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1 **Beyond pre-Columbian burning: the impact of firewood collection on forest fuel loads**

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Draft

6 Abstract

7 Government agencies in the United States adopted a prescribed burning policy based in part on paleo-
8 environmental evidence of pre-Columbian Native American burning regimes. However, biomass
9 collection by Native Americans in the pre-Columbian era left little direct or indirect evidence of its
10 magnitude or influence on fire regimes. In many developing countries, local peoples harvest biomass for
11 shelter, tool production, cooking, and heating, and often manage forests communally. The objective was
12 to use modern proxy biomass collection estimates analogous to pre-Columbian era practices in the
13 western US to estimate the potential impacts of regionwide firewood collection on fuel loads in the
14 Sierra Nevada range of California. A minimum of 59% of the forested area of the Sierra Nevada range
15 could have been completely stripped of 100 hr (2.54-7.62 cm diameter) surface fuel accumulation each
16 year in the pre-Columbian era, but upper estimates suggest Native American fuelwood requirements
17 may have exceeded the amount of 100 hr surface fuels accumulated over the entire range each year.
18 The collection and removal of the fuels from the surface fuel loads may have contributed to reduced fire
19 severities over that era. Dead wood collection in Nepal and India was found to reduce the threat of
20 forest fires. Including the effects of cultural practices on fuel loads may improve reconstructions of past
21 fuel and fire regimes, and may benefit modern management strategies.

22 **Keywords:** anthropogenic burning, biomass collection, fuelwood, Sierra Nevada Range, surface fuels

Introduction

In the Sierra Nevada range of California, USA, archeological evidence of human presence dates back approximately 10 000 years (Gassaway 2009). The specific Tribes that inhabited the large diverse extended region include the Maidu, Konkow, Nisenan, Northern, Central, and Southern Sierra Miwoks, Foothill Yokuts, Western Mono, Tübatulabal, Northern Paiute, Washoe, Owens Valley Paiute, and Kawaiisu (Anderson and Moratto 1996; Vale 2013). The Native Americans, i.e., Indigenous Peoples, of the Sierras were well adapted to the pyrolandscape of the region, applying their knowledge and skills to managing fire, a crucial disturbance process initiated both by lightning and Native Americans themselves (Taylor et al. 2016; Miller and Safford 2017; Steen-Adams et al. 2019; Nikolakis and Roberts 2020). Anthropological studies have documented use of the Indigenous Fire Management (IFM) approach in the Sierra Nevada to promote browse and visibility to benefit hunting; promote useful plant species and plant characteristics; and reduce fuels and the probability of dangerous fires that threatened villages, vegetal food, and other resources (Anderson and Moratto 1996; Parker 2002; Stewart 2002; Mason et al. 2012; Hankins 2013; Vale 2013; Pyne 2016; Steen-Adams et al. 2019; Nikolakis and Roberts 2020). Paleo-environmental records, such as fire scars in tree rings (Caprio and Swetnam 1995; Collins and Stephens 2007) and sedimentary charcoal (Brunelle and Anderson 2003; Beaty and Taylor 2009), provide evidence that fires prior to the 20th century were low-severity and occurred at frequent intervals, mean 8 - 10 year return interval for middle elevations in the Sierra Nevada (Wagener 1961; Dull 1999; Keeley and Stephenson 2000; Pausas and Keeley 2009; Barth et al. 2015).

The persistence of paleo-environmental evidence has understandably led to prescribed burning as the primary mechanism for Sierra Nevada forest restoration, which is broadly implemented as a lost land stewardship practice needing widespread re-adoption for restoring historical biodiversity, forest structure, and reduce fuels and the probability of uncontrolled high-severity fire (Miller and Urban 2000; Odion and Hanson 2006; Barth et al. 2015). Empirical and fire simulation research has similarly focused

