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Blending Indigenous and western science: Quantifying cultural burning impacts in Karuk Aboriginal Territory

Skye M. Greenler[1] | **Frank K. Lake**[2] | **William Tripp**[3] | **Kathy McCovey**[4] | **Analisa Tripp**[3] | **Leaf G. Hillman**[4] | **Christopher J. Dunn**[1] | **Susan J. Prichard**[5] | **Paul F. Hessburg**[5,6] | **Will Harling**[7] | **John D. Bailey**[1]

[1]Oregon State University College of Forestry, Corvallis, Oregon, USA

[2]U.S. Forest Service Pacific Southwest Research Station, Arcata, California, USA

[3]Karuk Tribe, Department of Natural Resources, Orleans, California, USA

[4]Karuk Tribal Member, Orleans, California, USA

[5]University of Washington School of Environmental and Forest Sciences, Seattle, Washington, USA

[6]U.S. Forest Service PNW Research Station, Wenatchee, Washington, USA

[7]Mid Klamath Watershed Council, Orleans, California, USA

Correspondence
Skye M. Greenler
Email: skye.greenler@oregonstate.edu

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Abstract

The combined effects of Indigenous fire stewardship and lightning ignitions shaped historical fire regimes, landscape patterns, and available resources in many ecosystems globally. The resulting fire regimes created complex fire–vegetation dynamics that were further influenced by biophysical setting, disturbance history, and climate. While there is increasing recognition of Indigenous fire stewardship among western scientists and managers, the extent and purpose of cultural burning is generally absent from the landscape–fire modeling literature and our understanding of ecosystem processes and development. In collaboration with the Karuk Tribe Department of Natural Resources, we developed a transdisciplinary Monte Carlo simulation model of cultural ignition location, frequency, and timing to simulate spatially explicit cultural ignitions across a 264,399-ha landscape within Karuk Aboriginal Territory in northern California. Estimates of cultural ignition parameters were developed with Tribal members and knowledge holders using existing interviews, historical maps, ethnographies, recent ecological studies, contemporary maps, and generational knowledge. Spatial and temporal attributes of cultural burning were explicitly tied to the ecology of specific cultural resources, fuel receptivity, seasonal movement patterns, and spiritual practices. Prior to colonization, cultural burning practices were extensive across the study landscape with an estimated 6972 annual ignitions, averaging approximately 6.5 ignitions per Indigenous fire steward per year. The ignition characteristics we document align closely with data on historical fire regimes and vegetation but differ substantially from the location and timing of contemporary ignitions. This work demonstrates the importance of cultural burning for developing and maintaining the ecosystems present at the time of colonization and underscores the need to work collaboratively with Indigenous communities to restore ecocultural processes in these systems.

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KEYWORDS
cultural burning, fire ecology, Indigenous stewardship, Klamath Mountains, landscape ecology, landscape–fire model

INTRODUCTION

Ecocultural fire processes have shaped ecosystems across the globe for millennia (Bowman et al., 2011; Kelly et al., 2020; Trauernicht et al., 2015). Understanding the interactions between humans, fire processes, and pathways toward co-existence with wildfire has taken on heightened urgency as the social, ecological, and economic impacts of wildfire have grown in recent decades (Bowman et al., 2020; Dunn et al., 2020; McWethy et al., 2019; North et al., 2022). Recently, many western scientific and management communities have shown heightened interest in supporting Indigenous fire stewardship practices that better balance relationships between people and fire (Eisenberg et al., 2019; Long et al., 2021; Roos, 2020). This increasing awareness follows decades of work from Indigenous communities to assert their sovereign rights to land stewardship, emphasize the importance of cultural burning, and build collaborative relationships and policies that facilitate integration of cultural burning into broader research, management, and restoration practices (Dickson-Hoyle et al., 2021; Lake, 2013, 2021; Varghese & Crawford, 2020).

Many fire-prone landscapes in the western United States have a long history of cultural burning—the purposeful use of fire by an Indigenous group for diverse purposes—to promote valued food, medicinal, and material resources and, in turn, altering wildfire spread and risk (Anderson, 2005; Huffman, 2013; Lake & Christianson, 2020; Long et al., 2021; Roos et al., 2021). Despite clear Traditional Ecological Knowledge and scientific evidence of substantial Indigenous fire stewardship, the influence of cultural burning has largely been excluded from fire history studies and the landscape ecology of fire (Kipfmueller et al., 2021; Lake, 2013; Lewis & Anderson, 2002; Thomassin et al., 2019). Many ecological models therefore have an incomplete understanding of historical processes, which perpetuates division between western scientists, managers, and Indigenous land stewards. This is particularly problematic because cultural burning often differs substantially from contemporary ignitions in location, timing, frequency, purpose, and technique (Clark et al., 2021; Huffman, 2013; Lake et al., 2017; Lake & Christianson, 2020).

The western Klamath Mountains in northern California are a diverse and highly fire-prone ecosystem that historically burned frequently with low or moderate severity but have recently experienced many uncharacteristically extensive or severe wildfires (Skinner et al., 2006; Taylor et al., 2021). Indigenous Knowledge holders in this region have a relatively unbroken understanding of cultural burning practices and have worked for decades to revitalize and remove barriers to cultural fire stewardship, evaluate the effects of cultural burning on important cultural species, and conduct interviews with knowledge holders to record Indigenous fire knowledge (Diver, 2016; Karuk Tribe, 2019; Mucioki et al., 2021; Norgaard, 2019; Sowerwine et al., 2019). These studies and interviews detail the specificity of cultural burning practices at fine spatial scales for species including California hazelnut (Hazel; *Corylus cornuta*), huckleberry (*Vaccinium ovatum*), beargrass (*Xerophyllum tenax*), tanoak (*Notholithocarpus densiflorus*), and sandbar willow (*Salix exigua*; Halpern et al., 2022; Hummel & Lake, 2015; Lake, 2007; Marks-Block et al., 2019, 2021; Rentz, 2003; Rossier, 2019). Several larger-scale studies describe regional cultural burning practices and global connections between Indigenous stewardship and conservation (Anderson, 2005; Fa et al., 2020; Hoffman et al., 2021; Lightfoot & Parrish, 2009; O'Bryan et al., 2021; Roos et al., 2018, 2021; Steen-Adams et al., 2019; Trauernicht et al., 2015; Wynecoop et al., 2019). However, few studies describe cultural burning practices at landscape scales (10^5–10^6 ha) that allow retention of place-based specificity but also facilitate inference across large areas (Roos, 2020; but see: Bird et al., 2012; Greenwood et al., 2022).

Landscape–fire models provide an opportunity to blend knowledge and evidence from diverse sources to provide vital insights into the role and influence of ecocultural fire regimes (Anderson & Rosenthal, 2015; Klimaszewski-Patterson et al., 2018; Prichard et al., 2023; Roos et al., 2021). By coupling fire–vegetation interactions, these models can explore interactions between Indigenous stewardship, topoedaphic variables, vegetation distributions, and lightning patterns to address critical questions about historical landscape dynamics and implications of contemporary management, adaptation strategies, or stewardship. However, most current models exclude cultural burning practices and therefore miss a critical component of the fire regime where there is strong history of Indigenous fire stewardship (Anderson & Barbour, 2003; Anderson & Moratto, 1996; Lake, 2013; Stewart, 2002).

Decades of work by the Karuk and neighboring Tribes has established a foundation to develop a

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landscape-scale reconstruction of cultural burning practices and incorporate cultural burning into fire and vegetation modeling (Karuk Tribe, 2019; Lake & Christianson, 2020; Long & Lake, 2018; Sarna-Wojcicki et al., 2019). In this study, we blended a comprehensive review of existing information and interviews, geospatial analyses, and simulation modeling to collaboratively reconstruct best estimates of cultural ignition location, timing, and frequency across a 264,399-ha landscape within the Karuk Aboriginal Territory (Figure 1A). This work was guided by three questions: (1) What are the characteristics of ecocultural fire regimes for key fire-maintained cultural resources across landscape biophysical gradients? (2) Given these factors, how does the annual probability of cultural ignition vary across the landscape? and (3) How does the probability of cultural ignition compare with contemporary wildfires?

METHODS

In this study, we used data and evidence that is often excluded from western science to center Indigenous Knowledge, voices, and values, and address limitations of current methodologies (Parbhakar & Mallory, 2022). Our estimated cultural burning parameters are informed by surviving generational knowledge, contemporary place-based knowledge, and landscape context, and are co-produced with partners from the Karuk Tribe and the Western Klamath Restoration Partnership (WKRP). Our parameters represent best estimates of how the study area would have been culturally stewarded and maintained if Indigenous burning and resulting landscape characteristics had been maintained for the last 150 years (i.e., without fire exclusion). This framing recognizes that knowledge is nonstationary and shifts with time and circumstance, and it is challenging to know with certainty what occurred historically given systemic genocide, forced assimilation, and attempted knowledge eradication (Eisenberg et al., 2019; Karuk Tribe et al., 2017; Norgaard, 2014, 2019). To help address this inherent uncertainty, we developed estimates within a Monte Carlo modeling framework that explicitly incorporates uncertainty (Figure 2).

