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Invited Research Article

Preservation biases are pervasive in Holocene paleofire records

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ABSTRACT

Fire and its controls span several spatial and temporal scales in the Earth System and sedimentary paleofire archives are the primary means of inferring how fire varies on timescales exceeding observational records. However, our understanding of the biases affecting paleofire records remains limited. We address this gap by assembling a dataset of Holocene paleofire records to test whether preservation biases interfere with paleofire interpretations. The dataset contains 40 records composed of a total of 17,225 charcoal accumulation rate (CHAR) samples. We find that the "Sadler effect," which is the observation that sedimentation rates decrease systematically when measured over longer timescales due to the incorporation of sedimentary hiatuses, is pervasive in these paleofire records. In the compiled dataset, the age ranges of measurement share a negative power law relationship with both accumulation rate (AR; AR = 0.4018*[sample age range]$^{-1.09}$) and CHAR (CHAR = 1.118*[sample age range]$^{-0.6655}$), indicating that longer time spans of measurement are more likely to incorporate longer period hiatuses into sediment records. This biases AR measurements, which subsequently bias CHAR values. Indeed, more than half of the paleofire records ($n = 21$) are composed of CHAR values which share a statistically significant negative relationship with the sample age range of their measurement. To our knowledge, our results are the first to identify this sedimentary bias in Holocene paleofire records. As a solution, we therefore provide an interpretative framework which outlines necessary steps to identify preservation bias in paleofire records and intervals. Lastly, we explore the implications of these findings for paleofire research.

1. Introduction

The occurrence and controls of fire operate across spatial and temporal scales in the Earth System (Bowman et al., 2009; Falk et al., 2007; Scott et al., 2014; Whitlock et al., 2010). Fire has been an Earth System phenomenon since the Silurian (Glasspool et al., 2004), and has since become an important control of global biogeography (Bond et al., 2004; Pausas and Ribeiro, 2013) and the evolution of plants (Bond and Keeley, 2005; Keeley and Rundel, 2005). Additionally, modern humans also directly affect fire variability via ignition and land management (Balch et al., 2017; Bowman et al., 2011) as well as indirectly via anthropogenic climate change (Barbero et al., 2015; Liu and Wimberly, 2016; Moritz et al., 2012). On longer timescales, humans have also been shown to impact fire activity across a range of spatial scales (Carter et al., 2021; Taylor and Scholl, 2012; Vachula et al., 2019). Sedimentary paleofire records play a vital role in understanding the variability of fire on timescales exceeding observational and dendrochronological records (Marlon, 2020; Scott, 2000; Scott et al., 2014).

Incomplete combustion produces by-products which can be preserved in sediments and used to make paleofire inferences. These paleofire proxies include macroscopic particulates such as inertinite and charcoal (Glasspool and Scott, 2010; Scott, 2000; Whitlock and Larsen, 2002), microscopic particulates such as soot or black carbon (Masiello, 2004; Thevenon et al., 2010; Wolf et al., 2014), and biomarkers such as polycyclic aromatic hydrocarbons (PAHs) (Denis et al., 2017; Karp et al., 2018). A thorough understanding of the spatial and temporal representation of these fire proxies is needed to make reliable interpretations of fire variability (Conedera et al., 2009; Remy et al., 2018), but many uncertainties remain regarding the preservation and fidelity of these proxies as recorders of fire history (Karp et al., 2020; Vachula, 2021; Vachula et al., 2018).

In addition to the potential preservation biases of these fire proxies,

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sedimentary archives can also bias paleoenvironmental inferences (Behrensmeyer and Kidwell, 1985; Kemp and Sadler, 2014). For example, a global surge in global fire activity thought to have begun in the late Neogene (ca. 7 Ma) (Herring, 1985) has been identified as the likely driver of the expansion of pyrophytic C4 grasslands and savannahs (Bond, 2015; Hoetzel et al., 2013; Keeley and Rundel, 2005). However, Vachula and Cheung (2021) recently showed that the inferences of increased fire activity since the late Neogene could alternatively be attributed to systematic sedimentary preservation biases.

The sedimentary bias identified by Vachula and Cheung (2021) in marine charcoal fluxes is a permutation of the "Sadler effect," which is the observation that sedimentation rates systematically decrease when made over longer time scales due to the incorporation of hiatuses (Sadler, 1999, 1981). For example, observations of global terrigenous sedimentation to the ocean would suggest exponential increases in the last 10 Ma in the context of the Cenozoic (Hay et al., 1988). However, a growing body of research shows that this recent increase of sedimentation is in fact a manifestation of the Sadler effect (Schumer and Jerolmack, 2009; Willenbring and Jerolmack, 2016).

Our understanding of fire across temporal scales has been increasingly highlighted as an area needing further research in the paleofire community (McLauchlan et al., 2020; Whitlock et al., 2010). Indeed, sedimentary records are helpful in resolving fire across temporal scales and help to inform future projections, but they require benchmarking as their sedimentation rates and physical sampling limitations can exceed observational timescales (Power et al., 2008). Importantly, we need to determine if sedimentary paleofire archives can record fire on different timescales faithfully. Although climate and fire models are informative in their projection of future fire scenarios in response to climate change (Liu and Wimberly, 2016; Rabin et al., 2017), they still require benchmarking with empirical data and must be informed by observational data (Hantson et al., 2016). Similarly, paleofire data can help to test the results of fire models, emissions datasets, and the imposed forcing in climate models (e.g., black carbon, aerosols) on historical timescales (Cheung et al., 2021; Liu et al., 2021; Molinari et al., 2021). Therefore, research resolving how fire varies and responds to forcing across time scales, as well as our ability to resolve these behaviors, is paramount to informing our understanding of future fire response to anthropogenic climate change.

