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RESEARCH ARTICLE

Paleoecological and paleolandscape modeling support for pre-Columbian burning by Native Americans in the Golden Trout Wilderness Area, California, USA

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Abstract
Context Though people have used fire to alter landscapes across North America for millennia, there remains a debate whether Native Americans altered California's mountainous forests to create an anthropogenic landscape.
Objective We use paleoecological reconstructions and paleolandscape modeling to test whether climate or Native Americans were the driving force of pre-historic forest composition change. Understanding pre-historic forests and land-use legacies becomes more critical in a warming climate as wildfires become deadlier and more extensive.
Methods We performed a sub-centennial pollen and charcoal reconstruction for the last 1200 years using standard techniques. We then used a forest succession model to quantitatively test drivers of change: climatic fires only, or the addition of Native American-set surface fires. Hypothesized periods of anthropogenic burning were inferred from the pollen record (more open canopy taxa than climatically expected). Modeled outputs were compared against the paleorecord to determine which drivers best explained changes in the empirical record. Periods of occupation from the archaeological record were compared to hypothesized periods of burning.
Results Pollen and charcoal reconstructions showed intermittent periods inconsistent with climatic expectations. Modeled scenarios including surface fires set by Native Californians during these periods had the greatest correlation with the observed paleoecological record. Inferred periods of burning corresponded temporally with site used based on the archaeological record.
Conclusions California's pre-historic forests were altered by the traditional use of fire as a tool by Native Americans. Modeled outputs hint that incorporating indigenous resources management practices could improve forest health and decrease the likelihood of catastrophic wildfires.

Keywords Paleoecology · Landscape modeling · California · Sierra Nevada · Cultural burning · Native Americans

Session: Land-use legacies and forest change: understanding the past to forecast the future.

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Introduction

The forests of California's Sierra Nevada range look very different today than they did only 150 years ago when European explorers first ventured into the area. Modern fire regimes based on recorded observations are inconsistent with pre-historic reconstructions primarily inferred from tree ring-based fire-scar studies. In the last 5 years, California Department of Forestry and Fire Protection (CALFIRE) Redbooks document that between 2014 and 2018 (CALFIRE 2019a) total area of land burned ranged between 2550 km^2 (2014) and 6800 km^2 (2018), including some of the largest recorded wildfires in California history (CALFIRE 2019b). Pre-Columbian fires in California are estimated to have burned between 23,000 km^2 and 53,500 km^2 annually (Martin and Sapsis 1992), a far greater area than even the recent upsurge. Where vast portions of Sierran forests have not experienced any fire in the last 100+ years, regional fire-scar studies demonstrate mean fire return intervals (time between fire events) between 5.3 and 13.5 years (Swetnam et al. 2009; Taylor et al. 2016) within the last 300–400 years. The land management policies that caused historical changes to forests of the Sierra Nevada of California are clear (Vankat and Major 1978; Roy and Vankat 1999), but the agents of change that shaped these forests prior to the historic period are much more uncertain. A possible agent in shaping these pre-Columbian forests is the practice of traditional resource management by Native Americans, especially through their use of fire as a tool.

Understanding California's pre-historic forests and land-use legacies is becoming more critical (Taylor et al. 2016) as modern forest fire severity increases (Miller et al. 2009) and costly, deadly, and extensive wildfires become more prevalent throughout the state (CALFIRE 2019b). Photographs and historic accounts portray the Sierra Nevada as being a "park-like setting", with grasses and a thin understory, patchy cohorts of mixed-age trees, and occasional stands of brush (Muir 1894; Lewis 1973; Stephenson et al. 1991; Parker 2002). A setting most likely the result of frequent low-intensity fires (Keeley and Stephenson 2000; Bliege Bird et al. 2012), many likely set by Native Americans as per historic accounts (Clar 1959; Bolton 1967; Lewis 1973). This image is in stark contrast to the thick understory present today, which has established since the AD 1850s due to fire exclusion, fire suppression, selective logging, and grazing (Silcox 1910; Martin and Sapsis 1992; Bowman et al. 2011). The recent increase in modern fires is likely due to both natural (drought) and anthropogenic causes (human ignition sources, urban encroachment into fire-prone areas, and build-up of underbrush fuels due to 100+ years of fire-suppression policies) (Taylor et al. 2016).

Fire is a prevalent, natural, and critical disturbance agent in California's Mediterranean climate of dry summers and wet winters. Lightning strikes are most common in summer months from June to September, peaking in August (Millar 1996; van Wagtendonk and Cayan 2008).Vegetation in chaparral, oak, and mixed-conifer forests are fire-adapted, evolving strategies such as obligate resprouting, facultative seeding, and serotinous cones (Keeley et al. 2012; Rundel et al. 2018). The frequency of fires changes with climate (Swetnam 1993; Dale et al. 2000, 2001; Flannigan et al. 2000; Swetnam et al. 2009; Keeley et al. 2011). Wetter and/or cooler climate conditions typically equate to less frequent fire disturbance, though large, high severity fires can occur in dry years.

Succession of fire-sensitive/shade-tolerant taxa such as fir (*Abies*) and incense-cedar (*Calocedrus decurrens*) occurs under conditions of more available soil moisture and less disturbance (Dale et al. 2001; Lenihan et al. 2003). Drier and/or warmer conditions typically equate to more frequent fire disturbance and a relative increase in fire-tolerant/shade-intolerant taxa such as oaks (*Quercus*) and grasses (Poaceae) (Peterson and Hammer 2001; Innes et al. 2006; Fites-Kaufman et al. 2007; Engber et al. 2011; Henne et al. 2012). Fire is commonly documented as having a critical role in maintaining oak woodlands (Higgins et al. 2000; Peterson and Hammer 2001; Peterson and Reich 2001; Bond and Keeley 2005; Engber et al. 2011; Crawford et al. 2015), and prescribed fires have shown the potential to decrease tree mortality during periods of drought (Van Mantgem et al. 2016).

Fire is also a tool used by hunter-gatherer societies throughout the world (Coughlan et al. 2018) to shape ecosystems and manage natural resources, including foodstuffs such as oak acorns (Anderson 1999; Bliege Bird et al. 2008, 2012). Ethnographic accounts (Voegelin 1938; Lewis 1973; Anderson and Moratto 1996) depict pre-Columbian Native Americans in California as proto-agricultural hunter-gatherers who regularly used fire as a traditional resource and environmental management (TREM) practice to improve productivity, increase natural yields, facilitate hunting, and clear travel corridors (Anderson and Moratto 1996; Dincauze 2000; Jordan 2003; Anderson 2005; Fowler 2008; Codding and Bird 2013; Lightfoot et al. 2013) in support of large pre-Columbian populations (Kroeber 1925; Baumhoff 1963).

