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Tree-Ring Based Reconstruction of Historical Fire in an Endangered Ecosystem in the Florida Keys

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Abstract: Big Pine Key, Florida, is home to one of Earth's largest swaths of the critically-endangered dry forests. Known as pine rocklands, this fire-adapted ecosystem must experience regular fire to persist and remain healthy. Pine rocklands are composed of a sole canopy species: the South Florida slash pine (*Pinus elliottii* var. *densa*), along with a dense understory of various woody and herbaceous species, and minimal surface moisture and soil development. Slash pine record wildfire activity of the surrounding area via fire scars preserved within the annual tree rings formed by the species. Our study used dendrochronology to investigate the fire history of the pine rocklands on Big Pine Key, specifically within and around the National Key Deer Refuge (NKDR) because it is the largest segment of unfragmented pine rockland on the island. We combined the results found within the NKDR with those of a previous study completed in 2011, and incorporated historical documents and reports of prescribed and natural fires through November 2019 into our evaluation of fire history on Big Pine Key. We conclude that prescribed burning practices are vital to truly restore natural fire behavior, and repeated burning on these islands in the future must be prioritized.

Keywords: dendrochronology; fire history; pine rocklands; prescribed fire; Florida Keys; sub-tropics

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1. Introduction

Contemporary pine rocklands are dominated by the fire-dependent South Florida slash pine (*Pinus elliottii* var. *densa* Little & K.W. Dorman; hereafter slash pine) and have a small natural geographic range. This ecosystem is currently only found in the US in parts of the southern Florida mainland and Florida Keys [1–4]. Pine rocklands have lost considerable area in the subtropical US because of factors including climate change, sea-level rise, tropical cyclone activity, and urbanization [4–10]. Previous research has shown that a typical low-severity fire in other pine rocklands in the area occurs about one-to-two times per decade, but many island areas in these forests lack sufficient burning to match historical levels [1,11], and burning between Keys is not always synchronous [10].

The historical presence of fire on Big Pine Key has varied widely and has been used or managed in different ways through time. The paleocharcoal record from Big Pine Key and the region extends the presence of fire in pine rocklands to 4500 cal yr BP [12,13]. Fires in the Everglades and Florida Keys are often caused by lightning during the increased thunderstorm activity of the wet season (May–October) [2,14]. In addition to lightning, prior to European contact and colonization, fires started by Indigenous people living in pine rocklands were often to protect and preserve key deer (*Odocoileus virginianus clavium*

Barbour & GM Allen) habitat, thus ensuring continual food and resource availability from the land and ocean [15,16]. During hunting trips, fire was also used as a tool to flush prey (often key deer) into open spaces or corral them into drier, less dense, lowlands [15,16]. The Keys began appreciable urban development and non-Indigenous/white homesteading in the late 1800s and early 1900s, and fire suppression became a dominant land management strategy around the same period [17].

Fire suppression is particularly detrimental to pine rocklands because without frequent, low-severity fire, the ecosystem experiences a distinct shift in vegetation from a pine rockland composition to a tropical wet forest known as hardwood hammock. These wetter hammocks have a plant community composed of various fire-intolerant hardwood, and are often closed canopy with high tree density [2,18]. In the absence of fire, and in addition to other anthropogenic disturbances (e.g., urban development), the distribution of pine rocklands in the US has been limited to select parts of the Everglades and the Florida Keys [19]. Additionally, in the Upper Keys, pine rocklands have been replaced with hardwood hammock via fire suppression and urban development since the mid-1900s, making areas in the Lower Florida Keys the largest contiguous areas of pine rocklands left in the US [19,20]. Overall, pine rocklands suffer in the absence of fire.

