# THE PINO FIRE DATABASE: ANALYSIS OF WILDFIRE MANAGED FOR RESOURCE OBJECTIVES ON SOIL EROSION AND ACCUMULATION

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ABSTRACT

Management of forests through thinning, prescribed burning, and wildland fire is increasingly necessary to reduce the risk of high severity fire. These types of fires are known to have major impacts on soil erosion, which could be detrimental to cultural resources. Understanding the effects of post-fire erosion on culturally sensitive sites warrants deeper investigation. For this reason, the Pino Fire Database of soil erosion measurements was created to facilitate analysis and interpretation of how wildfire managed for resource objectives impacts erosion at cultural sites in the southwestern Jémez Mountains, New Mexico. Such knowledge may provide managers with future treatment options for cultural resource preservation. Research for the study was conducted in ponderosa pine dominated forests susceptible to high severity wildfire. Data collection occurred from 2014 to 2018 and included soil, burn severity, ground cover, and topographical metrics. Intent and design of the database was to determine the effects of a sampled managed wildfire on cultural sites. Statistical application demonstrates that while a slight change in soil accumulation occurred, it was minimal in comparison to unburned control sites. Besides facilitating analysis, this database contributes to future studies on the effects of low severity wildfires managed for resource objectives to inform management decisions that prevent soil erosion and other negative impacts from high severity fire on cultural resources.

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## 1. INTRODUCTION

*Pinus ponderosa* (Ponderosa pine) forests are well adapted for frequent low severity fire regimes and have existed in the Southwest since at least 11,000 cal yr BP (Anderson et al., 2008; Weng and Jackson, 1999; Savage et al., 1996). However, alterations in fire regime make ponderosa pine forests extremely vulnerable to high severity fire. One major change to the low severity fire regime occurred in the 1680s when European settlers began excluding fire from fuels indirectly through grazing and logging activities as well as directly by suppressing wildfires (Covington and Moore, 1994). Suppression is an ongoing issue, however presuppression activities (thinning and burning) are not receiving enough allocated funds to treat larger areas. Fire suppression and exclusion leads to more ladder fuels and denser canopies over time (Covington and Moore, 1994) and in combination with a changing climate increases the area of high severity fires over the last couple decades in the southwestern United States (Singleton et al., 2019). Rising temperature since 1970 (Westerling, 2006) combined with droughts due to changes in rainfall patterns have caused drying across the Southwest (Seager et al., 2007). These conditions dry fuels, which exacerbate fire risk (Pechony and Shindell, 2010) and increase the frequency of large wildfire, lengthening wildfire durations and wildfire seasons. Higher temperatures also decrease snowpack volume (Seager et al., 2007), thus removing an important natural reservoir of water, increasing drought stress, and furthering the potential for high severity fires with drier fuels on the landscape.

While the term cultural resources is not well defined, it generally refers to prehistoric, historic, and contemporary tangible and intangible resources that maintain the identity of communities and link people, history, and place. Cultural resources include land, sacred sites, and objects as well as knowledge and customs (Carr, 2013). Archaeological sites in particular have become susceptible to high severity fire throughout the southwestern United States due to climate and human induced changes (Lentz et al, 1996; Ryan et al, 2012). Direct effects from the fire and its byproducts on these tangible cultural resources include charring or destruction of wooden structures. Stones and rock art can become discolored, cracked, or spalled (Lissoway and Propper, 1988; DeHaan, 1991; Jones and Euler, 1987; Pilles, 1984; Gaunt and Lentz, 1996). Experiments in the field and lab have shown that obsidian artifacts exposed to fire can crack, exfoliate, oxidize, or bloat, making them unmeasurable and sometimes unrecognizable (Treembour, 1990; Steffen et al., 2002: Lissoway and Propper, 1988). Fire also destroys surface pollen and other organic materials (Traylor et al, 1979), which may remove data from the record that influence interpretation.

Indirect effects on cultural resources arise from fire or are related to the fire's occurrence and include erosion, fire management activities, and damage from falling trees (Lissoway and Propper, 1988). When fire management activities such as fire line construction, fire retardants, mop-up, and rehabilitation interact with cultural resources, architectural damage, destruction, and displacement of artifacts may result (Traylor et al, 1979). Post-fire erosion also can lead to the destruction, burial, and redistribution of artifacts and other material remains (Johnson, 2004; Ryan et al, 2012).

Examples of cultural resources vulnerable to high severity fire in the Southwest are prehistoric pueblo and fieldhouse structures. Such sites have great significance to many people in the southwest United States such as the Pueblo of Jémez, a federally recognized indigenous sovereign nation. These structures are abundant in some ecosystems within the Santa Fe National Forest, New Mexico. Past occurrences of negative impacts by fire on cultural resources in New Mexico include the La Mesa Fire in Los Alamos (1977), the Dome Fire in the Jémez Mountains

(1996), the Cerro Grande Fire in Los Alamos (2000), and the Las Conchas Fire in Bandelier National Monument (2011). Effects on cultural resources from the fires are sooting, color change, spalling, cracking, oxidizing of stone architecture, and soil erosion, (Steffen, 2005; Ruscavage-Barz, 1999; Traylor et al, 1990; Nisengard et al, 2002).

Forest management is increasingly necessary to meet multiple objectives including risk reduction of high severity fire that impacts cultural resources. High severity fires negatively transform ecosystems not adapted to high severity wildfire such as ponderosa pine forests both directly (e.g., tree mortality, vegetation loss, and soil heating) and indirectly (e.g., erosion). Wildland fires in the Southwest burn at high severity and can have significant erosion, while low severity burned areas have low erosion in comparison (Biswell et al., 1973; Fernandes, and Botelho, 2003; Roberts et al., 2011). Soil erosion becomes highly problematic when ground cover, duff, and canopy are combusted during fire, preventing rainfall from being intercepted (Shakesby and Doerr, 2006; Neary et al., 2005). Lack of interception allows for the more rainfall to hit the soil surface and increase surface runoff, which lead to larger erosion events. Litter, one form of ground cover, consists of organic matter that reduces turbidity, erosion rates, and sediment yields (MacDonald and Stednick, 2003; Robichaud et al., 2010). Other post-fire effects that impact soil erosion include the creation of ash, intensive drying, and hydrophobia, reducing infiltration of rainfall and more overland flow and erosion (Kinner and Moody, 2008; Neary et al., 2005; Moody and Martin, 2001; Doerr et al., 2000).

Variables that influence the erosional effects of wildfires, such as slope, heavy rainfall, and ground cover have mainly been investigated through simulating rainfall in post-fire conditions and measuring debris and water flow (Johansen et al., 2001; Canon et al., 2010; Wagenbrenner & Robichaud, 2014). Debris flow post-fire can occur when rainfall flows on the soil surface rather than being absorbed into the soil (Cannon et al., 2003). Studies have shown that litter cover minimizes areas susceptible to raindrop impact, decreasing surface runoff and erosion (Foster, 1982; Pannkuk and Robichaud, 2003; Shakesby and Doeer, 2006). Additionally, slope exacerbates erosion and accumulation rates due to gravity impacting infiltration, overland flow, and soil movement (Fox and Bryan, 1999; Fox et al, 1997; Liu and Singh, 2004).

To mitigate high severity wildfire and its effects, forest managers reduce fuel loads (Stephens et al., 2012) by implementing treatments such as mechanical thinning and the use of wildfire and prescribed fire, which typically are low severity (Agee and Skinner, 2005; Lydersen, 2017; Stephens et al., 2009; Biswell et al., 1973; Fernandes, and Botelho, 2003; Roberts et al., 2011). Wildfire managed for resource objectives occur when a natural ignition (lightning) is managed by wildland fire crews; for prescribed fires, ignition is planned and implemented by wildland fire crews (Hiers et al., 2020; USDA and USDI, 1995). During burn season, typically in the spring and fall for ponderosa pine forests, wildfires managed for resource objectives are a less expensive tool that reduces the size and risk of future wildfires while more closely representing the ecosystem's historically frequent low severity fire regime (Ager et al., 2017; Huffman et al., 2017; Larson et al., 2013; North et al., 2012; Prichard et al., 2017; Riley et al., 2018; Thompson et al., 2016). Post-fire erosion mitigation is required when high severity burns occur. Should erosion mitigation be necessary, post-fire treatments such as seeding, mulching, straw wattles, and log terraces are used to mitigate runoff and protect bare soil (Robichaud, 2010; Foltz and Wagenbrenner, 2010).

More information on the impacts of wildfire warrants further research, especially as this relates to nonrenewable cultural resources. That rationale motivated design of a study by Dr. Connie Constan to better understand if wildland fire managed for resource objectives actually meet resource objectives to preserve cultural sites. Studying post-fire effects of the 2014 Pino Fire, a primarily low severity fire occurring in the southwestern Jémez Mountains, New Mexico, served as the focal point for data collection. Her research utilized erosion bridges placed on thinned archaeological sites pre- and post-fire or unburned control sites. This area is home to thousands of archaeological sites (Elliott, 1986) within several different forest types. Throughout the Southwest, these forest types have been impacted by large high severity fires (Veenhuis, 2002; Wilson et al., 2001). Field data were collected by the Forest Service over a four-year duration but was not centralized into a database and remained unanalyzed. Thus, an opportunity arose to create a database of these measurements for other managers and researchers to study and inform forest management practices. Data collected and compiled for research included variables similar to post-fire rainfall erosion models such as slope, rainfall, and ground cover (Elliott et al., 2006; Cannon et al., 2003; Moody and Martin, 2001; Miller et al., 2003).