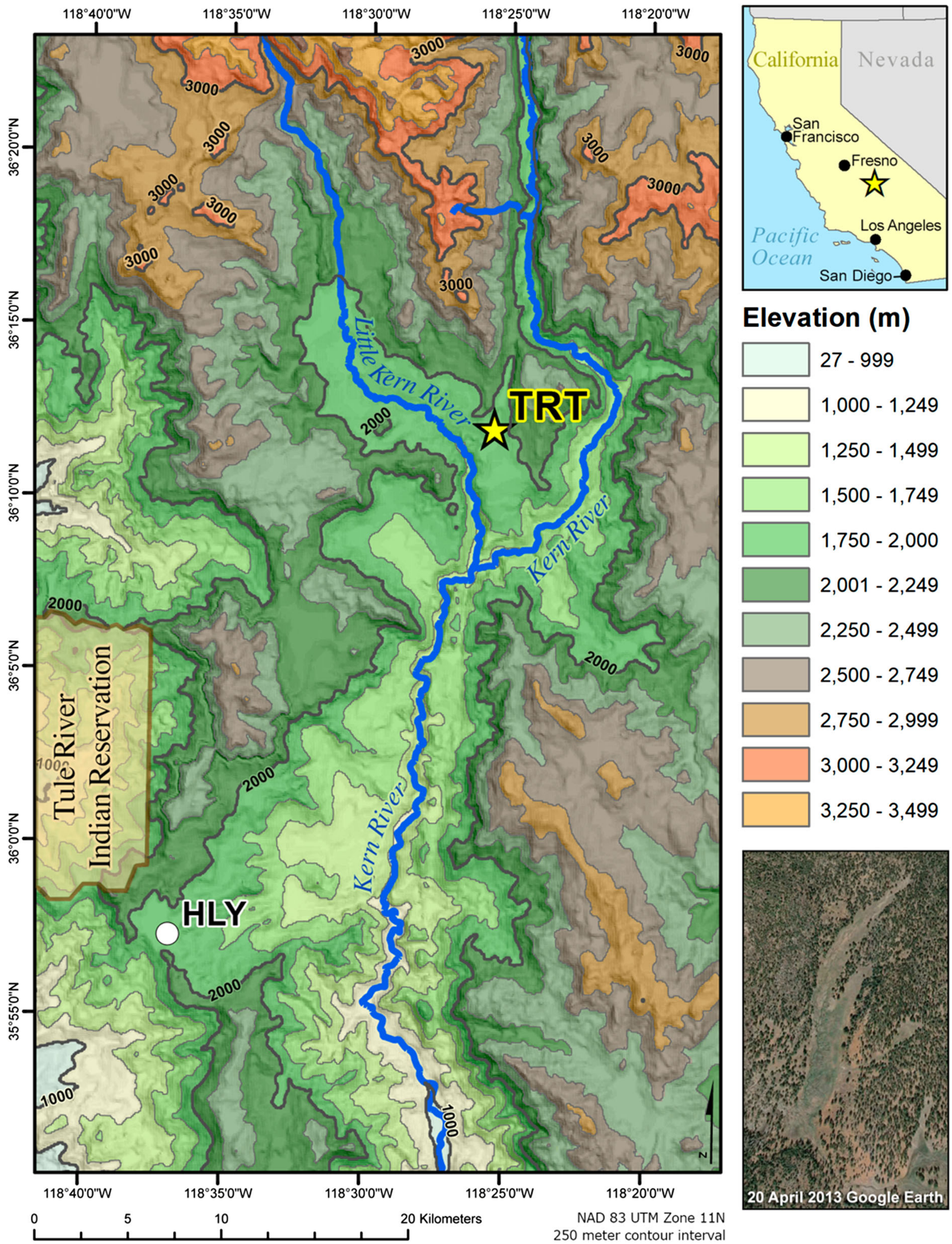
Because fires start from both climatic causes, such as lightning, and through human activity, as a tool, debate continues whether climate alone or the impact of human agency shaped the pre-Columbian forests of California's Sierra Nevada range (Parker 2002). Researchers in predominantly physical and atmospheric sciences claim that climate sufficiently explains fire history and forest composition. They argue that while people may have used fire as a tool their impact was negligible at the landscape scale (Minnich 1988; Griffin 2002; Vale 2002; Power et al. 2018; Vachula et al. 2019) because ecological adaptations in wildfire-prone areas evolved long before the introduction of humans. Researchers in predominantly social sciences argue that people employed fire as a resource management tool (Anderson and Carpenter 1991; Anderson and Moratto 1996; Anderson et al. 1997; Gassaway 2009; Cowart and Byrne 2013; Crawford et al. 2015; Taylor et al. 2016) specifically because local vegetation was fire-adapted (Coughlan et al. 2018). They claim that human activity, even in pre-historic hunter-gatherer societies, helped shape environmental legacies and should not be discounted. While Native American fire-use is well documented in ethnographies and stories (Powers 1877; Voegelin 1938; Lewis 1973; Parker 2002), physical evidence in the geologic record as to impact and extent is contentious and rare.

Previous work at Holey Meadow in Sequoia National Forest, California showed potential to identify pre-Columbian anthropogenic impacts on Sierran forests using a combination of paleoecologic (Klimaszewski-Patterson and Mensing 2016) and paleolandscape modeling (Klimaszewski-Patterson et al. 2018). The paleoecologial study qualitatively inferred prehistoric burning by Native Americans during cooler, wetter periods such as the pre-Medieval Climate Anomaly (pre-MCA; 1550–1050 cal BP) and Little Ice Age (LIA; 750–100 cal BP) by comparing empirical pollen-derived vegetation composition against annually-derived climatic expectations. A novel approach of paleolandscape modeling was added to the qualitative pollen inferences to quantitatively test the hypotheses of climate vs human-influenced fire regimes. The authors found initial modeling support that burning, of the kind indicated in ethnographic records, the pre-MCA and LIA best approximated the pollen record, and that climate-alone could not reproduce the observed record. Those results have not been tested at other sites to explore whether these impacts were local or regional in extent.

In this paper we test the extent to which climate or human agency shaped the pre-Columbian forest surrounding Trout Meadow, a wet meadow in Sequoia National Forest with extensive archaeological activity, 33 km to the northeast of Holey Meadow. We use a combination of reconstructed climate, empirical pollen-derived vegetation history, paleolandscape modeling, and local archaeological datasets to investigate evidence for TREM burning. We hypothesize (1) that evidence for TREM burning at Trout Meadow can be identified during climatically cooler, wetter periods using paleoecological proxies, (2) that models based on burning during periods of anomalous forest patterns identified in the paleorecord better approximate vegetation history than climate alone, and (3) that these periods of modeled burning reasonably correspond to periods of occupation post-priori identified in the spatially-adjacent archaeological record.

Study area

Trout Meadow (TRT; 36.2° N, 118.4° W; elev. 1890 m) is a spring-fed sedge meadow in the Golden Trout Wilderness Area, Sequoia National Forest, California near the southern tip of the Sierra Nevada (Fig. 1). The Sierra Nevada range is a granitic batholith up to 4400 m in elevation, trending north to south and separating the fertile Central Valley to the west from the dry Great Basin province to the east. Most precipitation occurs in winter months from Pacific frontal storms. Climate on the western slope is classified as primarily warm-summer/cool-winter Mediterranean at low/mid elevations, transitioning to Boreal at the highest elevations. On western slopes, chaparral and oak woodlands occur up to 1300 m elevation, mixed conifer and montane forests from 1300 to 2200 m elevation, followed by upper montane forests above (Anderson and Davis 1988). The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3000
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Little Kern River
Kern River
TRT
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Tule River Indian Reservation
0
5
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NAD 83 UTM Zone 11N
250 meter contour interval
California
Nevada
San Francisco
Fresno
Los Angeles
San Diego
Pacific Ocean
Elevation (m)
27 - 999
1,000 - 1,249
1,250 - 1,499
1,500 - 1,749
1,750 - 2,000
2,001 - 2,249
2,250 - 2,499
2,500 - 2,749
2,750 - 2,999
3,000 - 3,249
3,250 - 3,499
20 April 2013 Google Earth

◀**Fig. 1** Trout Meadow (TRT) study area indicated by star. Paleoecologic site Holey Meadow (HLY; Klimaszewski-Patterson and Mensing 2016) represented by white dot. Inset bottom right shows areal image of TRT

southern portion of the range splits into a double crest, bifurcated by the Kern River. TRT is located within the Kern River Basin on a western slope, oriented primarily north to south, and approximately 1250 m long and 155 m across at its widest point. The meadow is situated in a cold-air drainage within the mixed-conifer/montane zone.

Local tree species include *Abies concolor* (white fir), *Calocedrus decurrens* (California incense-cedar), *Pinus jeffreyi* (Jeffrey pine), *P. ponderosa* (ponderosa pine), *Quercus kelloggii* (California black oak), *Q. wislizeni* (interior live oak), and *Q. chrysolepis* (canyon live oak). *Sequoiadendron giganteum* (giant sequoia) and *Abies magnifica* (red fir) occur nearby, but are not local to the site. *P. monophylla* (single-leaf piñon pine) can be found within 3 km. Common shrubs occurring in the pollen record include: *Ceanothus* spp. (California lilac), *Chenopodium fremontii* (Fremont's goosefoot), *Chrysolepis sempervirens* (bush chinquapin), *Prunus virginiana* (chokecherry), *Rosa woodsii* (Wood's rose), and various Rosaceae spp. (rose family, including *Holodiscus discolor* (oceanspray), Nearby edible plants include: *C. fremontii*, *C. sempervirens*, *P. virginiana*, *Pinus* spp. (seeds), and *Quercus* spp. (acorns). Immediately surrounding the meadow, *A. concolor* occur primarily on north and east facing slopes, with *P. jeffreyi*, *P. ponderosa*, and *Q. kelloggii* occur on south and west facing slopes. An easily walked drainage leads to the Little Kern River, providing quick access to river resources including the endemic Little Kern golden trout (*Oncorhynchus mykiss whitei*).

Surrounding TRT is a spatially-extensive archaeological site identifiable by surface artifacts and numerous bedrock milling features, providing the opportunity for a paired paleoecological-archaeological investigation. Archaeological excavations (CA-TUL-2027/2077) were conducted adjacent to TRT in 2012 and 2013 through the United States Forest Service's Passport in Time outreach program. Reported analysis showed the meadow was used by Native Americans, at least sporadically, from 6000 cal BP until the 1800s (Kraus 2016).

