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What the past can say about the present and future of fire

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Abstract

Wildfires are an integral part of most terrestrial ecosystems. Paleofire records composed of charcoal, soot, and other combustion products deposited in lake and marine sediments, soils, and ice provide a record of the varying importance of fire over time on every continent. This study reviews paleofire research to identify lessons about the nature of fire on Earth and how its past variability is relevant to modern environmental challenges. Four lessons are identified. First, fire is highly sensitive to climate change, and specifically to temperature changes. As long as there is abundant, dry fuel, we can expect that in a warming climate, fires will continue to grow unusually large, severe, and uncontrollable in fire-prone environments. Second, a better understanding of "slow" (interannual to multidecadal) socioecological processes is essential for predicting future wildfire and carbon emissions. Third, current patterns of burning, which are very low in some areas and very high in others—are often unprecedented in the context of the Holocene. Taken together, these insights point to a fourth lesson—that current changes in wildfire dynamics provide an opportunity for paleoecologists to engage the public and help them understand the potential consequences of anthropogenic climate change.

Keywords: charcoal; wildfire; paleofire; climate change; climate communication

INTRODUCTION

The bushfires in eastern Australia in November and December of 2019 were a globally unprecedented natural and human disaster. Around 5.8 million hectares of typically fire-resistant eucalypt forest were burned, releasing an estimated 350 million tons of carbon dioxide (CO_2) (Boer et al., 2020; Sanderson and Fisher, 2020). Unusually large numbers of rapidly spreading bushfires were extremely difficult to control, and resulted in at least 30 deaths and the destruction of over 2,500 structures (Tarabay, 2020). Hundreds of millions of animals perished, likely pushing several critically endangered species in this global biodiversity hotspot—including the southern corroboree frog, the regent honeyeater bird, and the western ground parrot—toward extinction (Paul, 2020). Many more animals continue to perish after the fires due to habitat loss as a result of the unusual intensity of the burns. An estimated 30% of eucalypt woodland koala habitat was lost in New South Wales, and the media images of burned koalas, kangaroos, and cattle sparked a worldwide response, including a knitting movement to clothe burned fauna (Jager and Coutant, 2020), and over $7.8 million to a koala rescue effort that had an original gofundme goal of $25,000.

The severity and heartbreaking imagery from the bushfires, coming just months after unusually large human-set fires raged uncontrolled through the Brazilian Amazon rainforest, raised global awareness about the destructive power of extreme wildfires. And shortly before the August Brazilian fires, in June 2019, Arctic wildfires had emitted 50 megatons of CO_2—more than the years 2010–2018 combined (Geneva, 2019). The year before, the Camp Fire in California killed 85 people and destroyed 18,804 structures; it was the deadliest and most destructive wildfire in the state's history (US Census Bureau, 2019). British Columbia also had its largest burn in 2018 (over three million acres), surpassing the 2017 wildfire season. Also in 2018, the Attica wildfires in Greece were the second-deadliest worldwide since 2001—killing 102 people (the 2009 Black Saturday bushfires in Australia had killed 180). In 2017, Chile had its most destructive wildfire in its history (Bonnefoy and Chan, 2017), while half-way around the globe in Greenland, an unusually large number of active fires were identified in MODIS satellite data.

As majorities of the public in some developing countries have likely still never heard of climate change, and many in

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developed countries perceive little threat to themselves and their own families (Lee et al., 2015), raising global public awareness and understanding about climate change remains critical. Thus, these widely reported extreme wildfires are helping to convey what scientists have been trying to communicate for decades—that a rapidly changing climate directly threatens individuals, societies and ecosystems. The specific causes of individual bushfires and even of a particularly severe fire *season* are exceedingly difficult to attribute to anthropogenic climate change, but the collective evidence for human fingerprints on the climate system and on *trends* in wildfire activity are clear. The American Quaternary Association's fiftieth anniversary provides an opportunity to examine the contributions that paleofire research has made to understanding the dynamic nature of wildfires and their controls at the global scale, and how human activities are playing an ever-growing role in shaping them.