The database was designed to store all compiled data, allowing comparative analysis of the Pino Fire with unburned sites and their impacts on cultural resources. Objectives for creating the Pino Fire Database, as it will be referred to in this paper, were 1) to understand if wildfire managed for resource objectives will increase soil erosion and accumulation when compared to control sites and 2) to explore how soil erosion and accumulation will be influenced by ground cover (litter and vegetation), precipitation (large fall events), and topography (landform slope, elevation, and aspect). By meeting these objectives, land managers may better identify best practices regarding wildfires managed for resource objectives.

## 2. METHODS

### 2.1 Study Area

The study took place over four years in the southwestern Jémez Mountains in New Mexico (35°43'28.00"N, 106°36'45.00"W) in the Jémez Ranger District of the Santa Fe National Forest (Figure 1). The study area was originally designated as a prescribed burn to minimize adverse impacts on archaeological sites from wildfire (Dyer & Constan, 2014). One half of the study area burned in the lightning-caused Pino Fire that began in August 2014 and was managed for approximately one month, with a final burn area of 1745 ha (4,313 acres) (Evans, 2015; Fig. 1c). Rather than suppress it, a decision by the Forest Service was made to manage the fire by combining hand and aerial ignitions that address resource objectives to eliminate vegetative competition and fuel loading, improve aesthetics, and maintain and improve other resource uses (e.g., grazing and wildlife habitat). These objectives are consistent with the Jémez Pueblo management and the Collaborative Forest Landscape Restoration Program (CFLRP, 2007) strategies for the southwestern Jémez Mountains. The fire impacted six sites (Burn 1 - Burn 6) on the north side of the study area (Table 1). Seven sites set up for measurement were beyond the boundary of the fire and were used as control sites.

Soil parent material originated primarily from volcanic ash, andesite, tuff, pumice, and rhyolite (Soil Survey Staff, 2020; Table 1). The research area consisted mainly of a ponderosa pine forest (11 sites) dominated by small to mid-size trees 7.6-30.5cm in diameter (3-12in) with a dense canopy cover limiting growth of grasses, forbs, and shrubs. The remaining two sites included piñon-juniper with one site having a higher stem density of all tree species (Table 1). Aspect for each site was between 103 degrees and 335 degrees with slopes between 1 and 27 degrees (Table 1) and elevation between 2148 m - 2407 m (7049 ft - 7900 ft). Yearly precipitation between 2014-2018 on average was 298.8cm (62.3cm SE) with the majority occurring during the late summer (July-September). Yearly snowfall occurred (98.4cm, 38.1 SE) between November and April.

Soil burn severity for the Pino Fire was determined by the U.S. Forest Service and Remote Sensing Applications Center (RSAC) to be primarily low severity with only 21% burned with moderate or high burn severity (Evans, 2015, Figure 1c). Soil burn severity was also measured on each research site by Dr. Constan (2014), a key initiator of the project, and determined to be low on two sites and moderate on four sites (Table 1).

### 2.2 Precipitation Data

Precipitation data, archived on the Western Regional Climate Center website, were obtained in ten-minute intervals from Conejos, New Mexico (WRCC, 2021). The Conejos weather station is 2490m (8169ft) in elevation, located 968m (3175ft) from the nearest site and 5,700m (18,700ft) from the furthest site. Average site distance from the weather station was 3847m (12,621ft) for burn sites and 3423m (11230ft) for control sites.

### 2.3 Erosion bridge placement

Forest archaeologists and soil scientists identified 13 experimental sites adjacent to prehistoric fieldhouses (e.g., 1-4 room structures) or pueblos (e.g., large villages) that date between AD 1350 and 1700 (Elliott, 1986; Table 1). Each site was located near burn boundaries (e.g., roads) for safety and ease of data collection. Between two and four erosion bridges were installed for each site. The use of erosion bridges was developed by Ranger and Frank (1978) and provided more accurate data on micro-profiles of soil surfaces in a simple, reliable, and cost-effective way. Application of erosion bridges continue to be used for this purpose (Binh et al., 2008, Van De et al., 2008; Clarke and Walsh 2006; Sayer et al., 2004; Shakesby et al., 1991; Walsh et al., 1992). All sites were originally slated for a prescribed fire following one pre-fire measurement. However, the plan changed with the occurrence of the Pino Fire in August 2014. Six of the thirteen sites burned; burn severity documented at the site level was moderate (66%) and low (33%). Sites were then classified as burn treatment and control based on the Pino Fire (Table 1). Erosion bridges consist of two permanent metal rebar hammered into the ground 60 cm (2 ft) apart and a carpenters' level of 1.2 m (48 in) in length. Distribution and orientation of erosion bridges within sites is given in Table 1.

2.4 Erosion Bridge Data Collection

Two to four erosion bridges were installed in each site around the fieldhouses and pueblos (Figure 1). Placement of erosion bridges was generally parallel to contour with arrangement around cultural resources varying by site (Table 1). This was done to capture soil erosion and accumulation either upslope or downslope of the adjacent fieldhouse or pueblo. Measurements were taken by placing a carpenter's level on the metal rebar and using another level on top to make sure it was placed parallel to the soil surface. The carpenter's level had 12 evenly spaced holes (Figure 2) providing 12 measurements per bridge. Soil height, litter height, and component hit (e.g., soil, litter, rock, vegetation, etc.) were measured and recorded. Data collection occurred from the spring after snowmelt (May-June) and fall after monsoons (September-October) between spring 2014 and spring 2018, with one measurement before the Pino Fire on all sites. Topographical measurements (e.g., aspect, slope, elevation) were also taken at each site and recorded.

The collection of vegetation data occurred on line-intercept transects. Transects 15.2m (50ft) in length were centered down the middle of each erosion bridge with measurements at 0.3m (1ft) intervals (Warren and Olson, 1964) along the transect, recording the component hit. The component hit categories included soil, vegetation, rock, archaeological stone, wall stone, lichen, litter, wood, small wood, stick, large wood, moss, burnt litter, burnt stick, and ash. For sites where erosion bridges were lined up, a single transect was run through the center of all erosion bridges only once for the entire site. For other sites (both control and fire), data were collected from one transect per bridge (Table 1). In contrast, the control site transect data were only collected in spring 2013 and fall 2015, while burn sites were measured for each period. Preliminary interpretation of data collection on control sites showed that vegetation remained constant in time. Each component hit was summed within a transect and calculated as percent of total ground cover.

2.5 Database Construction

After all data were collected, an Excel database was constructed. PDF data measured and recorded throughout the study was categorized a RawData worksheet. Data included site data, bridge level data, and transect data were categorized into raw data (Table 2). Site level data included archaeological notes, topography, vegetation type, site number and bridge number. Erosion bridge data included the slope of the erosion bridge, who recorded the data, litter height, soil height, and component hit. Raw weather data from the Conejos station (date, temperature, and precipitation) was added into the database. To isolate rainfall, precipitation data was then separated into rain and snow.

A new worksheet (Table 3) was created showing calculated erosion metrics, allowing for erosion bridge data to be compared by bridge per period of time. Cumulative change in soil and litter height were calculated from raw soil height values (Dist.soil and Dist.litter; T2 -T1) (Figure 2). When Soil height (Dist.soil) from erosion bridge measurements hit another object besides soil (eg. rock or vegetation) data was recorded as NA. Calculations are shown in the datasheet “EB Main Calculation” with column names Dist.litter, Lit. Avg, Dist.soil, and Soil.Avg. Values with

0 listed in litter difference (Diff.litt) and soil difference (Diff.soil) are due to the cumulative periodic change calculation. Because the analysis focused on the difference between one period and the prior, the first period could not have a change and was therefore listed as 0. When measuring soil height True litter height was then calculated by taking the difference between litter height from soil height. Due to one site being especially rocky, true litter could not be calculated because of the amount of NA listed in the database. Litter and soil measurements were then averaged within each bridge. Because bridge variables were often the same for some sites, erosion bridge slope data by percentage were binned to improve the analysis. Precipitation data (rainfall) were added to understand how precipitation affects soil erosion and accumulation. Rainfall was calculated in in four different ways: total rainfall per period, highest daily fall per period, total rainfall events below 25.4mm (MedFall), and total rainfall events beyond 25.4mm within a given period (LargeRainfall). LargeRainfall1 would represent one large rainfall event per period while LargeRainfall2 represent two large rainfall events per time period. The cutoff of 25.4mm was selected to represent intense rainfall events following other rainfall experiments measuring erosion daily precipitation values and high intensity rainfall (Sidman et al., 2016; Cannon et al., 2010; Moffet et al., 2007; Moody & Martin, 2001). Soil type for each site was identified using web-based soil survey data collected by the United States Department of Agriculture and National Cooperative Soil Survey (Soil Survey Staff, 2020; Table 1).

## 2.6 Summary Data and Statistical Analysis

The Pino Fire Database includes specific predictors of soil erosion and accumulation such as precipitation, topography (aspect, slope, elevation), and vegetation ground cover. The program R was used to produce a data summary (R Core Team, 2019). To test if fire had a significant impact on soil height, a generalized linear model was run (Bates et al., 2014). Normality and correlations were inspected through the creation of histograms (ggplot) and a Pearson's correlation heatmap (ggcorr) (Wickham 2016; Schloerke et al., 2018). Numerical predictors had a normal distribution and there were no extreme outliers (Kassambara, 2020). The next step was to determine if soil height was impacted by precipitation, elevation, landform slope, erosion bridge slope, litter height, and burn severity (Bates et al., 2014). That was achieved using the following variables in the generalized linear model: True Litter Height, Large Rainfall 1, Large Rainfall 2, Aspect, Elevation, and Slope (Table 4). The most insignificant variable of the full model was removed and then run as a generalized linear model. The final model with the lowest Akaike Information Criterion (AIC) was then chosen. When the final two models had a difference in AIC of two or less, the model with fewer predictor variables was selected (Shumway and Stoffer, 2019) as the final model. While most data did not need to be transformed, erosion bridge slope data were binned into two categories to analyze in these generalized linear models.