Although some work has shown that paleofire inferences spanning millions of years are susceptible to sedimentary biases (Vachula and Cheung, 2021), the ability (and/or inability) of paleofire records to be reliably used to assess cross-scale temporal variability on shorter (decadal to multimillennial) time scales remains relatively unexamined, despite the fact that the bulk of paleofire records date to the Holocene. In this paper, we address this knowledge gap by collating a dataset of these paleofire records and determining whether preservation biases could interfere with paleofire interpretations.

2. Methods and data

Sedimentary charcoal data were downloaded from the World Data Center for Paleoclimatology (https://www.ncei.noaa.gov/products/paleoclimatology) between November 2020 and February 2021. By using the site's search tool and setting the biological material variable to "charcoal," datasets were examined and vetted for inclusion. To facilitate a comparison of sample age ranges of measurement with charcoal accumulation rates, only data including both top and bottom ages and depths of each sample were included in this analysis. This meant that many of the datasets that were initially screened ended up excluded as they did not provide the necessary information. Notably, the downloaded datasets included these data predominantly to facilitate peak analysis of charcoal accumulation rate time series (Higuera, 2009; Higuera et al., 2007). At the time of downloading, these search parameters yielded a total of 149 results, 47 of which included the necessary data for inclusion in the compiled dataset. The charcoal particles quantified in these studies were either >120, 125 or 180 μm in size, and so would typically be considered macroscopic charcoal particles (Vachula, 2019). Although meeting the necessary data requirements, six records (West Crazy, Latitude, Chopper, Granger, Noir, and Reunion) were rejected from the compiled dataset as they included numerous instantaneous deposition (slump) events (Kelly et al., 2013). For the remainder of the records, any null values were removed. Discrete slump intervals were removed from the Lucky, Picea, and Screaming Lynx records.

For each sediment sample, accumulation rates (AR) and charcoal accumulation rates (CHAR) were calculated using the following equations:

$$AR = \frac{bottom\ depth - top\ depth}{bottom\ age - top\ age} \quad (1)$$

$$CHAR = \frac{\#\ of\ particles}{volume\ of\ sediment\ (cm^3)} \bullet AR \quad (2)$$

Following Vachula and Cheung (2021), we compared the calculated AR and CHAR data with the sediment age and sample age range of measurement (difference between top and bottom age of each sample). To determine if AR and CHAR exhibit power law dependence on sample age range, which is indicative of incomplete sediment records, we fit power law regressions to these data using MATLAB. Additionally, we used Ordinary Least Squares (OLS) regression to characterize the relationships between CHAR and sample age range for each record in the dataset. The R^2 metric derived from OLS regression allows for the characterization of how much variation of CHAR can be explained by sample age range alone. Null hypothesis testing (with a threshold of $p < 0.05$) was used to assess the significance of the OLS regression results. Standard errors associated with the OLS results are heteroskedasticity robust, as we report Huber-White standard errors (Long and Ervin, 2000).

3. Results: compiled dataset and trends

The compiled dataset is composed of 40 sedimentary charcoal records and a total of 17,225 charcoal accumulation samples. These records are primarily located in western North America, with concentrations in Alaska and the Rocky Mountains (Fig. 1). The geographical clustering reflects the fact that most of the charcoal records fitting our criteria were constructed by authors and labs focusing on these regions. We underscore that the data needed to undertake our analysis (top and bottom depths/ages) is not always included in other relevant databases (e.g., Neotoma or the Global Paleofire Database (Power et al., 2010; Williams et al., 2018)) which could provide a more globally representative dataset. This shortcoming highlights the need to adopt more comprehensive and standardized data reporting in paleofire research (Hawthorne et al., 2018; Khider et al., 2019). Nonetheless, the charcoal records we compiled are primarily derived from lacustrine sediments and vary in terms of their temporal resolution, span, and sample number (Table 1). Although all of the charcoal records used radiocarbon dating to compute age-depth models, the number of age control points and the additional use of ^{210}Pb dating varied between records, as did resulting age model uncertainties (Table 1).

The compiled dataset shows that recent CHAR values greatly exceed those of the geologic past (Fig. 2). Namely, in the context of the last 12,000 years, the compiled dataset shows that CHAR values precipitously increase in the last 4000 years (Fig. 2A). In contrast, when considering only CHAR values dating to the last 1200 years, no such increase is present (Fig. 2B). Overall, the compiled dataset illustrates that across the 40 records considered, recent CHAR values are considerably greater in the context of the Holocene.

We find that the age range of measurement and AR share a negative power law relationship ($AR = 0.4018*[sample\ age\ range]^{-1.09}$; Fig. 3A). Additionally, CHAR and the age range of measurement also share a