The US Fish and Wildlife Service (USFWS), in coordination with local and regional wildland fire officials, ignites prescribed fires during optimal and safe weather conditions within the June–October wet period [21,22]. In the National Key Deer Refuge (NKDR), prescribed fire began unofficially in the 1970s and continued sporadically into the 2000s, with the most recent burn successfully completed in October 2019. However, use of prescribed fire on islands in Florida has not matched the same pace as those conducted on the mainland since the use of fire as a land management tool was reinstated and used by the Florida Forest Service [19,23]. Public opinion of fire in the Key communities is also often fractured, and reflective of the broader public in general. A lack of community-wide fire awareness and respect can lead to a misunderstanding of the natural place fire has on the landscape [24,25].

In the summer of 2011, fieldwork was conducted for a dendrochronological fire history reconstruction within the NKDR and included land on adjacent No Name Key [26]. The goal of that project was to establish the applicability of slash pine trees to dendrochronological analysis and determine the fire regime of the largest contiguous swath of pine rocklands left in south Florida. Immediately following final collections for that project, a prescribed fire escaped containment in another area within the NKDR and threatened homes in a nearby neighborhood. This fire event caused a reactionary and strong negative response to fire on the island, thus motivating further study into the historical activity of fire in the area. The purpose of this current study was to complete a fire history reconstruction using fire-scarred slash pine trees, then evaluate fire activity of pine rocklands on Big Pine Key using the reconstruction to support future management efforts in island communities in Florida.

2. Materials and Methods

The study site is within the NKDR, established in 1957, on Big Pine Key (24.70° N, 81.37° W) in the Lower Florida Keys (Figure 1). Slash pines are useful for fire history analyses because they produce annual rings [27] and can record fire events below a fatal temperature threshold. Big Pine Key has a tropical savanna climate, with distinct wet summers and dry winter seasons. The mean annual precipitation for the area is approximately 980 mm, with approximately 80% of rainfall occurring from thunderstorms between June to October [28]. Tropical cyclone activity is common and poses an annual disturbance risk to the Keys, with estimated return periods of three years for tropical storm-force winds and five years for hurricane-force winds [29].