on and supported the use of fire-based restoration of fuel loads and forest structure in the western U.S., including the Sierra Nevada (Charnley et al. 2007; Mallek et al. 2013; Higgins et al. 2015; DellaSala et al. 2017; Huffman et al. 2018; Nikolakis and Roberts 2020). Managers have been actively treating fuel, using overstory thinning, understory removal, pruning, pile burning, and whole-tree yarding, in order to prevent crown fire and protect mature trees (Agee and Skinner 2005). However, prescribed burning in the wildland-urban interface is hampered by severe fire risks of the prescriptions themselves under conditions of high fuel loads and accelerating effects of climate change (North et al. 2015; Liang et al. 2018; Weir et al. 2019; Navle 2020). In many areas, the benefits of these policies have not caught up to the fuel load problems while the synergistic effects of increasing drought and a hotter climate are amplifying the number of fire events, high-severity fires, and area burned (Running 2006; Odion et al. 2014; Westerling 2016).

Anthropogenic fire was not the only mechanism by which Native Americans reduced forest fuel loads and influenced fire regimes. Native Americans in the Sierra Nevada region collected biomass for various purposes, such as food, shelter, basketry, cordage, and firewood. Native Peoples collected herbs, grasses, reeds, and branches of shrubs and trees by hand and stone tools, and trees were felled by burning around the base to kill and topple the tree to make canoes, houses, and fill other resource requirements (Campbell 1999). For example, the wikiup was a shelter widespread among the peoples of the western slope of the Sierras. Wikiups were conical, and made from long poles, and ~345 square ft of incense cedar bark (Campbell 1999). Basketry was a central utilitarian cultural product in the Sierras for cooking, storage, fish traps, and carrying burdens, such as firewood, while cordage was made for fishing, hunting, and ceremonial purposes (Anderson and Moratto 1996).

Before the 19th century, firewood was the predominant source of heating and cooking worldwide (Guo et al. 2015). Peoples of the Sierra Nevada region typically used naturally dead wood from the forest floor for firewood, but would also prune dead limbs and use burden baskets or a

backpack with forked sticks and wood lashed together for transport (Campbell 1999; Fowler 2008). Although 6-16% of the total area of California (outside the deserts) may have burned per year in the pre-Columbian era (Stephens et al. 2007), biomass collection for firewood for daily cooking, heating, lighting, and ceremonial purposes would have likely been a more constant, as frequently as daily, and nearly ubiquitous impact across the landscape. Although biomass collection was practiced in the Sierras for 10 000 years or more (Anderson and Moratto 1996), little physical evidence remains of traditional biomass harvesting due to consumption and decomposition of the biomass itself, and the near complete eradication of Native American people and their culture from the landscape (Delcourt et al. 2004; Charnley et al. 2007). Consequently, quantitative estimates of biomass removed by peoples of the Sierra Nevada are lacking, and the impact of their traditional practices as an important alternative to fire for reducing forest fuel loads has potentially been overshadowed.

Due to the lack of physical evidence and cultural genocide perpetrated in the Sierras, reconstruction of the potential extent, intensity, and impact of biomass collection is dependent on international proxies. While dead wood collection may continue and reduce the threat of fires in forests in developing countries, such as Nepal and India (Chandran et al. 2011; Charmakar et al. 2021), the loss of fuelwood utilization in developed regions such as the United States and Europe may have increased fire hazard (Xanthopoulos et al. 2006). Today greater than three billion people from developing countries use wood based fuel as their primary source of energy (Rehfuess 2006). According to the Food and Agriculture Organization of the United Nations, wood fuel constitutes 7% of total primary energy sources globally, however 76% is used by developing countries, particularly in Asia and Africa (FAO 2002). More than 50% of households from developing countries still depend on woody biomass as their primary source is energy (IEA 2009). For example, many rural residents in the Himalayas depend on firewood for 90% - 100% of their cooking and heating fuel sources (Bhatt and Sachan 2004; Drigo 2016). The objective of this research was to use biomass collection estimates from practices by modern

peoples from montane regions of developing nations that are analogous to practices by Indigenous Peoples in the pre-Columbian era to estimate the impacts of fuelwood collection and consumption on fuel loads in the Sierra Nevada range of California. Inclusion of the impacts of cultural practices on pre-Columbian fuel loads may improve reconstructions of fuel and fire regimes, and emphasize lost practices that may benefit modern management strategies.