A paleoecological lens for wildfire confers advantages and disadvantages. In particular, it constrains our ability to examine individual events and their associated details with temporal or spatial precision, but enhances our ability to understand changing fire *regimes* in regions, biomes, continents, and at the global scale. "Fire regime" refers to patterns of burning on the landscape (e.g., Archibald et al., 2013), which can be characterized based on a variety of metrics including the location, timing or seasonality and frequency of fire, the typical size of the fire, and its severity in terms of the amount of biomass burned.

Specifically, this study has two aims. First, it reviews the primary sources of fire data, explains the strengths and limitations of paleofire data in particular, and identifies the primary controls of changing fire regimes. Second, it identifies insights from the paleofire literature to draw four lessons for the future, based on both individual studies and a variety of syntheses from the Global Charcoal Database (GCD; Power et al., 2008). Applying these lessons to our expectations about and responses to wildfire in a warmer and more densely-populated world can inform further advances in fire science and provide a stronger basis for living sustainably with fire.

Fire Data

The scientific understanding of fire history is based on data and evidence about past fires, their causes, and effects. The study of paleofires has generally focused on past wildfires, which are different than agricultural or controlled (prescribed) burns insofar as they are uncontrolled and unplanned, whether ignited by lightning or humans (Harrison et al., 2010). Our understanding of past wildfires is rooted in four primary sources of data: satellites, written records, fire scars on trees, and combustion residue in sediment and ice. Our understanding of current and recent (i.e., over the past few decades) global fire activity is derived primarily from satellite remote-sensing systems. Satellite data provide detailed and spatially comprehensive information about currently active fires (i.e., the energy radiated by fire: Ellicott et al., 2009) and recently burned areas from regional (e.g., Archibald et al., 2010) to global scales (Randerson et al., 2006; Chuvieco et al., 2008). Emissions of trace gases and particulates from fire are commonly estimated from satellite data and emission factors for specific gases as the product of burned area, fuel load, and combustion completeness for a particular time interval and spatial domain (van der Werf et al., 2006; Harrison et al., 2010). Burned areas from past fires are determined by analyzing the unique signatures left by charred vegetation and patterns of regrowth after fires (Giglio et al., 2006).

Satellite-based fire research has identified a slight global decline in fire activity over recent decades, with area burned shrinking by 24.3 ± 8.8% over the past 18 years (Knorr et al., 2014; Andela et al., 2017). The estimated decrease was largest in savannas and is due to the expansion and intensification of agriculture, which decreased the number and size of individual fires despite growing climate-driven fire risk. Discrete fire events can also be identified and analyzed using satellite data. For example, an analysis of over 23 million discrete fire events from MODIS data (Bowman et al., 2017) identified 478 extreme wildfire events between 2002 and 2013 across flammable biomes. The events were strongly associated with extreme fire weather conditions, and in the western United States and southeastern Australia, 114 were reported as economically or socially disastrous because of their location in suburban areas. Climate change projections suggest an increase in days conducive to extreme wildfire events by 20 to 50% in these disaster-prone landscapes.

Historical studies of fire are based on government records and statistics, analysis of aerial photos, field studies, and other documents. Most developed countries currently produce national fire statistics through government agencies such as the Canadian Forest Service, the United States National Interagency Fire Center (www.nifc.org), or the European Forest Fire Information System (http://effis.jrc.ec.europa.eu/). Information is available for some countries that have published burned area statistics back to 1900 (Zumbrunnen, 2011; Stamou et al., 2016). In the United States, estimates go back even further because information about fire was recorded as part of timber inventories (e.g., Reynolds and Pierson, 1941). Mouillot et al. (2005) compiled and synthesized historical data (including satellite and dendrochronological data to maximize spatial and temporal coverage) to produce a globally gridded dataset of estimated burned area annually for the 20th century. The data were compiled from direct information about burned areas via national or local statistics, storylines on fire history and human fire practices, fire-scarred tree ring records, analysis on fire affected trees, or tree age analysis at local or regional scales. The spatial resolution of the dataset captures general trends in burning at the state, province, or country level, depending on the continent. According to the historical compilation, globally-averaged burned area varied little over the 20th century until it began to increase during the 1980s and 1990s (Harrison et al., 2010). Given that the satellite-based compilation of global burned area shows a decline from 1998-2015, however, it is unclear whether the direction of the trend in global area burned reversed at the turn of the 20th century, or whether it has actually been continuously declining for many decades, as suggested by global paleofire data syntheses (Marlon et al., 2008) coupled with the satellite data (Andela et al., 2017). Such inconsistencies illustrate the difficulties in comparing fire history data from different sources, and to the need for research that can explain such discrepancies and reduce uncertainty in reconstructions from different sources.