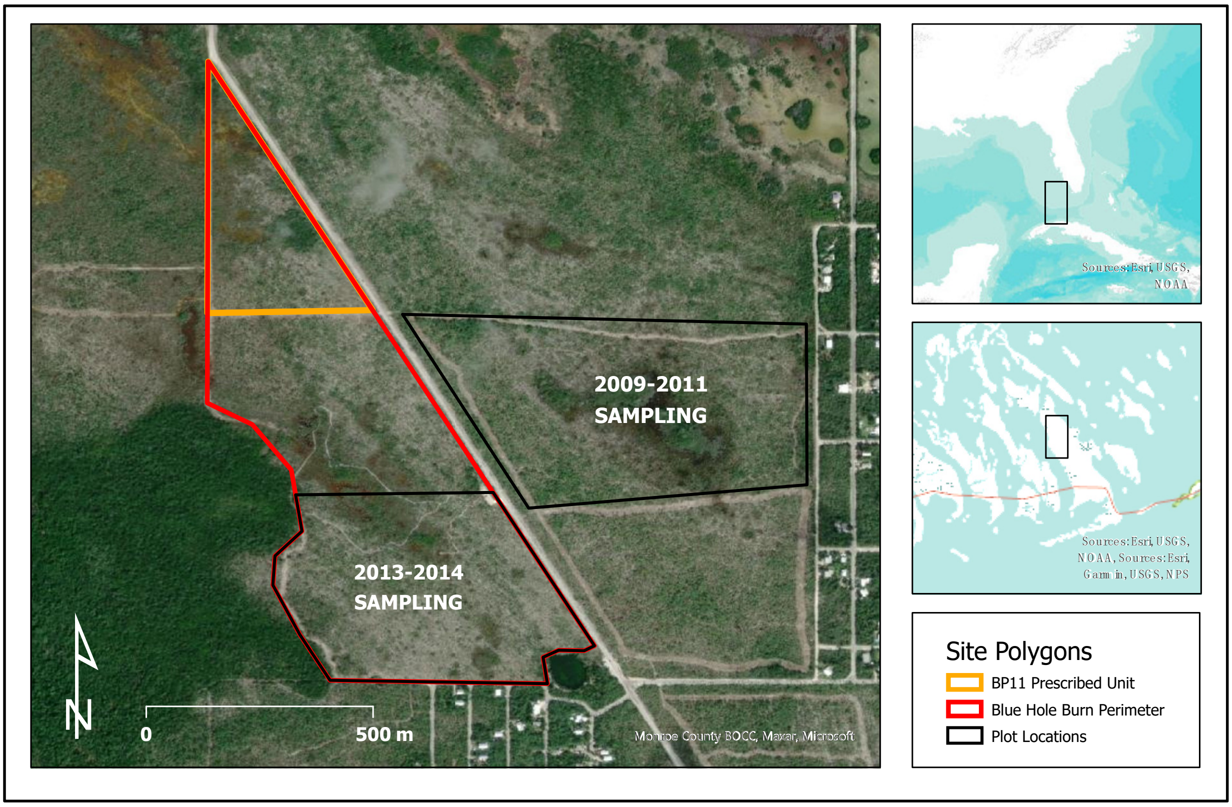

Figure 1. Map of 2011 planned burn unit (BP11; orange polygon), the 2011 Blue Hole Burn perimeter (red polygon), and the locations for plots from Harley et al. [26] and the current study (black polygons). Supplementary materials include GPS locations of individual trees in 2013–2014 sampling polygon and the FHX data for the same collection.

We collected 94 cross-section samples from within the southern half of the 2011 burn perimeter, and away from the freshwater marshes (Figure 1). We used a gridded network of plot-center locations set up previously by the US Fish and Wildlife Service with each centroid spaced 250 m apart and with no plot co-located with the initial sampling campaign completed in 2011 [26]. For each plot, we inspected and flagged up to 30 trees for potential collection based on the total number of visible fire scars present along the basal margin of the tree [30]. For plots BH5–7, we identified fewer fire-scarred trees and due to time constraints, focused our sampling efforts on plots BH1–4. For each tree, we recorded precise locations with a hand-held Garmin GPSMAP 62S handheld unit (variable error rate ± 4 m) and counted the number of visible fire scars present. From the flagged trees for each plot, we then selected 10–15 for sampling, focusing primarily on those trees with the highest scar counts, the best preservation, and considerable age based on established physical characteristics that denote older individuals [31,32].

We processed all samples using standard dendrochronological techniques [33]. We used the fire history and tree-ring data developed by Harley et al. [26] to crossdate fire-scarred samples and build a dataset for the NKDR. We used FHAES (Fire History Analysis and Exploration) to conduct fire history analyses [34], and the 'burnr' package in R to build our fire-history plots [35]. We calculated composite fire history metrics for total temporal length of our dataset and two separate categories: pre-NKDR establishment in 1957 and post-1957 (marking the formal establishment of the NKDR and federal land management). We applied threshold filters to the fire-scar dataset at 10% and 25% of recorder trees scarred in a given fire year as estimates for medium and large fires, respectively [36,37]. We normalized the temporal analysis data in 'burnr,' [35] and conducted a Student's t-test on the normalized data to evaluate statistical changes in fire return intervals through time. To ensure confidence in statistical results, fires recorded in less than three trees in the dataset

or occurring within a period with less than 10 trees recording fires were not included in our analysis.