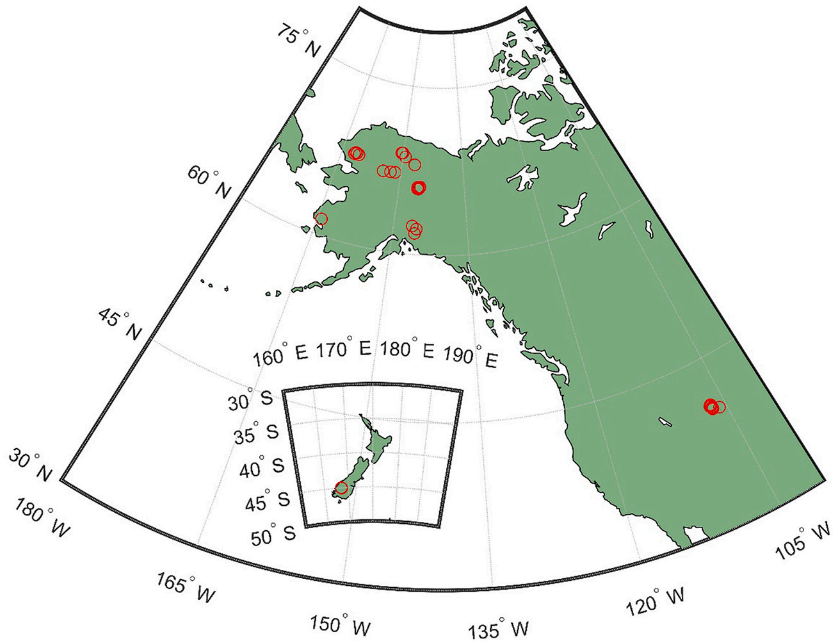

Fig. 1. Spatial distribution of compiled sedimentary charcoal datasets. Spatial distribution is geographically limited because the bulk of publicly available charcoal data do not include the necessary metadata for inclusion in our dataset (i.e. top and bottom ages and depths for each sample).

negative power law relationship ($CHAR = 1.118*[sample\ age\ range]^{-0.6655}$; Fig. 3B). These observations show that longer age ranges of measurement are more likely to incorporate longer period hiatuses into sediment records, and in doing so, bias AR measurements, which subsequently bias CHAR values.

Ordinary Least Squares (OLS) regression of CHAR on sample age range for each paleofire record in our compiled dataset shows that the Sadler effect biases nearly half of the records, with varying influence between each record. If there were no Sadler Effect biasing these measurements, there would be no correlations between these two variables; sample age range of measurement would not share a relationship with CHAR. However, of the 40 charcoal records in our compiled dataset, 21 display a significant negative correlation, with $p < 0.05$, between CHAR and sample age range of measurement (Fig. 4; Supplementary Information). Of the regression results that are significant, all of them have a negative coefficient, with a strong inverse correlation between sample age range and CHAR.

4. Discussion

4.1. Sedimentary bias affects Holocene paleofire records

Although the marked increase of recent CHAR values evident in Fig. 2 could reflect a veritable rise of fire activity in recent millennia (Han et al., 2020; Marlon, 2020; Mercuri et al., 2019; Vannière et al., 2016; Zhou et al., 2014), we must also consider that such an increase could result from the inflation of CHAR values due to the increased completeness of younger relative to older stratigraphic sections (Vachula and Cheung, 2021). Sedimentary hiatuses and periods of net erosion are more likely to be captured when measurements are made across longer age ranges, causing calculated sedimentation rates to systematically decrease (Paola et al., 2018; Sadler, 1981; Tipper, 2016). Conversely, more recent records are less likely to have been affected by periods of erosion or hiatus, making them more complete. Empirically, these accumulation rates share a negative power law relationship with their age range of measurement (Sadler, 1999), which highlights that this effect is important when considering data that span several temporal scales. We observe here that this effect also applies to paleofire proxies. Our comparison of the AR and CHAR values with the age range of their measurement reveals that the Sadler effect is present in these Holocene sediment records when considered in aggregate (Fig. 3) as well as when investigated individually (Fig. 4). Whereas the increased CHAR values of recent millennia might be thought to reflect increased fire activity alone, which is indeed supported by much previous research (Han et al., 2020; Marlon, 2020; Mercuri et al., 2019; Vannière et al., 2016; Zhou et al., 2014), our analyses suggest this may not the case. Rather, we propose that the Sadler effect is likely responsible for a component of the increased CHAR signal of recent millennia due to the increased preservation of more recent sediments relative to older sediments, leading to significant negative correlation between two variables that, in theory, should be uncorrelated.

To our knowledge, our results are the first to identify this sedimentary bias in Holocene paleofire records. Previous work has identified the effects of sedimentary biases on paleofire records spanning multi-million-year timescales (Vachula and Cheung, 2021), and other work has identified the impact of sedimentary biases on Quaternary sediments (Durkin et al., 2018; Glaser et al., 2012; Madof et al., 2019), but to our knowledge, little research has explored the possibility of sedimentary biases in Holocene paleofire records. Notably, an early examination of accumulation rates in mires and lakes of eastern North America found that accumulation rates dating to the last 330 years exceeded those of the preceding 17,000 years by four to five times (Webb and Webb III, 1988). Indeed, this observed log-normality of sediment accumulation rates was attributed to the phenomenon now referred to as the Sadler effect (Webb and Webb III, 1988), but to our knowledge no assessments have been made to assess the impact of these observations on paleofire inferences. We speculate that this may be due to both the difficulty of identifying hiatuses in lake sediment records (Schnurrenberger et al., 2003) and the underlying assumption that sediment records retrieved for paleoenvironmental study reflect generally constant accumulation (Blaauw and Heegaard, 2012; Webb and Webb III, 1988).

4.2. Detecting sedimentary biases in paleofire records

The dependence of AR and CHAR values on their measurement interval (sample age range) marks an important problem for the

Table 1
Datasets included in the compiled dataset and relevant geographical, sedimentological and paleofire data.