Fire histories from dendrochronological data come from fire-scarred trees or shrubs that can be accurately dated (Agee, 1993). Such records can yield information about particular events (e.g., Camarero et al., 2019) or mean fire return intervals spanning decades or centuries from diverse forests (Guyette et al., 2012), including boreal forests (Girardin, 2006), mixed temperate forests (Mundo et al., 2017; Holz et al., 2017; Stambaugh et al., 2018; Brown et al., 2019), dry mixed-conifer forests (Veblen et al., 2000); Mediterranean woodlands and forests (Christopoulou, 2013; Fulé, 2008; Pausas, 2004), wet sclerophyll forests, and forest-prairie or grassland ecotones (e.g., Hessl et al., 2016; Mazarzhanova et al., 2017). Extensive datasets of fire-scarred tree ring records are available for many parts of the world, and especially from the United States (Harley et al., 2018). These records document a close relationship between fire activity (frequency or area burned) and warm, dry periods, as well as increasing direct human impacts during the Industrial Era (via enhanced or suppressed ignitions), or indirect impacts through land-use changes such as intensified grazing or the introduction of invasive species (Holz et al., 2020). Reconstructions of fire frequency from giant sequoias in California show increased burning during the Medieval Climate Anomaly, for example, which was characterized by warm, dry conditions (Swetnam et al., 2009). Hundreds of fire-scarred tree ring records from western North America show reduced fire activity during the cool climate of the Little Ice Age, followed by a rapid increase in burning with Euro-American settlement of the West (Marlon et al., 2012). Eastern North American dendrochronological data often show relatively frequent fire prior to ca. 1930, commonly attributed to burning by indigenous people and European settlers, and less often to lightning-caused fires (Guyette et al., 2002; Guyette et al., 2006; Miller et al., 2017; Hutchinson et al., 2019). Subsequent declines in fire are widespread across the continent due to the advent of aggressive fire suppression practices. Fire-scarred tree ring data also provide information about burning from prairie-forest ecotones and areas of recent forest encroachment into grasslands or prairie (Jones and Bowles, 2016; Leys et al., 2018), but they are not available from tropical forests where species lack annual growth rings that can be dated, although some semi-arid species show potential (Oddi et al., 2016).

Paleofire Data

Unlike the fire history data described above, which typically provide precise spatial and temporal information about burning in a given year or precise area, paleofire data (from sediment and ice) record multidecadal to millennial-scale variations in a continuum of combustion products ranging from large particles of charred biomass to soot aerosols (Conedera et al., 2009). The most common paleofire data sources are charcoal particles, black carbon or soot, and geochemical tracers. Charcoal records from lake sediments are the most prevalent source of paleofire data with individual records coming from many different depositional contexts around the world—peat bogs, forest soils, ocean floors, alluvial fans, etc (Whitlock and Larsen, 2001). Measurements of charcoal variations through time include particle counts, areas (e.g., length to width ratios using imaging technologies), and weight measurements (Marlon et al., 2016).