3. Results

From the 94 sampled trees, we successfully dated 63 fire-scarred slash pine samples to annual resolution. We removed the remaining 31 samples from further analyses due to heavily decayed wood, the prevalence of extensive beetle galleries that obscured ring boundaries and scars, and low ring counts (e.g., samples with less than approximately 50 rings). We dated a total of 385 fire scars and 55 separate fire events across all years in the dataset, spanning from 1819 to 2014 (Figure 2), but due to low sample depth prior to 1890 ($\leq$10 trees), statistical data represent 1890 and later. Our fire history statistics indicate that a difference of less than 1.75 years between the three classes (composite, 10%, and 25%) was not statistically significant, likely due to the large standard deviation for the >25% class (Table 1). However, we did find a statistically significant difference (t = 3.1925; $p < 0.01$) between the pre- and post-NKDR establishment fire regimes, suggesting a shift in fire activity with fires occurring more frequently before 1957 than after 1957 (Table 2). Evidence of a distinct drop in fire frequency post-1957 is especially important given the concerted efforts of the USFWS and various burn partners to ubiquitously employ prescribed fire—even with a stressed social license for fire in the island communities in the presence of the prescribed fire, more fire is necessary if we are to return to a pre-NKDR establishment regime.

Table 1. Composite and filtered fire history statistics. Values are in years.

Blue Hole Burn (*n* = 63)	MFI [1]	SD [2]	WMPI [3]	WSD [4]	Range
All	3.03	1.49	2.91	1.46	1–7
>10% (*n* = 27)	3.57	1.85	3.40	1.80	1–8
>25% (*n* = 20)	4.76	3.43	4.23	3.15	1–14

[1] Mean fire interval; [2] Standard Dev of MFI; [3] Weibull median probability interval; [4] Weibull standard dev.

Table 2. Fire history statistics for pre- and post-management periods. Values are in years.

Period	MFI [1]	SD [2]	WMPI [3]	WSD [4]	Range
1911–1956 (*n* = 14)	3.38 *	1.71	3.25	1.63	1–7
1957–2014 (*n* = 8)	7.57 *	4.43	7.14	4.06	2–14

[1] Mean fire interval; [2] Standard Dev of MFI; [3] Weibull median probability interval; [4] Weibull standard dev; * is significant to $p < 0.01$.

Similar to the results found by Harley et al. [26], widespread fires occurred prior to NKDR establishment, such as the 1955, 1951, and 1940 fires which scarred seven trees across the plot network for this study, and the 1955 fire scarred trees across Key Deer Blvd and into the area for the previous study conducted by Harley et al. [26]. Additionally, this study also recorded the 2004 and 2000 fires, both part of a concerted prescribed burning effort by the USFWS. Of the three largest fires in our fire-scar dataset (2011, 1990, and 1977), all three were prescribed fires occurring over a span of 35 years with no indication of shifts in fire size (via number of fire-scarred trees). Finally, the most recent fire to have occurred within the NKDR was a successful prescribed fire conducted from 28 October–1 November 2019, encompassing 115 acres in the same location as the 2011 burn perimeter. This most recent burn does not have a presence in the fire scar record for this study, but we felt it important to include as an update given the nature of the 2011 burn event. While a comparison among the number of fire-scarred trees and ignition source (e.g., natural vs. prescribed) would be interesting to see, records of fire before the 1970s are hard to find and documentation on fires stops pre-NKDR establishment. Thus, unfortunately not much is known on the specific cause of fires recorded in the fire-scar record before that time. Although, given active fire suppression in general at the time, and a lack of federal or

state-sponsored prescribed burning on the island overall, the likely cause was accidental ignition or arson.