This research was conducted under a Practicing Pikyav Research Agreement (https://nature.berkeley.edu/karuk-collaborative/?page_id=165) with the Karuk Tribe but does not necessarily reflect the knowledge or views of all Tribal members and descendants. All Indigenous Knowledge references have been reviewed by Tribal collaborators and were developed under the principles of free, prior, and informed consent. As such, this study is not intended to limit or otherwise inform the regulation of cultural burning or other forms of Indigenous stewardship, but rather to provide information to draw upon as we work to restore balanced human–fire relationships. Tribal culture and Indigenous Knowledge inform Tribal members on when, where, and how to burn. This study is not a surrogate for Indigenous Knowledge, practice,

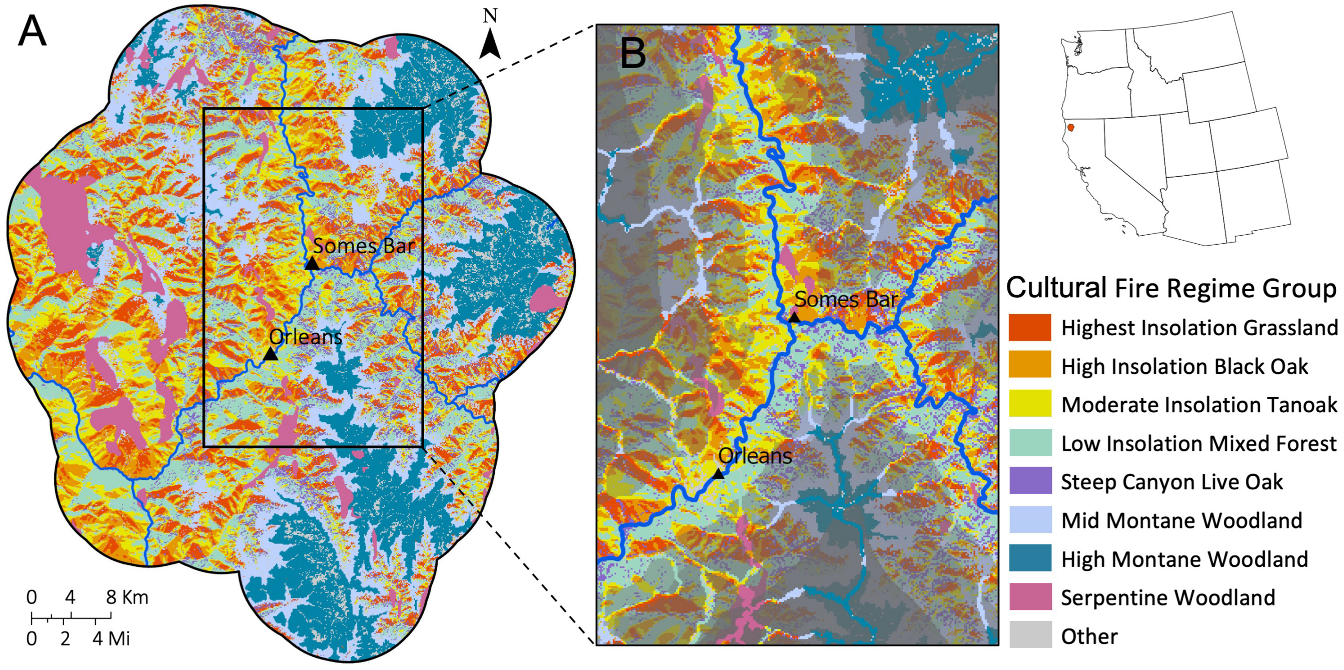

FIGURE 1 Cultural fire regime group distribution across study landscape (A), with inset displaying cultural ignition frequency mask for the Somes Bar and Orleans area (B).

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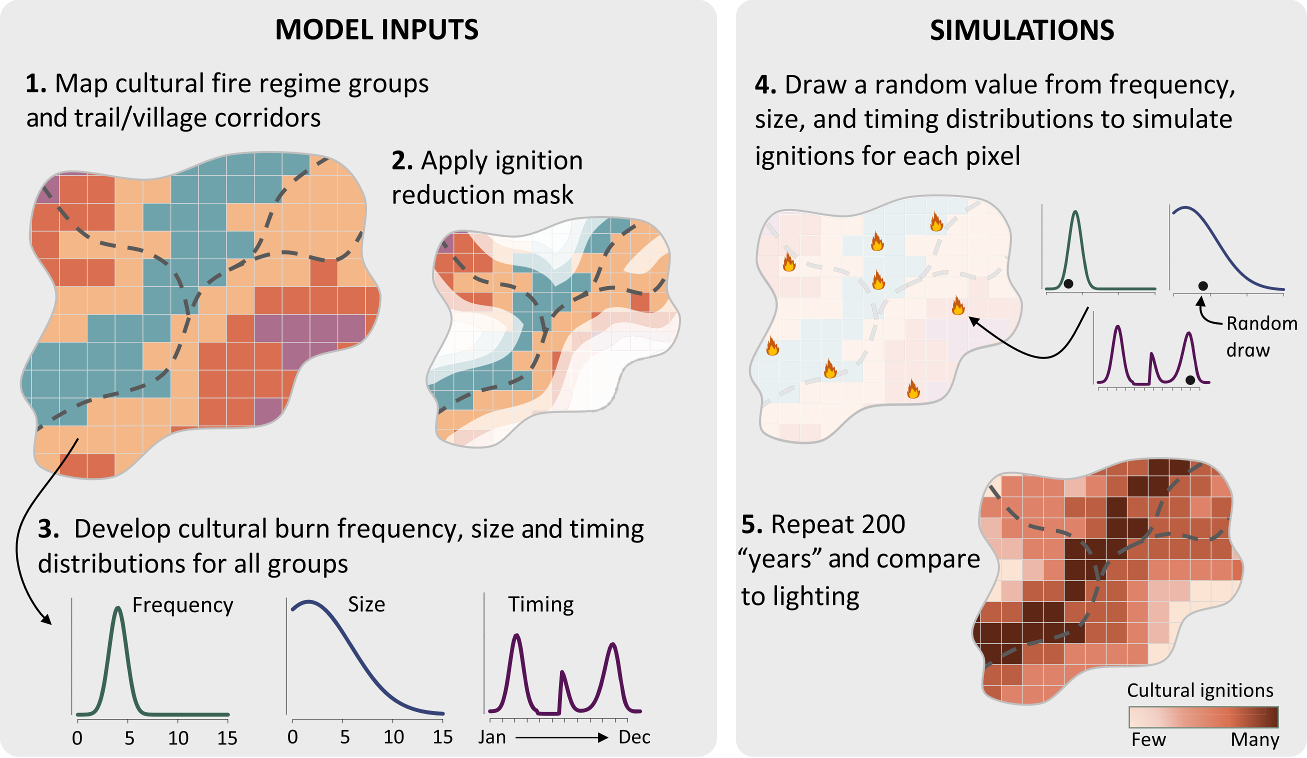

FIGURE 2 Conceptual diagram of cultural ignition modeling process on example landscape with four vegetation types (represented by different colors in left panel) and one high human use network (dashed line).

and belief systems. Our work sacrifices place-based specificity to develop estimates over large spatial scales and may not capture cultural fire regime characteristics associated with specific locations, family groups, objectives, or other specific scenarios.

Study landscape

Our 264,399-ha study landscape is situated in the western Klamath Mountains of northern California surrounding Somes Bar and Orleans in the homelands of the Karuk, Yurok, and Hupa Peoples (Figure 1). The region is renowned for extraordinary biodiversity, endemic species, and climate refugia due to varied biogeoclimatic gradients and historical frequent, low- to moderate-severity fire regimes (Perry et al., 2011; Skinner et al., 2006; Whittaker, 1960). As with many frequent-fire ecosystems, Indigenous burning practices together with lightning ignitions strongly shaped fire dynamics in this region and the resulting biodiversity, resources, and landscape structure (Figure 3; Anderson & Rosenthal, 2015; Bliege Bird et al., 2008; Huffman, 2013; Ray et al., 2012; Trauernicht et al., 2015). Historical fire return intervals varied with biophysical and cultural influences, but were often quite frequent (<10 years) especially in drier, lower elevation areas (Metlen et al., 2018; Perry et al., 2011; Skinner et al., 2006; Taylor & Skinner, 2003).

A legacy of Euro-American colonization and fire exclusion policies have dramatically altered fire processes and vegetation patterns across the landscape, leading to increased climate change vulnerability, uncharacteristically severe wildfires, and decreased abundance of key cultural resources (Hagmann et al., 2019, 2021; Knight et al., 2020; Taylor et al., 2016, 2021). Fire exclusion has caused pronounced changes across the landscape; however, effects are particularly notable in lower elevation prairie/oak woodland and mixed-evergreen forests, which have transitioned from open-hardwood woodlands or grasslands to much denser, conifer-dominated forests (Karuk Tribe, 2019; Knight et al., 2020; Skinner, 1995; Skinner et al., 2006). Given the close connections between human and environmental health, colonization and fire exclusion are locally considered to have created a "genocide forest" (public communications, Chook-Chook Hillman [Karuk], Oregon Public Broadcasting, 9 September 2018, https://www.opb.org/news/article/northwest-plants-animals-wildfire-help/) resulting in many socio-cultural disparities for Tribal communities including high rates of physical and mental health ailments and food, economic, and safety insecurities (Anderson, 2006; Norgaard, 2014, 2019; Sowerwine et al., 2019).