## 3. RESULTS

### 3.1 Soil Erosion and Accumulation Changes between Control and Burn Sites

The first assessment was to determine if erosion and accumulation differed between control and burn sites using boxplots and inspecting compiled data. Figure 3 shows soil erosion and accumulation (a) and litter deposition or loss (b) for each period of time. Erosion and litter data were also added cumulatively (first period – n period) for further analysis (Figure 4). Visual significances for soil and litter values between burn and control sites were not apparent. The most visually apparent trend occurred from spring 2015 – fall 2015 where litter was reduced and the greatest amount of soil erosion occurred. This trend was most likely due to interobserver error. The cumulative data boxplot showed minimal changes in soil accumulation and a slight accumulation of litter over time. Six weeks post-fire, burn sites recorded 0.24cm (1.27+SE) more soil erosion than control sites and four years post-fire had 0.86cm (2.37+SE) of soil accumulation compared to control sites. Litter six weeks post-fire in burn sites accumulated 1.12cm (1.29+SE) more than control sites and 1.41cm (3.0+SE) four years post-fire.

3.2 Environmental Predictors of Soil Erosion and Accumulation

The correlation heatmap revealed that soil height was positively had a high Pearson's correlation coefficient with true litter height (+0.595) and LargeRainfall (+0.366; Figure 5). Predictors that were correlated with each other included elevation and landform slope (+0.54), litter height and LargeRainfall (+0.488), and elevation with aspect (-0.342).

Construction of the generalized linear model started with the full model (all predictor variables) to determine if fire had a significant impact on soil erosion and accumulation. The results of the generalized linear model building process revealed that fire was not a statistically significant predictor of soil height with a p-value of 0.19. Elevation (p=0.76), aspect (p= 0.45), and landform slope (p= 0.76) were not significant predictors of soil height. The model building process revealed that the random effect (bridges for each site) had a variance of 0. Therefore, the accounted variability of the random effect is 0. When comparing the model against the same model without a random effect, the estimates for each variable were the same. Ultimately the model is the same without the variance components, and so the bridge within site was excluded from the final model. The equation for the final model was:

$$\text{Soil Erosion or Deposition} = 1.956 + 0.5008(\text{Litter Height}) + 0.2825(\text{LargeRainfall2})$$

A scatter plot with regression lines were created for the continuous litter predictor variable (Figure 6) and the correlation heatmap revealed litter height was positively correlated with soil erosion and accumulation (p-value = 0). Large rainfall events (above 25.4mm) occurring two times per period were positively correlated with soil erosion and accumulation (p-value = 0.002). The $R^2$ value for the final model was 0.383.

## 4. DISCUSSION

A post-fire report of the Pino Fire revealed that soil nutrients improved, native plants and grasses regenerated, and the threat of large high-intensity crown fire was reduced, helping protect cultural resources and nearby watersheds (Carril et al, 2014). The assessment shows that the set objectives of the CFLRP were met. While the report looks at the larger context of the Pino Fire, it does not take a systematic longitudinal approach to assess post-fire erosion on surrounding cultural resources.

For this reason, a main objective for building the Pino Fire Database was to compile data that could be used to determine whether the Pino Fire increased soil erosion and accumulation when compared to control sites over an extended period of time. Wildfire of low severity usually leads to minimal soil erosion and accumulation (Biswell et al., 1973; Fernandes, and Botelho, 2003; Roberts et al., 2011), which was an initial hypothesis for this project. However, the Pino Fire Database analysis demonstrated that the Pino Fire had no significant impact on soil and accumulation at the experimental sites. While soil erosion and accumulation between burn and control sites did not significantly differ, temporal differences were observed that are likely associated with needle cast and heavy summer precipitation events. Based on the Pino Fire Database analysis, the low severity wildfire managed for resource objectives may have minimized soil erosion and accumulation similar to prescribed fire treatments. Other probable factors influencing the primarily low fire severity of the Pino Fire were pre-fire treatments such as thinning and the management of the wildfire itself. These treatments and management techniques led to an effective way of mitigating soil erosion and accumulation on these sites.

An additional objective of creating the Pino Fire Database was to determine how topography, ground cover, and rainfall interacted with the Pino Fire to help predict the level of soil erosion and accumulation. The database analysis aligns with existing research (Elliott, 1998; Pannkuk and Robichaud; Cannon et al., 2010; Moffet et al., 2007; Moody & Martin, 2001 MacDonald and Stednick, 2003; Robichaud et al., 2010) that highlights the significance of litter cover and larger intensity rainfall events on soil movement. While topography was not a significant variable, this may have been due to the Pino Fire study sites being located on low to moderate slopes. Steep slopes greater than or equal to 30% are known to have the greatest effect on soil erosion and accumulation (Gartner et al, 2008). This critique of the project explains the importance of considering a broader range of slope when determining future study sites for testing management methods to treat forests while minimizing erosion.

Throughout the Southwest, numerous cultural resources exist within forests at risk of high severity fire (Lentz et al, 1996; Ryan et al, 2012) which demonstrate a need for forest treatments that minimize impact on these resources. Thinning and management of the Pino Fire within the Jémez Mountains are one type of treatment used to protect ancient fieldhouses and pueblos that are vulnerable in fire suppressed forests. Cumulatively, the Pino Fire had no soil erosion, instead accumulating 0.86cm (± 2.37SE) of soil over four years compared to the control sites post-fire. This suggests that the Pino Fire, on top of pre-thinning had little impact on soil erosion and accumulation and may be an effective strategy to try elsewhere. The Pino Fire did have some direct impacts on cultural resources in a few sites. These included color change and sooting of masonry stone and artifacts (Carril et al, 2014), revealing that even with low severity fire, effects on cultural resources need to be addressed. Other impacts of fire on cultural resources such as cracking, crazing, spalling, melting, and carbon contamination warrant consideration before deciding if prescribed fire or wildfire managed for resource objectives are the correct treatment.

The Pino Fire Database was constructed to test post-fire erosion and accumulation in one forest type (mostly ponderosa pine, with two piñon-juniper sites) and soil composition. While this research cannot be generalized, results suggest that future wildfires managed for resource objectives primarily consisting of low and moderate severity could be tested elsewhere. To conclude if wildfires managed for resource objectives can be implemented as a treatment across more archaeological sites in the Jémez Mountains, further experiments are needed to measure erosion and accumulation affecting cultural resources by wildfire managed for resource objectives. These should be conducted across more soil types, forest types, topography (mainly slope), and fire severity gradients to determine if soil erosion and accumulation rates are similar in other fire treated (low and moderate severity) areas.

A major challenge of prescribed fire-scale studies is that they are often heavily influenced by micro-scale variation and atmospheric dynamics, limiting the interpretation of results (Hiers et al., 2009; Clements et al., 2007; Achtemeier, 2012). For that reason, variation and dynamics within the Pino Fire means that data retrieved from experimental sites may not accurately represent post fire effects, such as soil erosion and accumulation across the full range of conditions. Future studies should strive for a larger sample size incorporating a greater range of variation in site characteristics. Continued research addressing such variation will inform management decisions that include the protection of cultural resources.

The significance placed on preserving cultural resources for current and future generations demands a strong ethical approach to inform research and forest management practices. Restoration ecology differs from preservation by returning disturbed habitats to an earlier state (Clewell and Aronson, 2012). With large portions of forest in the southwest remaining overly dense, managers focus on treating the forest, mimicking historical densities. Managing forests also aligns with the concept of conservation, established by Pinchot (Eckersley, 1992). Forest resources, intrinsic to art, music, and ritual, require careful consideration when implementing treatments (Fischer-Kowalski & Weisz 1999; Habeerl et al., 2006). While forests must be managed, cultural resources must also be protected, aligning with Muir's concept of preservation (1909).

Protecting cultural resources within a wildfire or prescribed fire is a legal requirement that fulfills multiple use goals. Legislation of the National Historic Preservation Act (NHPA, 1966) concretized cultural resource protection. Until 1992, traditional cultural properties and religious sites were not covered by the NHPA. Enaction of the National Environmental Policy Act (NEPA, 1969) also mandated protection of important historic, cultural, and natural aspects of national heritage. Executive orders provided increased protection for cultural resources, especially those of indigenous people of the Southwest United Sates, along with tribal consultation and coordination for practices affect their communities (1996, 2000). While tangible cultural resources can easily be identified and documented, intangible cultural resources may not be known to forests managers and remain vulnerable. Examples include traditional knowledge and spiritual beliefs linked to or reflective of those sites. Laws and executive orders protecting both tangible and intangible cultural resources have expanded over time, however ongoing dialogue and engagement between tribal and U.S. federal governments is essential.

Post-fire impacts on cultural resources are still prevalent within all types of fire treatments. The strategy of implementing low severity fire around archaeological sites mitigates most of these impacts, but negative ones may occur. Developing a better understanding of how wildfire managed for resource objectives affects archaeological sites will lead to better management decisions that protect cultural resources. The intention and design of the Pino Fire Database provides a template for post-fire data analysis, contributes to existing literature, and offers insight for land managers to determine best practices regarding wildfire use for cultural resource preservation.

## REFERENCES


Agee, J. K., & Skinner, C. N. (2005). Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211(1–2):83–96.

Ager, A. A., Barros, A. M., Preisler, H. K., Day, M. A., Spies, T. A., Bailey, J. D., & Bolte, J. P. (2017). Effects of accelerated wildfire on future fire regimes and implications for the United States federal fire policy. *Ecology and Society* 22(4).

