosure of site locations is prohibited by 36 CFR 296.18. Therefore, the raw data cannot be released to the public. Derived data are included in this published article and its supplementary information files.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Received: 29 August 2025 Accepted: 7 March 2026

Published online: 25 March 2026

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