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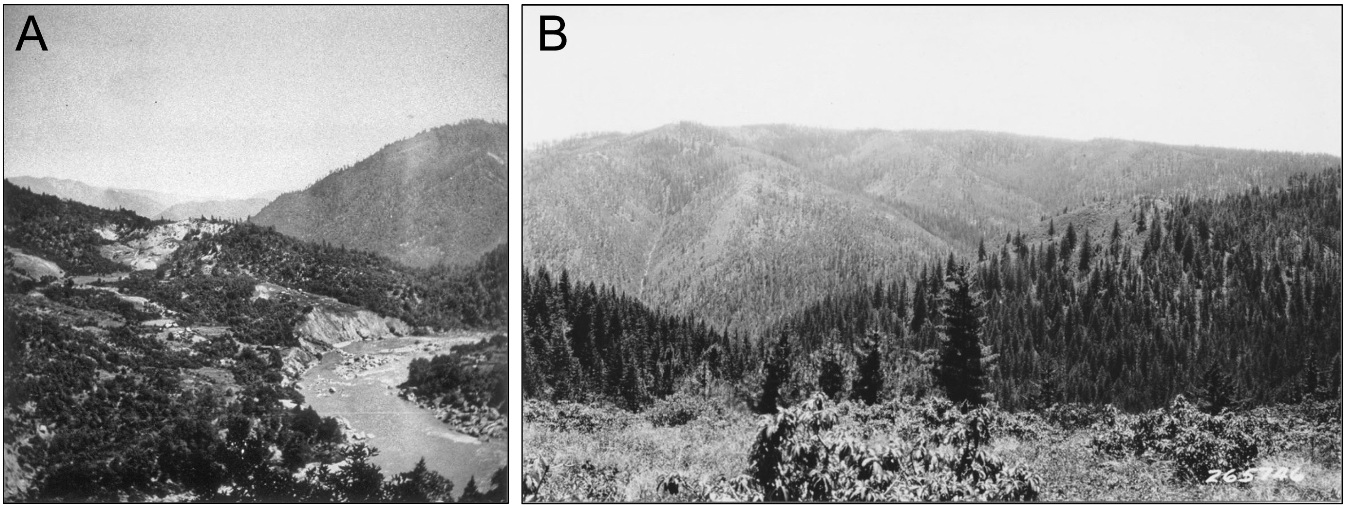

FIGURE 3 Landscape photographs from the early 1900s display the heterogenous vegetation and fuel mosaics common across the study landscape that were sustained by interactions between frequent cultural burning, lightning, and underlying biophysical gradients. Photograph (A) was taken by Alfred Kroeber between 1900 and 1920 of a low-elevation landscape near villages at the confluence of the Klamath and Salmon Rivers (Kroeber, https://portal.hearstmuseum.berkeley.edu/catalog/9d275512-6506-4242-9cfc-ef8a94a38a12). Photograph (B) was taken by Albert Wieslander in 1928 on the Siskiyou crest looking south across the western portion of our study area. The slope in the middle of the image is a low-insolation mixed-evergreen forest, while the slope in the background contains mid-montane and high-insolation woodlands. The young, even-aged Douglas-fir stand in the middle of this photograph likely established after cultural burning declined on the landscape around 1850, which resulted in what a Karuk elder described as "a whole bunch of little Christmas trees coming up...in the 1870s" (Mavis McCovey, Karuk, in Lake, 2007: 540). Image (A) is courtesy of the Phoebe A. Hearst Museum of Anthropology and the Regents of the University of California, photographed by Alfred Kroeber, 15-1373. Image (B) from the Wieslander Vegetation Type Mapping Collection is courtesy of the Marian Koshland Bioscience, Natural Resources and Public Health Library, University of California, Berkeley, http://guides.lib.berkeley.edu/Wieslander.

Knowledge review

To develop estimates of the timing, frequency, and location of cultural ignitions across the study landscape, we conducted a comprehensive review of publicly available information about cultural burning practices and historical landscape conditions from published interviews with Indigenous Knowledge holders, syntheses of place-based knowledge and Indigenous stewardship practices, ethnographic documents, books, reports, and theses (Appendix S1: Box S1). We augmented this review with information from historical maps, vegetation plot networks, and information on the physiology, phenology, and ecology of key cultural use species. We focused primarily on literature related to Karuk practices but included references from the neighboring Yurok and Hupa Peoples as well. Estimates and assumptions from this review were collaboratively reviewed and adjusted with a core group of Karuk knowledge holders, Tribal members, and descendants including co-authors F. Lake, W. Tripp, K. McCovey, L. Hillman, and A. Tripp.

To identify pertinent literature, we reviewed all publicly available documents and references in the Karuk Tribe's Sípnuuk Archive (Karuk Tribe et al., 2017) and searched Google Scholar and Web of Science with the key words "Karuk" and "burn" or "fire." We recorded quotes from all sources referencing Indigenous fire stewardship practices and landscape conditions related to cultural burning and categorized information according to vegetation zones described within the Karuk Climate Adaptation Plan (2019; Appendix S1: Box S1). We included both Indigenous and non-indigenous authors in our review, however, non-indigenous sources were generally considered as secondary to Indigenous authors and voices.

Cultural fire regime group delineation

We delineated eight cultural fire regime groups—major vegetation communities with unique Indigenous fire stewardship characteristics—within our study landscape (Lake et al., 2017; Lake & Christianson, 2020; Steen-Adams et al., 2019). First, we defined four general vegetation groups using LANDFIRE 2.0.0 biophysical settings (BpS) data at a 90 × 90 m resolution: (1) low-elevation mixed-evergreen (conifer and hardwood) forests, (2) montane forests, (3) woodlands on serpentine soils, and (4) other conditions including riparian, chaparral, or

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nonvegetated (Rollins, 2009). Next, we subdivided the low-elevation mixed-evergreen forests into mesic and dry groups based on annual average solar insolation using a break point of 1,100,000 WH/m^2 (Karuk Tribe, 2019). We further subdivided the dry mixed-evergreen group into three subgroups of equal size based on average March solar insolation estimates to capture fine-scale differences in fuel receptivity with the unfolding of spring and associated varying vegetation communities and Indigenous fire stewardship practices (Karuk Tribe, 2019; Whittaker, 1960).

We then assigned all low-elevation, mixed-evergreen forests with a slope of >70% to a separate group due to the unique vegetation and cultural fire regimes on these sites (Karuk Tribe, 2019; Skinner et al., 2006). Finally, we divided the montane forest type into mid- and high-montane conditions using a 1375-m elevation threshold based on the estimated elevation belt under which summer smoke inversions occur (Downing et al., 2021; Estes et al., 2017; Karuk Tribe, 2019). Following site reconnaissance and conversations with local land stewards, we reclassified serpentine areas using geologic maps of serpentine parent materials from the 1987 California Geologic Survey Weed Quadrangle map (Wagner & Saucedo, 1987). We calculated solar insolation with the Area Solar Radiation Tool in ArcGIS Pro (Version 2.6) as annual and monthly averages at a 90-m resolution using a day interval of 14 and 1 h interval of 0.5.

We then developed geospatial delineations of where cultural burning likely had the strongest influence across the study landscape based on distance from the historical village corridor (Klamath River, Salmon River, and Wooley Creek) and trail/traversable ridge networks (Chartkoff & Chartkoff, 1975; Lake, 2013; Peters & Oritz, 2016; Theororatus, 1980). We categorized distance to river as: 0–1.6 km, 1.6–3.2 km, 3.2–6.4 km, and >6.4 km (0–1, 1–2, 2–4 and >4 mi.) and mapped trail/traversable ridge networks using data from Lake (2007, 2013) augmented with trails from early historical maps listed in Appendix S1: Section S1. From our review and authors' personal knowledge, we anticipate cultural ignitions often occurred within 100 m of trails/traversable ridges and adjacent flats, hence, we applied a buffer of 200 m (656.2 ft) centered on trail networks and adjacent gently sloped or flat topography (≤15%) that was >1.6 ha (4 ac) and intersected the trail or 200 m buffer.

Quantifying ecocultural fire practices

For each of the eight cultural fire regime groups, we developed quantitative estimates of the burn timing (calendar date) and frequency (fire return interval) for accessible locations on the landscape where cultural burning practices were most tightly related to cultural resource, vegetation, and fuels based on our knowledge review. Key to quantifying ecocultural fire practices for use in western scientific methods like simulation modeling is linking qualitative Indigenous Knowledge with quantitative parameters. We began this process by first assigning key cultural use species to each cultural fire regime group (Garibaldi & Turner, 2004; Karuk Tribe, 2019). We then developed qualitative descriptions of the cultural fire stewardship practices necessary to enhance and maintain these sites and resources indefinitely through our knowledge review process. Finally, we converted the qualitative descriptions of ignition timing and frequency to quantitative probability distributions by assuming that described frequency or timing ranges (ex. 5–7-year fire frequency, or time range between 15 February and 25 March) represented the inner 75% of the probability distribution. We used standard normal probability distributions to approximate cultural burn frequency, mixture distributions to define timing parameters, and truncated normal distributions for fire size.

Timing mixture distributions were developed using normal, skew normal, and uniform distributions to represent early spring, early summer, and fall burning periods. For each cultural fire regime group, burning periods were weighted differently depending on cultural resource stewardship objectives, site characteristics, and seasonal movements of people through the landscape. Assigned weights for the three periods summed to 90%, with the final 10% allocated evenly to all days—except during a spring period when burning is very uncommon—to account for occasional burning that occurred outside the primary windows.