Anderson, R. S., Allen, C. D., Toney, J. L., Jass, R. B., & Bair, A. N. (2008). Holocene vegetation and fire regimes in subalpine and mixed conifer forests, southern Rocky Mountains, USA. *International Journal of Wildland Fire* 17(1):96-114.

Achtemeier, G. L. (2012). Field validation of a free-agent cellular automata model of fire spread with fire–atmosphere coupling. *International Journal of Wildland Fire* 22(2):148-156.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. arXiv preprint arXiv:1406.5823.

Biswell, H. H. (1973). *Ponderosa Fire Management: A Task Force Evaluation of Controlled Burning in Ponderosa Pine Forests of Central Arizona*. Tallahassee: Tall Timbers Research Station.

Cannon, S. H., Gartner, J. E., Rupert, M. G., Michael, J. A., Djokic, D., & Sreedhar, S. (2003). Emergency assessment of debris-flow hazards from basins burned by the Grand Prix and Old Fires of 2003, Southern California. *U.S. Geological Survey Open-File Report* 0*3:*475.

Cannon, S. H., Gartner, J. E., Rupert, M. G., Michael, J. A., Rea, A. H., & Parrett, C. (2010). Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. *Geological Society of America Bulletin* 122(1–2):127–144.

Carr, G. (2013). Protecting intangible cultural resources: Alternatives to intellectual property law. Michigan Journal of Race & Law, 18(2):363-390.

Carril D., Park, D., Constan, C., Orr, M., Boone, C., (2014). *Wildfire Outcome Report.* Pino Fire. Pino Fire NM-SNF-000381. Santa Fe National Forest. D-03 Jemez Ranger District.

Clarke, M. A., & Walsh, R. P. D. (2006). Long-term erosion and surface roughness change of rain-forest terrain following selective logging, Danum Valley, Sabah, Malaysia. *Catena* 68(2–3):109–123.

Clements, C. B., Zhong, S., Goodrick, S., Li, J., Potter, B. E., Bian, X., Heilman, A. E., Charney, J. J. Perna, R., Jang, M., Lee, D., Patel, M., Street, S., & Aumann, G. (2007). Observing the dynamics of wildland grass fires: FireFlux—A field validation experiment. *Bulletin of the American Meteorological Society* 88(9):1369-1382.

Clewell, A. F., & Aronson, J. (2012). Ecological restoration: principles, values, and structure of an emerging profession. Island Press.

Constan, C. (2014). *Pino Fire BAER Heritage Assessment Special Report*. Forest Report 2014-10-013B.

Covington, W. W., & Moore, M. M. (1994). Southwestern ponderosa forest structure: changes since Euro-American settlement. *Journal of Forestry* 92(1):39-47.

DeHaan, J.D. (1991). *Kirk's Fire Investigations*, 3rd Edition. Englewood Cliffs, NJ.

Doerr, S. H., Shakesby, R. A., & Walsh, R. P. D. (2000). Soil water repellency: Its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews* 51(1–4):33–65.

Eckersley, R. (1992). Environmentalism and political theory: Toward an ecocentric approach. State University of Newe York Pressss. 33-45, 49.

Elliott, M. L. (1986). *Overview and Synthesis of the Archeology of the Jémez Province, New Mexico*. Museum of New Mexico, Office of Archaeological Studies.

Elliott, M. L. (1998). Coalition Period Adaptations in the Jemez Region: Origins of the Jemez Phenomenon. In *63rd Annual Meeting of the Society for American Archaeology*, Seattle, Washington.

Elliot, W. J., Miller, I. S., & Glaza, B. D. (2006). Using WEPP technology to predict erosion and runoff following wildfire. In *ASAE Annual Meeting American Society of Agricultural and Biological Engineers*:1.

Evans, A. 2015. 2014 Wildfire Season: An Overview, Southwestern U.S. *Ecological Restoration Institute and Southwest Fire Science Consortium*, Northern Arizona University:20.

Fernandes, P. M., & Botelho, H. S. (2003). A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire* 12(2):117-128.

Fischer-Kowalski, M., & Weisz, H. (1999). Society as hybrid between material and symbolic realms: Toward a theoretical framework of society-nature interaction. Advances in human ecology, 8, 215-252.

Foltz, R. B., & Wagenbrenner, N. S. (2010). An evaluation of three wood shred blends for post-fire erosion control using indoor simulated rain events on small plots. *Catena* 80(2):86-94.

Foster, G. R. (1982). Modeling the erosion process. In Haan, C.T., Johnson, H.P. and Brakensiek, D.L., Eds.,Hydrologic modeling of small watersheds. ASAE Monograph No. 5, *American Society of Agricultural and Biological Engineers*, St. Joseph, MI:297-380.

Fox, D. M., Bryan, R. B., & Price, A. G. (1997). The influence of slope angle on final infiltration rate for interrill conditions. *Geoderma*, 80(1-2):181-194.

Fox, D. M., & Bryan, R. B. (1999). The relationship of soil loss by interrill erosion to slope gradient. *Catena* 38(3):211-222.

Gartner, J. E., Cannon, S. H., Santi, P. M., & Dewolfe, V. G. (2008). Empirical models to predict the volumes of debris flows generated by recently burned basins in the western U.S. *Geomorphology* 96(3–4):339–354.

Gaunt, J. K., Lentz, S.C. (1996). Ceramic artifact analysis. In Lentz, S.C.; Gaunt, J.K.; Wilmer, A.J. *Fire Effects on Archaeological Resources, Phase 1: The Henry Fire, Holiday Mesa, Jemez Mountains, New Mexico*. Gen. Tech. Rep. RM-GTR-273. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station:47-60.

Hiers, J. K., O'Brien, J. J., Mitchell, R. J., Grego, J. M., & Loudermilk, E. L. (2009). The wildland fuel cell concept: an approach to characterize fine-scale variation in fuels and fire in frequently burned longleaf pine forests. *International Journal of Wildland Fire* 18(3):315-325.

Hiers, J. K., O'Brien, J. J., Varner, J. M., Butler, B. W., Dickinson, M., Furman, J., Gallagher, M., Godwin, D., Goodrick, S. L., Hood, S. M., Hudak, A., Kobziar, L. N., Linn, R., Loudermilk, E. L., McCaffrey, S., Robertson, K., Rowell, E. M., Skowronski, N., Watts, A. C., & Yedinak, K. M. (2020). Prescribed fire science: The case for a refined research agenda. *Fire Ecology* 16(1):11, s42408-020-0070–0078.

Huffman, D. W., Meador, A. J. S., Stoddard, M. T., Crouse, J. E., & Roccaforte, J. P. (2017). Efficacy of resource objective wildfires for restoration of ponderosa pine (Pinus ponderosa) forests in northern Arizona. *Forest Ecology and Management* 389:395-403.

Johansen, M. P., Hakonson, T. E., & Breshears, D. D. (2001). Post-fire runoff and erosion from rainfall simulation: Contrasting forests with shrublands and grasslands. *Hydrological Processes* 15(15):2953–2965.

Jones, A. T., & Euler, R. C. (1987). Effects of forest fires on archaeological resources at Grand Canyon National Park. *North American Archaeologist* 7(3):243-254.

Kassambara, A. (2020). Pipe-friendly framework for basic statistical tests. R package version 0.6.0.

Kennedy, J. J., & Quigley, T. M. (1994). Evolution of Forest Service organizational culture and adaptation issues in embracing ecosystem management. ME Jensen and PS Bourgeron, editors, 2, 16-26.

Kinner, D. A., & Moody, J. A. (2008). Infiltration and runoff measurements on steep burned hillslopes using a rainfall simulator with variable rain intensities. *Scientific Investigations Report 2007-5211,* U. S. Geological Survey.

Larson, A. J., Belote, R. T., Cansler, C. A., Parks, S. A., & Dietz, M. S. (2013). Latent resilience in ponderosa pine forest: effects of resumed frequent fire. *Ecological Applications* 23(6):1243-1249.

Lentz, S. C. (1996). *Fire Effects on Archaeological Resources, Phase I: The Henry Fire, Holiday Mesa, Jemez Mountains, New Mexico (No. 273).* Rocky Mountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture.

Lissoway, J. and Propper, J. (1988). Effects of fire on cultural resources. *Effects of Fire in Management of Southwestern Resources Symposium;* 1988 November 14-17; Tucson, AZ.

Liu, Q. Q., & Singh, V. P. (2004). Effect of microtopography, slope length and gradient, and vegetative cover on overland flow through simulation. *Journal of Hydrologic Engineering* 9(5):375-382.

Lydersen, J. M., Collins, B. M., Brooks, M. L., Matchett, J. R., Shive, K. L., Povak, N. A., Kane, V. R., & Smith, D. F. (2017). Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. *Ecological Applications* 27(7):2013-2030.

MacDonald, L.H., Stednick, J.D. (2003). Forests and water: A state-of-the-art review for Colorado. *Colorado Water Resources Research Institute Completion Report 196*, Colorado State University, Fort Collins, Colorado.

Miller, J. D., Nyhan, J. W., & Yool, S. R. (2003). Modeling potential erosion due to the Cerro Grande Fire with a GIS-based implementation of the Revised Universal Soil Loss Equation. *International Journal of Wildland Fire* 12(1):85-100.

Moffet, C. A., Pierson, F. B., Robichaud, P. R., Spaeth, K. E., & Hardegree, S. P. (2007). Modeling soil erosion on steep sagebrush rangeland before and after prescribed fire. *Catena* 71(2):218–228.

Moody, J. A., & Martin, D. A. (2001). Post-fire, rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. *Hydrological Processes* 15(15):2981–2993.

