

Local and regional wildfire activity in central Maine (USA) during the past 900 years

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Abstract Climatic and environmental change has a direct effect on wildfire frequencies and distributions throughout many regions of the world. Reconstructions from natural archives such as lake sediments can extend temporally limited historical records of regional wildfire activity over longer timescales through sedimentary charcoal analysis or examining polycyclic aromatic hydrocarbon (PAH) concentrations. To date, little work has been completed on sedimentary PAH distributions from lacustrine records in the Northeastern United States, making it difficult to assess how accurately PAHs trace fire activity in the region, the spatial scope of the signal (local vs. regional), or if certain compounds do a more adequate job of tracking fire than others. In this study, we examine PAHs and macrocharcoal from a varved sedimentary record from Basin Pond, Fayette, Maine (USA). We find that a drastic increase in the concentrations of 12 measured PAHs occurred during the

nineteenth to twentieth centuries due to industrialization of the region. Additionally, elevated concentrations of the PAH retene were found to be coeval with known large-scale regional wildfire events that occurred in 1761–1762, 1825, and 1947 (A.D.). We used the ratio of the PAHs retene and chrysene to infer differences in biomass burning versus anthropogenic combustion sources because retene is associated with conifer resin whereas chrysene is associated with fossil fuel burning. Our new Basin Pond PAH records, along with a local signal of fire occurrence from charcoal analysis, offers the prospect of using this multi-proxy approach as a method for examining long-term wildfire frequency at both the local and regional scale in the Northeastern US.

Keywords Varve · Wildfire · PAH · Retene · Charcoal · New England

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Introduction

Wildfires are an important consequence of global climatic and environmental change. Understanding fire frequency and anthropogenic impacts on wildfires is critical in the context of climate change because they directly impact atmospheric composition, ecosystem diversity, and land management practices (Clark and Royall 1995; Gill and Bradstock 1995; Werf et al.

2004; Denis et al. 2012; Kirchgeorg et al. 2014). Fire frequency is expected to increase in the US in most global warming scenarios, and costs relating to wildfire management and damage have been increasing in recent years (U.S. Forest Service 2015; National Interagency Fire Center 2016). Furthermore, there is uncertainty about how human disturbance, particularly in the Northeastern United States, has affected natural burning patterns due to our lack of continuous fire history records for pre-settlement times (Clark and Royall 1995). Therefore, long term wildfire reconstructions are an important source of information for understanding climate-wildfire feedbacks and how climate influences natural wildfire regimes (Denis et al. 2012).

While wildfires are a less common phenomena in the Northeastern US than in other regions of the world, large events can occur and significantly impact the landscape. Due to limited historical wildfire records in the region, reconstructions from natural archives including lake sediments and tree rings are needed to extend fire history over longer timescales. In the Northeastern US, tree-ring studies are temporally limited due to human disturbance on forest ecosystems and land clearance practices (Lorimer 1977; Parshall et al. 2003; Barton et al. 2012). Therefore, most wildfire reconstructions are based on macrocharcoal distributions in lacustrine sediments (Swain 1973; Fahey and Reiners 1981; Clark and Royall 1995; Clark et al. 1996; Parshall et al. 2003; Pederson et al. 2005). Although this method has greatly increased our knowledge of past wildfire activity, there are some limitations. Charcoal analysis can require large volumes of sediment depending on sediment composition and charcoal abundance (Whitlock and Larsen 2001; Denis et al. 2012). Furthermore, many existing charcoal records in the Northeastern US are poorly resolved, not continuously sampled, and only provide a local signal of burning (Marlon et al. 2008; Zennaro et al. 2015), making determining a regional signal of fire activity difficult.

Molecular compounds that can be used as markers of burning have become increasingly studied in paleoenvironmental reconstructions of wildfire activity (Yunker et al. 2002; Denis et al. 2012; Kirchgeorg et al. 2014). One such compound class is polycyclic aromatic hydrocarbons (PAHs). PAHs, produced through natural and anthropogenic processes, were first found in soils and have since been studied across

different ecosystems and environments, including lakes (Blumer 1961; Grimalt et al. 2004; Bianchi and Canuel 2011). Pyrogenic PAHs are made through the incomplete combustion of organic material (Page et al. 1999), and can be used to trace regional combustion processes such as fossil fuel burning or forest fire activity (Page et al. 1999; Yunker et al. 2002; Denis et al. 2012). Therefore, the historical record of certain PAHs, or groups of PAHs, in sediment cores can be used as proxies for the frequency and size of wildfires or anthropogenic activity in pre-industrial times (Musa Bandowe et al. 2014). In one such study conducted by Musa Bandowe et al. (2014), a suite of PAHs were used to investigate variations in anthropogenic activity and climate over the past 2600 years from a sediment record from Holzmaar, Germany. This study found that PAH concentrations were highest during industrialized times, indicating that PAHs can be valuable proxies for tracking anthropogenic activity in a region. Another important conclusion of this study was that the PAH, retene, likely tracks natural forest fires or anthropogenic combustion of soft wood. However, retene was not directly compared to other fire proxies (i.e. charcoal or sulfur) used in this study, making it unclear how accurately retene is tracing natural fire activity in the region (Musa Bandowe et al. 2014).