Materials and Methods

Study Area

The study area includes the entire Sierra Nevada range, California (34° 49' – 40° 24' N, 117° 54' – 121° 37' W), excluding the alpine zone. Native American population densities were greatest and permanent settlements most frequent below the winter snowline, 1000–1250 m elevation, with higher elevations occupied during the warm season (Anderson and Moratto 1996). The climate is Mediterranean with dry summers and wet winters (van Wagten donk 2006). Greater than half of the total precipitation falls as snow, and precipitation decreases from north to south and from high to low elevation (Table 1). Vegetation communities vary from oak-pine woodlands (*Quercus* and *Pinus* genera) at lower elevations, mixed conifer forests at mid-elevations (*Pinus*, *Abies*, *Calocedrus*, *Pseudotsuga*), upper montane and sub-alpine forests (*Pinus* and *Abies*), to chaparral shrublands (Liang et al. 2017). The Level IV Ecoregions of California delineate the Sierra Nevada Range in California, excluding the alpine zone, as covering an area of 49 728 km² (Griffith et al. 2016). Forests in the Sierras cover an area of 34 000 km² (Liang et al. 2017).

Published Data Sources

Due to the spread of disease from Europeans explorers, colonists, and European Americans, and the subsequent unprecedented mortality rates from novel diseases among Indigenous Peoples throughout the Americas (Dobyns, 1993; Delcourt et al. 2004), the historic demographic records

concerning Indigenous population sizes are largely underestimates of pre-contact populations, and modern estimates are consequently inexact (Anderson and Moratto 1996). Anderson and Moratto (1996) estimated that the pre-contact population of Indigenous Peoples in the Sierra Nevada range was 90 000-100 000, and they estimated the number of settlements as 2571-2857 (based on an average of 35 inhabitants/settlement, 5 houses of 7 residents each).

Rationale for the selection of published sources and proxy areas concerning fuelwood collection and fuel loads can be found in the Supplementary Information (S1). Studies by Bhatt and Sachan (2004) and Pandeya and Yadava (2016), conducted in the state of Uttarakhand, India, and Guerrero et al. (2006) in the state of Chihuahua, Mexico, were used as modern fuelwood collection analogs. Bhatt and Sachan (2004) calculated per capita firewood collection along an elevational gradient, 500 to >2000 m, in Garhwal Himalaya district. Because the Sierra Nevada is 6-10° latitude north of Garhwal Himalaya, the sample elevations from Bhatt and Sachan (2004) were selected by adjusting by 677-1129 m for latitudinal difference (latitudinal temperature gradient 1° latitude = 0.7° C (La Sorte et al. 2014); topographic lapse rate 0.62° C per 100 m (Mokhov and Akperov 2006)). The sample at 1500-2000 m, with mean firewood collection 0.73 Mg/capita/yr, and >2000 m, with mean firewood collection 1.02 Mg/capita/yr, were used herein based on the latitude and elevation conversion (Table 2) (Bhatt and Sachan 2004).

Pandeya and Yadava (2016) calculated household firewood collection from two villages adjacent to Garhwal Himalaya in Almora and Chamoli districts (see elevation, latitude, and climate data, Table 1). The sample from Almora District was at Farika Village, 1500-1650 m, and mean firewood collection was 0.66 Mg/capita/yr (Table 2). The sample from Chamoli District was at Ramara Village, 2000-2100 m, and mean firewood collection was 1.08 Mg/capita/yr (Table 2) (Pandeya and Yadava 2016).

The Sierra Tarahumara region of the Sierra Madre Occidental range is named for the Indigenous Tarahumara Peoples that inhabit the rugged mountains and valleys (Guerrero et al., 2006). The Sierra

Nevada range is 8.6-14.2° latitude north of the proxy area in Magullachi ejido, Chihuahua State, Mexico (see latitude and climate data, Table 1), for an adjustment range 970-1600 m (Magullachi sample elevation 2300 m, adjusted to a Sierra Nevada equivalent elevation range of 697-1330 m). Magullachi mean firewood consumption was 1.72 Mg/capita/yr (Table 2) (Guerrero et al. 2006).