Muir, J. (1909). Our national parks. Houghton Mifflin. 369-370

Neary, D. G., Ryan, K. C., & DeBano, L. F. (2005). *Wildland Fire in Ecosystems: Effects of Fire on Soils and Water* (RMRS-GTR-42-V4; p. RMRS-GTR-42-V4). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Nisengard, J. E., Harmon, B. C., Schmidt, K. M., Madsen, A. L., Masse, W. B., McGehee, E. D., Garcia, K. L., Issacson, J., Dean, J. S. (2002). Cero Grande Fire Assessment Project: An Assessment of the Impact of the Cerro Grande Fire on Cultural Resources at Los Alamos National Laboratory, New Mexico. *Cultural Resource Report No. 211*. Los Alamos National Laboratory.

North, M., Collins, B. M., & Stephens, S. (2012). Using fire to increase the scale, benefits, and future maintenance of fuels treatments. *Journal of Forestry* 110(7):392-401.

National Historic Preservation Act, 54 U.S.C. §§ 300101-307108 (1966)

S. 684 — 102nd Congress: National Historic Preservation Act Amendments of 1992.

Pannkuk, C. D., & Robichaud, P. R. (2003). Effectiveness of needle cast at reducing erosion after forest fires. *Water Resources Research* 39(12):1333.

Pechony, O., & Shindell, D. T. (2010). Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences* 107(45):19167-19170.

Pilles, P. J. (1984). The effects of forest fires on archaeological sites. *49th Annual Meeting of the Society for American Archeology*; 1984; Portland, OR.

Prichard, S. J., Stevens-Rumann, C. S., & Hessburg, P. F. (2017). Tamm Review: Shifting global fire regimes: Lessons from reburns and research needs. *Forest Ecology and Management* 396:217-233.

Pueblo of Jemez Comprehensive Forest Management Plan (2007).

R Core Team (2019). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Ranger, G. E., & Frank, F. F. (1978). 3-F erosion bridge--a new tool for measuring soil erosion. *Range Improvement Studies.*

Riley, K. L., Thompson, M. P., Scott, J. H., & Gilbertson-Day, J. W. (2018). A model-based framework to evaluate alternative wildfire suppression strategies. *Resources* 7(1):4.

Roberts, S. L., van Wagtendonk, J. W., Miles, A. K., & Kelt, D. A. (2011). Effects of fire on spotted owl site occupancy in a late-successional forest. *Biological Conservation* 144(1):610-619.

Robichaud, P.R., Wagenbrenner, J.W., Brown, R.E. (2010). Rill erosion in natural and disturbed forests: 1. Measurements. *Water Resources Research* 46(10).

Savage, M., Brown, P. M., & Feddema, J. (1996). The role of climate in a pine forest regeneration pulse in the southwestern United States. *Ecoscience* 3(3):310-318.

Sayer, A. M., Walsh, R. P. D., Clarke, M. A., & Bidin, K. (2004). The role of pipe erosion and slopewash in sediment redistribution in small rainforest catchments, Sabah, Malaysia. *IAHS Publication* 288:29-36.

Schloerke, B., Crowley, J., Cook, D., Briatte, F., Marbach, M., Thoen, E., Elberg, A., & Larmarange, J. (2018). Ggally: Extension to ggplot2. *R Package Version* 1(0).

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H., Harnik, N., Leetmaa, A., Lau, N., Li, C., Velez, J., & Naik, N. (2007). Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316(5828):1181-1184.

Sidman, G., Guertin, D. P., Goodrich, D. C., Thoma, D., Falk, D., & Burns, I. S. (2016). A coupled modelling approach to assess the effect of fuel treatments on post-wildfire runoff and erosion. *International Journal of Wildland Fire* 25(3):351.

Shakesby, R. A., WALSH, R. D., & COELHO, C. A. (1991). New developments in techniques for measuring soil erosion in burned and unburned forested catchments, Portugal. *Zeitschrift für Geomorphologie*. *Supplementband* (83):161-174.

Shakesby, R., & Doerr, S. (2006). Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews* 74(3–4):269–307.

Shumway, R., & Stoffer, D. (2019). *Time Series: A Data Analysis Approach Using R.* CRC Press.

Singleton, M. P., Thode, A. E., Sánchez Meador, A. J., & Iniguez, J. M. (2019). Increasing trends in high-severity fire in the southwestern USA from 1984 to 2015. *Forest Ecology and Management* 433:709–719.

Soil Survey Staff. (2020). Natural Resources Conservation Service, United States Department of Agriculture. *Web Soil Survey*. Available online at the following link: http://websoilsurvey.sc.egov.usda.gov/. Accessed [7/19/2020].

Starker, T. J. (1934). Fire resistance in the forest. *Journal of Forestry* 32(4):462-467.

Stephens, S. L., Moghaddas, J. J., Hartsough, B. R., Moghaddas, E. E., & Clinton, N. E. (2009). Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest. *Canadian Journal of Forest Research* 39(8):1538-1547.

Steffen, A. (2002). The Dome Fire pilot project: extreme obsidian fire effects in the Jemez Mountains. *The Effects of Fire and Heat on Obsidian Symposium*; 1999, April 23-25, Sacramento, CA, 159-202.

Stephens, S. L., Boerner, R. E., Moghaddas, J. J., Moghaddas, E. E., Collins, B. M., Dow, C. B., Edminster, C., Fiedler, C. E., Fry, D. L., Hartsough, B. R., Keeley, J. E., Knapp, E. E., Mclver, J. D., Skinner, C. N., & Youngblood, A. (2012). Fuel treatment impacts on estimated wildfire carbon loss from forests in Montana, Oregon, California, and Arizona. *Ecosphere* 3(5):1-17.

Thompson, M. P., Freeborn, P., Rieck, J. D., Calkin, D. E., Gilbertson-Day, J. W., Cochrane, M. A., & Hand, M. S. (2016). Quantifying the influence of previously burned areas on suppression effectiveness and avoided exposure: A case study of the Las Conchas Fire. *International Journal of Wildland Fire* 25(2):67.

Traylor, D., Hubbell, L., Wood, N., Fiedler, B. (1979). *The La Mesa Fire Study: Investigations of Fire and Fire Suppression on Cultural Resources in Bandelier National Monument*. Manuscript on file, USDI National Park Service, Bandelier National Monument, 173.

Traylor, D., Hubell, L., Wood, N., & Fiedler, B. (1990). The 1977 La Mesa Fire Study: An investigation of fire and fire suppression impact on cultural resources in Bandelier National Monument. *Southwest Cultural Resources Center Professional Papers*, 28.

USDA and USDI. 1995. *Federal Wildland Fire Policy.* [Online] Available: http://www.fs.fed.us/land/wdfire.htm, Accessed [August 16, 2002].

Van De, N., Douglas, I., McMorrow, J., Lindley, S., Thuy Binh, D. K. N., Van, T. T., Thanh, L. H., & Tho, N. (2008). Erosion and nutrient loss on sloping land under intense cultivation in Southern Vietnam. *Geographical Research* 46(1):4–16.

Veenhuis, J. E. (2002). *Effects of Wildfire on the Hydrology of Capulin and Rito de los Frijoles Canyons, Bandelier National Monument, New Mexico (No. 2)*. US Department of the Interior, US Geological Survey.

Walsh, R. P. D., Coelho, C. D. O., Shakesby, R. A., & Terry, J. P. (1992). Effects of land use management practices and fire on soil erosion and water quality in the Agueda River Basin, Portugal. *GEOÖKO plus* 3:15-36.

Wagenbrenner, J. W., & Robichaud, P. R. (2014). Post-fire bedload sediment delivery across spatial scales in the interior western United States. *Earth Surface Processes and Landforms* 39(7):865-876.

Warren, W., & Olsen, P. F. (1964). A line intersect technique for assessing logging waste. *Forest Science* 10(3):267-276.

Weng, C., & Jackson, S. T. (1999). Late Glacial and Holocene vegetation history and paleoclimate of the Kaibab Plateau, Arizona. *Palaeogeography, Palaeoclimatology, Palaeoecology* 153(1-4):179-201.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase western US forest wildfire activity. *Science* 313(5789):940-943.

Wickham, H. (2016). *Ggplot2-Elegant Graphics for Data Analysis*. Springer International Publishing. Cham, Switzerland.

Wilson, C. J., Carey, J. W., Beeson, P. C., Gard, M. O., & Lane, L. J. (2001). A GIS-based hillslope erosion and sediment delivery model and its application in the Cerro Grande burn area. *Hydrological Processes*. 15(15):2995-3010.