Interpreting PAH abundances as proxies for wildfires becomes more complicated when moving into modern (post-industrialization) time periods. Industrialization and widespread use of fossil fuels has caused increases in concentrations of most PAHs (Simoneit 1986). Fortunately, different combustion sources, such as combustion from fossil fuels or biomass combustion, can be distinguished by the ratios of specific PAHs, such as retene/(chrysene + retene), fluoranthene/(fluoranthene + pyrene), and anthracene/(anthracene + phenanthrene) (Yunker et al. 2002; Yan et al. 2005; Kuo et al. 2011; Denis et al. 2012). In particular, the retene/(chrysene + retene) ratio has been used by past studies to distinguish between biomass burning and fossil fuel combustion, as lower values (0.15–0.5) tend to indicate a fossil fuel combustion source while higher values (> 0.8) indicate a soft-wood combustion source (Yan et al. 2005; Kuo et al. 2011; Denis et al. 2012). However, to our knowledge, little work on PAH distributions from lacustrine sedimentary records have been completed at high-resolution in the Northeastern

US, making it difficult to assess how accurately PAHs trace fire activity in the region, the spatial scope of the signal (local vs. regional), and if certain compounds do a better job of capturing fire history than others.

To address these issues, we present an organic geochemical analysis of a 900-year sedimentary record with sub-decadal resolution from Basin Pond, Maine, USA. Past studies of Basin Pond have focused on paleoenvironmental reconstructions using pollen and charcoal, as well as sedimentological analyses spanning the Holocene (Gajewski et al. 1987; Gajewski 1988; Clark and Royall 1994, 1996; Clark et al. 1996; Frost 2005). The goal of this study was to reconstruct a continuous, highly-resolved record of local and regional wildfire activity and to better understand differences in fire history recorded in lacustrine sediments by PAHs and macrocharcoal. We compare our reconstructions with historical records of large regional fires to assess the accuracy of the sediment records as wildfire proxies.

Study site

Basin Pond is a small (0.14 km² area) lake with a maximum depth of 32.6 m located in Fayette, ME (44°28'N, 70°03'W) at an elevation of 124 m above sea level (Fig. 1) (Gajewski et al. 1987; Frost 2005). Basin Pond has no fluvial inlets, with the main sources of water from groundwater and precipitation. The sole outlet is a small, dammed stream running westward into the adjacent David Pond (Frost 2005). Most of the 0.53 km² catchment area is located within the “Basin Pond Conservation Area” with one residential building in the watershed (Frost 2005). The catchment is dominated by a well-developed forest of deciduous hardwoods and evergreen trees, with hemlock being the most abundant species (Frost 2005).

Basin Pond is unique in that the sedimentary record is comprised of annual laminations, or varves, due to a permanent meromictic water column (Wetzel 1983; Frost 2005). A persistent chemocline was found throughout the year to be sufficient to prevent turnover of the water column during the breakdown of thermal stratification during the early spring and late fall. This chemical stratification aids in the permanent anoxic conditions at depth, allowing for the preservation of annual couplets in the sedimentary record (O'Sullivan 1983; Zolitschka et al. 2015). The Basin Pond varves are biogenic in nature, with couplets being comprised

of a lighter, diatom-rich layer and a darker, humus layer (Frost 2005).

Materials and methods

Core collection

Primary field work at Basin Pond was conducted in March 2014. Sediment coring was performed from ice in the deepest part of the lake at 32 m (44°27'27"N, 70°03'09"W) using a UWITEC gravity coring system. Core BP2014-3D (52 cm), captured an undisturbed sediment–water interface, and was subsampled in the field at 0.5 cm resolution for radioisotopic dating. Core BP2014-5D (174 cm) was taken and immediately capped. In the Department of Geosciences at University of Massachusetts Amherst, cores were split, photographed, and subjected to non-destructive down-core logging using an Itrax XRF core scanner at 100 µm resolution.

Age model

The age model for Basin Pond core BP2014-5D is primarily based on a varve count chronology of the uppermost 80 cm confirmed through radioisotopic dating of the upper sediments and radiocarbon dating of plant macrofossil samples (Fig. 2; Table 1). Varve counts were completed using X-Ray radiograph images with 100 µm resolution. Laminations in the upper 80 cm of the sediment record appear continuous with no apparent hiatuses, and were counted three times for the creation of the varve count chronology with minimal error. The upper 15 cm of sediment were also dated using radioisotopic analysis. Subsamples from core BP2014-3D were freeze dried, homogenized, and measured for ²¹⁰Pb activity on a Canberra GL2020R Low Energy Germanium Detector, following the methods detailed by Woodruff et al. 2013. Ages for ²¹⁰Pb measurements were estimated assuming a constant rate of supply of unsupported ²¹⁰Pb activity (Appleby and Oldfield 1978). In addition, radiocarbon dating of 5 discrete samples were conducted on terrestrial macrofossils (Table 1; Fig. 2). Radiocarbon age estimates were calibrated using the “IntCal13” calibration to years before present in the ‘R’ program ‘BChron’ (Parnell 2016). No corrections