Paleoecological reconstruction

Methods

We recovered duplicate sediment cores (349 and 323 cm in length) from TRT in July 2013 using a 5-cm diameter modified Livingstone square rod piston corer. Sediment was extruded into pre-split ABS plastic tubes in the field and wrapped in plastic wrap before transport back to the University of Nevada Reno Paleoecology lab. Cores were described, photographed, and placed in 4 °C cold storage. Sediment was qualitatively described by feel (sand, silt, clay). Continuous 1-cm samples were processed for total organic matter (%TOM) and total inorganic matter (%TIC) using the loss-on-ignition method at 550 °C and 950 °C (Dean 1974), and percent charcoal (%CHAR) was calculated on separate samples using the chemical assay method (Winkler 1985).

Sixteen wood and charcoal samples throughout the core were selected for AMS radiocarbon dating. We used IntCal13 (Reimer et al. 2013) and Bacon v2.2, a Bayesian age-model program (Blaauw and Christen 2011) to create our age model. Bacon uses Markov Chain Monte Carlo (MCMC) iterations to produce estimates of accumulation histories. Dates are modeled using a students-t distribution, making the age-depth model more robust against outlying dates.

Twenty-nine (29) 1-cm thick samples (0.625 cm^3) at a 47-year average interval were processed for pollen analysis using standard chemical digestion (Faegri and Iverson 1964), with the addition of exotic *Lycopodium* tracer spores to calculate absolute pollen concentration (Stockmarr 1971). An average of 360 terrestrial pollen grains per sample were counted at 400 × magnification and identified to the lowest taxonomic level using laboratory reference collections and guides (Kapp 1969). Pollen percentages were calculated based on the sum of terrestrial pollen, excluding Cyperaceae. Pollen accumulation rate was calculated by dividing pollen concentration by the number of years in the sample. Pollen zones were identified using CONISS (a stratigraphically-constrained incremental sum of squares cluster analysis) via the 'rioja' package in R (Grimm 1987; Juggins 2015).

We calculated a vegetation response index (VRI: *Abies* − *Quercus*/*Abies* + *Quercus*) to identify shifts between shade-tolerant/fire-sensitive *Abies* and shade-intolerant/fire-adapted *Quercus* following methods established by Klimaszewski-Patterson and Mensing (2016) at Holey Meadow (HLY), ~ 33 km (20 miles) to the southwest. Positive VRI indicates a greater proportion of *Abies* to *Quercus* and a more closed canopy, which is climatically expected during the LIA. Negative VRI indicates a greater proportion of *Quercus* to *Abies* and a more open canopy, conditions climatically expected during the MCA (Fig. 2). We expect that during periods of cool and wet climate, a human-influenced system would have a VRI that reflected an open forest, more similar to the expected response during a warm and dry climate period.

Tree ring-based studies supply the only available independent, annually-resolved climate records in the Sierra Nevada spanning the last 2000 years. We reconstructed climate at TRT using Palmer Drought Severity Index (PDSI) values, a climatic index of relative dryness, from the North American Drought Atlas (NADA; Cook et al. 2004, 2008, 2009) grid cell 047. NADA is a gridded network (2.5° cells) of compiled tree-ring reconstructions used to calculate PDSI, which reasonably captures the potential magnitude and effect of drought (NCAR 2013).

Results

The sediment core from TRT spans the full Holocene epoch (10,900 cal BP). Nine ^{14}C dates from the top 115 cm were used to generate the Bacon age model (Table 1 and Fig. 3). The top 90 cm used in this study span the last 1300 years and include the Modern period (AD 1850-2013), the cool and wet Little Ice Age (LIA; 750–100 cal BP), the warm and dry Medieval Climate Anomaly (MCA; 1050–750 cal BP), and relatively cooler, wetter conditions preceding the MCA (pre-MCA; 1550–1050 cal BP).

Sediment was predominantly humified peat, with the top 25 cm containing a thick mass of nearly impenetrable roots. Fine to coarse sand co-occurs within the peat from 55 to 68 cm depth. %TOM remained between 40 and 60% throughout the core except for two intervals with low values (< 25%) from 505 to 68 cm (875 to 730 cal BP) and 37–17 cm (560–200 cal BP) (Fig. 4). %TIC was consistently less than 4%.

Twenty-eight terrestrial pollen taxa, indeterminate, and unknown grains, were identified. Taxa with at least 2% maxima are presented in Fig. 4. CONISS was calculated using taxa with at least 1% maxima and indicated three main and two minor zones of change. Pollen zones closely conformed to known climatic periods of the MCA and LIA.

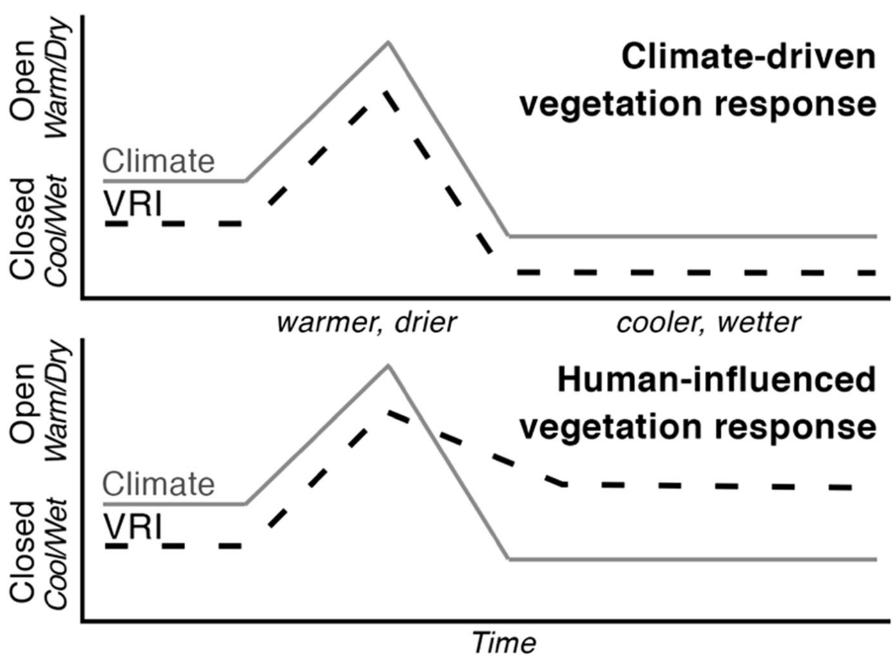

Fig. 2 (Left) Conceptual model of the vegetation response index (VRI; dashed line) under both a climate-driven system (changes in VRI corresponds with climate (solid line)) and a human-influenced system (changes in VRI do not necessarily correspond only with climate)

Table 1 Trout Meadow (TRT) radiocarbon dates. Weighted mean (wmean) and 2 range calculated by Bacon (Blaauw and Christen 2011)

Core	Depth (cm)	CAMS Lab#	^{14}C Age	cal BP 2Σ min	cal BP wmean	cal BP 2Σ max	Material
TRT-13-2	12	168,592	185 ± 30	20	150	230	Charcoal
TRT-13-2	17	168,593	195 ± 30	150	210	290	Charred wood
TRT-13-2	17 (rep)	168,601	190 ± 30	150	210	290	Charred wood
TRT-13-2	17 (rep)	168,602	205 ± 30	150	210	290	Charred wood
TRT-13-2	30	164,057	375 ± 30	320	400	500	Charcoal
TRT-13-2	54	168,594	680 ± 110	530	660	820	Charcoal
TRT-13-2	72^{+}	168,595^{+}	380 ± 90	660*	890*	1120*	Charcoal
TRT-13-2	97	168,596	1520 ± 90	1190	1360	1510	Charcoal
TRT-13-2	115	168,596	1685 ± 35	1520	1620	1750	Charcoal