We used two fire size distributions: one for low-elevation mixed-evergreen forests and serpentine sites ≤914 m (based on estimated elevation of mid-montane forests described in Karuk Tribe, 2019) and another for mid-montane, high-montane, and serpentine sites >914 m due to insufficient information to develop unique estimates for each group separately (Figure 1). Final parameter estimates were adjusted following review by local Indigenous Knowledge holders and experts.

Quantitative landscape modeling

Given the inherent variability and uncertainty surrounding the cultural fire regime estimates, we estimated annual probability of ignition for each pixel, ignition dates, and total annual ignitions across the study landscape using an iterative Monte Carlo procedure. While ignition probability is typically calculated using a mean fire frequency and size, Monte Carlo simulation allowed

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us to sample from the probability distribution to account for known variability and uncertainty (Vose, 2000).

We calculated the probability of ignition for each 90×90 m pixel on the landscape, on an annual time step, using Equation 1:

$$\text{Annual Probability of Cultural Ignition} = \left(\frac{1}{f} \times \frac{8100}{s}\right) \times r, \tag{1}$$

where,

$f =$ annual cultural fire return interval derived by drawing random values from the ignition frequency distribution for the associated cultural fire regime group;

$s =$ fire size in square meter derived by drawing random values from the fire size distributions for the associated cultural fire regime group;

$8100 = 90 \times 90$ m pixel size in square meter;

$r =$ probability reduction variable for each location.

For each iteration, the location specific probability reduction variable, r, was applied according to distance from the river corridor and position along trail/traversable ridge networks. For locations within 1.6 km (1 mi.) of the river corridor or along trail networks r was set to 1, for locations 1.6–3.2 km (1–2 mi.) from the river r was set to 0.5, for locations 3.2–6.4 km (2–4 mi.) from the river r was set to 0.25 and for all other locations r was set to 0.1.

To convert ignition probability to an estimated ignition occurrence, we compared each probability to a randomly generated value from a uniform distribution between 0 and 1 and populated an ignition occurrence if the probability of ignition was greater than the random value. All simulation modeling was completed in program R version 3.6.1 and probability distributions were developed using the sn and truncnorm packages (Azzalini, 2021; Mersmann et al., 2018; R Core Team, 2019).

Comparison of cultural and lightning ignitions

We compared modeled cultural ignitions to inventoried ignitions from 1980 to 2016 recorded in the USDA Forest Service Fire Program Analysis Fire Occurrence Database (Short, 2017) and lightning strike probabilities calculated using 1990–2010 data from the National Lightning Detection Network (Cummins & Murphy, 2009). To balance overweighting individual lightning strikes in lower lightning density areas while retaining fine-scale resolution, we averaged lightning strike density calculated at 1 and 3-km neighborhoods.

RESULTS

General factors influencing cultural burning characteristics

From our knowledge review, we identified four general factors that influence timing and frequency of cultural burns in the western Klamath Mountains: (1) fuel receptivity, (2) seasonal travel of Indigenous people through the landscape, (3) plant ecology and resource conditions, and (4) spiritual practices. These factors formed the basis for our ignition parameter estimates.

Fuel receptivity, if and how fuels burn in a fire, encompasses both site- and neighborhood-level effects (McKemey et al., 2020). Burns cannot be conducted when fuel moisture is above the moisture of extinction, but may strategically occur when fuel moistures are near this threshold in order to protect above-ground or below-ground biota (Anderson & Lake, 2013; Andrews, 2018). Fuel receptivity in adjacent areas can also influence cultural burn timing when areas with lower fuel moisture (due to aspect, understory fuel type, elevation, time of day, or shading) abut areas with moist fuels, which can serve as firebreaks (Karuk Tribe, 2019).

Seasonal travel across the landscape also influences spatial and temporal cultural ignition patterns and is coupled with factors such as changes in resource availability, fuel loading/connectivity, ease of access, and annual spiritual and subsistence practices (Anderson & Rosenthal, 2015; Hummel & Lake, 2015; Peters & Oritz, 2016; Turner et al., 2011). In the Karuk Territory, this is often discussed in relation to movement to and from the high country in the summer and early fall, when trails are free of snow and high-country plant and animal resources are abundant and of high quality (Appendix S1: Box S1).

Specific physical and morphological characteristics of highly valued species are also important drivers of cultural burn frequency and timing (McKemey et al., 2020; Oritz, 2008; Smith, 2016). Burn seasonality and frequency impact the quality, quantity, and gathering access for many important foods such as acorns, nuts, seeds, berries, fungi, and geophytes as well as basketry/fiber resources, in all cultural fire regime groups (Anderson, 2005; Anderson & Lake, 2013; Karuk Tribe, 2019; Lake, 2013). Burn frequency is tied to plant anatomical and molecular structure such as blade or shoot length, pliability, and uniformity, which are critically important for basketry (Peters & Oritz, 2016; Rentz, 2003). Burn timing is often linked to other biotic indicators such as plant phenology and physiology, insect life cycles, or animal movement patterns (Armatas et al., 2016; Halpern et al., 2022; Karuk Tribe, 2019).

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Finally, spiritual beliefs and practices impact the frequency, timing, and location of cultural burning. For example, cultural burning is rarely, if ever, used as a management tool during a period in the spring when specific celestial indicators are absent from the night sky, which coincides with reproductive seasons for many species, such as mammals, birds, and pollinating insects that would be impacted by understory burning (Karuk Tribe, 2019). It is of note that knowledge is not monolithic and there is some variability in Karuk knowledge holders' beliefs regarding spring burning; however, we do not model any ignitions during this period to align with publications from the Karuk Department of Natural Resources (DNR) (Karuk Tribe, 2019; Tripp, 2017).

Based on information on these four factors from the knowledge review and expert knowledge from authors and collaborators, we defined the inner 75th percentile for the timing distribution of the spring burning period as 10 February to 20 March, early summer as 23 June to 14 July, and fall as 27 September to 11 November (Figure 4; Appendix S1: Figure S1). The spring burning period generally is prior to hardwood budbreak and aligns with increasing fuel receptivity on drier, exposed aspects. The early summer period occurs as cool season grasses and forbs begin to senesce. The fall burning period tends to align with leaf, acorn, and other nut abscission, and reduced photosynthetic rates of many species (Anderson, 2005; Pullen, 1996). An alternative timing distribution that includes occasional ignitions during the spring period when cultural burning is rare is included in Appendix S1: Figure S2 but was not used in modeling.

Cultural fire regime group characteristics

The eight cultural fire regimes we delineated represent major vegetation groups with unique cultural fire stewardship characteristics and cover 93.9% of the study landscape (Appendix S1: Table S1). Descriptions of the general characteristics for each group, cultural burn parameters for maintenance burning at accessible locations, and examples of the information used to develop these estimates follow. See Appendix S1: Box S1 for a full list of quotes from the knowledge review for each group.

Highest insolation, grassland-capable sites occur in areas mapped as low-elevation mixed-evergreen forest along ridges and south-facing slopes that receive the highest incoming spring solar radiation. Forbs, grasses, and white oak (*Quercus garryana*) are key cultural use species in this zone, which we estimate were burned, on average, every 2–7 years, primarily in the early summer or fall and occasionally in the early spring (Jimerson & Carothers, 2002; Karuk Tribe, 2019; Lake, 2007; Long, Lake, & Lynn, 2018). Burn timing depends, in part, on fuel moisture and dominance of cool versus warm season grasses and forbs present as the fuel bed (Karuk Tribe, 2019; Tappeiner II et al., 1992). Many sources in our knowledge review describe "large tracts of grassy land, which....were burned off every year during the dry seasons" (Lucy Thompson, 1916:85), that "prairies were burned back all the time… [in the] spring and fall" (Mavis McCovey, Karuk, in Lake, 2007:540), and that the Hupa "would annually burn the prairies to keep the forest back, generate new fresh shoots for animal feed; and…regenerate various medicinal-ceremonial herbs" (Kathy Heffner, Wailaki, in Busam, 2006:145). These grassland-capable sites covered 10.5% of the study landscape.

High-insolation, black oak woodlands occur in low-elevation mixed-evergreen forests with slightly lower spring insolation values than grassland sites (Cocking et al., 2012; Jimerson et al., 1996; Jimerson & Carothers, 2002). Black oak (*Quercus kelloggii*), hazel, ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), and manzanita (*Arctostaphylos* spp.) are important cultural use species in this group (Long et al., 2016; Marks-Block et al., 2019, 2021). Cultural burning is often tied to hazel stewardship and occurs primarily in the early spring and fall and occasionally in the early summer approximately every 3–8-years. Burn timing depends, in part, on the type and diameter of shoots needed for basketry as described by Wilverna Reece (Karuk), "Fires (for hazel) were most commonly set in the late fall, although the time of burning could be changed so that stems would be the desired size for weaving" (Rentz, 2003:18). Burn frequency is, in part, influenced by whether the stand is being stewarded for hazel shoots or nuts as told by Bessie Tripp (Karuk) "And that hazel grow (first the sticks) small, that's what they make baskets with. Next year it be just full of those nuts" (Karuk Tribe, 2010: 41). These sites covered 11.6% of the study landscape typically adjacent to grasslands and tanoak stands.