As did the Sierra Nevada pre-Columbian peoples (Campbell 1999; Wheat 2016), rural Himalayan people similarly use burden baskets and backpacks of forked sticks to transport firewood today, and photos of active transport and stored wood suggest that the sizes of collected firewood mostly fall within the size range of 100 hr fuels, i.e., 2.54-7.62 cm diameter (Brown 1974; Pandeya and Yadava 2016). Nagothu (2001) measured fuelwood transported in head loads by villagers in Rajasthan, India, and fuelwood sizes ranged from 3 – 5 cm in diameter. Yearly accumulation rates of 100 hr fuels in the pre-Columbian era forests of the Sierra Nevada are not available. The yearly 100 hr fuel accumulation rate was sampled over a 10-year period by Fry et al. (2018) in the Sierra San Pedro Martir (SSPM) mountain range and national park, Mexico (31° 37' N, 115° 59' W), and the mean 100 hr fuel accumulation rate in sample plots was 0.03 Mg/ha/yr.

Calculations

Firewood collection catchment size per capita (CSc) was calculated using the Farika Village (FV), Ramara Village (RV), the two Garwhal Himalaya (GH1 = 1500-2000 m sample, and GH2 = >2000 m sample), and ejido Magullachi (MXM) samples with the following equation:

$$\text{Eq. 1} \quad \text{CSc} = \text{Fwc}/\text{Ar}$$

Where Fwc is the amount of firewood collected per capita per year (Mg/yr) and Ar is the 100 hr fuel accumulation rate from SSPM (Mg/ha/yr). Firewood collection catchment size per capita was converted to catchment size per household (CSh) and catchment size per settlement (CSs) by multiplying the per capita values by the estimated 7 residents per household and estimated 35 residents per settlement, respectively, for pre-contact peoples in the Sierra Nevada range from Anderson and Moratto (1996).

Total area within the Sierra Nevada range impacted by pre-Columbian firewood collection per year (TCS) was calculated by multiplying CSc by the total population size across the Sierras of 90 000-100 000 people from Anderson and Moratto (1996). Total firewood (TFw) collected across the Sierra Nevada Range was calculated by multiplying the amount of firewood collected per capita per year (Mg/yr) by the population size of the Sierras.

Results

The estimated total amount of firewood collected (TFw) per year across the Sierras was between 59 670 – 171 600 Mg/yr (Table 2). Estimated CSc, CSh, and CSs ranged respectively from 22.1 – 57.2 ha, 154.7 – 400.4 ha, and 773.5 – 2002.0 ha (Table 2). Variation among estimates of TFw, CSc, CSh, and CSs were related to elevation differences among modern proxy firewood collection sample locations, i.e., lower elevation FV and GH1 vs. higher elevation RV and GH2, and TFw variation was also related to the estimated total population size of pre-Columbian peoples inhabiting the Sierras. Less firewood is required at lower elevations due to milder winter temperatures and for smaller populations. Magullachi, Mexico, had the greatest TFw, CSc, CSh, and CSs estimates, and was the highest elevation proxy sample location with the lowest annual mean minimum temperature (Table 1), although other cultural and technological differences may also contribute to the variation.

The estimated total catchment size (TCS) of the Sierras impacted by firewood collection ranged between 19 890 – 57 200 km² (Table 2). TCS represented between 59% and 106% of the total forested area of the Sierra Nevada range for proxy estimates from India, and between 151% and 168% of the total forested Sierra Nevada Range for proxy estimates from Mexico. TCS varied based on the same factors influencing TFw, including the estimated total population size of pre-Columbian peoples inhabiting the Sierras.