$^{+}$Outlier sample

*Date assigned based on MCMC estimate of accumulation at depth

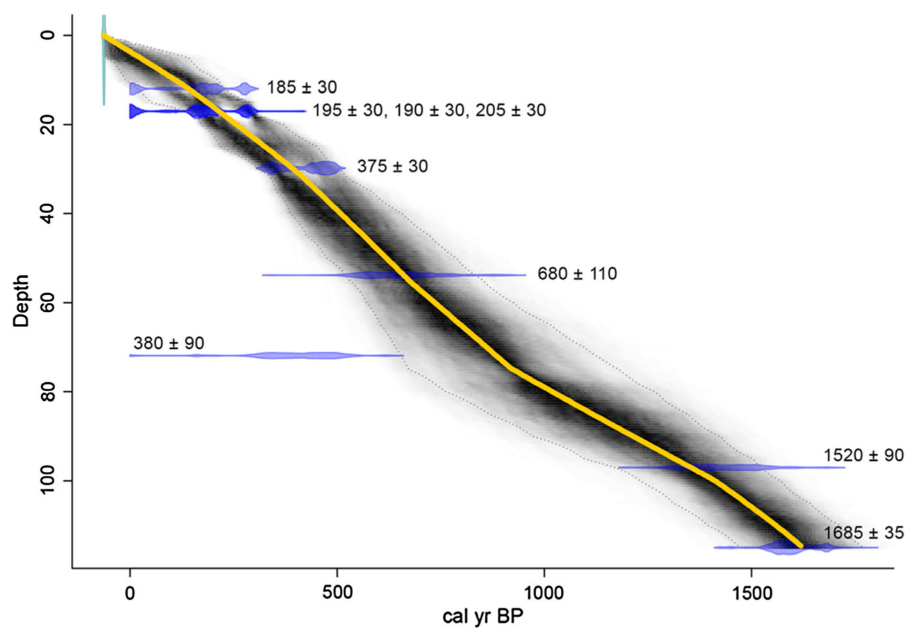

Fig. 3 Trout Meadow (TRT) age model. Yellow line indicates the "best" single model for each depth based on the weighted mean average. Blue bars represent calibrated radiocarbon ages at two sigma error calculated by Bacon 2.2 (Blaauw and Christen 2011) using IntCal13 (Reimer et al. 2013). Dotted grey line bounding the grey cloud of points represents the 95% confidence interval

Cyperaceae, *Gaeumannomyces* spp., and unknown non-pollen palynomorph (NPP) spore types Fungal 1–3 were identified and counted (Fig. 5). They were not included in analysis, but demonstrate the site as a wet meadow. *Gaeumannomyces* (Fig. 6a) is an NPP fungal pathogen known to attach to the roots of *Carex* spp (Mazurkiewicz-Zapałowicz and Okuniewska-Nowaczyk 2015) and was included given the low occurrence of identifiable Cyperaceae pollen grains. Unknown NPP Fungal 1, 2, and 3 (Fig. 6b–d) appear to co-occur with both Cyperaceae and *Gaeumannomyces*.

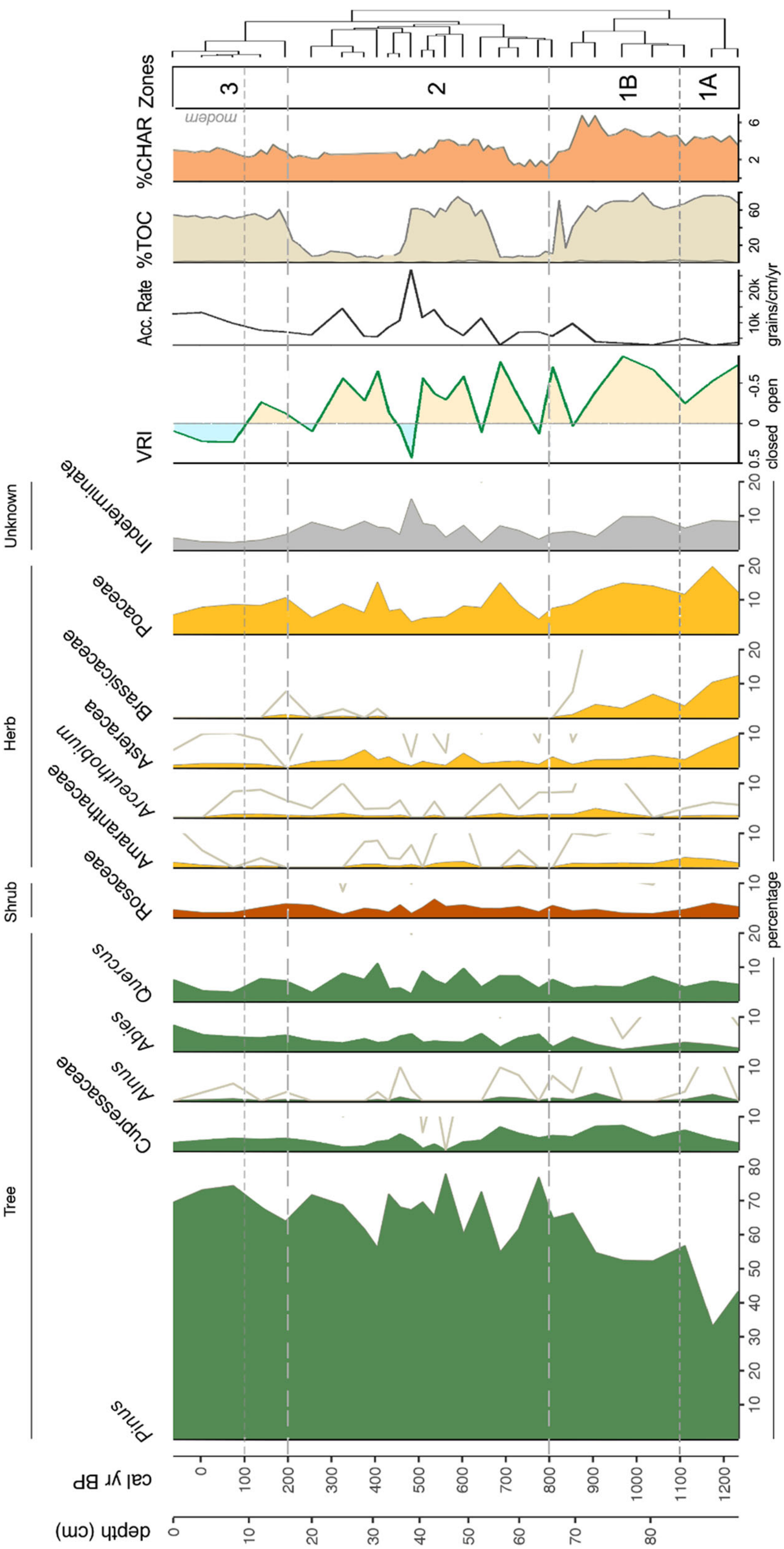

Fig. 4 Pollen diagram of taxa with ≥ 2% maxima, VRI, pollen accumulation rate (Acc. Rate), %TOC and percent charcoal (%CHAR). Pollen zones identified by CONISS