Fig. 1 Location of Basin Pond, ME and bathymetric map. **a** Map of the Northeastern US with Maine highlighted in gray and Basin Pond indicated by a star. **b** Map of Maine with estimated ranges of known large wildfire events ($> 400 \text{ km}^2$ acres burned) from historical records within 100 km of Basin Pond, adapted from Coolidge (1963). Shaded locations indicate the fires of 1761–1762 AD (yellow), 1825 AD (blue), and 1947 AD (red). **c** Bathymetric map of Basin Pond. (Color figure online)

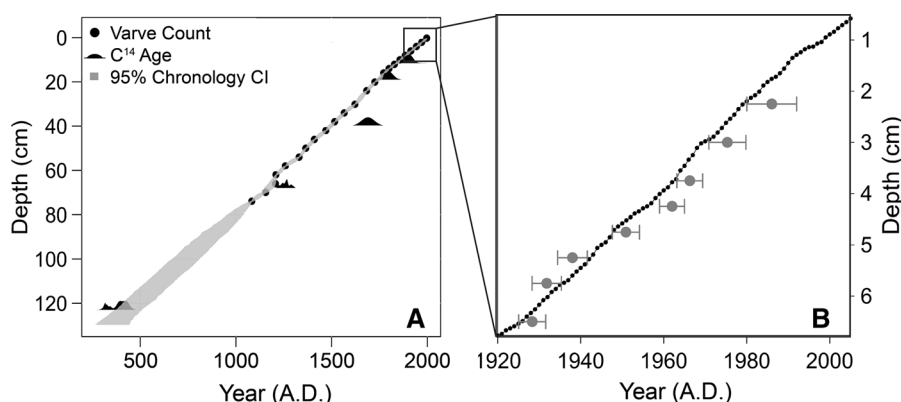
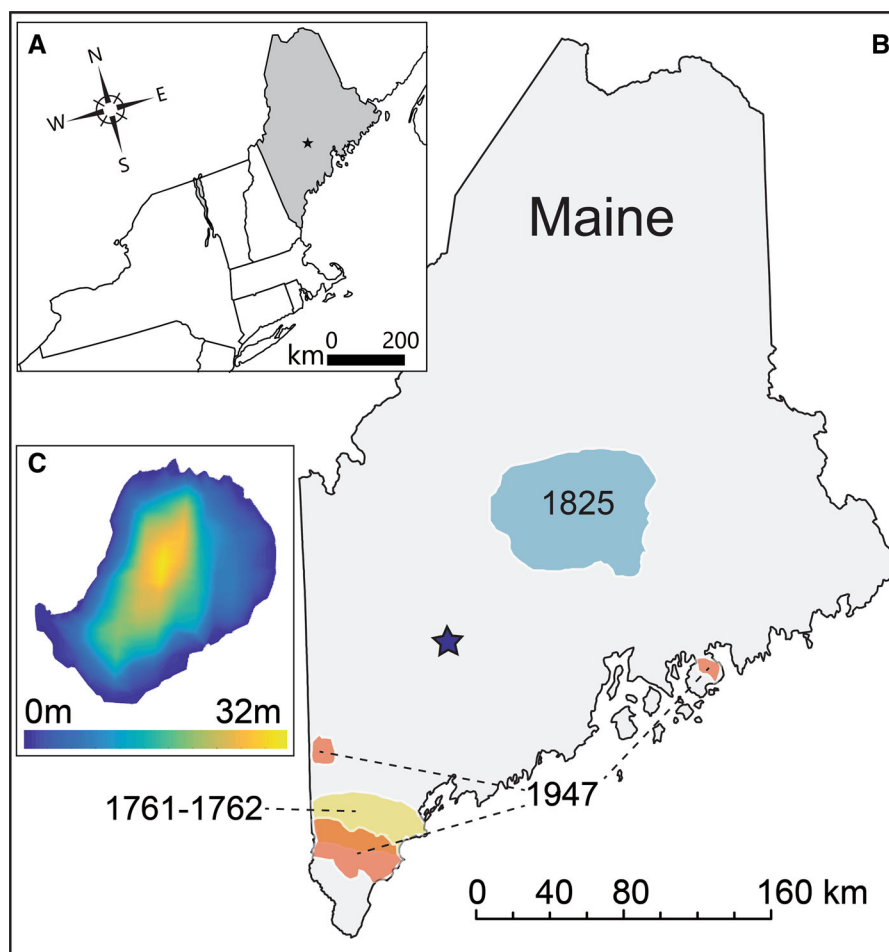


Fig. 2 **a** Age-depth model for the sedimentary record of Basin Pond, with age measured in Years AD. Black markings indicate dated positions through varve counting (varve counts every 4 cm are marked), radiocarbon dating, and ^{210}Pb dating. Gray

shading indicates the 95% confidence interval at any given depth. **b** Age model for 1920 AD—present day. Gray points indicate ^{210}Pb dates with associated errors, while black points are varve counts