Moderate insolation, tanoak woodlands tend to occur on sites with intermediate spring solar insolation between drier oak woodlands and more mesic mixed-evergreen forests across 11.8% of the study area (Atzet et al., 1992; Barbour et al., 2007; Jimerson et al., 1996; Tappeiner II et al., 1992; Whittaker, 1960). Tanoak is the primary cultural use species in this zone, with Pacific madrone (*Arbutus menziesii*) and golden chinquapin (*Chrysolepis chrysophylla*) in some stands. We estimate tanoak stands are burned every 3–7 years, primarily in the fall. Burning in tanoak stands helps control competing vegetation, facilitates acorn gathering, and reduces acorn filbert weevil (*Curculio occidentalis*) and filbertworm populations (*Cydia latiferreana*;

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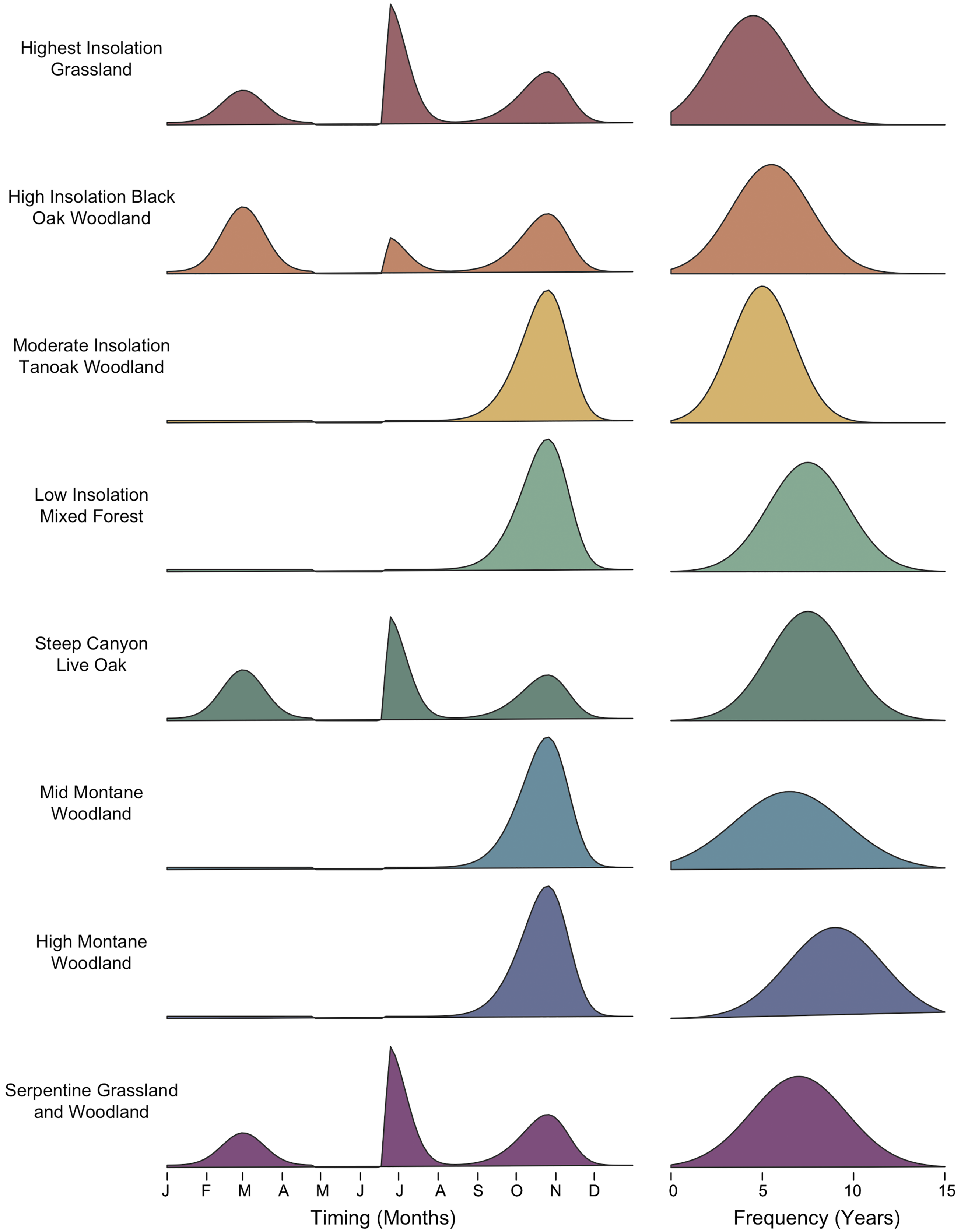

FIGURE 4 Probability distributions for cultural burn timing and frequency derived from normal and skew normal distributions. Distributions incorporate variability of cultural burning practices and estimate uncertainty. Areas where curves are taller represent greater likelihood of ignition, but ignitions can occur across displayed ranges. For the timing distributions, 10% of the distribution weight was allocated evenly to all days except a spring period.

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Halpern et al., 2022). The importance of these practices is described by Craig Erwin (Yurok), "the acorn gathering ground, it had to be burned, but it was a slow fire…And that kept the disease down. Now we don't have acorns hardly… There's so much of this worm" and Pheobe Maddux (Karuk), "They also burn where the tan oak trees are, least it be brushy where they pick up acorns" (Harrington, 1932:64, Riley-Thron, 2001:176).

Low-insolation, mixed-evergreen forests generally occur on north-facing stands and in cooler, low-elevation settings or draws, which comprise 16.8% of the study landscape (Atzet et al., 1992; Jimerson et al., 1996). Edible berries, Douglas-fir (*Pseudotsuga menziesii*), big-leaf maple (*Acer macrophyllum*), and tanoak are key cultural species in these areas (Rossier, 2019; Whittaker, 1960). Burning occurs on a 5–10-year frequency, typically in the fall when fuel moistures are lower. This zone is burned to maintain open overstory and understory conditions, reduce competition for important cultural use species, and stimulate berry production. Klamath River Jack (1916) describes the importance of burning for berries saying, "Every year Indians burn. Fire burn off old wood and lots of berry come." Lisa Hillman (Karuk, Yurok) describes using fire to promote intermediate light conditions that favor huckleberry, "Part of tending [huckleberry] would be to burn off… and get rid of some of those lanky overstory…that are just blocking out the light" (Rossier, 2019:317).

Canyon live oak (*Quercus chrysolepis*) sites occur on steep, xeric slopes at lower elevations across 6.3% of the study area (Skinner et al., 2006). These stands intermix with other low-elevation zones, but support a distinctive vegetation community and fuels (Long, Gray, & Lake, 2018; Skinner et al., 2006). Less has been recorded about cultural burning in live oak stands; however, contemporary legacy trees with architecture indicative of Indigenous burning exist across the study landscape (Long et al., 2021). The Karuk DNR describes the unique cultural fire regime associated with this group, "burning in areas with…live oak sprouts in June…would trigger a flush of fresh browse with peak nutrient loading in a time when grasses are curing out and inedible…Browsed live oak sprouts about 5–7 years old are then used to make dip net hoops" (2019). Burning to promote sprouts for browse was repeatedly discussed by knowledge holders in the review, including reflections from Klamath River Jack: "fire make new sprout for deer and elk to eat" (1916), and Mavis McCovey, "he [father] said they just burned all the time…so that there was no danger of fire. And…so that the deer and elk would have something to eat" (Lake, 2007:540). Canyon live oak is not a highly preferred acorn in Karuk Territory, but its acorns are a high-value food for wildlife and burning to reduce acorn pests likely occurred in the fall as well (Halpern et al., 2022). We estimate these sites were burned on a 5–10-year cycle, likely throughout the year.

Mid-montane woodlands generally occur at mid elevations within the summer smoke inversion zone (Jimerson et al., 1996; Karuk Tribe, 2019; Whittaker, 1960). It was challenging to differentiate references to mid-montane forests and high-montane forests within the knowledge review, but burning within both zones was often tied to producing high-quality beargrass for basketry, development of open, high-quality browse for ungulates, and maintenance of trails and flat meadows (Anderson, 2005; Anderson & Moratto, 1996; Baldy, 2013; Hart-Fredeluces & Ticktin, 2019; Huntsinger & McCaffrey, 1995; Turner et al., 2011). Cultural fire practitioners describe frequent fall burning for beargrass along ridges in montane forests, saying "the beargrass has to be burned before it can be used because it's very coarse and it will cut you…so in the fall, [Karuk Peoples would] go and they'd set the beargrass patch on fire…then in spring, that beargrass comes up just like a fine grass" (Craig Erwin in Smith, 2016:135). Meadows and patch edges within montane forests also contained berry and nut producing plants that benefited from semifrequent fire that recycled nutrients, reduced overstory shading, and ameliorated understory competition (Anderson, 2005; Long et al., 2021; Rossier, 2019).

Mid- and high-montane areas were also "burned to facilitate the pursuit of game" (Driver, 1939:379), as described further by Earl "Scrub" Aubrey, Jr. (Karuk), saying, "On the times we went hunting…late in the season we did a lot of burning…You had to burn that underbrush, (because) without burning (the deer) did not have food." (Lake, 2007:406,414). Many sources also describe regularly burning off trails, especially in the fall after hunting and gathering in the high-country including Glenn Moore Sr. (Yurok), "they can tell the weather…so when they'd leave (the high country, they would) just touch everything off" and Mavis McCovey, "they just burned along [the trails] …so where the trail went was open area under the trees" (Lake, 2007; 546, 564). We estimate burning in mid-montane areas occurred primarily in the late summer and early fall every 3–10 years. Mid-montane areas comprise 15.3% of the study area.

High-montane woodlands are similar to those in mid-montane areas but have a slightly lower frequency of 6–12 years due to generally further travel distance from villages, slower vegetation growth, and increased probability of lightning. This zone also covers 15.3% of the study area.