Discussion

The estimates found herein suggest that the fuel load of the Sierra Nevada range would have been substantially altered by firewood collection absent any other biomass collection or burning practices during the pre-Columbian period. A minimum of 59% of the forested area of the Sierra Nevada range could have been completely stripped of 100 hr fuels every year based on accumulation rates from the SSPM and international fuelwood collection proxies, and upper estimates suggest that 100 hr fuel accumulation of the entire region would not have been adequate to support the fuelwood needs of the region's population. Thus, surface fuels in the 100 hr category were less available and continuous over substantial areas surrounding settlements. Reduction of surface fuels that lessen surface fire intensity and/or the continuity of fuels across the landscape will reduce the probability of running, continuous spread, crown fires, and tree mortality rates (Scott and Reinhardt 2001; Raymond and Peterson 2005). Charmakar et al. (2021) found that scheduled collection of 80% of dried and decayed surface fuels in community managed forests dominated by *Pinus* and *Quercus* in Nepal reduced the threat of forest fire. The Indian government's forest management policy that permits commercial and household collection of accumulated ground fuels, e.g., dry surface fuel, pine cones, and pine needles, as an alternative to prescribed burning for fuels reduction has successfully reduced fire and fire damage in Uttarakhand chir pine (*Pinus roxburghii*) forests (Chandran et al. 2011). In the pre-Columbian Sierras, fuel loads and fire severities were not just reduced by frequent anthropogenic and natural burning, which are the expected outcomes of modern land management practices (Klimaszewski-Patterson et al. 2018), but fuel reduction due to firewood collection would also have contributed in the intervening years between prescribed and natural fires to control the severity of future fires.

When 100 hr surface fuels were exhausted or less convenient, Native Peoples in northern California would exploit other fuel sources such as manzanita, *Arctostaphylos spp.*, other fuel classes, i.e., 10 hr (0.64 – 2.54 cm diameter) or 1000 hr (>7.62 cm) fuels, or prune dead limbs from standing trees using long poles (Campbell 1999). Exploitation of ladder fuels such as dead limbs increases crown

base height and will decrease torching (Scott 1998; Fulé et al. 2001). Nagothu (2001) estimated in Rajasthan, India that approximately 75% of fuelwood collection was derived from fallen dry wood, which is easier and less time consuming to collect, while the remaining 25% came from pruning and occasionally felling live trees. We did not encounter in our literature review of fuelwood use specifically by Native Americans any estimates of the proportion of collected fuelwood or harvesting rate for attached branches. However, one may assume that crown base heights were elevated within settlement catchment areas.

Similarly, data concerning proportions and rates of fuelwood collection among various surface fuel size classes is not available. Photos found in Pandeya and Yadava (2016) and Guerrero et al. (2006) suggest that 10 hr fuels were a relatively small proportion of fuelwood collected by participants in those studies. Fuels in the 10 hr size class may present a poor return on effort due to rapid consumption rates. Photos in Guerrero et al. (2006) suggest a bias toward 100 hr and larger fuels in the 1000 hr range, but Native Peoples of the Sierra Tarahumara do employ tricycles, mules, or trucks for fuelwood transport in addition to bundles, making larger sizes more efficient (Guerrero et al. 2006; Quiroz-Carranza and Orellana 2010). Fuelwood was exclusively transported using burden baskets and bundles by participants in Pandeya and Yadava (2016), with an apparently strong bias towards 100 hr fuels based on photo evidence. Nagothu (2001) also report the size range of fuelwood transported in head loads fell only within the 100 hr fuel size class. In the pre-Columbian era, the weight of carrying 1000 hr fuels may have been prohibitive over longer distances, especially by children, making a stone axe and chopping necessary and potentially limiting the frequency and catchment area for large size-class fuelwood. Nevertheless, shifting between fuel size classes, even on a limited and highly localized basis, would have the effect of reducing the fuelwood catchment size, but not necessarily the total mass of fuelwood utilized.