Table 1 Results of radiocarbon analysis of Basin Pond macrofossils from core BP2014-5D

Sample depth (cm)	Description	Lab ID	^{14}C age (years)	Calibrated age range [years BP (1950)]		Median age [cal yr BP (1950)]
				(1 σ)	(2 σ)	
11.5	Hemlock needle	OS-117501	95 \pm 20	49–236	33–253	106
19	Hemlock needle	OS-117502	205 \pm 25	19–282	1–295	170
40	Hemlock needle	OS-117504	310 \pm 35	321–431	303–468	384
68	Hemlock needle	OS-107506	835 \pm 20	715–764	700–781	740
123	Wood	USGS-9906	1700 \pm 35	1569–1673	1546–1694	1603

The laboratories used were the U.S. Geological Survey's Eastern Geology and Paleoclimate Science Center (USGS), and the Woods Hole Oceanographic Institute NOSAMS Facility (OS). ^{14}C ages were converted to calibrated ages using the "BChron" package for R (see text for more detail)

for 'old' carbon were made on these terrestrial macrofossils.

Organic geochemical analyses

One-hundred and thirty-six discrete samples were extracted from core BP2014-5D at 0.5-cm resolution, continuously from the sediment water interface to 68 cm depth. After freeze drying, samples were homogenized and extracted using a Dionex accelerated solvent extractor (ASE 200) with a solvent mixture of dichloromethane (DCM) and methanol (MeOH) (9:1, v/v). The resulting total lipid extract was then separated into apolar (9:1 hexane:DCM v/v), ketone (1:1 hexane:DCM v/v), and polar (1:1 DCM:MeOH v/v) fractions using alumina oxide column chromatography. PAHs were found to elute in the ketone fraction of each sample.

PAHs were identified and quantified on a Hewlett Packard 6890 series gas chromatograph coupled to an Agilent 5973 mass spectrometer (GC–MS) using a Restek Rtx-5 ms column (60 m \times 250 μm \times 0.25 μm). The oven program increased from 70 to 130 $^{\circ}\text{C}$ at a rate of 20 $^{\circ}\text{C min}^{-1}$, then from 130 to 320 $^{\circ}\text{C}$ at a rate of 4 $^{\circ}\text{C min}^{-1}$, and held at the final temperature of 320 $^{\circ}\text{C}$ for 20 min. Samples were run in Selected Ion Monitoring (SIM) mode, where ion masses of 17 PAHs were targeted (Table 2). Sixteen PAHs were identified from a RESTEK SV Calibration Mix PAH Standard, while an additional PAH was identified from a CHIRON AS standard (Table 2). External calibration curves were created for all 17 PAHs based on varying injection concentrations and were used to calculate PAH concentrations in core

BP2014-5D. Sedimentary compounds were identified by interpretation of characteristic mass spectra fragmentation patterns, relative retention times, and by comparison with the PAH standards and the literature. Levoglucosan, an organic biomarker that is commonly used to trace vegetation burning in sedimentary records (Fabbri et al. 2002; Lopes dos Santos et al. 2013; Shanahan et al. 2016), was searched for but not detected in the Basin Pond sediments.

Charcoal analysis

Macroscopic charcoal analysis was analyzed on the same core and at the same intervals as for organic geochemical analyses. 1 cm^3 of wet sediment was taken and soaked in a solution of 10% potassium hydroxide (KOH) solution for 2 weeks to oxidize non-charcoal organic matter, and then sieved over a 125 μm mesh (Enache and Cumming 2006; Schlachter and Horn 2010). Charcoal pieces per sample were counted using a microscope at 40 \times magnification. Charcoal classification was determined based on three criteria: the macrocharcoal in question had to have been completely black and reflective, breakable upon touch, and have organized plant cellular structure (Whitlock and Larsen 2001).

Results

Out of the 17 PAHs (Table 2) we searched for, 5 were not present in most samples, including naphthalene, acenaphthene, anthracene, indeno(1,2,3-cd) pyrene, and dibenz(ah)anthracene. Four PAH were found in

Table 2 PAH present in laboratory standards and searched for in Basin Pond sediments, with major ions for each compound

Retention order	Compound	Major ion	Standard used
I	Naphthalene	128	Restek
II	Acenaphthylene	152	Restek
III	Acenaphthene	153	Restek
IV	Fluorene	166	Restek
V	Phenanthrene	178	Restek
VI	Anthracene	178	Restek
VII	Fluoranthene	202	Restek
VIII	Pyrene	202	Restek
IX	Retene	219	Chiron
X	Benzo(a)anthracene	228	Restek
XI	Chrysene	228	Restek
XII	Benzo(b)fluoranthene	252	Restek
XIII	Benzo(k)fluoranthene	252	Restek
XIV	Benzo(a)pyrene	252	Restek
XV	Indeno(1,2,3-cd)pyrene	276	Restek
XVII	Dibenz(a,h)anthracene	278	Restek
XVI	Benzo[g,h,i]perylene	276	Restek

most samples throughout the record (benzo(b)fluoranthene, pyrene, retene, and chrysene). The remaining 8 compounds [phenanthrene, fluoranthene, benzo(k)fluoranthene, benzo(a)anthracene, acenaphthylene, benzo(a)pyrene, benzo[ghi]perylene, and fluorene] searched were mainly only found in the upper 15 cm of sediment.