Serpentine grasslands and woodlands occur across broad elevational gradients in areas with ultramafic lithology and alkaline soils on 6.1% of the study area. Important cultural species on these sites include grasses

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and forbs (including geophytes), Jeffrey pine (*Pinus jeffreyi*), and incense cedar (*Calocedrus decurrens*; Barbour et al., 2007; Skinner et al., 2006; Whittaker, 1960). Given similar site characteristics, it is challenging to separate references about burning in grasslands and serpentine areas. We suspect some of the prairies described in the knowledge review have serpentine components. Thus, we generalized that burning practices in serpentine areas was similar to high-insolation grassland sites to promote first foods, medicines, and basketry materials, manage tree and shrub encroachment, and stimulate browse for wildlife. Mavis McCovey describes many of these components in her discussion of burning on an important serpentine flat, saying, "There's all kinds of stuff at…(specific) Flat…ironwood (*Holodiscus discolor*) …those little iris plants (*Iris* sp.)…and the little tick brush (*Ceanothus intergerrimus*). …They used it for medicine, they used it for fine basket(s)…They burn for that too…" (Lake, 2007:542–543). Given lower productivity on serpentine sites, we estimate a 4–10-year burn frequency with burning primarily occurring in the early summer and fall with occasional early spring burning.

Our review of publicly available information and interviews did not support development of fire size distributions for individual cultural fire regime groups and thus we relied on expert opinion from Tribal collaborators to develop fire size estimates. Following their guidance, we used one fire size distribution with a mean of 4.42 ha (10.9 ac) and 80th percentile of 8.1 ha (20 ac) for low-elevation sites and a size distribution with a mean of 21.11 ha (54.64 ac) and 80th percentile of 40.47 ha (100 ac) for higher elevation sites (Appendix S1: Figure S3).

Simulated annual ignitions

Based on the 200-year Monte Carlo simulation, there were 6972 ± 75 (mean ± SD) annual cultural ignitions on average across the 264,399-ha study landscape (Figure 5A,C). Of these, 13.4% of ignitions occurred during the spring burning period from 10 February to 20 March, 10.6% occurred during the summer from 23 June to 14 July, 48.7% occurred during the fall from 28 September to 11 November, and the remaining 27.3% occurred outside the core time windows (Figure 5C). By applying the mean of the estimated fire size distribution used in the modeling, we estimate these ignitions would annually burn 39,772 ha (15.0% of the landscape). However, cultural burning is often patchy so many areas within these perimeters may not actually receive fire in every burn (Long et al., 2021).

In the 200-year simulation, 70.2% the pixels received at least one cultural ignition. Of those pixels, 79.2% were ignited 1–10 times, 18.9% were ignited 11–20 times, and 1.9% were ignited ≥21 times. The 29.8% of pixels that did not directly receive a cultural ignition would likely receive fire that spread from adjacent areas. Overall, ignition density across the study area was 264.1 ignitions/year/100 km^2 (Figure 5A). However, ignitions were much more common on low-elevation sites along the river corridor with an average of 6466 annual ignitions in low-elevation mixed-evergreen and low-elevation serpentine sites and 506 ignitions in higher elevation sites.

DISCUSSION

In this work, we demonstrate extensive and spatially variable ecocultural fire regimes across a 264,399-ha landscape within Karuk Aboriginal Territory, with ignition patterns closely linked to topoedaphic gradients that facilitate fire use throughout the year (Figures 1A and 5A). The application of fire was in close alignment with changes in fuel receptivity and continuity, phenology and physiology of key cultural use species, seasonal movement patterns and uses throughout the landscape, and specific spiritual beliefs and practices (Karuk Tribe, 2019; Lake, 2007; Long et al., 2021). These ignitions would have spread fire to many parts of the landscape and promoted diverse mosaics of culturally significant vegetation assemblages—now almost entirely absent on the landscape—within a topoedaphic template that was suitable to support them (Figure 3; Anderson & Rosenthal, 2015; Bliege Bird et al., 2008; Larson et al., 2020; Taylor & Skinner, 1998). This work represents one of the first broad-scale and culturally grounded quantitative estimates of the spatial and temporal characteristics of a cultural fire regime. It also demonstrates the potential magnitude of error associated with minimizing the influence of Indigenous fire stewardship on fire regimes, ecological processes, and available resources (Anderson, 1999; Knight et al., 2022; Lake, 2013; Stewart, 2002).

While western scientists and managers are not directly entitled to this information, it holds immense power to better understand historical processes and drivers of resilience and to help facilitate collaborative and inclusive contemporary management when it is openly shared with consent (Baldy, 2013; Dickson-Hoyle et al., 2021). Indigenous Knowledge systems and stewardship practices have developed in response to shifting local environments for millennia. Such knowledge systems communicate strong histories of facilitating the resilience and adaptation of coupled human-natural systems critical for contemporary landscapes under intensifying

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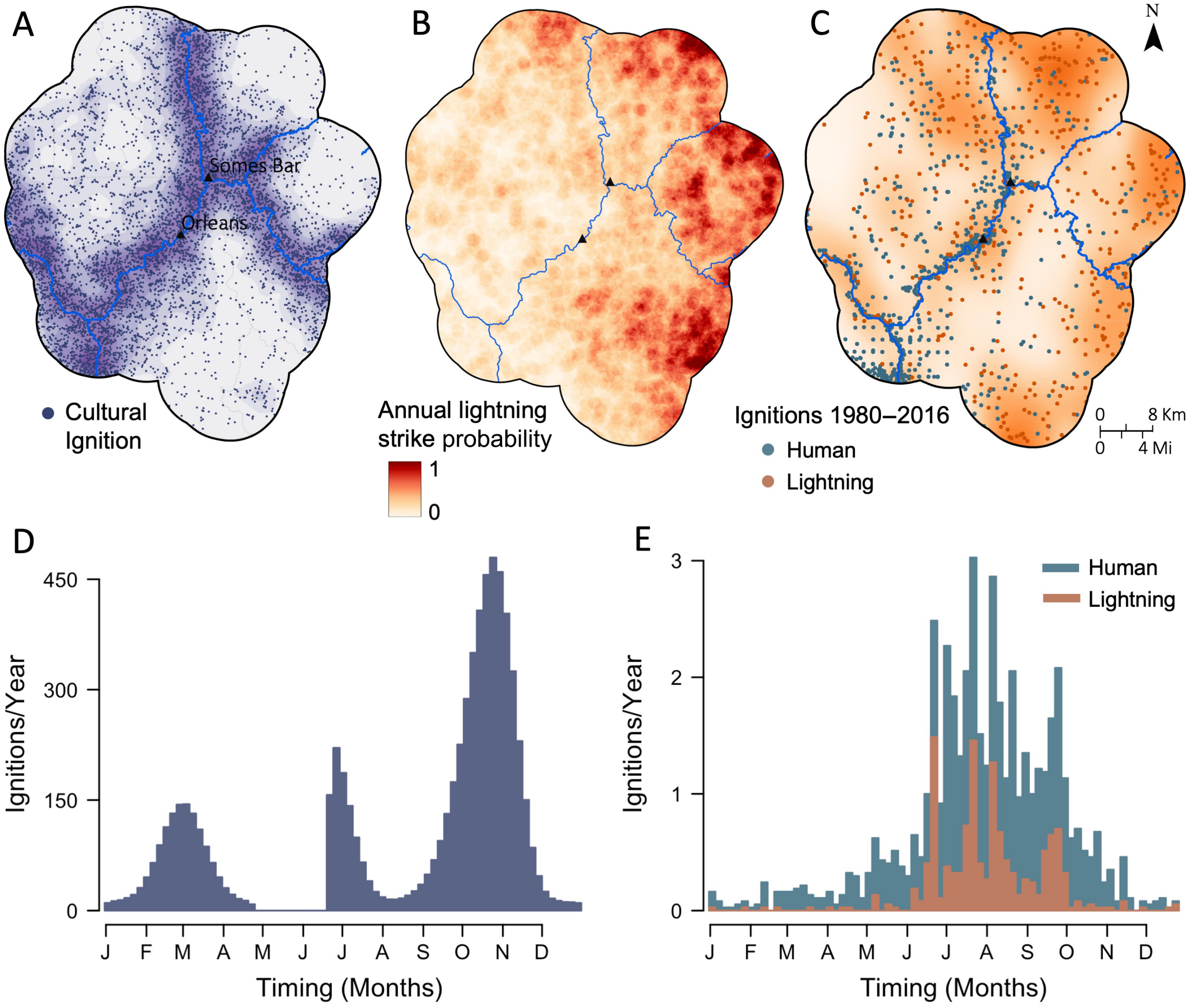

FIGURE 5 Spatial and temporal distribution of annual cultural ignitions on the Somes Bar landscape (A, D), contemporary lightning strike patterns (B), and contemporary ignition patterns (C, E). Maps depict cultural ignitions from one simulated year (A), annual lightning strike probability within a 2 km window (B), and human and lightning ignition locations and interpolated density recorded between 1980 and 2016 from Short (2017; C). Graphs display cultural ignition timing averaged more than 200 simulated years (D) and a stacked bar chart of ignition timings for all ignitions recorded on the Somes Bar landscape from 1980 to 2016 with lightning in orange and human ignitions in blue (E).

wildfires and climate change (Berkes & Turner, 2006; Fernández-llamazares et al., 2021; Prichard et al., 2021). In northern California, there is increasing support for adaptive co-management that incorporates Indigenous Knowledge, modern tools, and western science to collectively advance ecocultural revitalization, landscape restoration, and community wildfire risk reduction (Armatas et al., 2016; Diver, 2016; Eisenberg et al., 2019). This work, grounded in Indigenous Knowledge, voices, and practices, provides a spatially explicit baseline estimate of cultural burning to anchor future research and management that explicitly incorporates fire as an ecocultural process (Prichard et al., 2023).