Each type of paleofire record offers unique abilities to examine a different dimension of fire history or to consider changes in fire in a particular environmental or human context. Paleofire data from peatlands are an important source of fire history data in the tropics, for example, where few undisturbed lakes may exist. Reconstructions of fire from traces of levoglucosan, vanillic acid, and other aerosols in ice cores are increasingly used to understand long-term variations in biomass burning on broad spatial scales (McConnell et al., 2007; Grieman et al., 2018; Legrand et al., 2016; Bhattarai et al., 2019). Each record type also presents unique challenges, however. When peatlands burn, for example, large portions of the record can be consumed, creating temporal gaps and increasing uncertainty in the timing of past burns. Likewise, records of fire in ice are particularly dependent on a clear understanding of atmospheric transportation and deposition of trace gases and how such processes have changed over time because they can travel such long distances. The continuous accumulation of marine sediments over hundreds of thousands of years in coastal areas can yield extremely long continuous fire-history records, but constraining the source area for such data is challenging. Marine records have a large potential charcoal or source area, and upper atmospheric winds and ocean currents can complicate particle transportation and deposition. Analyses of variability in clay or mineral ratios with known source areas alongside charcoal particle variations can mitigate these complicating factors, however, and strengthen interpretation confidence (Daniau et al., 2013).

All fire history data from natural archives, whether from trees, sediments, or ice, require establishment of carefully-documented and detailed information about the chronology of changes in the record, how the timeline was developed, and how much uncertainty exists for different intervals or points in time. Dendrochronological records, commonly based on counts of annual rings that form as trees grow, can provide accurate and precise information about the timing and location of individual fire events, while layer counting in ice cores can provide accurate and precise information about the timing of fire emissions in the past but not of their spatial location since trace gases are widely dispersed through the atmosphere. Sediment records are usually dated using radiocarbon technologies, but also with 210Pb, pollen-based correlations, and stratigraphy markers (e.g., volcanic tephras). Methods used to develop unusually long stratigraphies, for example from marine sediments, are typically based on 234U/230Th ratios or orbital tie points (Marlon et al., 2016).

Community efforts to understand broad-scale changes in biomass burning, to discriminate between natural and anthropogenic fire-regime changes, and to provide benchmarks for global simulations of fire activity led to the development of a global repository for paleofire data, the Global Charcoal Database (GCD; Power et al., 2008; Mooney et al., 2011; Vanniere et al., 2011; Daniau et al., 2012; Marlon et al., 2016). These data have been used to gain insight into fire and its controls on diverse spatiotemporal scales, with research continuing based on an expanding publicly-available database of over 1000 records (www.paleofire.org).

Most paleofire records in the GCD are quantified using particle counts or area measurements per unit volume of sediment (i.e. pieces cm^{-3}). The amount of time that a given volume of sediment represents changes over time, however, depending on lake or wetland productivity and processes that affect erosion, such as changes in vegetation cover, climate, and weather. As a result, charcoal concentration values are converted to charcoal influx or accumulation rates (pieces cm^{-2} yr^{-1}) to account for changes in the amount of sediment accumulating in a given year or other standardized time period. Charcoal concentrations are multiplied by the sediment accumulation rate (cm yr^{-1}). Because charcoal is measured using dozens of different techniques, comparisons of multiple records processed differently are standardized to allow comparisons of features and trends on a common scale of standard deviation units (Power et al, 2010). As a result, synthetic reconstructions of fire from diverse paleofire records only show changes in charcoal abundance relative to a pre-set base period, which can be influenced by local geography, fuel types, and climate conditions as well as fire regime characteristics.

Paleofire records from environments with high rates of sediment deposition or that preserve annual laminations (e.g., Swain, 1973; Tolonen, 1978; Clark, 1988; Dodson et al., 2005) provide an opportunity to develop detailed reconstructions with sub-decadal or even annual time resolution not only of trends in charcoal or other combustion products, but of the frequency of discrete fire events (Higuera et al., 2011). In such cases, individual local fire events are inferred from 'peaks' in charcoal accumulations deposited during and shortly after large fires within a few kilometer radius of the lake. Only charcoal peaks that surpass a "backround" accumulation rate threshold are considered a fire event (Long et al., 1998; Higuera et al., 2011). In areas with relatively infrequent, stand-replacing crown fires, such as in boreal forests, charcoal peaks can be confidently associated with independent evidence of nearby fires to calibrate longer-term reconstructions (Kelly et al., 2013). The reconstruction of fire frequency changes through time is a powerful tool with important management implications, since the mean fire return interval for a given location is a common metric used by forest managers and can directly inform planning and management goals. However, in order to capture individual fire events in a record, typical fires in the area must be large or severe, and must occur less frequently than the typical amount of time represented by a single sample (i.e., the sediment accumulation rate must be higher than the typical time between fires in order to resolve individual events). As a result, fire frequency reconstructions are unavailable in most parts of the world, and variations in charcoal accumulation rates are instead used as a general indicator of changes in fire type, area, or biomass burned (e.g., Ohlson et al., 2011).