Anderson and Moratto (1996) estimated that all Native American settlements combined in the Sierra Nevada would have used a total of 52 195 Mg/yr of firewood annually, based on 2860 settlements with 5 houses each and 10 kg of daily firewood use per household. This estimate is less than the lowest estimate found herein, but within reasonable range of that lowest estimated total. Based on the field samples from Bhatt and Sachan (2004) and Pandeya and Yadava (2016), the daily firewood use per household used by Anderson and Moratto (1996) would be applicable to settlements at the lower elevations in the Sierra Nevada range, i.e., <1000 m. Any permanent settlements or seasonal camps above 1000 m, such as Yosemite Valley, would have required more firewood for heating per day.

Anderson and Moratto (1996) also estimated that each Native American settlement in the Sierra Nevada would require a 5-10 km² catchment area for procuring resources, e.g., hunting, vegetal foods, for cooking, construction materials, and cultural items. The greatest estimate of settlement catchment size for firewood collection herein was 20.01 km², and two other estimates were >10 km² and the least being 7.7 km², which did not include any other resource collection activities. Additional research and estimates on the impacts of wickiup construction, basketry, and other biomass uses should also be conducted to provide a full accounting of effects on fuels loads and the amount of area required to support these other biomass collection activities.

Although Mexico is physically and perhaps environmentally closer to the study area in California, USA, the methods for firewood collection and use in Uttarakhand, India, are likely more analogous to pre-Columbian Native American practices. Pre-Columbian peoples of the Sierra Nevada only had access to fuelwood for cooking and heating, and in that sense the villagers observed in the Himalayan region at 1500 m and higher and the ejidos of the Sierra Tarahumara shared that complete reliance on fuelwood for cooking and heating (Bhatt and Sachan 2004; Guerrero et al. 2006). Firewood collection by Native Sierrans and villagers in the Himalayas was conducted exclusively using basketry, tied bundles, or the armload for at-home use (Potts 1997; Campbell 1999; Pandeya and Yadava 2016). Commercial sale of

fuelwood at local markets is facilitated by more efficient transportation options in the Sierra Tarahumara (Ghilardi et al. 2007; Rios et al. 2018). Although, peoples of both the Himalayas and Sierra Tarahumara collected both green and surface fuels of relatively small diameter branches easy for carrying (Guerrero et al. 2006; Pandeya and Yadava 2016; Rios et al. 2018), live trees were also cut and split into logs for firewood in Mexico (Guerrero et al. 2006; Rios et al. 2018). Another practice facilitated by Mexico's more diverse transportation options and that was not likely for pre-Columbian peoples. These sources of variation from the practices of both the peoples of Uttarakhand and the Sierra Nevada suggest caution concerning the applicability of estimates from Guerrero et al. (2006) as a proxy for Native Sierran fuelwood use.

For questions related to the relative efficiency of Native American fuelwood use to be resolved, further research will be required employing their actual heating, ceremonial, and cooking methods using the available fuels of the region. A wide variety of cooking and heating methods were encountered in Mexico, e.g., traditional clay wood-burning stoves, iron wood stoves, half-drum heaters, campfires, and fire pits, and the use of half-drum heaters in winter was described as tending to "spend a lot of firewood" (Guerrero et al. 2006). In much of the Himalaya region, clay wood-burning ovens are used that are very similar to traditional clay wood-burning ovens in Mexico (Guerrero et al., 2006). Miwok and Northern Maidu used open fires in shallow depressions and/or ringed by rocks and meat was cooked on coals and rocks (Potts 1977; Campbell 1999). Earth ovens were also used to cook and steam food (Campbell 1999), and water boiled in baskets with heated rocks to cook acorns and other foods (Anderson and Moratto 1996). Native Sierran peoples used sweat houses with fires ringed by heated rocks that were sprinkled with water to produce steam (Potts 1977). These methods were probably inefficient in comparison to ovens, but perhaps comparable to campfires, fire pits, and half-drum heaters used by study participants in Guerrero et al. (2006).