PAH concentrations were calculated for each of the 12 detectible compounds. With the exception of retene, all the PAH distributions are similar, with extremely low concentrations ($0\text{--}0.1\text{ }\mu\text{g g}^{-1}$) below 15 cm. Concentrations begin to increase drastically from 15 cm and peak at roughly 5 cm depth ($1.0\text{--}1.6\text{ }\mu\text{g g}^{-1}$), before decreasing in concentration to levels observed at the top of the record ($0.6\text{--}1.0\text{ }\mu\text{g g}^{-1}$). Retene was the most abundant PAH present and varied in concentration from 0.1 to $10\text{ }\mu\text{g g}^{-1}$ throughout the record, with the largest peak in concentration occurring in the upper 5 cm of sediment. Charcoal counts varied from 8 to 254 pieces per cm^3 (cc), with the highest peak occurring in the upper 5 cm of sediment.

Discussion

Our analysis of the varved sedimentary record from Basin Pond reveals how local and regional fire history

can be recorded in Northeastern US lacustrine sediment records by organic biomarkers in comparison with sedimentary charcoal counts. We first examine the known historical wildfire data and subsequently provide an in-depth comparison of the Basin Pond macrocharcoal and PAH records. In the following discussion, we divide our records into three main periods: pre-historic (1100–1750 AD), historic (1750–1950 AD), and modern times (1950 AD to present day).

Historical wildfire data

In Maine, historical records document several large wildfire events ($> 400\text{ km}^2$) dating back to the mid-eighteenth century (Coolidge 1963). While these have occurred throughout the state, we will focus on large wildfires estimated to have occurred within 80 km of Basin Pond. The most recent outbreak in October 1947 AD saw numerous fires burn over 800 km^2 acres across southern Maine over a week, and became known as “The Week Maine Burned” (Butler 1979). The largest estimated wildfire during the historical period occurred in 1825 AD and became known as the “Miramichi Fire” (Butler 1979). During this event, an estimated $12,000\text{ km}^2$ of land was burned throughout Maine and New Brunswick, with roughly 3350 km^2 of land burned in central Maine; this was one of the largest

wildfires in North American history (Coolidge 1963; Butler 1979). The earliest known large wildfire events, noted in historical records, occurred in 1761–1762 AD throughout southern Maine. The estimated extent of these fire events is less well-constrained, as maps of the burn regions and historical accounts from individual towns do not all agree (Coolidge 1963). Nonetheless, the fires of 1761–1762 AD burned across much of the same areas that were burned during the 1947 AD fire outbreak (Fobes 1948; Fig. 1).

Age model considerations

A robust chronology is essential to compare the proxy records developed here with those of historical fires. While it appears that the varve chronology of Basin Pond is continuous, and the varve counts are in good agreement with the ^{210}Pb ages (Fig. 2), we note some differences with the radiocarbon ages. Four of the five radiocarbon dates trend slightly younger than the varve count chronology (Fig. 2), with 2 samples (BPR-022 and BPR-026) having calibrated ages and associated errors that fall entirely outside the varve count chronology (by 15 and 65 years, respectively). The most plausible explanation for the discrepancy involves the isotopic fractionation correction. Generally, in order to remove the effects of isotopic fractionation in radiocarbon analysis, the modern fraction of macrofossils is corrected to the value it would have if its original $\delta^{13}\text{C}$ were -25‰ , unless measured on each macrofossil sample. In laboratory analysis, $\delta^{13}\text{C}$ was unreported for all samples, so the fraction modern in each sample was corrected for isotopic fractionation using an estimated base value of -25‰ . With the exception of the basal sample, the Basin Pond macrofossils selected for analysis were eastern hemlock needles, which have $\delta^{13}\text{C}$ values of -29 to -30‰ (Domec et al. 2013). This difference can produce calibrated ages skewed younger by several decades. Other possible explanations for younger radiocarbon ages include slight error in the varve chronology or the minor inclusion of modern carbon during sample processing. With these issues in mind, we use the varve count chronology as the age model; we note that the varve chronology is in good agreement with the ^{210}Pb ages and that past studies of Basin Pond also utilized the varve chronology as an acceptable age model (Gajewski et al. 1987; Gajewski 1988; Clark et al. 1996; Frost 2005).