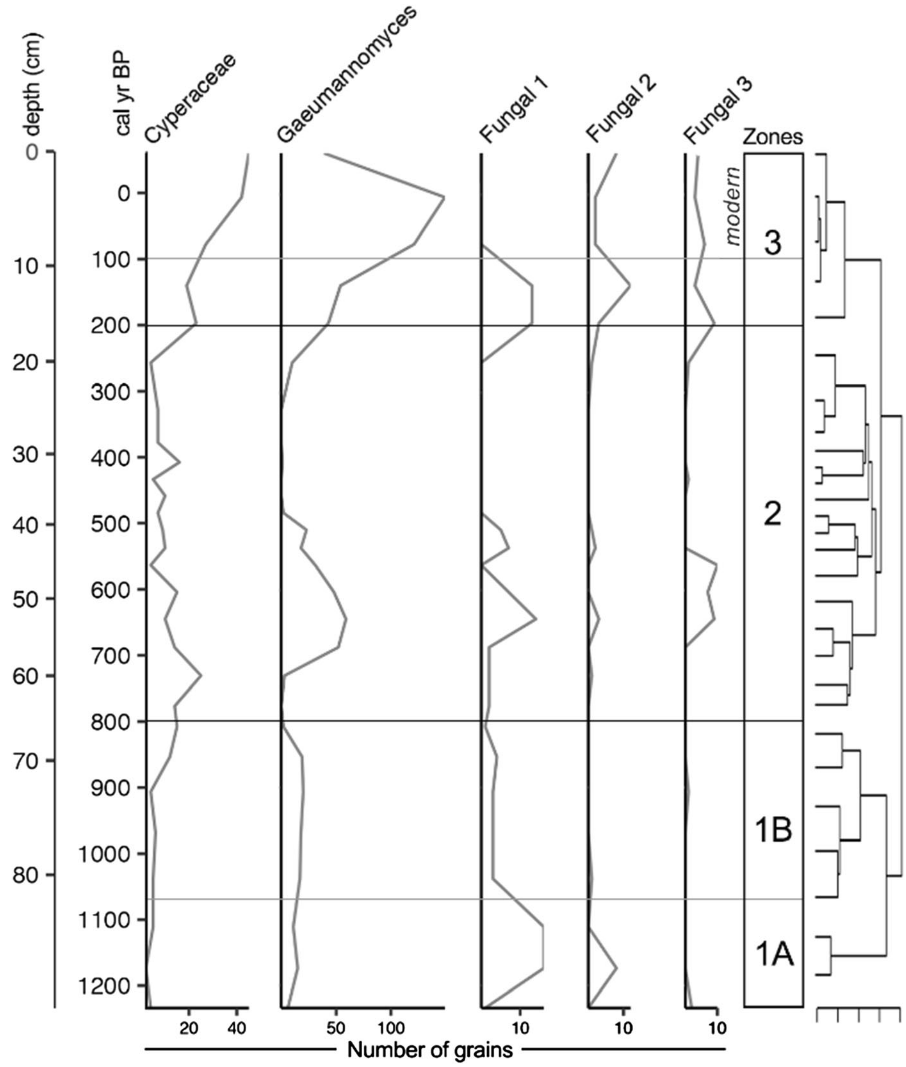

Fig. 5 Cyperaceae and wet meadow indicator non-pollen palynomorphs (NPPs; Fig. 6) shown with pollen zones/CONISS

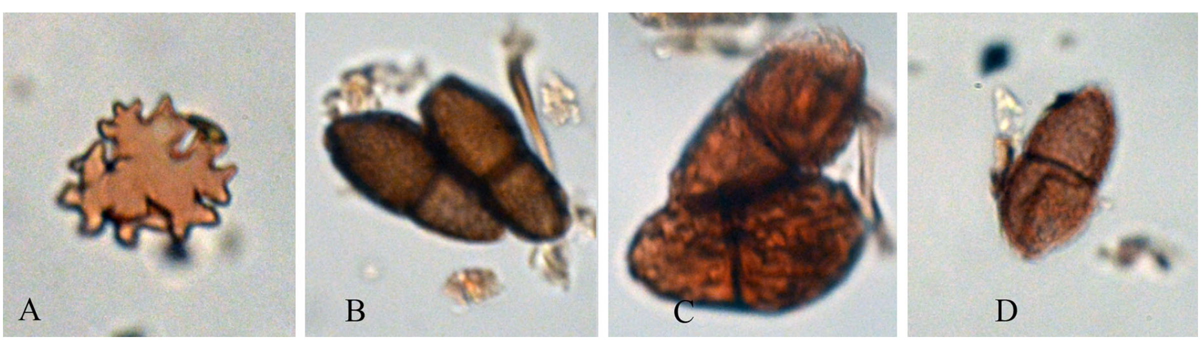

Fig. 6 *Gaeumannomyces* (**a**), and unknown spores Fungal 1 (**b**), Fungal 2 (**c**) and Fungal 3 (**d**) NPP

Zone 1 (1250–800 cal BP; 90–65 cm) was a period of markedly low pollen accumulation (~ 3000 grains/cm/year) with the highest percentages of both total organic carbon (TOC) and charcoal. *Pinus* steadily increased throughout the period (33-65%) while Poaceae (19.6%), Brassicaceae (12.2%), and Astearceae (9.3%) decreased from their maxima. Cupressaceae (7.3%) reached maxima in 1B, *Alnus* (2.2%) peaked in 1A and again in 1B, while *Abies* (0.4%) was at a minimum. VRI varied but remained predominantly negative (open canopy). Zone 1A (1250–1100 cal BP; 90–83 cm) and 1B (1100–800 cal BP; 83–65 cm) are differentiated by relative high percentages of herbaceous taxa Poaceae, Brassicaceae, and Astearceae, with their maxima in Zone 1A. Zone 1B has a maximum of %CHAR (6.9%), and independently corresponded closely with the MCA.

Zone 2 (800-200 cal BP; 65-16 cm) encompasses the transition from the MCA and the LIA until European contact. %TOC dropped considerably (from ~ 60 to 15%) and remained under 15% except for a period between 700 and 450 cal BP, when it recovered to 50–60% levels (Fig. 2). Decreases in %TOC coincide with decreases in Cyperaceae, *Gaeumannomyces* spp., and fungal NPP. %CHAR was relatively constant at 2%, except for an increase to 3% between 700 and 475 cal BP coinciding with increased %TOC. Pollen accumulation rate was highest in this zone, with a maxima ca 450 cal BP. *Quercus*, Rosaceae, Asteraceae, and Poaceae percentages were high, with *Quercus* reaching a maximum (11%) ca 400 cal BP concurrent with a spike in Poaceae (14.9%). *Pinus* reached a maximum (77.7%), but oscillated in relative abundance (54.7–77.7%) through this zone. Cupressaceae percentages declined while *Abies* increased from previous levels. Brassicaceae pollen abruptly disappeared from the record at 800 cal BP and minimally reoccurred 400 years later.

Zone 3 (200 cal BP–AD 2013; 16–0 cm) includes the transition from the LIA to the modern period (beginning AD 1850). %TOC remained constant through this zone at ~ 55%. Pollen accumulation rates increased slowly but consistently. VRI remained negative (open canopy) until 100 cal BP when it shifted to a positive state (closed canopy) and remained so through the end of the zone. This was the only instance in the last 1300 years that VRI remained positive for more than a 50-year period. *Abies* reached maxima (7.5%) and *Quercus* increased (from 2.9 to 6.2%) concurrently with *Abies* (from 4.7 to 7.5%) in the last 50 years.

Anomalous forest structure

Pollen from Trout Meadow (TRT) demonstrates distinct periods of both vegetation and fire reconstructions not responding as expected by climate (Fig. 7). These periods are most noticeable pre-MCA (Zone

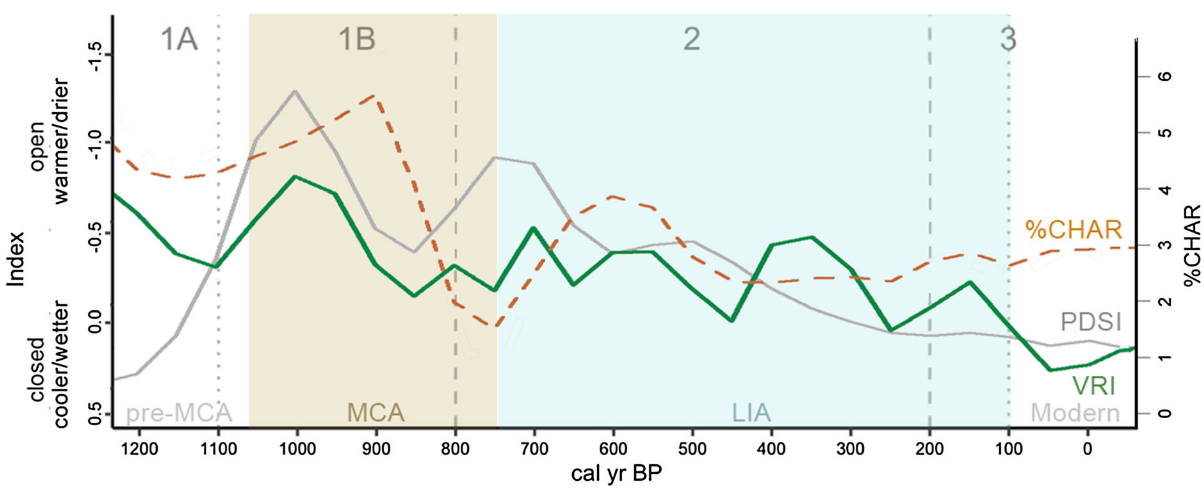

Fig. 7 Changes over time in climate reconstruction (PDSI; solid grey line), pollen-derived vegetation response index (pVRI; solid green line), and percent charcoal (%CHAR; dashed orange line) using a 50-year smooth spline for each record. Brown background indicates the Medieval Climate Anomaly (MCA), blue background the Little Ice Age (LIA)

1A) and punctuated throughout the LIA and the modern period (Zones 2–3).