Comparison to regional estimates and models

The quantitative estimates of cultural ignition location and frequency are closely aligned with descriptions of Indigenous burning from many tribes across the region, as well as global models of Indigenous fire stewardship (Appendix S1: Box S1). Substantial cultural burning and resource stewardship surrounding villages and the trail/traversable ridge networks that connected village sites to more distant gathering areas, sacred grounds, or seasonal villages-camps is well documented among tribes in the western United States (Anderson & Rosenthal, 2015;

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Dahl Aldern & Goode, 2014; Lake, 2013; Roos et al., 2021; Turner et al., 2011). In mountainous areas, trails were integral connections between diverse montane environments and permanent villages at lower elevations; often heavily traveled as part of seasonal gathering of resources that did not occur in high quantity or quality at lower elevations; and likely maintained as safe and open travel corridors through periodic cultural burning (Knight et al., 2022; Theoratus, 1980; Turner et al., 2011). Warburton and Endert (1966) describe the extensive use of and long distances traveled along trails in the Klamath Mountains noting: "It was common sight in the 1880s to see five or 10 Indian men and women heading for their homes with heavy burdens of food, over almost obscure trails…having come ten to fifteen miles in one day over steep trails."

Intentional and relatively intensive resource stewardship surrounding villages is well documented (Bird et al., 2020; Keeley, 2002; Long et al., 2021; Roos et al., 2021); however, the extent of this influence has been questioned and diminished in some publications (DellaSala et al., 2022; Vale, 2002). Sources within our knowledge review consistently described frequent burning within several miles of villages and for specific resources and purposes beyond this zone. Kathy McCovey (Karuk) describes this in detail saying, "From the village site, the women burned about a two-mile radius for fine-grain material. That's oak woodlands, grasslands for basketry material, medicinal plants… After that was another two-mile donut area and it was felt that the men burned those areas for the coarser grain mosaic, for the deer feed and stuff like that…Four miles further, you're probably getting a combination of men burning as they come in from the high-country hunting, and you're getting some lightning strikes. Probably about five or six miles out of town" (Karuk Tribe—UC Berkeley Collaborative, 2023). These estimates align with Ron Goode's descriptions of burning in the Central Sierras by the North Fork Mono (Dahl Aldern & Goode, 2014); Kat Anderson's estimate of 5–10 km^2 (1.3–1.8-km radius) per village site in the Anderson (1999); and the 85 km^2 (5.2 km radius) zone of influence suggested for the Luiseño in southern California by White (1963).

These cultural burn frequency and timing estimates are also very similar to those described by other tribes in the region and proposed by western scientists and ethnographers. Pullen (1996), and Anderson and Rosenthal (2015) catalog dozens of references to cultural burning frequency and timing in southern Oregon and northern California, the majority of which are described as annual or occurring every 2–3 years. Anderson and Rosenthal (2015) further describe Indigenous uses for 16 California chaparral plants that were only abundant in their culturally useful form for one to several years (average = 2.3) after fire.

Fire frequency and timing

The fire return intervals and timings estimated within this study are consistent with dendrochronological fire history reconstructions within the region that report fire frequencies varying by aspect, elevation, annual precipitation, and observed lightning patterns. Within our study area, a recent dendrochronological fire history reconstruction reported median fire return intervals of 3–6 years between 1700 and 1900 when all fire scars were included (Knight et al., 2022). A similar study ~60 km north of the modeled landscape, but >8 km from the nearest river village corridor, reported a 14.6-year median fire return interval prior to colonization with shorter fire return intervals on higher insolation south and west facing slopes (Taylor & Skinner, 1998). A review of 10 cross-dated fire history studies from northern California and southern Oregon reported an 8-year average median fire return interval for dry mixed-conifer, yellow pine, and mixed-evergreen forest sites and a 13–14-year average in moister sites (Metlen et al., 2018). Individual sites with fire return intervals of 1–2 years were reported for all vegetation groups in this review, except in higher elevation red fir. Notably, reviews by Metlen et al. (2018) and Taylor and Skinner (1998) omitted fires that only scarred one tree from their analysis, which is known to bias results against documenting small-scale Indigenous patch burning (Roos et al., 2019). Omitting fires that scarred only one tree increased estimated median fire return interval estimates from 4–10 to 13–40 years in a montane landscape near our study area (Skinner, 2003)

Lightning strikes are relatively common in the Klamath Mountain ecoregion, and historical fire regimes and landscape vegetation patterns were most likely a result of interacting lightning and cultural ignitions (Figure 5). There are roughly 12 lightning strikes/year/100 km^2 in the Klamath ecoregion, which is higher than the California coast and Central Valley regions that average four strikes/year/100 km^2 but substantially lower than the Cascade and Sierra Nevada Mountains that average around 20 strikes/year/100 km^2 (Skinner et al., 2006; van Wagtendonk & Cayan, 2008). The majority of strikes (95%) occur at elevations above 600 m, and approximately 70% occur in June, July, and August (Figure 5B,E; van Wagtendonk & Cayan, 2008). Many of these lightning strikes do not cause ignitions, and years with greater number of lightning strikes often have lower total area

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burned because in these years lightning often derives from wet storms rather than dry convective storms (Miller et al., 2012; Rorig & Ferguson, 1999). Furthermore, lightning strikes that ignite fires are often spatially and temporally clustered, impacting specific areas and cultural resource availability unpredictably (Anderson, 1999; Anderson & Rosenthal, 2015; Keeley, 2002; Miller et al., 2012).

Fire scars from dendrochronological records also offer a coarse-grain estimate of seasonality based on the scar position within the annual tree growth ring. Fire scars in the region occur most often in the late-wood (midsummer to late summer) and dormant season (late summer or fall), with only about 20% of ignitions occurring in early-wood (late spring and early summer; Knight et al., 2022; Metlen et al., 2018). High-elevation red fir forests, which burn most frequently in the late summer or fall dormant season, are a notable exception (Metlen et al., 2018). These timing distributions are generally congruent with the modeled cultural ignition timings combined with lightning ignitions that primarily occur in the summer months but would be very unlikely from lightning alone (Figure 5E).

Between 1980 and 2016 few lightning ignitions were recorded in the spring or later fall, suggesting that many, or most, of the spring and fall fires recorded in dendrochronological studies were Indigenous in origin (Figure 5D,E). Contemporary human ignitions temporally overlap with estimated cultural burn timing to some degree. However, they are over an order of magnitude less frequent and also occur during a spring period when reproducing animals are most vulnerable and cultural burning is very rare (Figure 5D; Collins et al., 2019).

Landscape-scale influence

The extensive cultural ignition density modeled in this study would promote vegetation patterns that differ dramatically from contemporary landscapes but are consistent with historical reconstructions in the region and descriptions of landscape conditions from Indigenous Knowledge holders. Fire return intervals less than 10 years in lower elevation forests would promote substantially lower tree density and fuels and dominance of fire-tolerant/shade-intolerant hardwoods and pines over less fire-tolerant Douglas-fir (Barbour et al., 2007; Merschel et al., 2021). Knight et al. (2020) estimate contemporary forest basal area and density of Klamath mixed-conifer forests are 7.4 and 4.0 times higher, respectively, than colonization era estimates from the 1880s, and the relative basal area of oak has dropped from 15.3% to 0.1%. Karuk elder Mavis McCovey vividly describes this densification and compositional change, saying; "(my father) talked about how…they burned so frequently and so often that all these fir trees grew up around here after he was a boy. He said there was a whole bunch of little Christmas trees coming up… He was born in [18]68 so in the 1870s… the fir trees were just starting to grow around here because the Indians kept the villages and the sides of the hills so well burned. They were mostly just oak trees" (Lake, 2007:540; Figure 3).

Historically, cultural burning combined with lightning ignitions maintained mosaics of open meadows and prairies across the landscape that have since been steadily invaded by trees and shrubs following fire exclusion (Figure 3). Between 1944 and 1985, the area occupied by grassland openings in the Klamath region decreased from an estimated 25.8% to 15.6% (Skinner, 1995). If a constant rate of infilling is assumed, the openings may have occupied 44% of forest area in 1850 and would occupy only 4% in 2022. Analysis of historical images and tree establishment dates from a serpentine grassland just south of our study area found a 50-fold increase in small tree density from 1890 to 2000 and a decrease in grass area from ~52% to 9% between 1942 and 2009 (Sahara et al., 2015).

Interactions between the cultural fire regimes mapped in this study, lighting ignitions, and underlying topoedaphic gradients would result in coarse- and fine-grain resource and fire behavior mosaics that currently do not exist on the landscape (Figure 3; Anderson, 2005; Anderson & Rosenthal, 2015; Karuk Tribe, 2019; Prichard et al., 2021, 2023; Stewart, 2002). In low-elevation areas along the river corridor, frequent fire would promote diverse vegetation assemblages with spatial distributions tightly coupled to underlying topoedaphic conditions and decoupled from the homogenizing effects of succession and climate (Dunn, 2018; Johnston et al., 2016; Mucioki et al., 2021; Taylor et al., 2016). In higher elevation areas interactions between ecocultural fire processes and lightning ignitions likely promoted a highly heterogeneous vegetation mosaic (Anderson & Moratto, 1996; Bliege Bird et al., 2008; Hessburg et al., 2019). These mosaics emerge from fires interacting with past fire footprints and functioning as ongoing ecocultural processes rather than the series of discrete disturbance and recovery events characteristic of many contemporary landscapes (Anderson & Barbour, 2003; Eisenberg et al., 2019; Perry et al., 2011; Trauernicht et al., 2015).