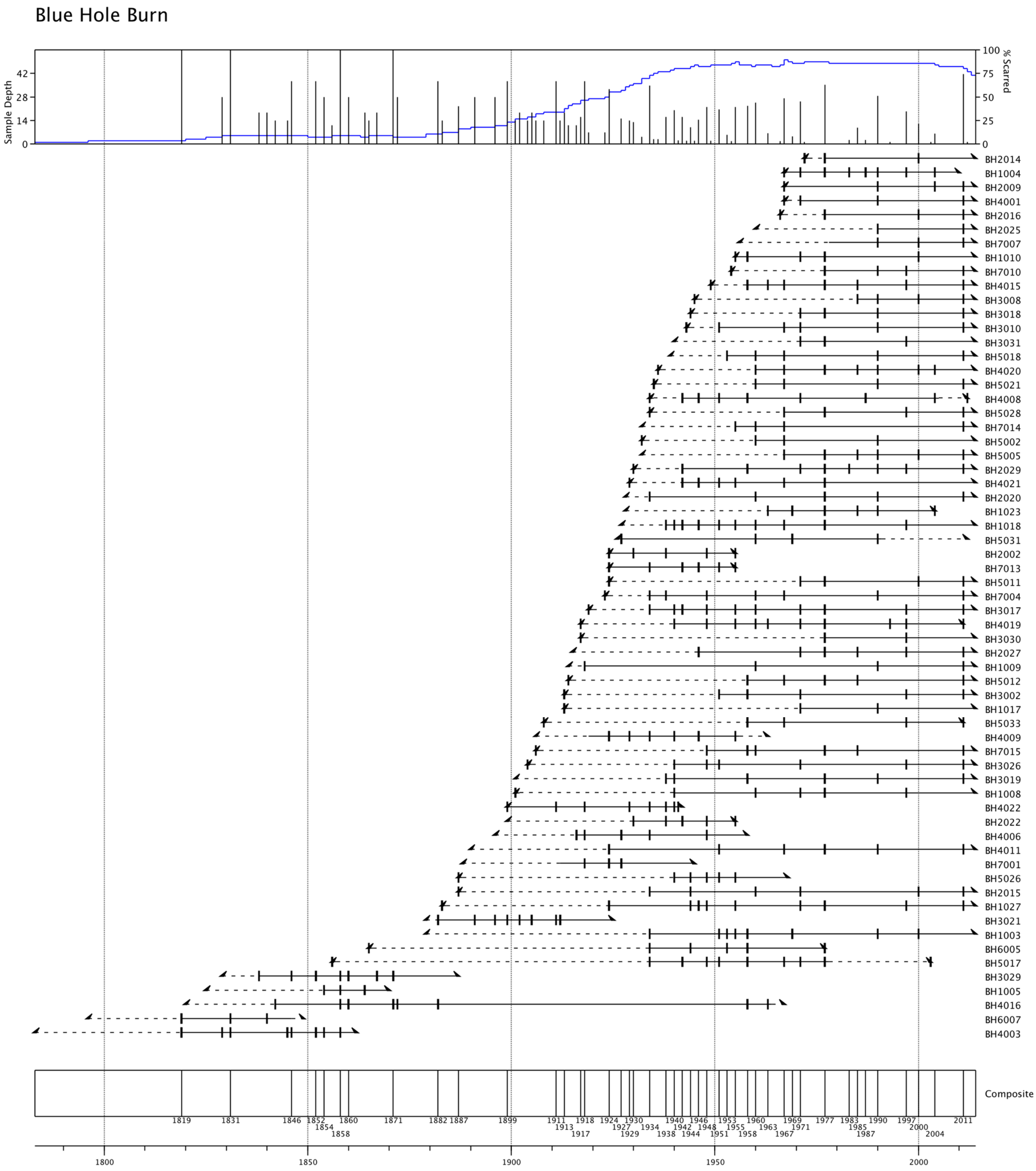

Figure 2. Fire history of the Blue Hole site (n = 63). A high-resolution copy and raw fire-scar data are provided in supplemental materials to view this graph with finer clarity.

4. Discussion

MFI and WMPI results from this study corroborate results from previous fire history research in pine rocklands, which found return intervals between two and 10 years [2,11,26]. Short MFI and WMPI values indicate a higher frequency of forest fires, translating to lower-severity fires. While we cannot rule out high-severity fires for the study site, the presence of fire scars back to 1819 indicates high-severity, stand-replacing fires are unlikely to have occurred. With the results found in Harley et al. [26], fire on these islands clearly has occurred in the past at a more frequent pace than what is seen now. However, given limitations in data collection and availability of historical records, it becomes difficult to determine the exact cause of past fires, and to produce historic fire perimeters.