FIGURES

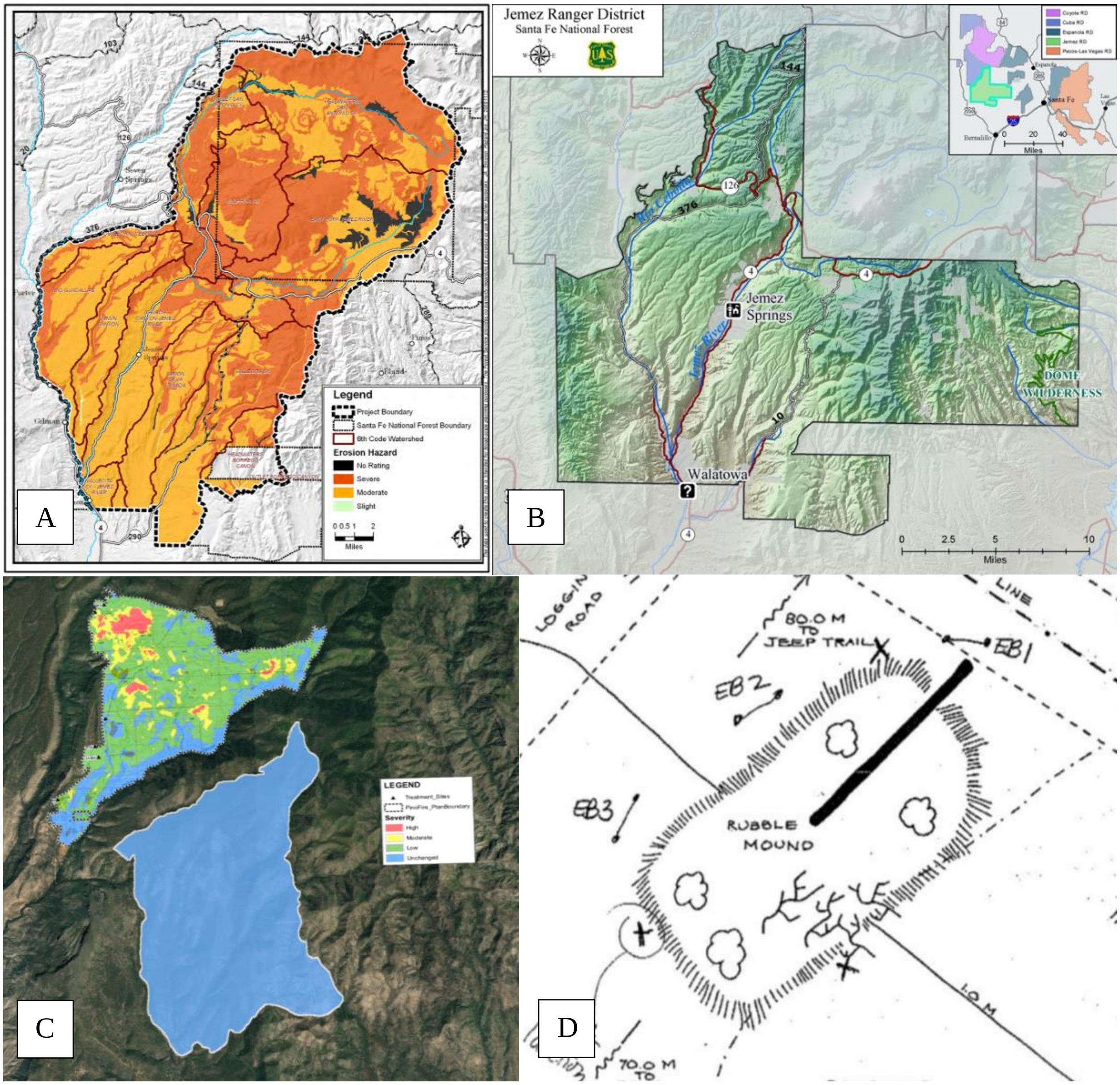



Figure 1. Erosion hazard map of the southwest Jemez (a), Jemez Ranger District, part of the Santa Fe, National Forest (b; USDA). A blue polygon of Pino South (control unit) and the burned unit (Pino North) shown as BARC map (c). An example of site layout with 3 erosion bridges (EB 1-3) placed around a cultural resource (d).

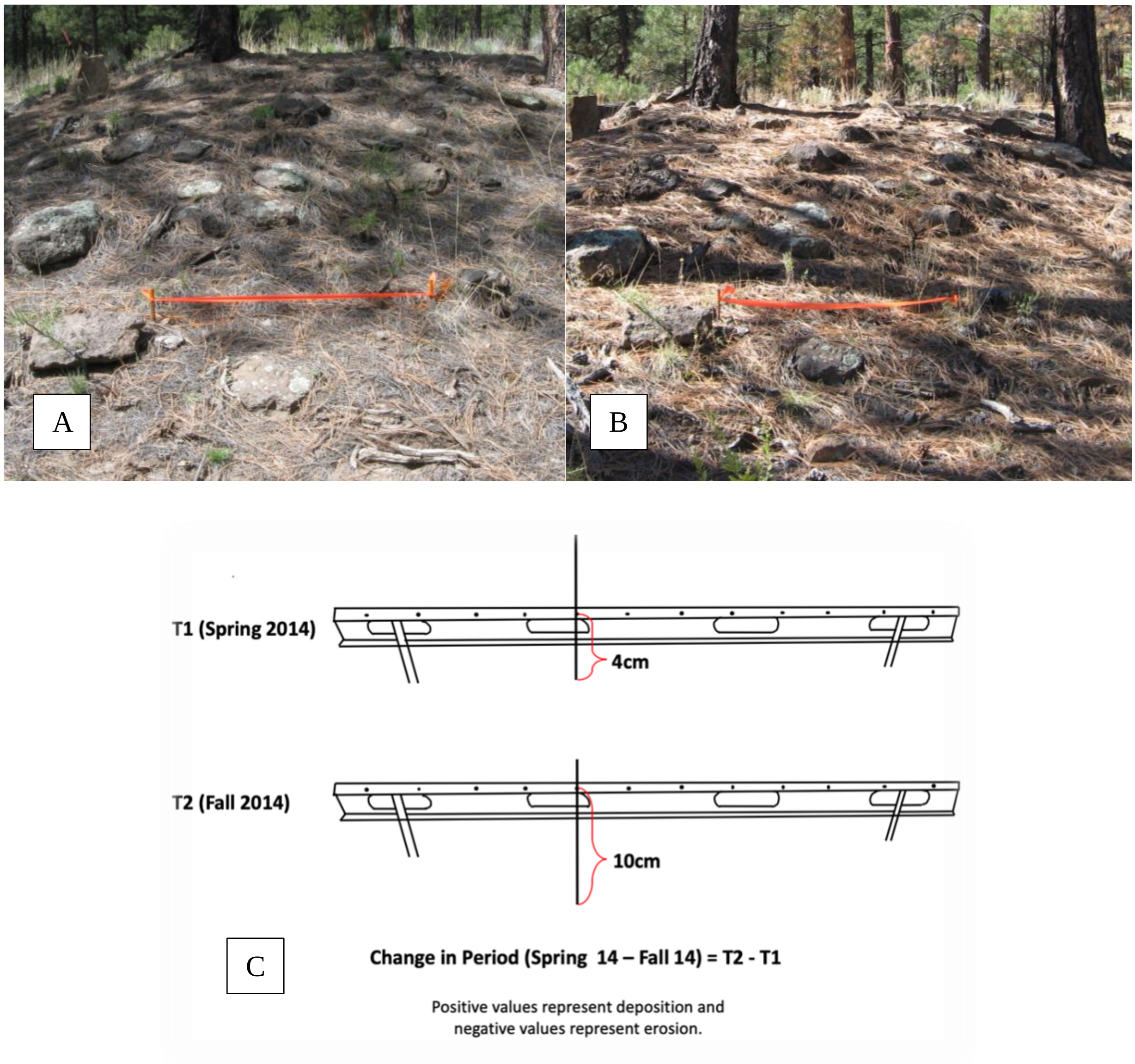



Figure 2. A site photograph with the erosion bridge location showing just before the burn in Spring 2014 (a) and the same bridge in Fall 2014 (b; 6 weeks post fire). Change in soil erosion and accumulation between two periods of time is calculated at each pin (c).

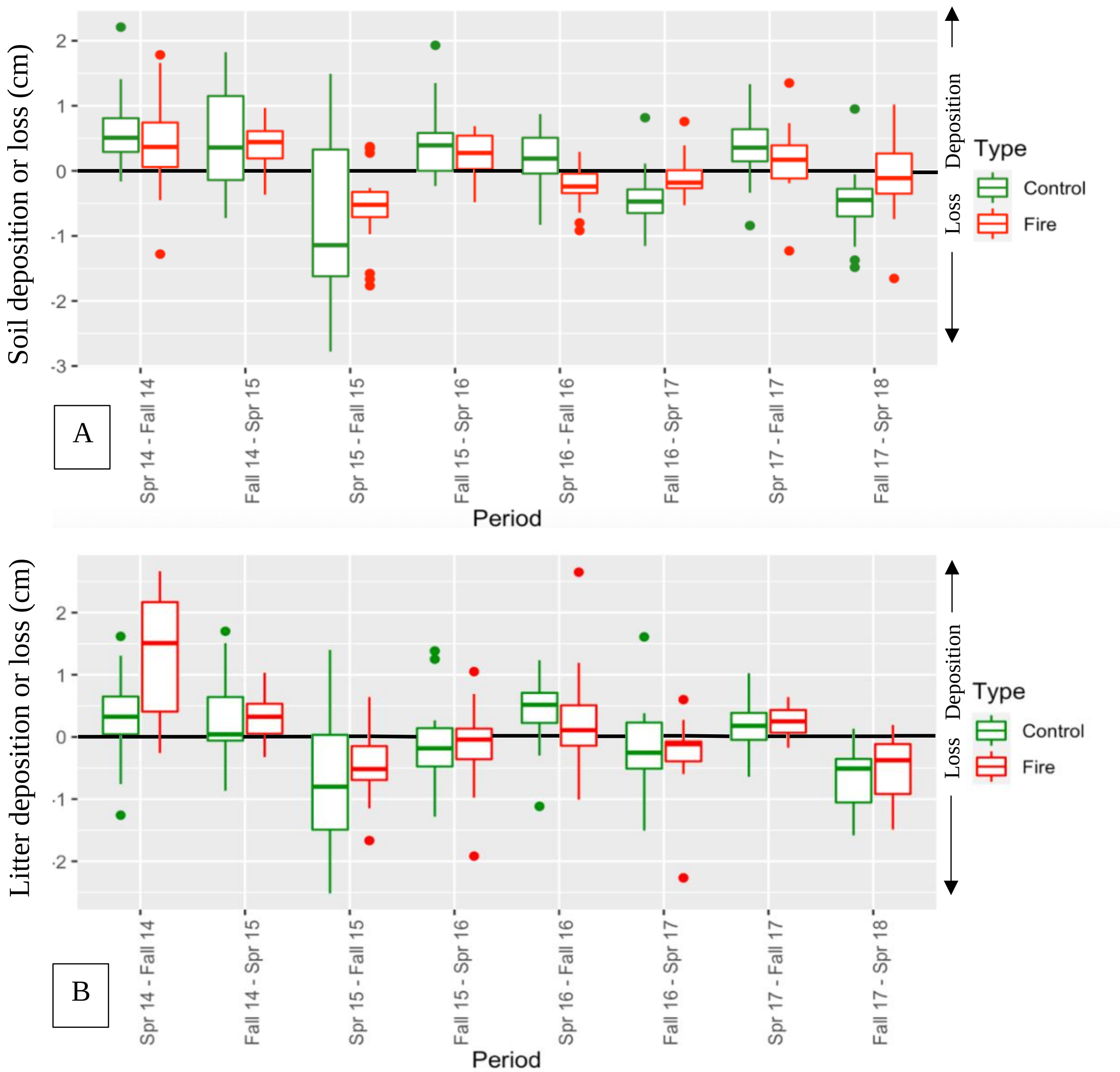



Figure 3. Change in soil height (a) and litter height (b) for each period in time for control (green) and burned sites (red). The boxes represent the first and third quartile of changes in soil and litter height with the center line in each box representing the median value of average changes in soil and litter height. Green and red points represent outliers from the data set. Vertical red and green lines represent the minimum and maximum values that are not outliers. The black horizontal line represents zero, or no change in erosion or accumulation.