The basin pond charcoal record

Macroscopic charcoal analysis has commonly been employed in recent decades as an indicator of local fire activity (Whitlock and Larsen 2001). Wildfire characteristics, such as size and intensity, have large influences on charcoal production, distribution, and deposition in lacustrine sediment records. Other factors affecting charcoal transport and deposition in lakes include atmospheric patterns at the time of the fire (Gardner and Whitlock 2001) and distance from the lake. In light of these complex factors affecting charcoal abundance in lacustrine sediments, past studies have generally found that while large charcoal particles ($> 1000 \mu\text{m}$) tend to be deposited near a lake (Clark and Patterson 1997), smaller particles can be transported much greater distances. In large fires (with convective columns $> 1000 \text{ m}$), charcoal particles $< 200 \mu\text{m}$ can be transported tens of kilometers (Clark 1988; Whitlock and Larsen 2001). Despite this, there have been instances where charcoal analysis fails to detect either known fire events or events detected in other natural archives such as tree rings (Holz et al. 2012).

The Basin Pond charcoal record demonstrates large peaks occurring after both the 1947 AD and 1825 AD fire events (Fig. 3), even though the estimated ranges of burned area are thought to be outside the normally accepted range of macrocharcoal distribution. The most likely explanation is that the burn area estimates for the historical fire events, while reasonably accurate, do not represent all fires that took place in the region during those time periods. Importantly, these fire events were not one large fire, but were comprised of numerous smaller fires taking place at the same time (Coolidge 1963). The estimated burn areas of each are likely not all-inclusive, making it possible that the 1947 AD and 1825 AD fires could have been within range of Basin Pond for a charcoal signal to be recorded. In the pre-historic record, elevated charcoal abundances occur during a period from 1520 to 1630 AD, indicating a possible time of increased local fire activity (Fig. 4).

Basin pond PAH records

A major feature of the Basin Pond record is a dramatic increase in all PAH concentrations between pre-historic and historic times (Figs. 3, 4), which is related

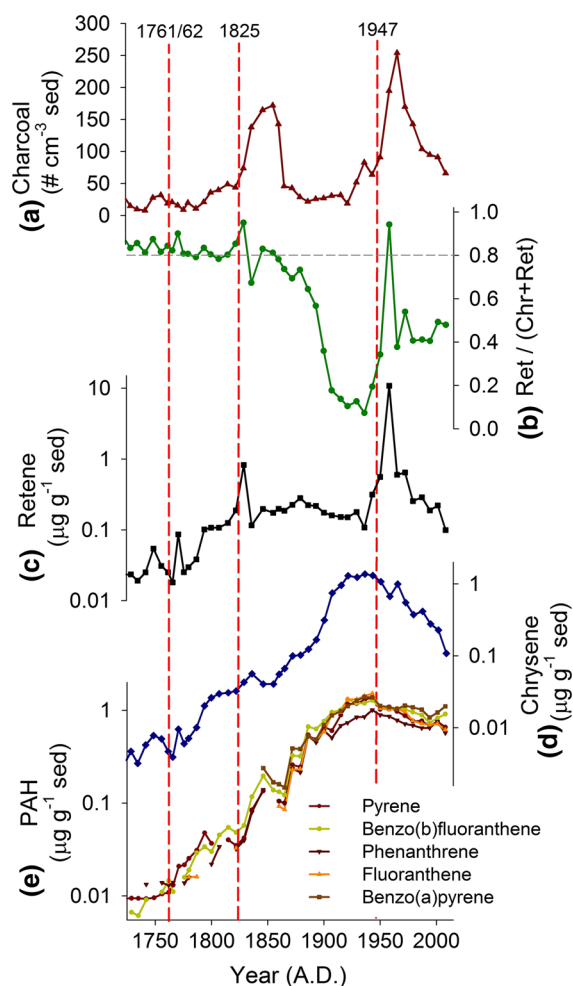


Fig. 3 Fire reconstructions from the historical period (1725 AD to present day). From top to bottom: charcoal counts per cm^3 sediment (red triangles), the retene/(chrysene + retene) ratio (green circles), retene concentrations (black squares), chrysene concentrations (blue diamonds), and the top 5 most abundant PAH (excluding retene and chrysene) measured in the sedimentary record. All PAH concentrations are reported in $\mu\text{g g}^{-1}$ sediment extracted. (Color figure online)

to increased population and industrialization of the region. Industrialization is likely the driving factor of the simultaneous increases in all PAHs in the mid-nineteenth century (Fig. 3), as coal and other fossil fuels were increasingly used in the region. Furthermore, population increases led to more wood being used as a heat source during winter months, which possibly also led to higher PAH concentrations. It is important to note, however, that retene shows a slightly different distribution than the other PAHs.

Retene is produced from the breakdown of abietic acid, which is prevalent in conifer tree resin (Ramdahl 1983; Ahad et al. 2015). Conifers are an important component of ecosystems in the Basin Pond region (Ramdahl 1983; Denis et al. 2012). While forest composition across the region has been significantly altered in historical times due to human activity, a well-balanced mixture of conifers (hemlock, pines, and spruce) was dominant in pre-settlement times throughout central and southern Maine (Cogill et al. 2002). Furthermore, past studies on the Basin Pond sedimentary record indicate conifers have been abundant throughout the past millennia, ranging from 15–25% in historical times to 30–40% in pre-historic times (Gajewski et al. 1987). While it is important to recognize these ranges are based on pollen distributions and are approximate estimates, it is evident that conifers have dominated forest composition over the past millennia at this site. Thus, we interpret retene as an indicator of regional biomass burning throughout the period of record. The retene record exhibits several sharp increases in concentration superimposed on the overall increasing trend following the fire outbreaks of 1761–1762 AD, 1825 AD, and 1947 AD (Fig. 4).