If climate and climatically-induced factors (such as fire disturbance) were the only driving force of forest composition change, we would expect changes in vegetation (via VRI) and charcoal production (%CHAR) to be consistent with changes in local climate reconstructions (PDSI) (Figs. 4, 7). Though there is relative agreement during the MCA (1050–750 cal BP) between all three proxies, periods before and after the MCA are inconsistent with climatic expectations. During the wetter/cooler period preceding the MCA (pre-MCA), VRI and %CHAR indicate forest conditions almost as open and disturbed as at the height of drought during the MCA. During the LIA, as PDSI indicates progressively wetter conditions, we do not observe the expected increase in positive VRI that should result from the succession of shade-tolerant, fire-sensitive taxa (closed forest). Instead, there are periodic fluctuations towards negative VRI indicating disturbance which promoted more shade-intolerant/fire-adapted taxa (open forest). Based on VRI and steady increases in %CHAR throughout the LIA, there appears to be qualitative evidence for TREM burning facilitating the observed vegetation response both pre-MCA and periodically throughout the LIA.

Paleolandscape modeling

Because paleoecology is an empirical, historical science that cannot allow for experimentation, we use observed paleo proxies (above) and landscape change modeling (Solomon et al. 1980; Pastor and Post 1985; Aber and Federer 1992; He et al. 1999, 2008; Miller and Urban 1999; Shugart 2002; Mladenoff 2004; He 2008) to quantitatively test climate and TREM burning hypotheses.

Methods

LANDIS-II is a stochastic, spatially-explicit raster-based landscape change model designed to simulate interactions between natural disturbances, forest management, and succession (Scheller and Mladenoff 2004; Scheller et al. 2007). LANDIS-II is appropriate for this study because it simulates fire extent, fire severity, vegetation, and human management practices over long periods of time and at a fine temporal and spatial scale. LANDIS-II models individual arboreal and herbaceous species based on life history traits such as age of maturity, longevity, fire and shade tolerance, seed dispersal distance, ability to resprout, and reproduction post fire events. Trees are represented as age and species cohorts, with multiple cohort types possible at a single site. We model a 64 km^2 area centered on TRT with a raster cell size of 1-ha.

Previous work by Klimaszewski-Patterson et al. (2018) at Holey Meadow provided methods for paleoclimate reconstructions, LANDIS-II climate proxies, and other parameterization development methods. LANDIS-II parameters for slope, ecoregions, initial vegetation communities, species life history traits, baseline fire regions, fire weather, fuel type, and harvest parameters come from Syphard et al. (2011) and Klimaszewski-Patterson et al. (2018).

Dynamic Biomass Fuels System (DBFS; Syphard et al. 2011) and Dynamic Fire System (DFS; Sturtevant et al. 2009) LANDIS-II extensions generated modeled fire fuels and wildfire outputs. Five-year timesteps approximate median extra-local fire return intervals (Taylor 2007). DBFS classifies cells into season-independent fuel types used by DFS based on species age and values, time-since-last-fire, cohort biomass, and conifer mortality. DFS simulates fire ignition (*e.g.* lightning strike), fire initiation (*e.g.* ignition catches and causes the cell to burn), severity, and spread based on fire weather, topography, and calculated fuel types. Fire's rate of spread, duration, and severity are dependent on randomly selected fire weather at time of ignition and availability of adjacent cells to burn (Sturtevant et al. 2009). Cohort death is determined by the differential between the severity of the fire and the cohort's fire tolerance. Ignition rates are based on observations (Syphard et al. 2011) and adjusted linearly based on PDSI values (Klimaszewski-Patterson et al. 2018) to better reflect paleoclimate conditions.

The Base Harvest (BH) extension approximates TREM-like burning (Klimaszewski-Patterson et al. 2018) because DFS does not simulate low-mortality ground fires or surface fires. BH has been used by other studies as a proxy for prescribed burn treatments (Sturtevant et al. 2004; Scheller et al. 2011; Syphard et al. 2011); it does not simulate fire dynamics, but rather removes species age-cohorts selectively

Table 2 Hypothesized periods of TREM-like burning (cal BP) based on observations of negative VRI peaks (more open forest) in the pollen record

Scenario	Hypothesized periods of TREM burning (cal BP)
H_C: Climate only	–
H_W: Burning during climatically cool, wet periods and negative VRI peaks	1550–1250, 1100–1050, 750–700, 650–550, 450–350, 250–150
H_P: Burning preceding all periods of negative VRI peaks	H_W periods + 1100–1000, 850–800

(Syphard et al. 2011) based on management areas. Thus these modeled surface fires are constrained within defined areas and cannot spread beyond allowable extents or convert into crown fires. To allow surface spread we used the partial stand spread approach at a 5-year cumulative timestep, with each "burned" area between 0.1 and 0.6 km^2. Partial stand stochastically allows members of species-age cohorts to persist in the stand rather all be "burned". The 5-year timestep captures the 6–14 year fire return estimate in the Sierra Nevada for a cluster of trees equating to 1-ha, the equivalent size of a modeled cell (Swetnam et al. 2009) To "burn", at least 20% of the sites within a randomly selected stand must contain at least one cohort of *Pinus contorta, P. ponderosa*, *P. jeffreii*, *Abies concolor*, *A. magnifica*, *Quercus kelloggii*, *Q. wislizeni*, or *Q. chrysolepis* between 1 and 500 years of age. Twenty percent was selected to account for mixed-conifer stands, with *Pinus* and *Quercus* as preferential resources (*e.g.* food) over *Abies*. If the selected stand is smaller than 0.1 km^2, the event may spread to an adjacent stand that meets the above criteria and is within the same management area. Management areas were based on existing stands (Syphard et al. 2011) and the concept of the wildland-habitation interface (WHI; Klimaszewski-Patterson et al. 2018) to better approximate the application of TREM-like fire to increase resource productivity and preserve floral food species (Bean and Lawton 1973; Lewis 1973; Anderson and Moratto 1996). WHI areas are based on 1000 m spatial buffers around archaeological sites and have a 50% increase in "burning" over non-WHI areas with the assumption for more active management near identified sites of use.

The modeling period is from 1550 to -50 cal BP, with a period of analysis from 1050 to 100 cal BP. This provides 500 years of initialization to allow for a successional cycle more reflective of past climate than modern conditions. 1550–1050 cal BP are excluded due to the initialization period and the last 150 years are excluded due to the recorded historical removal of TREM burning practices.

We created three scenarios to test hypotheses of the drivers in fire disturbances at TRT (Table 2): climate-

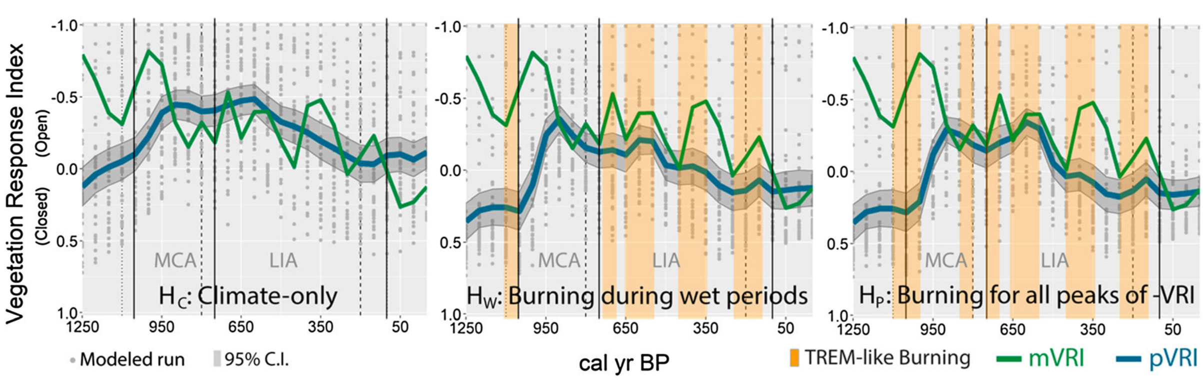

Fig. 8 Comparisons of modeled vegetation response index (mVRI; green line) and pollen-based VRI (pVRI; blue line with grey 95% confidence interval) 50-year smooth spline. Points represent individual model iterations. Dashed vertical lines indicate empirical pollen zonation, solid vertical lines delineate Medieval Climate Anomaly (MCA) and Little Ice Age (LIA). Orange columns represent periods of hypothesized TREM-like burning during observed negative VRI (-VRI) peaks

Table 3 Descriptive and statistical results of modeled wildfires and TREM-like burning scenarios from 1050 to 100 cal BP

Scenario	Max. area TREM burned	Avg. area wildfire	Avg wildfire + TREM burn	MCA (1050–750 cal BP)		LIA (750–100 cal BP)	
				r/*p* val	τ/*p* val	r/*p* val	τ-*p* val
$H_{C:\ Climate}$	–	0.28%	0.28%	−0.62/ 0.14	−0.52/ 0.14	*0.46/ 0.10*	0.27/ 0.19
$H_{W:\ Wet\ Pds.}$	5.30%	0.17%	2.47%	−0.50/ 0.26	−0.20/ 0.54	**0.60/ 0.02**	**0.42/ 0.04**
$H_{P:\ All\ pollen}$	5.23%	0.16%	2.79%	*−0.71/ 0.08*	−0.43/ 0.24	*0.51/ 0.06*	*0.34/ 0.10*

Bolded values show statistical significance at p-value ≤ 0.05. Italicized at p-value ≤ 0.10

only wildfires (H_C); wildfire plus TREM-like burning when pollen deviates from climatic expectations, that is negative pVRI peaks indicating more open forest during periods of cool/wet climate (H_W); and wildfires plus TREM-like burning during all negative pVRI peaks regardless of climate, meaning all periods with peaks in more open forest (H_P). Current estimates are that 6–16% of pre-historic California burned annually from all fires (Martin and Sapsis 1992; Fites-Kaufman et al. 2007). Because the southern Sierra Nevada is thought to have had low population density, we allow up to 6% TREM-like burning (≤ 30% per 5-year timestep). Each scenario includes forty iterations. Identification of pollen deviation periods (peaks in negative VRI indicating more open forest conditions than expected) were based on 50-year smooth splines to correspond with modeled biomass outputs.