Given the diversity of environmental constraints on the creation of paleofire records, from the accessibility of undisturbed depositional contexts, the requirement of continuous sedimentation, and the availability of appropriate dating material, it is remarkable that so many records exist. In most cases, the simplest of measurements, such as particle counts of a single size class, provide an opportunity to gain at least a qualitative understanding of how the prevalence of wildfire in a local area or region varied through time. Further measurements and analysis can allow the reconstruction of both trends and peaks in fire activity over time (Calder et al., 2015; Walsh et al., 2015), the establishment of synchronous fire events at multiple sites, periods of regionally high or low biomass burning, and interactions with climate, vegetation changes, and human activities when the fire data are combined with other data such as pollen, phytoliths, atmospheric trace gases, and archaeological data (e.g., Williams et al., 2015; Inoue et al., 2016). Describing increases and decreases in burning has been undertaken to assess its importance on the landscape during different climate and vegetation conditions and during different periods of human history. Paleofire research also examines the cause of particular fire events (e.g. Stahle et al., 2017). Beyond description, paleofire research often strives to assess the causes of fire-regime changes, and specifically to disentangle climatic from anthropogenic influences on past burning.

FROM FIRE TO FIRE REGIMES

Fire emerges from the interaction of oxygen, heat, and fuel, often visualized as a "fire triangle" (Fig. 1). Without any one of these three elements, fire cannot exist. While oxygen, heat, and fuel are the requirements for the physical process of combustion to occur—that is, to ignite a single flame—these same components have also varied over Earth's history to determine the relative prevalence of fire around the world. Despite the limited ingredient list, the myriad ways in which each triangle component is expressed through space and time makes fire ecology highly complex (Pausas and Keeley, 2009; Whitlock et al. 2010; Moritz et al., 2011). Thousands of geological and paleoecological studies conducted worldwide reveal the dynamic nature of fire on Earth as it has responded to shifts in oxygen, heat, and fuels over millennia. Identifying the relationships between these components and their connections to other species, including humans, has been a primary objective of paleofire research (Scott et al., 2013). The results of individual studies

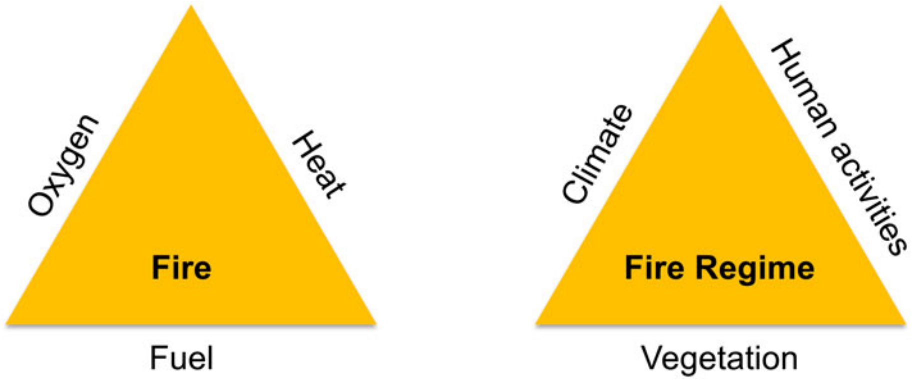

Figure 1. Different drivers of individual fire events versus fire regimes that vary over space and time. Oxygen, heat, and fuel are needed to cause a flame to become a fire (left). Fire regimes (right), which describe patterns of change in the location, type, timing, and other aspects of discrete fire events are driven by variations in climate, vegetation, and human activities over space and time.

reveal many details about fire-climate-vegetation-human linkages in particular places, and collectively illuminate systematic patterns of changing fire regimes through time and across space. The wealth of paleofire research provides an opportunity to consider how the relative importance of the controls of fire have shifted over time, which in turn enables an assessment of modern fire-regime changes in a long-term context.