Site	Latitude, Longitude	Elevation (m asl)	Age range (years cal BP)	Total core length (cm)	Number of samples	Mean (std dev) depth resolution (cm)	Mean (std dev) age resolution (yr)	Sieve Size (μm)	Radiocarbon age control points (#); ^{210}Pb (Y/N)	Mean (std dev) sample age uncertainty range (yr)#	Publication
Hudson	61.90, −145.67	860	7053 to −55	416.0	674	0.58 (0.20)	9.2 (5.9)	>180	13; Y	–	(Barrett et al., 2013)
Gem	40.88, −106.73	3101	1544 to −62	95.5	191	0.50 (0)	7.3 (3.6)	>125	4; N	–	(Calder et al., 2015)
Super Cub	62.30, −145.35	486	6784 to −57	156.5	536	0.29 (0.09)	12.8 (4.8)	>180	7; Y	–	(Barrett et al., 2013)
Gold Creek	40.78, −106.68	2917	2073 to −62	126.0	126	1.00 (0)	16.9 (5.5)	>125	5; Y	–	(Calder et al., 2015)
Minnesota Plateau	62.54, −146.24	827	7013 to −56	220.0	440	0.50 (0)	16.1 (3.4)	>180	8; Y	–	(Barrett et al., 2013)
Hidden	40.50, −106.61	2704	2176 to −54	102.0	102	1.00 (0)	21.9 (2.7)	>125	3; N	–	(Calder et al., 2015)
Hinman	40.77, −106.83	2501	1738 to −62	83.0	83	1.00 (0)	21.7 (16.2)	>125	3; Y	–	(Calder et al., 2015)
Loon	67.93, −161.97	90	3003 to −64	196.0	771	0.25 (0.03)	4.0 (0.9)	>120	4; Y	–	(Chipman and Hu, 2017)
Perch	68.94, −150.50	400	9467 to −58	209.5	419	0.50 (0)	22.7 (13.3)	>125	10; Y	–	(Chipman et al., 2015)
Kirkpatrick	−45.03, 168.57	570	1537 to −63	192.0	192	1.00 (0)	51.2 (32.8)	>125	13; N	51.2 (32.8)	(McWethy et al., 2014)
Dimple	68.95, −150.20	400	1184 to −58	104.0	394	0.26 (0.08)	3.2 (0.6)	>180	8; Y	–	(Hu et al., 2010)
Perch 2	68.94, −150.50	400	4912 to −58	89.3	337	0.26 (0.06)	14.7 (3.2)	>180	4; Y	–	(Hu et al., 2010)
Dukes Tarn	−44.96, 168.49	830	808 to −61	167.0	167	1.00 (0)	122.2 (44.2)	>125	9; N	122.2 (44.2)	(McWethy et al., 2014)
Eileen	40.90, −106.67	3135	2686 to −62	116.0	116	1.00 (0)	23.7 (7.5)	>125	6; N	–	(Calder et al., 2015)
Middle Rainbow	40.65, −106.62	3001	2229 to −61	88.0	88	1.00 (0)	26.0 (14.8)	>125	3; N	–	(Calder et al., 2015)
Round	40.47, −106.66	3071	3616 to −62	119.9	240	0.50 (0.01)	15.3 (6.9)	>125	4; N	–	(Calder et al., 2015)
Seven	40.90, −106.68	3276	4243 to −60	128.0	256	0.50 (0)	16.8 (5.8)	>125	5; N	–	(Calder et al., 2015)
Summit	40.55, −106.68	3149	2892 to −60	81.5	163	0.50 (0)	18.1 (9.0)	>125	6; Y	–	(Calder et al., 2015)
Teal	40.58, −106.61	2689	1837 tp −61	95.5	96	0.99 (0.05)	19.8 (12.9)	>125	4; N	–	(Calder et al., 2015)
Tiago	40.58, −106.61	2700	2899 to −46	130.5	248	0.50 (0)	11.4 (5.9)	>125	4; Y	–	(Calder et al., 2015)
Whale	40.56, −106.68	3059	2354 to −61	101.0	101	1.00 (0)	23.9 (9.4)	>125	6; N	–	(Calder et al., 2015)
Epilobium	65.97, −145.57	366	3711 to −59	112.5	410	0.27 (0.07)	9.2 (3.4)	>180	5; Y	–	(Kelly et al., 2013)
Jonah	66.07, −145.08	274	3218 to −58	169.8	629	0.27 (0.07)	5.2 (1.1)	>180	3; Y	–	(Kelly et al., 2013)
Landing	65.90, −145.78	394	7256 to −58	109.0	406	0.27 (0.07)	18.0 (4.3)	>180	4; Y	–	(Kelly et al., 2013)
Lucky	66.02, −145.53	366	1865 to −58	106.8	391	0.27 (0.07)	4.9 (1.6)	>180	2; Y	–	(Kelly et al., 2013)
Picea	65.88, −145.59	269	10,369 to −58	151.0	565	0.26 (0.06)	18.5 (10.0)	>180	6; Y	–	(Kelly et al., 2013)
Robinson	65.97, −145.70	304	2112 to −59	106.8	397	0.27 (0.07)	5.5 (0.9)	>180	2; Y	–	(Kelly et al., 2013)
Screaming Lynx	66.07, −145.40	276	10,642 to −57	390.3	1512	0.26 (0.04)	7.1 (4.1)	>180	11; Y	–	(Kelly et al., 2013)
Windy	66.04, −145.75	245	2808 to −58	109.8	399	0.28 (0.08)	7.2 (2.6)	>180	3; Y	–	(Kelly et al., 2013)
Keche	68.02, −146.92	740	11,487 to −57	321.0	1243	0.26 (0.04)	9.3 (1.4)	>125	5; Y	–	(Chipman et al., 2015)
Tungak	61.43, −164.20	25	35,433 to −62	353.5	707	0.50 (0)	50.2 (49.5)	>125	5; Y	–	(Chipman et al., 2015)
Upper Capsule	68.63, −149.41	800	12,103 to −47	328.0	315	1.00 (0)	36.8 (14.1)	>125	6; N	–	(Chipman et al., 2015)
Chickaree	40.33, −105.85	2796	4508 to −60	604.7	1201	0.50 (0.03)	3.8 (1.2)	>125	25; Y	138.9 (50.9)	(Dunnette et al., 2014)
Little Isac	67.94, −160.80	210	3000 to −57	55.3	191	0.29 (0.09)	16.0 (5.3)	>180	9; Y	325.1 (71.7)	(Higuera et al., 2011)
Poktovik	68.03, −161.37	160	3002 to −57	70.8	233	0.30 (0.15)	13.1 (9.9)	>180	9; Y	193.2 (55.9)	(Higuera et al., 2011)