The Biomass Succession and Biomass Output extensions (Scheller and Mladenoff 2004) simulated annual biomass output at 50-year timesteps to match the pVRI 50-year timestep. We calculated modeled VRI (mVRI) using a 1:1 conversion factor (Keller et al. 2002) between species biomass (*Abies* and *Quercus*) and pollen-derived VRI (pVRI). We generated 50-year smooth splines for mVRI and pVRI and used both two-tail Pearson correlation coefficient and Kendall rank correlation at 95% confidence interval. We use Pearson r to measure linear correlation between mVRI and pVRI and Kendall tau (τ) to investigate non-parameteric model fit, for each climatic period (MCA and LIA).

Results

We modeled three scenarios to test whether climate alone (H_C) or the addition of TREM burning (H_W and H_P) best approximate the observed pollen record at TRT. Visual comparison of mVRI and pVRI (Fig. 8) show that hypotheses of TREM burning better reflect both magnitude and changes in pollen than climate alone. Both H_W and H_P capture increases in negative mVRI from 600 to 500 cal BP and 250 to 150 cal BP.

TREM-like burning during periods where pollen deviated from climatic expectations (H_W) best approximates the pVRI record with strong significance in both statistical measures during the LIA (r 0.60 *p* value = 0.02; τ 0.42 p-value = 0.04), though no correlation during the MCA (r −0.50 p-value = 0.26; τ −0.20 p-value = 0.54). Over the analyzed period from 1050-100 cal BP, a maximum of 5.3% of the study area was affected annually by TREM-like burning when the prescription was applied, with an overall average of 2.47% of the study area burned by all sources annually. There is a better visual fit but weaker statistical correlation when TREM-like burning is applied to all negative VRI periods regardless of climate (H_P). The LIA shows possibility of correlation (r 0.51 p-value = 0.06; τ 0.34 p-value = 0.10) and possible negative correlation during the MCA (r −0.71 p-value = 0.08; τ −0.43 p-value = 0.24). A maximum of 5.23% of the study area was affected annually by TREM-like burning when prescribed, with an overall average of 2.79% burned by all sources annually.

Table 4 Comparison of reported obsidian hydration (OH)-based calendar dates (Kraus 2016) with modeled periods of hypothesized TREM burning

OH-based periods of site use (60-year range, cal BP)	Overlapping modeled periods of hypothesized TREM burning (cal BP)
1518 (1548–1488), 1437 (1467–1407)	H_W, H_P (1550–1250)
1135 (1165–1105)	Closest H_W (1100–1050), H_P (1100–1000)*
998 (1028–968)	H_P (1100–1000)
869 (899–839)	H_P (850–800)
749 (779–719), 693 (723–663)	H_W, H_P (750–700)
586 (616–556)	H_W, H_P (650–550)
443 (473–413), 320 (350–290)	H_W, H_P (450–350)
187 (217–157), 160 (190–130)	H_W, H_P (250–150)

A 60-year range is applied around each OH-derived calendar date

The climate-only scenario (H_C) showed the least statistical correlation and visual correspondence to pVRI. The LIA has a possible weak statistical correlation with pollen (r −0.42 p-value = 0.10; τ −0.27 p-value = 0.19) (Fig. 8; Table 3) and the MCA indicates a possible negative statistical correlation (r −0.62 p-value = 0.14; τ −0.52 p-value = 0.14). Mean study area burned annually was 0.28%. Averaged over all iterations, maximum study area burned in a single year was 0.62%. This scenario also shows the highest incidence of area burned by wildfire, which is consistent with expectations (Martin and Sapsis 1992).

Archaeological comparisons

Though we recognize there is controversy surrounding conversion of obsidian hydration (OH) dates to calendar dates (Anovitz et al. 1999; Stevenson et al. 2000; Seddon 2005; Rogers 2008), using calculated absolute dates allows us to investigate whether our modeled TREM fire periods have potential archaeological support. Using lithics from archaeological excavations (CA-TUL-2027/2077) adjacent to the meadow, Kraus (2016) reported sixty-seven calendar dates calculated from OH rates, ranging from 6745 to 160 cal BP. Kraus calculated calendar dates using Stevens' (2005) Western Sierra effective hydration temperature (EHT) and Coso obsidian generalized hydration rates, with a reported EHT standard deviation (SD) of 28.4 years, and not including other sources of error. Twenty-three of those samples have reported OH dates that occur in the last 1600 years, all sourced to Coso quarries, specifically Sugarloaf Mountain and West Sugarloaf. We apply a 60-year range around reported OH dates (corresponding to EHT SD) and compare against modeled intervals of hypothesized TREM burning (Table 4). All but one calculated OH date range fall within a period of modeled hypothesized TREM burning, including periods during the MCA (H_P). The one outlier OH date (1135 cal BP) range is within 5 years of a modeled TREM burning period and likely within unknown sources of OH dating error. All modeled hypothesized periods of TREM burning (H_W and H_P) have an OH range that falls within them). We recognize the archaeological sample of OH dates used for comparison is small because they occur after 1600 cal BP, though they are the sum of two prior studies (Skinner and Thatcher 2013; Kraus 2016). That the dataset is immediately adjacent to our paleoecological study site makes it relevant for comparison and worth preliminary exploration. We find initial agreement between our periodic modeled TREM burns and potential archaeological site use.

Discussion

We find reasonable evidence to suggest a Native American land-use legacy observable in pre-historic forest structure near Trout Meadow (TRT). Archaeological evidence indicates TRT was inhabited at least intermittently within the last 3500 years, and the meadow is surrounded by both bedrock mortars and *Quercus*. Based on modeled results and observed