The analysis found herein introduces the potential influence pre-Columbian Native American fuelwood collection had on forest fuel loads, and thus made deliberate choices to apply the analysis across a broad diverse region using generalizable mean conditions and ranges. Even though Sierran peoples were largely semi-nomadic hunter gatherers, their occupancy included permanent structures below the mean snowline in valleys, i.e., <1400 m on average, and summer hunting camps at higher elevations, all within the Sierra Nevada boundary (Merriam 1917; Gifford 1932; Morgan 2009). Thus, although the location of their fuelwood collection may have moved from winter to summer, the full impact would have remained within the forested Sierra Nevada and a regionwide approach to estimates is reasonable. Spatially and temporally explicit variation in permanent and seasonal settlements, population sizes, accessibility in rough terrain, fuel loads, and fire regimes could impact the effects of firewood collection across the landscape. Such variation can be modeled with spatially explicit data about the landscape and archaeological data to evaluate more specific and localized contexts, problems, and anthropological and management questions. Spatially explicit landscape models of the influence of Native American practices on fire regimes have not incorporated reduction of fuels by practices other than burning (Klimasweski-Patterson 2018). Integrating fuelwood collection practices in such models may improve accuracy and our understanding of Native American impacts on fire regimes and forest structure, with humans as permanent integral actors in the functioning of the system instead of relatively low probability stochastic disturbance agents. Such analyses would also improve estimates of variation in Native American resource catchment areas and movement patterns across the landscape, and inform our understanding of the feedback effects of their interactions with their environment on the daily and seasonal patterns and practices of the peoples of the Sierra Nevada range (e.g., Morgan 2008). Confronted with degraded modern systems and climate change heralding intensifying future disturbance, the generalized findings found herein should prompt further evaluation of modern fuel

reduction prescriptions and evaluations of historical, modern, and future fire regime, behavior, and management scenarios.

Due to the loss of frequent, patchy, low-severity anthropogenic fires more than a century ago, the wildfire cycle is out of balance and the threat of large and destructive fires is increasing (Miller and Safford 2012; Dennison et al. 2014; Anderson 2018; Singleton et al. 2019). In the modern post-suppression forest composed of overly dense second-growth forests that burn at higher severities (Habeck 1994; Barth et al. 2015; Lauvaux et al. 2016; Hessburg et al. 2019), fuel accumulation rates today are many times greater than pre-Columbian rates. Burning at higher severity creates a positive feedback by increasing live and dead fuel, i.e., dense chaparral cover and unconsumed dead snags and downed logs, respectively (Coppoletta et al. 2016). Our own field samples found the mean accumulation rate for 100 hr fuels in mixed conifer stands after the 2012 Chips Fire in Lassen and Plumas National Forests was 0.58 Mg/ha in plots burned at moderate- to high-severity, which is 19 times greater than the rate from the SSPM used herein (Paudel et al. In Review). Traditional biomass collection practices by a small pre-Columbian population would not be adequate to manage modern fuel loads. However, substantially increased surface fuel removal efforts by government agencies and expanded dead biomass collection by the much larger modern population of the region or corporate entities, either for fuelwood, non-timber forest products, or innovative uses related to carbon capture and burial, can be sustainable management options.

Recent clarion calls for the increased use of fire as an efficient low-cost method for reducing fuel buildup that leads to high-severity crown fires recognize that fire policy has not worked well because of a conservative tendency towards continued suppression, which undermines the potential utility of burning for reducing fuels and future extreme fire events (North et al. 2015). However, conservative application of existing policy may not be the only barrier. Climate change may be shortening the window each year where prescribed fire can be used to efficiently extract forests from the fuel build-up situation