One issue that arises with interpreting PAH distributions in relation to biomass burning is that PAHs can be produced by multiple sources (biomass burning or fossil fuel combustion). The retene/(chrysene + retene) ratio (hereafter $R/C + R$) aids in delineating between combustion sources and can also be a more robust indicator of past fire history than individual PAH concentrations alone, which can show greater variability due to multiple sources (Yan et al. 2005; Kuo et al. 2011). The $R/C + R$ ratio has been utilized to distinguish fossil fuel combustion (ratio values of 0.15–0.5) and biomass combustion (values > 0.8) as primary sources of PAHs (Yan et al. 2005; Kuo et al. 2011; Denis et al. 2012). All Basin Pond pre-historic samples have $R/C + R$ ratios above 0.8, indicating that PAHs largely derive from biomass burning (Fig. 4). Entering the historic period, the ratio shows a steady decrease in the mid-nineteenth century from pre-historic levels (0.95–0.99) to < 0.6 , only disrupted by a sharp increase to above 0.95 after the 1825 AD fire. Values drop drastically as industrialization of the region accelerated, and remained lower than 0.8 in all but one sample through the rest of the historic period and modern times (Fig. 3). The sample following the 1947 AD fire is the only sample in

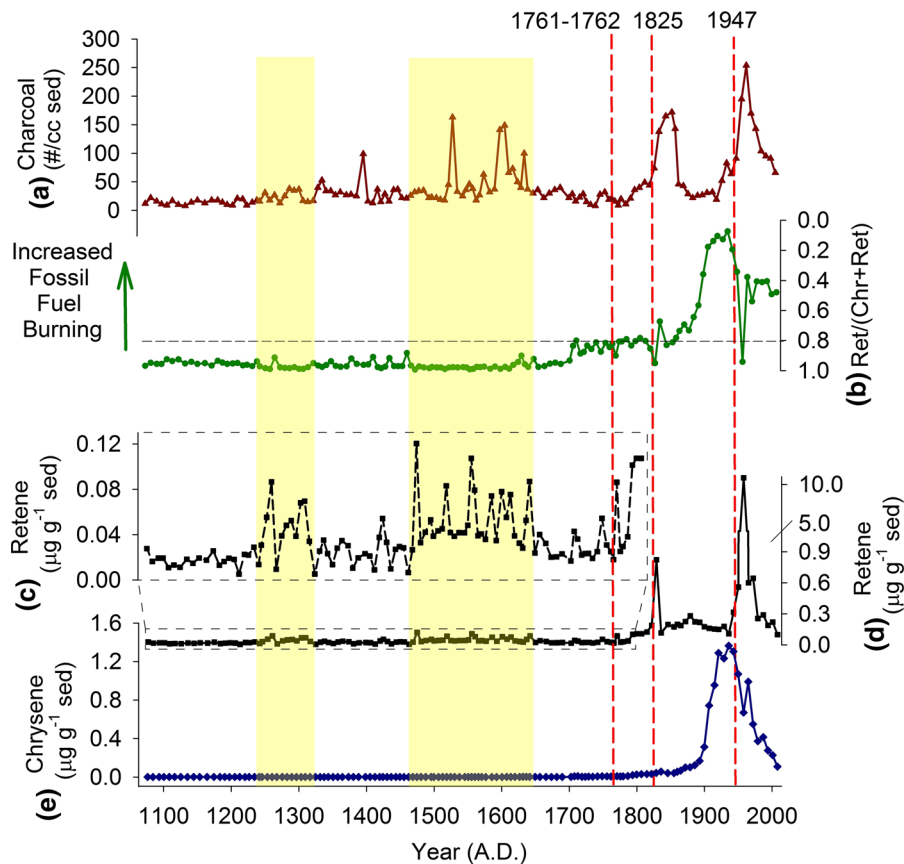


Fig. 4 Fire reconstructions from Basin Pond, ME since 1100 AD; **a** charcoal counts per cm^3 sediment (red triangles), **b** the retene/(chrysene + retene) ratio (green circles), **c**, **d** retene (black squares and black dashed squares) and **e** chrysene concentrations (blue diamonds), measured in $\mu\text{g g}^{-1}$ sediment extracted. Due to the drastic increase in retene concentrations in the historic period from background levels, pre-historic retene has been plotted twice (dashed black line) in **c**, **d**. Note the difference in the y-axis scale between plots **c**, **d** and also the scale break in plot **d**. The retene/(chrysene + retene) ratio,

shown in plot **b**, used as an indicator of PAH combustion source, remains above 0.8 throughout the pre-historic record, while decreasing below 0.8 from regional industrialization marked with several increases to above 0.8 following fire events (0.8 marked by dashed, horizontal line). Fire events of 1761–1762 AD, 1825 AD, and 1947 AD are marked by dashed vertical lines. Increased periods of fire activity outside of those noted in historical records, which are suggested by our data, are shaded in yellow. (Color figure online)

modern times to reach above 0.8. Therefore, the $R/C + R$ ratio appears to track wildfire activity in the region quite well during the historical and modern periods and results are consistent with wildfire events noted by retene concentrations.