(continued on next page)

Table 1 (*continued*)

Site	Latitude, Longitude	Elevation (m asl)	Age range (years cal BP)	Total core length (cm)	Number of samples	Mean (std dev) depth resolution (cm)	Mean (std dev) age resolution (yr)	Sieve Size (μm)	Radiocarbon age control points (#); ^{210}Pb (Y/N)	Mean (std dev) sample age uncertainty range (yr)[#]	Publication
Raven	68.05, −161.73	118	3008 to −57	80.8	301	0.27 (0.05)	10.2 (2.6)	>180	8; Y	160.5 (73.9)	(Higuera et al., 2011)
Ruppert	67.07, −154.25	230	13,960 to −52	482.8	1062	0.45 (0.11)	13.2 (5.8)	>180	17; Y	–	(Higuera et al., 2009)
Uchugrak	68.05, −161.73	21	3004 to −57	103.0	392	0.26 (0.06)	7.8 (1.4)	>180	8; Y	141.3 (49.0)	(Higuera et al., 2011)
Wild Tussock	67.13, −151.38	290	7841 to −53	151.5	551	0.27 (0.08)	14.3 (5.3)	>180	6; N	–	(Higuera et al., 2009)
Xindi	67.11, −152.49	240	18,033 to −53	290.0	580	0.50 (0)	31.2 (25.6)	>180	10; Y	–	(Higuera et al., 2009)

[#] "-" values denote studies for which sample-scale age uncertainty values were not reported.

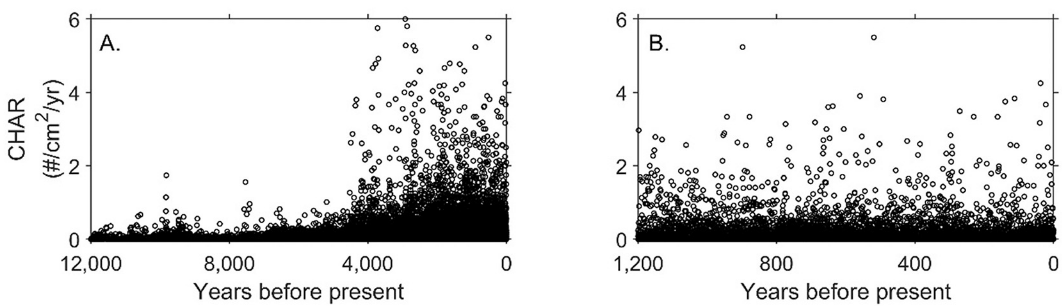

Fig. 2. Age distribution of compiled charcoal accumulation rate measurements at two temporal scales. Precipitous increases of recent CHAR values exist when viewing the data in the context of the Holocene (A). At centennial timescales, no such increase of more recent CHAR values is evident (B).

interpretation of these metrics. Importantly, this means CHAR values may fluctuate as a function of the scale of the measurement interval (sample age range), as opposed to actual fire activity. Our OLS regression results show that the ability of sample age range to explain the variations of CHAR values is not homogenous but varies between individual paleofire records. This additional source of uncertainty has important implications for our ability to reconstruct fire activity from sedimentary records. Unfortunately, it is difficult to unequivocally correct for these uncertainties (Schumer and Jerolmack, 2009; Vachula and Cheung, 2021). However, we can provide a solution in the form of relatively straightforward steps to identify potentially biased patterns in individual records and therefore to prevent problematic interpretations. Using two examples of paleofire records included in our compiled dataset, Screaming Lynx and Tungak, we outline necessary steps of an interpretative framework to (1) recognize a significant Sadler effect bias in a paleofire record and (2) identify intervals wherein CHAR values may be inflated or deflated by a preservation and sampling bias. This interpretative framework thereby serves as a solution to the problems posed by Sadler effect bias on paleofire records.