and fire danger we have created (Wimberly and Liu 2014; Prichard et al. 2017; Ximenes et al. 2017; see Clarke et al. 2019 for a contrasting viewpoint). The danger of large high-severity fire today and moving forward may necessitate a greater shift in forest management policy in favor of labor and energy intensive fuel management programs that reduce fuels manually on a scale not experienced since the pre-Columbian era. Klimaszewski-Patterson et al. (2018) stated that anthropogenic burning is consistent with traditional Native American cultural lifeways, and to favor open forests with frequent surface fires, increase biodiversity, and enhance resources, land use management strategies with Native American practices in mind is entirely appropriate (Anderson 1999, 2005; Fry and Stephens 2006; as cited in Klimaszewski-Patterson et al. 2018). Active management is validated, and the preservation approach to wilderness and wildlands must be questioned because humans were a driver of ecological processes in the Sierras for millennia (Anderson 2018). Our estimated effects of pre-Columbian fuelwood collection on fuel loads should have the same effect as our understanding of the effects of anthropogenic burning, validating expansion of intensified removal of surface and ladder fuels, i.e., supplementing prescribed burning, thinning, salvage logging of marketable timber, underburning, and other existing treatment options, as management policy that can exist as part of a functioning ecosystem.

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Table 1: Climate data for proxy wood collection sample locations in Farika and Ramara villages in Uttarakhand, India (Pandeya and Yadava, 2016), ejido Magullachi in Chihuahua, Mexico (Avila-Marioni and Ramírez-Vega, 1997), and for a sample of locations at mid-elevations from the northern to the southern ends of the Sierra Nevada range, California (Western Regional Climate Center, https://wrcc.dri.edu/Climate/west_coop_summaries.php).

Climate Station	Period of Record	Latitude (N)	Elev (m)	Mean Max Temp (°C)	Mean Min Temp (°C)	Mean Annual Precip (cm)
Uttarakhand, India						
Ramara	2011-2013	30° 02'	2050	15.23	4.58	765.00
Farika	2011-2013	29° 50'	1600	21.12	5.87	450.00
Chihuahua, Mexico						
Magullachi	–	27° 58'	2300	19.50	-1.00	800.00
Sierra Nevada Range, California						
Greenville (Sta. ID 043621)	1894-2008	40° 08'	1085	19.11	-0.22	997.46
Quincy (Sta. ID 047195)	1895-2016	39° 58'	1039	19.44	0.67	1019.81
Sierra City (Sta. ID 048207)	1910-2000	39° 34'	1289	18.50	3.72	1592.07
Hetch Hetchy (Sta. ID 043939)	1910-2016	37° 57'	1180	19.20	4.72	901.70
Yosemite Park HQ (Sta. ID 049855)	1905-2016	37° 45'	1216	20.16	3.33	921.00
Springville Tule HD (Sta. ID 048463)	1896-2008	36° 13'	1280	18.60	4.20	940.05
Tehachapi (Sta. ID 048826)	1893-1997	35° 08'	1225	19.78	5.06	281.43

Table 2: Fuelwood consumption per capita (Fwc) at Farika Village (FV) and Ramara Village (RV) (Pandeya and Yadava, 2016), two different elevations in Garwhal Himalaya (GH1 and GH2) (Bhatt and Sachan, 2004), and ejido Magullachi, Mexico (MXM) (Guerrero et al., 2006), estimated pre-Columbian peoples' total amount of firewood collected for a population of 90 000 and 100 000 inhabitants of the Sierra Nevada range region (TFw-90 and TFw-100, respectively), firewood collection catchment sizes per capita (CSc), household (CSh), and settlement (CSs), as well as the total catchment size within the Sierra Nevada range influenced by firewood collection for a population of 90 000 and 100 000 inhabitants of the region (TCS-90 and TCS-100, respectively).

	Fwc (Mg/yr)	TFw-90 (Mg/yr)	TFw-100 (Mg/yr)	CSc (ha)	CSh (ha)	CSs (ha)	TCS-90 (km²)	TCS-100 (km²)
FV	0.663	59,670	66,300	22.1	154.7	773.5	19,890	22,100
RV	1.078	97,020	107,800	35.9	251.5	1257.7	32,340	35,933
GH1	0.730	65,700	73,000	24.3	170.3	851.7	21,900	24,333
GH2	1.019	91,710	101,900	34.0	237.8	1188.8	30,570	33,967
MXM	1.716	154,440	171,600	57.2	400.4	2002.0	51,480	57,200