Climate

Both oxygen and heat become elements of climate in the context of changing fire regimes. Changes in the composition of Earth's atmosphere provide a key constraint on wildfire prevalence. Atmospheric oxygen (O_2), in particular, can influence wildfire wherever fuel and ignition sources are present (Belcher et al., 2010). Oxygen levels today are 21%, but below 18.5% O_2, modeling and experiments indicate that fire activity would be greatly suppressed. Below 15% O_2, fire is unable to ignite or propagate (Belcher and McElwain, 2008). In contrast, oxygen levels between 19-22% would rapidly enhance wildfire spread, while levels above 35% would cause wildfires to become so hot that they would consume most terrestrial vegetation (Scott, 2000; Lenton, 2001). Geological evidence suggests that wildfire activity first occurred during the Silurian (ca. 420 mya) and the Carboniferous (ca. 400 mya) periods (Scott and Jones, 1994; Glasspool et al., 2004). Fires were also prevalent during the Permian, ca. 250–300 mya (Scott and Glasspool, 2006; Yan et al., 2016), when oxygen levels were higher than today.

Oxygen also affects fire locally through winds, which supply it and can make fires burn more rapidly. But when considering fire regimes, the influence of wind is through its effects on moisture and fire behavior rather than just oxygen, and thus winds become a function of changing climate. The absence of direct evidence for changing wind patterns over millennia, however, effectively places wind beyond the purview of paleofire studies. Large changes in atmospheric circulation that altered patterns of wind direction and speed would have affected fire regimes by influencing vegetation types and migration and impacting important fire-regime characteristics such as shifting typical fires from low to high-severity in a given region. Foehn winds, for example, play an important role in shaping fire regimes in mountainous areas, so as topography changes over long time scales their effects could become more important (Zumbrunnen et al., 2009). Large shifts in atmospheric circulation during deglaciation may have had substantial impacts on dominant wind flows along ice sheet margins, for example, which in turn could have influenced fire-regime shifts by drying out vegetation or altering patterns of fire ignition and spread. Unusually high fire activity from 10,000-9,000 cal yr BP in the St. Lawrence region of North America could be attributable to a shift in atmospheric circulation (e.g., jet stream position or strength and associated pressure gradients and storm trajectories) as the Laurentide ice sheet was retreating (Carcaillet and Richard, 2000), for example, but only model experiments could disentangle such forces from other climate and vegetation shifts at that time. The importance of oxygen for a fire is thus analogous to the importance of climate for influencing fire regimes.

Heat represents one side of the original fire triangle, but in the context of fire regimes, heat can be considered in relation to both ignitions and changing climate conditions. The heat required to ignite fires has come primarily through lightning and volcanic activity for most of Earth's history, with lightning of primary interest during the Quaternary. Lightning strikes are abundant on Earth, occurring an estimated 44 ± 5 flashes per second on average, with about 78% of those located between 30°S and 30°N latitudes (Christian et al., 2003). Lightning is particularly important at mid and high latitudes, and especially in boreal forests (Veraverbeke et al., 2017). However, many wildfires today globally are ignited by humans, especially in fire-prone environments (Ganteaume et al., 2013; Guo et al., 2015; Syphard and Keeley, 2015). The history of human fire use and how its importance has grown over time are contested (Bowman et al., 2011; Williams et al., 2015; Oswald et al., 2020). Bowman et al. (2009) suggest that human mastery of fire may have begun with the expansion of tropical savanna biomes 7–8 mya.