To determine if an individual charcoal record could contain a Sadler effect bias and to quantify its impact on CHAR values, one must determine if the sample age ranges of measurement and corresponding CHARs share a statistically significant negative relationship. Both of our example datasets, Screaming Lynx and Tungak (Fig. 5), exhibit a negative power law relationship, indicating a possible preservation bias affecting CHAR values. OLS regression shows that in both Screaming Lynx and Tungak, sample age range and CHAR are significantly negatively correlated, an indication of present bias. By comparing the sample age range of charcoal samples with the CHAR values (Fig. 6), we can identify intervals of sedimentation which could be inflated or deflated by the Sadler effect. By identifying periods in the records when notable changes in CHAR values correspond with changes of the age ranges of their measurement, one can determine potential zones of preservation-driven CHAR biases. For example, in the last 500 years of the Screaming Lynx record, the increases of CHAR correspond to significant decreases of the sample age range of measurement, indicating the potential of preservation bias inflating these CHAR values. Similarly, ca. 12,000 years before present in the Tungak record, an increase in the magnitude of CHAR values corresponds with a similarly pronounced decrease of sample age ranges of measurement, indicating that these CHAR values may be inflated by preservation biases. Conversely, the greatest sample age ranges of measurement in the Screaming Lynx record occur between 9000 and 6000 years before present, when CHAR values are also the lowest, which could indicate that preservation biases have deflated these CHAR values. By following these same steps in the analysis of other paleofire records, one can identify the potential impacts of preservation biases on CHAR values and modify paleofire interpretations accordingly. In this way, this interpretative framework provides a diagnostic solution to minimize the impacts of preservation biases in charcoal-based paleofire research.

Age control is an important additional consideration for minimizing the impacts of preservation biases in paleofire records. Good age control can minimize age uncertainties and the variability of sample age ranges. In this sense, age control is itself a preemptive solution to the problems posed by preservation biases. Likewise, although hiatuses are difficult to identify in lacustrine sediments (Schnurrenberger et al., 2003), additional age control can help to pinpoint them. Regardless of any advantages one age-depth modelling package might have over another, increased density of age control points along the length of a core always improves the age uncertainty of age-depth models (Blaauw et al., 2018; Telford et al., 2004; Zimmerman and Wahl, 2020). To this end, additional age control points may have been able to minimize the variability of sample age ranges in the Screaming Lynx and Tungak charcoal records (Fig. 6). However, we readily acknowledge and respect that logistical and fiscal realities may have precluded additional dates. Nonetheless, our analyses underscore that well constrained age chronologies are an additional tool to minimize the impacts of preservation biases in paleofire research. Further, we suggest that consideration of

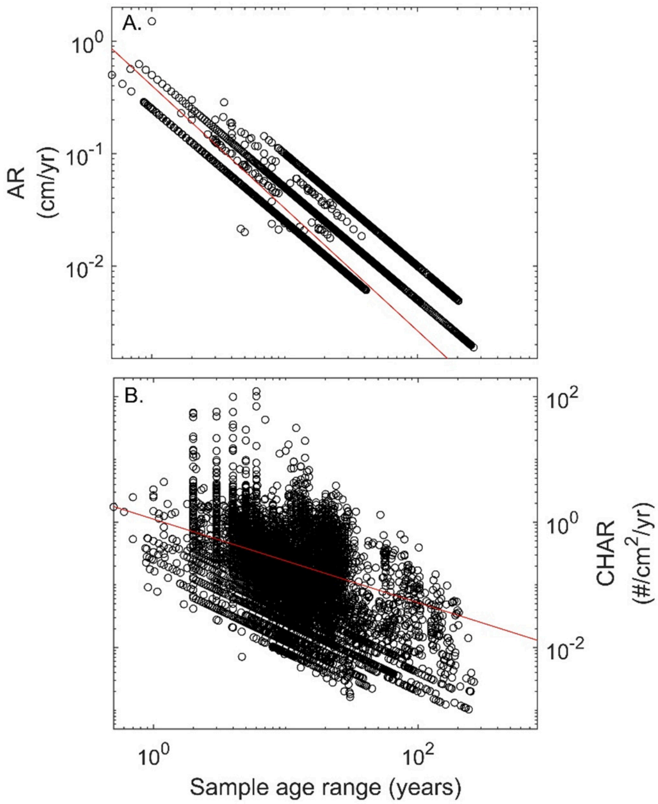

Fig. 3. The dependence of accumulation rates (AR; panel A) and charcoal accumulation rates (CHAR; panel B) on the sample age range of measurement. In each panel, a red line illustrates the power law fit to the data (AR = 0.4018*[sample age range]$^{-1.09}$ and CHAR = 1.118*[sample age range]$^{-0.6655}$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

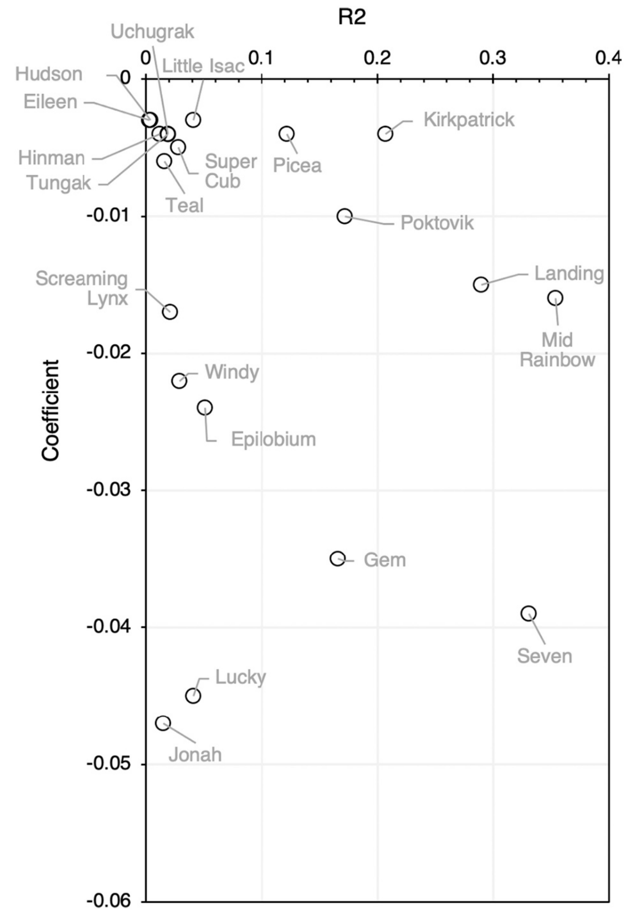

Fig. 4. Ordinary Least Squares (OLS) regression results of CHAR on sample age range. Significant results (as determined by null hypothesis testing; $p < 0.05$) are shown, and all results can be found in SI Tables 1–5. Points are labeled with their site name and their position reflects the strength of the regression (R^2) and the slope of the regression line (Coefficient). Note that in all records with a significant correlation, the coefficient is negative.