The abundant edges and ecotonal gradients created and maintained by an active ecocultural fire regime are characteristic of ecologically and socially resilient

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landscapes that provide highly valued resources to both humans and wildlife (Anderson & Rosenthal, 2015; Laris, 2002; Mistry et al., 2016; Turner et al., 2003). The spatiotemporal dynamics of these edges and gradients would vary across the landscape with shifts in cultural fire regimes and biophysical characteristics. For instance, edges influenced by soil or hydraulic convergence zones with high-resource diversity may be carefully maintained through fire stewardship (Ring, 2011; Turner et al., 2003). For the last 150 years of fire exclusion, these ecoculturally maintained edges and mosaics have been homogenized across the landscape with significant consequences for cultural resource abundance, wildlife habitat, and the potential contagious spread of large and severe fires across the landscape (Greenwood et al., 2022; Hessburg et al., 2019; Karuk Tribe, 2019; Moritz et al., 2011; Mucioki et al., 2021; Prichard et al., 2023; Skinner, 1995).

Relations to precolonization populations

Precolonization population and village estimates for Indigenous people in California vary substantially with methodology and assumptions. Population estimates for the Karuk Tribe range from 1500 to 2700, and calculated population density estimates range from 0.47 to 0.94 people per km^2 (Binford, 2001; Cook, 1956, 1976; Kroeber, 1925, 1936). Generally, estimates developed during the mid to late 1900s incorporated more sources of evidence, produced higher estimates, and are considered more accurate, however many of these estimates still target the 1800–1850 period in which Euro-American diseases likely had already caused substantial depopulation (Baumhoff, 1963; Boyd, 2021; Bright, 1978; Chartkoff & Chartkoff, 1975; Pullen, 1996). Archeological evidence also suggests that 75% of Karuk village sites were south of Ukanom Creek, which is the northernmost extent of the study area (Bright, 1978; Chartkoff & Chartkoff, 1975).

Based off these estimates, we approximated there were 2000 people residing within and stewarding the study landscape. We approximated roughly 50% of the population was actively engaged in low-elevation cultural burning and 25% of the population burned in the high-country. Given these estimates, the modeled average of 6972 annual cultural ignitions represents 6.5 ignitions/person/year in the low country and 1.0 ignition/person/year in the high country. Estimates using more conservative population estimates (1900 total people evenly distributed across the ancestral territory) result in 11.6 and 1.7 ignitions/person/year in the low country and high country, respectively.

Karuk and Yurok village maps published in the early 1900s document 92 villages within the study area (Bright, 1978; Kroeber, 1925; Pearsall, 1928), however Konomihu villages are not included in this count and authors and project collaborators have direct knowledge of additional, unmapped villages. Thus, we believe it is reasonable to increase the count by at least 15% for a minimum of 106 villages (Kroeber, 1925). Within a village, groups of women and men often had different fire stewardship responsibilities and would burn and steward different resources (Karuk Tribe, 2019; Norgaard, 2019). The estimate of 106 villages would equate to 11 ignitions per village per season (early spring, early summer, fall) per group (females or males). These population and village estimates are rough approximations and likely conservative due to the extensive impacts of settler colonialism and incomplete anthropological records. They also do not represent official estimates from the Karuk Tribe.

Limitations, omissions, and broader applicability

As with all large-scale investigations, we strove to explain broad patterns at the expense of local specificity. While there are many benefits to this approach (e.g., alignment with increasing consideration of landscape-scale processes in contemporary management), the omission of site-level specificity has consequences when considering cultural burning. As a highly nuanced and placed-based ecocultural process, the characteristics of cultural burning are far more diverse than the small subset incorporated into this modeling process (Huffman, 2013; Lake & Christianson, 2020; Long et al., 2021). Our use of Monte Carlo simulation procedures helps to address this issue, but still does not capture all complexities, especially for linked processes. We did not intend for this modeling exercise to perfectly represent reality but rather to examine the broad patterns and processes associated with an active ecocultural fire regime on the study landscape. In defining the spatial distribution of cultural fire regime groups, we relied on linkages between descriptions of cultural burning practices, vegetation assemblages, and biophysical characteristics to map groups across the landscape. These boundaries are meant as a faithful abstraction of reality that allow protection of site-specific information and extrapolation to areas where less knowledge exists but should not be considered a substitute for respectful, reciprocal, and relational collaboration with Tribes (Dickson-Hoyle et al., 2021).

In this work we have focused primarily on a maintenance-level fire regime that would perpetuate

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stable or semistable landscapes that have been actively stewarded by Indigenous people for millennia and across generations. Most contemporary Klamath landscapes are not in this condition at present (Hagmann et al., 2021; Karuk Tribe, 2019), and cultural burning does not always seek to maintain landscape conditions. Corrective burning at higher intensities is sometimes applied to aid in establishment or maintenance of desired vegetation conditions and fire regimes (Lewis, 1994). Many contemporary landscapes are dramatically departed from historical ecocultural conditions and require additional restoration investments, Tribal stewardship, and time for resource regrowth before they can be returned to maintenance burning cycles (Hagmann et al., 2021, 2022; Long et al., 2021; Prichard et al., 2021).

Indigenous fire stewards may also adjust practices as climate change shifts phenological indicators, fuel moistures, or desired landscape conditions as they have done for millennia (Berkes & Turner, 2006; Mucioki et al., 2021; Turner & Spalding, 2013). The historical documents, data, and interviews we used primarily represent knowledge and practices from a cooler and moister period that occurred between ~600 and 100 cal. year. BP (Crawford et al., 2015). While we integrate this information with contemporary knowledge and practices, present day cultural burning may differ.

Given the place-based nature of Indigenous fire stewardship, the results we present are not directly transferable to other landscapes. However, the general modeling process could serve as a template to explore similar questions in other landscapes when developed collaboratively with local Indigenous fire stewards. In this initial work, we parameterized estimates using a blend of historical and contemporary information, but future work could more explicitly consider differences between historical and contemporary cultural fire regimes.

CONCLUSIONS

Cultural burning exerted extensive influence on northern California fire regimes at the landscape-scale, which we have quantitatively estimated using a spatially explicit modeling framework that blends Indigenous Knowledge and western science (Figure 2 and 5). When combined with lightning ignitions, the simulated cultural ignitions closely align with reconstructions of historical fire frequency, burn seasonality, and vegetation characteristics across the study landscape (Figure 5; Knight et al., 2020; Skinner, 1995; Taylor & Skinner, 1998). In our simulations, the density of annual of cultural ignitions varied spatially, but cultural burning clearly had a pronounced impact on vegetation, resources, and other fire dependent processes across the landscape based on the large area of fire stewardship surrounding villages and extensive trail network (Anderson & Rosenthal, 2015; Keeley, 2002).

Frequent burning undoubtedly shifted vegetation composition, structure, and spatial patterning across the landscape and strengthened the linkage between vegetation communities and underlying topoedaphic gradients (Figures 1B and 3). The resulting mosaic of vegetation and ecological edges support diverse resources for both humans and wildlife (Long et al., 2021). Although the total number of simulated ignitions on this landscape is large, ~7000, it corresponds to roughly 6.5 ignitions per Indigenous fire steward in the precolonization era, which would support the abundance, consistency, and quality of food, material, and medicinal resources required for communities to live and thrive on the landscape (Anderson & Moratto, 1996). This study demonstrates the need to critically consider the influence of Indigenous fire stewardship as a key component in shaping historical landscapes, promoting valued resources and landscape conditions, and restoring resilient ecocultural landscapes. This work additionally substantiates the importance of working with Indigenous communities in fire-prone ecosystems in alignment with their culturally based climate adaptation and wildland fire management strategies.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

A subset of the data used for this manuscript is culturally sensitive and cannot be shared publicly to protect location information and knowledge sovereignty. The R Code

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(Greenler, 2024a) developed for our analyses is available on Figshare at https://doi.org/10.6084/m9.figshare.21401952.v1; some dates used in this R code have been jittered to protect cultural knowledge. The data (Greenler, 2024b) required to run the analyses are available on Figshare at https://doi.org/10.6084/m9.figshare.21401964.v1; plot IDs in this dataset have been randomized to protect culturally sensitive location information, allowing users to run the analyses but preventing the results from being viewed spatially. Spatial files of the study domain and broad-scale landscape delineations (Greenler, 2024c) are available on Figshare at https://doi.org/10.6084/m9.figshare.22129481.v1; finer scale spatial data are not accessible to the public. Access to restricted data (specific ignition timing date ranges and fine-scale cultural fire regime map) may be available through the Karuk Department of Natural Resources (PO Box 282, Orleans, CA 95556; Phone: 530-627-3446) under a Practicing Pikyav Research agreement or non-disclosure agreement.

ORCID

Skye M. Greenler https://orcid.org/0000-0002-4454-8970
Susan J. Prichard https://orcid.org/0000-0002-6001-1487
Paul F. Hessburg https://orcid.org/0000-0002-0330-7230

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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