Archaeological evidence suggests that early hominins moved into northern latitudes from Africa without the habitual use of fire, and that it was only after ~300,000 to 400,000 years ago that fire became a significant part of the hominin technological repertoire (Karkanas, 2007; Roebroeks and Villa, 2011). The subsequent human use and importance of fire has shifted in association with cultural and technological developments, first from domestic uses over hundreds of thousands of years, then expanding to foraging uses over tens of thousands of years, to agricultural fire during the Holocene, and finally to industrial uses during the past few centuries (Bowman et al., 2009). Disentangling the relative influence of lightning versus these human-started fires has been a primary focal area of paleofire research and is explored further below.

A focus on changing fire *regimes* requires consideration of climate processes affecting heat at broad spatial and long temporal scales. Changes in radiative forcing, for example, have important consequences for fire regimes over millennial scales (Daniau et al., 2012), while shifting patterns of atmospheric circulation that determine land and ocean surface temperatures, precipitation, and the distribution of snow and ice (Bartlein, 2014; Vanniere et al., 2008). Fischer et al. (2018) examine extensive paleoenvironmental data from the past 3.5 million years, including paleofire records, to identify the effects of warming on ecosystems analogous to what models predict for the coming century. They note that late-successional evergreen vegetation in Mediterranean areas was replaced by flammable, drought-adapted vegetation in response to climate warming of just 1-2°C in the past when drought thresholds are reached. Likewise, regional hydroclimatic fluctuations, can push tropical forests into fire-dominated savanna (Hirota et al., 2011), and grasslands into desert, as evidenced by the Green-Sahara—desert transition that occurred at the end of the African Humid Period (Kröpelin et al., 2008). Such shifts are linked to temperature changes, such as those caused by variations in summer insolation that affect monsoons and other circulation patterns. Small changes in global mean temperature can therefore have enormous impacts on vegetation and fire regimes. The role of heat as a function of climate changes more broadly and their effects on fire are explored in more detail below.

Vegetation

Once ignited, fire requires fuel to sustain combustion. Vegetation serves as fuel for fires when it is abundant and dry; it can also prevent, reduce, or extinguish fire when it is sparse and/or wet. Vegetation characteristics thus shape the existence and behavior of fire, and changes in these characteristics can be both a cause and effect of changes in a fire regime over time. Evidence for such interactions between fire and vegetation are as old as the evidence for fire itself. Charcoal from the Late Devonian document burning when plants first began spreading beyond wetlands, with new plant types developing that could survive on dry land (Scott, 2000, 2001). Peaks of charcoal in marine sediments around 7–8 mya indicate that fire increased when grassland and savanna biomes expanded globally, suggesting the establishment of sustained fire-vegetation-climate feedback cycles in these environments (Keeley and Rundel, 2005). In Australia, fire became progressively more important with the development of sclerophyll vegetation in particular (Martin, 2006; Lynch et al., 2007). Evidence from the late Cenozoic shows increasing accumulations of microcharcoal associated with aridity and the expansion of steppe taxa in which fire easily propagates (Miao et al., 2016). Paleofire records from modern grasslands are sparse, and as the boundaries and ecological communities within biomes shift over time, even defining where and when grasslands existed in the past in order to analyze them is challenging (Leys et al., 2018). Nevertheless, the existence of fire-dependent ecosystems demonstrates that fire regimes are not only controlled by fuel biomass, but are themselves a major evolutionary force that affects vegetation structure and composition, and thus species interactions (Bond et al., 2005; Gill et al., 2009; Feurdean and Vasiliev, 2019).

Today, about 18 percent of all anthropogenic carbon dioxide emissions come from biomass burning over hundreds of millions of hectares, primarily in the woody and grassland savannas of Africa and Australia (Jacobson, 2014). Yet, fire has a long history in most places on Earth, even in rainforests and on islands once thought to be fire-free (Burney, 1987; Horn et al., 2000; Hope et al., 2009; Whitlock et al. 2015). Remotely-sensed fire data and analyses show that fire in low-productivity ecosystems is limited by low biomass, while in high-productivity ecosystems, it is more sensitive to high temperatures (Pausas and Ribeiro, 2013).