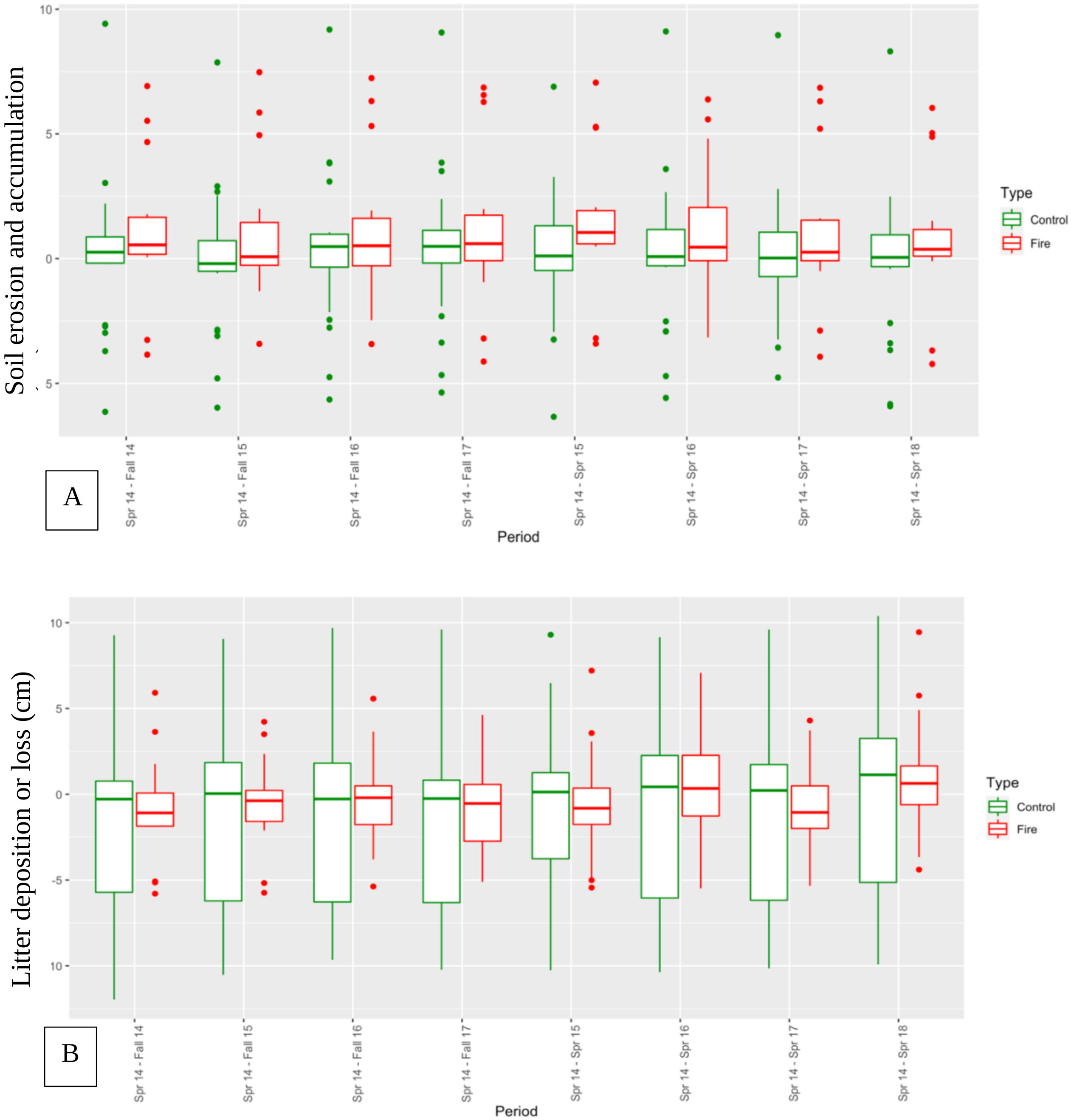



Figure 4. Cumulative change in soil height (a) and litter height (b) for each period in time for control (green) and burned sites (red). The boxes represent the first and third quartile of changes in soil and litter height with the center line in each box representing the median value of average changes in soil and litter height. Green and red points represent outliers from the data set. Vertical red and green lines represent the minimum and maximum values that are not outliers. The black line represents no change in erosion or accumulation.

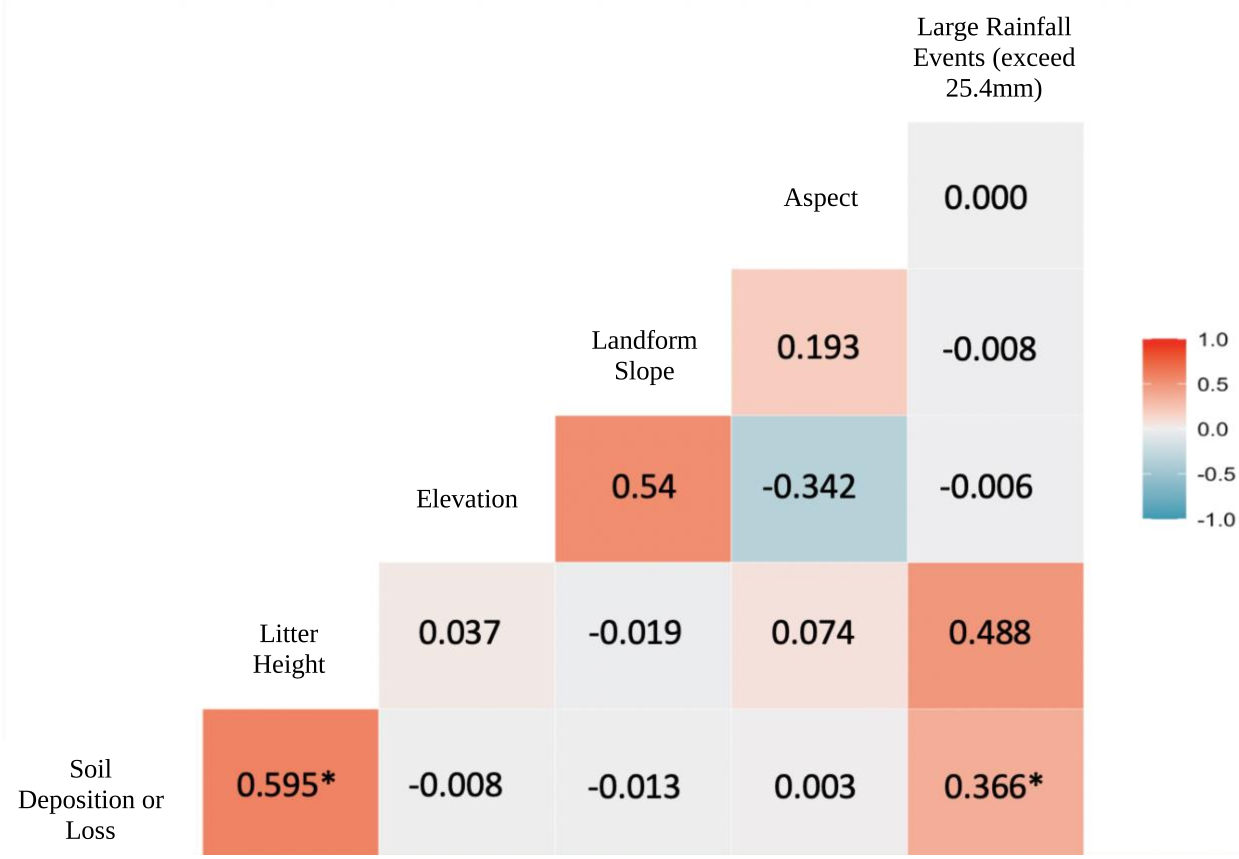



Figure 5. Heatmap showing correlation of each numerical variable. Values are Pearson correlation coefficients (r). An asterix (*) after a number indicates significance at $p \leq 0.05$ for the general linearized model.