Comparison of wildfire proxies

Two of three known regional wildfire events (the 1825 AD and 1947 AD fires) are evident in the Basin Pond retene and charcoal records. The 1761–1762 AD fires, while evident in the retene record, are not apparent in the charcoal record (Fig. 4). The 1761–1762 AD event

is the earliest known wildfire outbreak in the region, and information on the estimated range and magnitude of the fires is limited (Coolidge 1963). If the 1761–1762 AD event was of smaller magnitude or farther from the site than historical records indicate, distribution of charcoal would be limited.

The macrocharcoal and retene concentrations show a strong similarity throughout time, with both records suggesting coeval periods of increased fire activity (Fig. 4). However, one noticeable difference is that the retene record shows more variability, supporting the idea that each proxy is tracking wildfires on different spatial scales. PAH signals can be indicative of

regional events, as PAHs can be moved much greater distances through aeolian transport than macroscopic charcoal (Page et al. 1999). Therefore, it is likely that retene is tracking regional fire events, while charcoal is primarily tracking fires closer to Basin Pond. The best example of this discrepancy between records occurs during the period of increased fire activity from 1520 to 1630 AD, where several peaks in the charcoal record indicate increased burning whereas in the retene record, the timing of this increase is slightly longer (Fig. 4). The period of increased fire activity in the retene record is evident from 1470 to 1640 AD, beginning almost 40 years prior and ending slightly earlier to that indicated by the charcoal record. This suggests that while local burning began roughly 500 years ago, regional events had been occurring for several decades prior. Furthermore, another increased period of fire activity is present in the retene record from 1240 to 1320 AD, but is not present in the charcoal record (Fig. 4), indicating that while there were regional fires during this period, there was seemingly no local fire activity.

One interesting difference between the two proxies is the lag of the charcoal peaks in comparison to retene after the 1825 AD and 1947 AD fire events. In both fire events, retene concentrations exhibit maximum values 4 and 9 years after the fire, respectively. However, in the charcoal record, this peak is delayed to 20 and 17 years, respectively. Since all charcoal and PAH samples were from the same depths, this suggests that these offsets are real. We hypothesize that this is caused by charcoal and PAH having differing transport and environmental residence times. Lag times associated with charcoal deposition in sedimentary records are a common occurrence, with lags on the order of several years (Whitlock and Millspaugh 1996) to several decades (Patterson et al. 1987). In Basin Pond sediments, retene demonstrates sharp increases in activity almost immediately after the wildfire events, while charcoal shows a more gradual increase over several samples, suggesting that retene is a more rapid indicator of wildfires in a sedimentary record than charcoal.

Retene: A proxy for regional wildfire activity?

Our data support that retene concentrations are a useful proxy for wildfire activity in the Basin Pond record over the past 900 years, yet caution must be

taken when applying this proxy to longer time scales due to the nature of PAH production. PAH profiles are specific to the type of organic matter being combusted (Yang et al. 2007). In the case of retene, a large shift in regional forest composition over time may impact the PAHs produced from biomass burning. In the Northeastern US, large shifts in forest composition have occurred throughout the Holocene, including regional hemlock declines (Foster et al. 2006) or European deforestation in recent centuries (Foster and O'Keefe 2000). These shifts may alter the sedimentary PAH profiles and thus influence how PAHs trace fire activity in the region. Therefore, we suggest more research should be done on PAHs in lacustrine records in the Northeastern US over longer time scales to investigate how large-scale vegetation changes over time may alter sedimentary PAH distributions and the effects on how wildfire histories are recorded.

Conclusions

Our analysis of the varved Basin Pond sedimentary record reveals generally good agreement between charcoal counts and retene concentrations with historical records of past large fire events occurring in 1761–1762 AD, 1825 AD, and 1947 AD in central and southern Maine. We find that retene tracks regional fire activity while macrocharcoal counts track localized burning. A dramatic increase in PAH concentrations is seen coincidentally with industrialization of the region in the historic period (1750 AD—present day). To distinguish between PAH sources, the retene/(chrysene + retene) ratio allowed for the distinction of regional fire events from fossil fuel combustion. Although there are differences between the timing of fire events indicated by the retene and charcoal records, overall similarities between these records highlight the potential of using retene as a proxy for wildfire activity in the Northeastern US. Furthermore, the use of retene and the retene/(chrysene + retene) ratio is a novel method to tracking wildfires in the Northeastern US, and should be investigated in more detail in future wildfire studies in this region, focusing on longer timescales and different ecosystems.

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