preservation biases and how they might affect a given charcoal record also be incorporated into the decision-making process to obtain additional radiocarbon dates.

4.3. Implications for paleofire research and our understanding of fire in the Earth System

In addition to quantifying total CHARs, many paleofire studies use peak analysis, a series of statistical methods, to identify peaks in CHAR time series (Higuera et al., 2010). These peaks are interpreted to reflect episodes of local fire activity and can therefore be used to calculate fire frequency variations through time (Finsinger et al., 2014; Higuera et al., 2007). Because of the variability of sedimentation rates, the first step of peak analysis requires interpolation of the raw CHAR time series to a consistent temporal resolution. Although this process creates a synthetic reflection of raw CHAR data (Crawford and Vachula, 2019), it is a necessary step to undertake peak analysis. This necessity is problematic in light of our analyses; temporal interpolation of CHARs overlooks changes in the age range of measurements which could inflate or deflate CHAR values and subsequently alter peak analysis results. As such, we suggest that paleofire researchers use caution when undertaking peak analysis and ensure that changes in the sample age ranges of measurements do not correspond with significant CHAR changes or identified fire episodes (as shown in Fig. 6).

Although our findings are thought-provoking, their limited geographic resolution highlights an important gap in paleofire data reporting. Indeed, because the datasets included in this analysis required top and bottom depths/ages, we were forced to exclude many otherwise appropriate paleofire records due to the insufficiency of detail reported. Although the Neotoma and Global Paleofire databases are valuable resources (Power et al., 2010; Williams et al., 2018), our study underscores that more comprehensive reporting of charcoal measurement parameters is needed to evaluate broader trends in these datasets. Although our analyses have highlighted an important oversight in paleofire research, the bulk of currently available data is insufficiently reported to determine its full extent. We therefore recommend that these measurement details (top and bottom depth/age) be included in future datasets shared within these frameworks and that more comprehensive and standardized data reporting be adopted by paleofire practitioners (Hawthorne et al., 2018; Khider et al., 2019).

Whereas we focus on the role of preservation bias in affecting CHAR values and paleofire interpretations, our findings have important implications for other paleoenvironmental research similarly reliant upon reliable accumulation rates in lacustrine sediments. For example, analyses of pollen accumulation rates (Giesecke and Fontana, 2008; van der Knaap, 2009), elemental fluxes (Burgay et al., 2021), carbon and mineral accumulation rates (Anderson et al., 2012), or biomarker fluxes (Richter et al., 2021) could all be similarly affected by preservation biases if age ranges of measurement vary along the length of a record. Although a thorough exploration of these potential impacts is beyond the scope of this article, we assert that consideration of this previously unrecognized phenomenon is of the utmost importance for reliable paleoenvironmental interpretations.

Our analysis shows that increases of recent CHAR values may be inflated by preservation biases and therefore may not reflect true

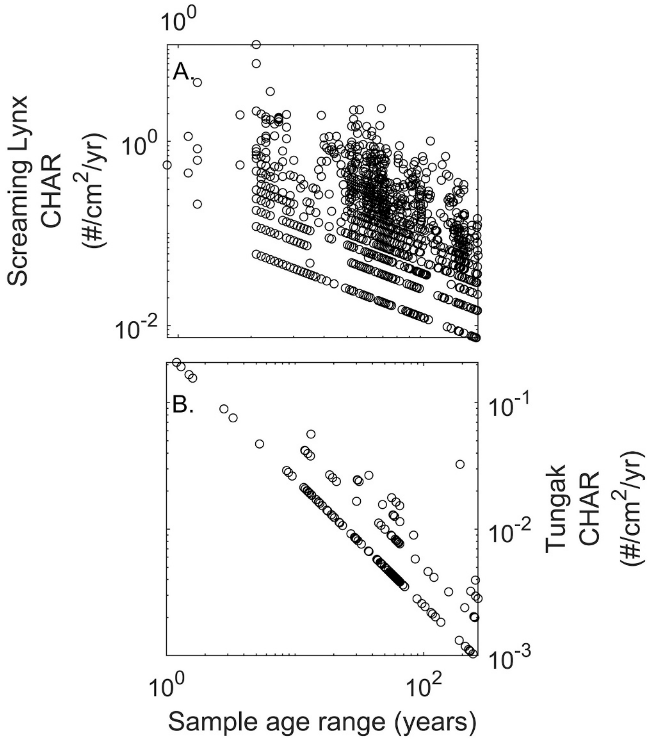

Fig. 5. The dependence of charcoal accumulation rates on the sample age range of measurement in the Screaming Lynx (A) and Tungak (B) charcoal records suggests that Sadler effect biases may exist in both records.

increases of fire activity. Marlon (2020) identified twelve globally-distributed charcoal sites which each show precipitous increases of CHAR values in recent sediments in the context of the Holocene. The high CHAR values were deemed unprecedented and were interpreted to reflect an equally unprecedented severity of recent fires (Marlon, 2020). This recent increase of fire activity has been demonstrated in terrestrial (Vannière et al., 2016) and marine (Mercuri et al., 2019) records alike. Further, other work has tied CHAR variations to climate variables, which suggest climate-driven CHAR increases in recent sediments (Han et al., 2020; Zhou et al., 2014). In contrast, our analyses suggest that these unprecedented charcoal surges ought to be examined with more scrutiny. Specifically, if the age ranges of their measurement correlate with the CHAR values, it would suggest these recent surges of fire activity may partly reflect preservation biases. This conclusion has important implications for the field and highlights the need to incorporate assessments of preservation biases into studies of fire in Earth History.