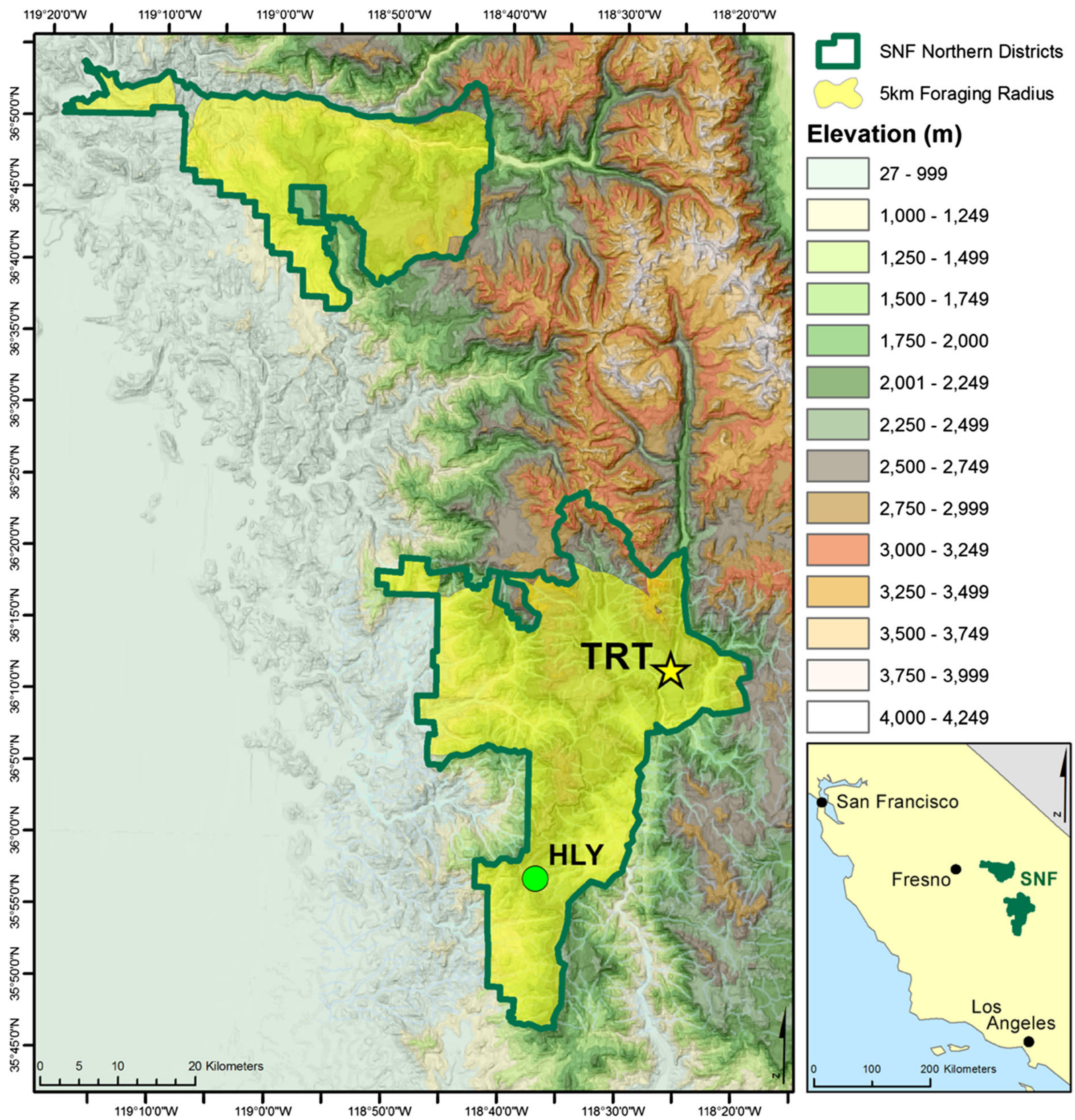

Fig. 9 Total area (yellow) within a 5-km foraging radius surrounding identified bedrock mortar and pre-historic milling stations Sequoia National Forest's (SNF) northern district. TRT: Trout Meadow (this study). HLY: Holey Meadow (Klimaszewski-Patterson and Mensing 2016)

paleoproxy records, the most likely result of pVRI variability in relation to climate is via intermittent active management by Native Americans who took advantage of the site's physiographic characteristics to maximize resources as needed. It is possible that either (1) the site required little active management by Native Americans because its physiographic situation is conducive to *Quercus* persistence and establishment, and/or (2) the site was inconsistently used due to low population densities (Harvey 2019) or because it is located at the fringes of (ethnographically recognized) Tübatulabal (Pahkanapïl) territory (Voegelin 1938; Ramirez et al. 2010).

Previous work by Klimaszewski-Patterson et al. (2018) at nearby Holey Meadow (HLY; Figs. 1, 9) also showed modeled support for TREM burning. HLY's pVRI signal is not punctuated by short-lived increases in *Quercus* like TRT. This could be because HLY (1) required more regular TREM fire to manage for oak resources as the meadow is more consistently wet, both from its spring and situation on the windward slope of the western crest, and/or (2) is easily accessible from the foothills and located near the territorial transition between two ethnolinguistic groups, potentially resulting in more consistent and active use given the social admixture of the groups (Voegelin 1938). The authors noted that modeled consistent TREM burning through the LIA showed strong statistical correlation with mVRI. Such consistent application of TREM burning at TRT had poor statistical correlation in the model, further supporting intermittent land use history at TRT.

Arguments for climatic forcing explaining VRI variability rely on inherent properties of TRT's location. The site's topographic position within the Kern River Basin results in a rain shadow effect, reflected by the modern presence of *Pinus monophylla* within 3–km. Strong slope aspect results in differentiation of *Pinus*, *Quercus*, and *Abies,* and topographic relief may provide potential micro-refugia that allowed persistence of long-lived tree species through otherwise less favorable climatic conditions. Climatic fires and other disturbances near TRT may have been decoupled from strong climatic forcing due to these microrefugia and the rugged terrain. While these arguments are valid, they do not account for the extremely low modeled average percentage of the study area burned annually by wildfire (0.28%), nor explain abrupt, relatively short-lived changes in pVRI towards negative conditions during cooler, wetter conditions in the absence of wide-spread wildfire.

We recognize that none of our scenarios capture pVRI conditions during the MCA well. Posteriori archaeological evidence suggests 6000 years of site use with considerable occupation between 3500 and 1350 cal BP (Kraus 2016). Though population densities are speculated to have been lower than other portions of the Sierra Nevada, TREM burning may have resulted in land-use legacy extending prior to model initialization. Ideally, we would initialize climate in the model for a period longer than 500 years, but there is no reliable annually-resolved climate data before 1550 cal BP available at this time.

Pre-Columbian Native American presence can be physically identified through non-ephemeral cultural remains such as bedrock mortars, milling stations, middens, and lithic scatters. But lack of archaeological presence does not equate to lack of pre-historic land use, as many organic cultural tools (*e.g.* wooden arrow shafts, basketry) and effects (*e.g.* coppicing, pruning, selective harvesting, sowing) are lost to taphonomic processes (*e.g.* decay, regrowth). If TREM burning was only used to improve resource yields, one could argue human influence on forest structure should be locally limited and expected near food processing sites such as bedrock mortars (BRMs) and milling stations. Five kilometers is considered a reasonable daily foraging distance from food processing locations (Bettinger et al. 1997; Morgan 2008). Using this foraging radius as a spatial buffer from known BRMs in the northern district of Sequoia National Forest (SNF) shows that the vast majority of the district could have been actively managed by TREM burning (Fig. 9), most likely low to mid elevations which support fuels conducive for surface fires.

We did not test TREM burning practices increasing over time, as would be expected with increasing population densities. Such tests are beyond the scope of our hypotheses in this paper. Modeling results suggest promise, however, for testing such archaeological-based questions of land-use intensity and history, and could improve model fit through the LIA.

Conclusions

We find both empirical and modeling support that climate alone did not dictate forest composition, and that traditional Native American land-management practices were necessary to create the observed pre-Columbian environmental legacy at Trout Meadow. We find the strongest statistical and qualitative evidence for a Native American land-use legacy via TREM burning when pollen reconstructions deviate from successional expectations during climatically cooler, wetter periods. Though not exclusive, these periods correspond temporally to periods of occupation post-priori identified in the spatially-adjacent archaeological record.

This work supports earlier pollen-based studies by Anderson and Carpenter (1991), Crawford et al. (2015) and Klimaszewski-Patterson and Mensing (2016) for anthropogenically-modified landscapes in California, while adding a new sub-centennial paleoecological site to the literature. This study also supports previous observations that climatic fires and disturbances may not have been the only force to drive forest composition change, and that additional ignitions set by Native Americans were necessary (Reynolds 1959; Vankat 1970). Fire use and purpose, as documented in the ethnographic record to create patchy, mixed-age, resource-diverse, and productive landscapes for subsistence (Voegelin 1938; Lewis 1973; Anderson and Moratto 1996; Anderson 1999; Dincauze 2000; Fowler 2008; Gassaway 2009; Lightfoot and Parrish 2009; Lightfoot and Lopez 2013; Lightfoot et al. 2013; Codding and Bird 2013) were most likely necessary to generate the park-like settings observed in the AD 1850 s (Vankat 1977).

To further refine when Native Americans used specific areas of the Sierra Nevada would require dating bedrock mortars and other milling features—however at this time there are no agreed upon non-destructive methods for dating these features. Additional paleoecological and paleolandscape modeling studies towards the edges of hypothesized foraging radii and near ecotonal (ecologically-sensitive) boundaries would further test the extent to which anthropogenic impacts are chronicled in the geologic record.

While large, severe fires occurred in the past, the combined paleoenvironmental record and modeled result demonstrate a decrease in fire intensity in the centuries prior to European arrival and fire management. As we move towards more active fire management of federal lands, we can note the practices, implementation, and timing of Native American TREM burning. By actively engaging tribal communities and recognizing pre-historic land-use legacies on Sierran forests, modern land management policies could move towards a more comprehensive and holistic approach to natural resources management that may improve forest health, increase resource yields, and decrease the likelihood of catastrophic fires.

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