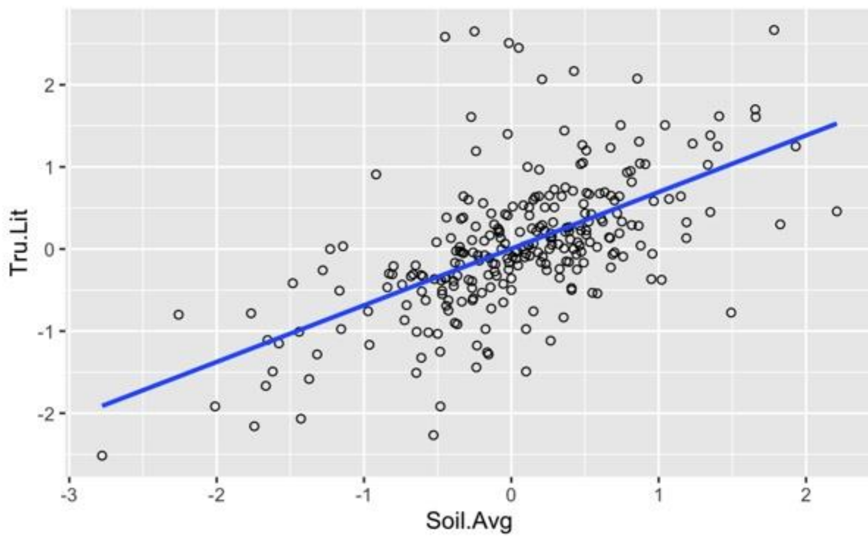
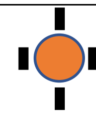
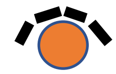
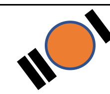
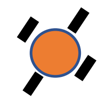
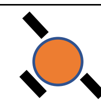
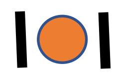
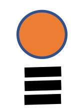
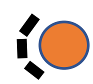
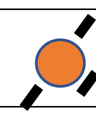
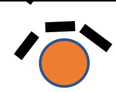



Figure 6. Scatter plot of litter variable with regression line.

# TABLES

Table 1. Features of each experimental site. Bridges are shown (in black) around each archaeological site.

| Site | Arc Site | Vegetation Type | Elevation (m) | Slope (%) | Aspect (degrees) | Severity | Dominant Soil Type | Bridge Arrangement |
|---|---|---|---|---|---|---|---|---|
| Control1 | Fieldhouse | Ponderosa | 2362.5 | 15 | 330 | NA | Laventana family |  |
| Control2 | Fieldhouse | Ponderosa | 2392.4 | 20 | 230 | NA | Laventana family |  |
| Control3 | Fieldhouse | Ponderosa | 2347.3 | 10 | 152 | NA | LaCueva family |  |
| Control4 | Fieldhouse | Ponderosa | 2148.5 | 5 | 310 | NA | Sawyercanyon family |  |
| Control5 | Fieldhouse | Piñon/Juniper & Ponderosa | 2268.6 | 5 | 235 | NA | Burnac family |  |
| Control6 | Fieldhouse | Piñon/Juniper & Ponderosa (greater stem density) | 2307.9 | 1 | 206 | NA | LaCueva family |  |
| Control7 | Pueblo | Ponderosa | 2363.4 | 27 | 250 | NA | LaCueva family |  |
| Burn1 | Fieldhouse | Ponderosa | 2407.9 | 10 | 309 | Moderate | LaCueva family |  |
| Burn2 | Fieldhouse | Ponderosa | 2406.4 | 22 | 335 | Moderate | LaCueva family |  |
| Burn3 | Fieldhouse | Ponderosa | 2366.8 | 10 | 220 | Moderate | Jemez family |  |
| Burn4 | Fieldhouse | Ponderosa | 2222.0 | 10 | 310 | Low | Cajete |  |
| Burn5 | Fieldhouse | Ponderosa | 2386.6 | 8 | 103 | Low | LaCueva family |  |

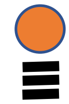
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Burn6 | Pueblo | Ponderosa | 2365.2 | 10 | 110 | Modera<br>te | Jemez family |  |

Table 2: Compiled raw data organized by site, bridge, and transect.

| | **Column Name** | **Description** | **Data Type** | **Units** |
|---|---|---|---|---|
| Site Data | Project Name | If the site occurred on Paliza North (managed fire) or Paliza South (control) | Nominal | NA |
| | Site | Determines the site | Nominal | NA |
| | Bridge | Which Erosion Bridge it is within the site | Ordinal | NA |
| | Easting | Eastward-measured distance geographic point (x-coordinate) | Numerical | Grid Refe |
| | Northing | Northward-measured distance geographic point (y-coordinate) | Numerical | Grid Refe |
| | Pre/Post | Did the site receive fire (post) or not (pre) | Nominal | NA |
| | Recent Precip. | Was there recent precipitation on the landscape. Determined by data collectors. | Nominal | NA |
| | Treatment Notes | If the data collected is pre or post burn (Pino Fire) and the year and season | Notes | NA |
| | Year | The year the data was collected | Numerical | Year |
| | Elevation | Elevation recorded of the site (ft) | Numerical | Feet |
| | Aspect (°) | Aspect of the site (measured in degrees) | Numerical | Degrees |
| | LandformSlope (%) | The landform slope (measured in percentage) | Numerical | Precent |
| | Forest Type | What is the species makeup of the overstory | Nominal | NA |
| | Arc Notes | Notes on the archaeological objects/structures that are adjacent to the site | Notes | NA |
| | | | | |
| Erosion Bridge Data | EB Slope (in/ft) | The slope of the erosion bridge | Numerical | Percent |
| | Recorder | Who recorded and who measured the data | Nominal | NA |
| | Bridge Damage | Was the erosion bridge damaged when data was recorded | Nominal | NA |
| | Camera Image | The image number for the photo that was taken for that respective bridge | Ordinal | NA |
| | Dist to litter (1-12) | Distance the pin travels through the erosion bridge to hit the litter layer. Essentially distance to litter from top of erosion bridge. | Numerical | Centimete |

| | | | | |
|---|---|---|---|---|
| | Dist to soil (1-12) | Distance the pin travels through the erosion bridge to hit mineral soil. Essentially distance to mineral soil from top of erosion bridge. | Numerical | Centimete |
| | Surface component (1-12) | What is hit initially on the ground surface when the pin is put through one of the 12 holes in the erosion bridge. | Nominal | NA |
| | Bridge Notes | General notes collected when the data was being collected | Notes | NA |
| | | | | |
| Transect Data | Transect Data | What was hit when the transect data was collected. What object hit are included in columns Labeled "Rock" up to the "veg Basal" column. Then the total hits are listed in the total column. | Nominal | NA |
| | Transect Notes | Notes taken when the vegetation transect data was collected | Notes | NA |

Table 3: Finalized database. Blue shaded boxes represent EB Main Calculations worksheet

| **Column Name** | **Description** | **Data Type** | **Units** |
|---|---|---|---|
| Type | A control site or a burn site (where Pino Fire occurred). | Nominal | NA |
| Site | The site number, distinguishing different sites. | Nominal | NA |
| Bridge | The erosion bridge number within a site. (some notes repeated among the bridges within a site) | Ordinal | NA |
| Period | The span of time representing erosion or deposition. | Ordinal | NA |
| Easting | Geographic coordinates (x-coordinate) | Numerical | Grid Re |
| Northing | Geographic coordinates (y-coordinate) | Numerical | Grid Re |
| Diff.lit. (1-12) | Cumulative differences in Dist.litter values (T1-T2) | Numerical | Centim |
| Lit.Avg | The difference in litter values between two periods of time (shown in period column). | Numerical | Centim |
| Lit-soil | Actual total litter height (litter distance - soil distance) light orange columns are values only for calculation purposes | Numerical | Centim |
| Tru.Lit (1-12) | Cumulative difference of Lit-soil column (T1-T2) | Numerical | Centim |
| TrueLitterHeight | Average of Tru litter values for each bridge during each period | Numerical | Centim |
| Diff.soil. (1-12) | Cumulative differences in Dist.soil values (T1-T2) | Numerical | Centim |
| Soil.Avg | Bridge average values for Diff.soil. (diff.soil values averaged per bridge per period) | Numerical | Centim |
| Elevation | The elevation for the site (ft) | Numerical | Feet |
| LandformSlope | The landform slope around the erosion bridge | Numerical | Percent |

| | | | |
|---|---|---|---|
| EB.Slope | Slope of the Erosion Bridge (in %) | Numerical | Percent |
| EB.Slope.Bin | EB.Slope in two different bins. 1=(0-16°), 2=(17-36°) | | |
| Aspect | Aspect of the site (in degrees) | Numerical | Degrees |
| TotalFall | Calculated as total rainfall during that period of time. (in millimeters) All precipitation data taken from Conejos weather station, NM (near Valles Caldera). 35°43'4.98"N, 106°35'10.00"W | Numerical | Millime |
| HighestFall | Calculated as highest daily rainfall event during that period of time. (in millimeters) | Numerical | Millime |
| MedFall | Calculated as number of daily rainfall events greater than 25.4 mm. within a period of time (period column) | Numerical | Millime |
| LargeRainfall | Calculated as number of rainfall events greater than 25.4 mm. within a period of time (period column). Number (0,1,2) represents occurrence of daily rainfall events in a period of time. | Numerical | Millime |
| Vegetation | Overstory vegetation classification (Ponderosa or PJ/Ponderosa) | Nominal | NA |
| Burn Severity | The burn severity of each respective site (determined on a site by site basis) | Ordinal | NA |

Table 4. Summary of linear regression results using all data

| Model | Regression Variables | Variable p-value | Model AIC |
|---|---|---|---|
| Full Model | TrueLitterHeight | 0.000 | 525.1 |
| | LargeRainfall1 | 0.940 | |
| | LargeRainfall2 | 0.003 | |
| | Aspect | 0.152 | |
| | Elevation | 0.166 | |
| | Slope | 0.312 | |
| Final Model | TrueLitterHeight | 0.000 | 464.2 |
| | LargeRainfall1 | 0.990 | |
| | LargeRainfall2 | 0.002 | |