Our identification of the scale-dependent inflation and deflation of CHAR values has important implications for our understanding of fire in the Earth System. Whereas the reliability and fidelity of paleofire archives in recording the spatial dimensions of paleofire research have received much attention (Adolf et al., 2018; Gilgen et al., 2018; Vachula, 2021; Vachula et al., 2018), relatively less research has examined the uncertainties and reliability of paleofire data in the temporal dimension. Indeed, the need for further understanding of how fire operates across temporal scales has increasingly been highlighted in the paleofire field (Falk et al., 2007; McLauchlan et al., 2020; Whitlock et al., 2010). Our work shows that temporal sampling (i.e., the age ranges of measurement) inherently affects the paleofire inferences derived from sedimentary charcoal. Therefore, more care is needed when using sediment records to understand how fire changes across temporal scales. Our work represents an important step forward in recognizing this problem and outlining a means of recognizing these uncertainties.

5. Conclusions

We compile a dataset of Holocene paleofire records to determine whether preservation biases could affect the interpretation of these archives. We find clear evidence that Sadler effect biases are pervasive in these paleofire archives. Further we show that the influence of preservation biases can explain significant, non-negligible proportions of CHAR variations in the records that compose our compiled dataset. As a solution, we outline an interpretative framework of the necessary steps to recognize a Sadler effect bias in paleofire records and within sections of individual records. The bulk of paleofire records date to the Holocene and this research represents the first examination and identification of preservation biases in these records (to our knowledge). Therefore, further work is needed to integrate assessment of preservation bias into the interpretation of paleofire records. In light of recent calls for more

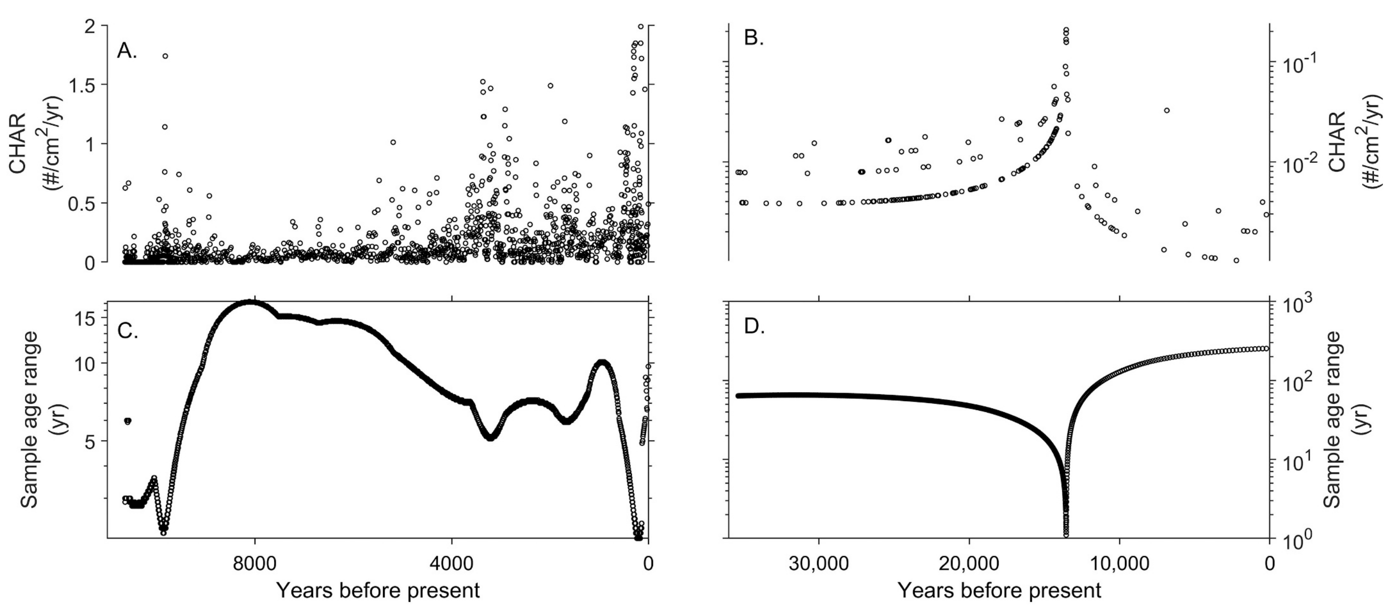

Fig. 6. To identify intervals in the Screaming Lynx (left) and Tungak (right) charcoal records wherein CHAR values may be inflated or deflated by preservation bias, we compare the CHAR values (A and B) with the sample age ranges of the charcoal samples (C and D).

research examining fire across temporal scales, our work serves as a cautionary tale that the reliability of paleofire archives is not necessarily consistent across temporal scales.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2022.111165.

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