While we did not identify a statistical difference between our filter classes, Harley et al. [26] did find a difference between filter classes. However, we conclude the reason was due to the fragmented nature of the region of the NKDR we sampled in. Specifically, our sampling plots were adjacent to the Pine Heights neighborhood, potentially limiting spatial extent of larger fires (via active suppression). In addition to urban development in places where larger fires are found, the rocklands themselves are not large, contiguous swaths of forest, but rather naturally patchy, mosaicked networks of interconnected hardwood hammocks and coastal wetlands [11,26,38,39]. Thus, broad scale (+1000 of acres) fires like those that can occur in western forests, do not occur in pine rocklands. Therefore, it is possible that standard thresholds, or filters, for medium and large fires may need to be modified to fit the natural fire activity of the pine rocklands.

We identified a statistical difference in fire frequency between pre- (1911–1956) and post-NKDR establishment (1957–2014) periods, with fires occurring more frequently in the pre-1957 period. The management history of Big Pine Key offers some insight into potential causes for the change in fire frequency through time. Currently, Big Pine Key is a Census Designated Place, with a population of approximately 5000 people [40], but people lived and traveled on Big Pine Key before 1900 [17]. Indigenous peoples of south Florida existed at least 12,000 years before the first contact with Europeans in 1500 AD [15], but the Keys and Dry Tortugas region of the Atlantic remained sparsely populated until the early to mid-1900s [15–17]. Total population was low in the early 1900s, with a total of 17 people living on the island by 1910 [16,17]. Prior to 1950, most property on Big Pine Key was owned by railroad companies, with little residential development [16,17].

The low population and general lack of an urban center allowed for the continuation of sporadic key deer hunting practices into the 1940s [17]. This use of fire for hunting practices kept fire frequencies high and severity low. However, from the 1940s to the early 1970s, all fire was actively suppressed on Big Pine Key until the USFWS initiated prescribed burning. Even so, the prescribed burning did not match the fire frequency seen before the NKDR was officially established, nor did it keep pace with prescribed burning initiatives on the mainland. Further investigation into the relationship and history of fire and hunting, particularly as it fits within the narrative of Indigenous burning practices, is imperative if we are to center the appropriate voices in future burning projects.

Prescribed burning practices have been a part of USFWS management of pine rockland ecosystems within the NKDR for several decades [2,3]. These best management practices have been effective since their inception in the NKDR which was aimed at moving the fire regime back to natural frequencies as seen in the tree ring and sediment charcoal records [4,12,13,26]; however, it comes after decades of suppression and lower than normal fire frequency. Most often this means prescribed fire often then plays "catch up" with the fuel loads to restore natural fire activity. Aggressive, mechanical thinning is required in conjunction with prescribed burning for continued survival for this endangered ecosystem [41]. The 2011 burn incident report [42] and the successful 2019 prescribed burn indicate these land management practices are extremely valuable to pine rocklands. Our study and Harley et al. [26] demonstrate that regardless of current public perception, fire has been a part of the landscape on Big Pine Key since at least the early 1800s, and while we do not have fire scars before 1819, fire is likely to have occurred before then as well.

In an age when reactionary fire suppression tends to be a dominant response, our results indicate fires in the NKDR occur with less frequency than seen in approximately 50 years even with current burning regimens. A persistent lack of sufficient fire moving forward could increase the likelihood of even more ecologically destructive fires on Big Pine Key. The prescribed burns that citizens have come to fear and criticize may be necessary to prevent the actual loss of the pine rockland ecosystems and destruction of surrounding communities from fire.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/fire4040079/s1. The FHX dataset and GPS locations of all trees, which will also be stored in the International Multiproxy Paleofire Database, a permanent, public archive maintained by the Paleoclimatology Program of the National Oceanic and Atmospheric Administration in Boulder, Colorado (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/fire-history, accessed on 3 August 2015), or upon request to the authors.

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