Vegetation characteristics, often associated with specific climates, can also inhibit fire, such as when fuels become too sparse to carry fire, or their structure inhibits fire spread. Analyses of pollen, charcoal, and phytolith assemblages from Ounjougou, Mali offer one example. In the early Holocene, expansive tropical grasslands and gallery forests with low biomass production supported low levels of fire activity. Increasing rainfall and greater seasonality led to higher biomass production, however, and increased charcoal production with higher inferred fire activity (Neumann et al., 2009). Shifts in forest species composition, such as a reduction in conifers and an increase in broadleaf species, can also reduce fire activity by decreasing fuel flammability (Blarquez et al., 2015; Feurdean et al., 2017). Even different conifer species with different structural forms can affect the continuity of fuels and thus their flammability. Increased burning in boreal forests are evident, for example, where *Populus* and *Picea glauca*-dominated forests are replaced by highly flammable *Picea mariana* forests (Hu et al., 2006; Higuera et al., 2009). One unusually high-resolution record from Kettle Lake in the Great Plains of North America reveals a tight coupling between high fire activity during moist intervals when grass cover was extensive and fuel loads were high versus intervals with low fire activity when fuels loads decreased as a result of greater aridity (Brown et al., 2005). Such examples highlight the interplay of vegetation abundance, flammability, effective moisture, and fire over time—complex dynamics that can drive substantial ecosystem change even in the absence of land-use changes or human fire use.

Human activities

The routine human use of fire for foraging and hunting has shaped many environments for tens of thousands of years (Pyne, 1997, Bowman et al., 2011). Paleofire data from large islands provide some of the strongest evidence linking human activities to widespread fires because fire was often extremely limited or absent prior to the arrival of humans. The establishment of cultivation at 5 ka is coincident with a large increase in fire in New Guinea, for example, and also with local evidence of anthropogenic fire use on the island (Haberle et al., 1991; Haberle and David, 2004). Likewise, McWethy et al. (2010) have shown that a dramatic increase in burning occurred within 200 years of Maori arrival at all but the wettest sites in New Zealand.

Ample evidence of the growing influence of human use of fire for agriculture comes from China. The gradual expansion of intensive land use in China are recorded in black carbon mass sedimentation rates (Wang et al., 2013), and black carbon in a sediment core from Daihai Lake, Inner Mongolia, suggest the appearance of early agriculture and the expansion of human land use at ca 8000 and 3000 ka, respectively (Han et al., 2012). In Turkey, sediment records of fire, vegetation, and geochemistry from the Bereket basin in the Taurus mountains during the past three millennia detail human-induced change in the area. In the Bereket surroundings, fires appear to have catalyzed a simplification of the vegetation structure and associated increases in soil erosion, pasture expansion, and intensive cultivation (Kaniewski et al., 2008). Leunda et al. (2020) use paleofire data from the Central Pyrenees in Spain to show the transition from climate-driven fire regimes in the early-to-mid-Holocene to human-driven landscape change over the last 3700 years. Many similar examples exist throughout Europe. While there are almost no paleofire records from India, one short sediment core from a reservoir in northern Karnataka, indicates well-defined periods of burning that coincide with periods of open vegetation as defined by pollen analysis, and with periods of high settlement densities and intensive land use evidenced by archaeological data c. AD 1300-1600 (Morrison et al., 1994).

Unless paleofire records are collected adjacent to archaeological sites, which is rare, is it difficult to know whether shifts in fire regimes are the result of changes in climate, vegetation, cultural practices, or some combination of two or more of these factors. Recent methodological advances are improving our ability to clearly identify the advent of human impacts on fire on millennial times scales, however. Research by Vachula et al. (2019) provide one example in a study that used organic geochemical biomarkers, including polycyclic aromatic hydrocarbons (PAHs) and sterols, to reconstruct fire activity in Beringia and human presence over the past 32,000 years. Understanding human use of fire in Beringia can shed light on the timing and pathway of human arrival to the Americas, which remains an important topic of debate in archaeology and anthropology. The debate centers on whether a "swift peopling" of the Americas from Asia occurred during the last Glacial termination via the Bering Land Bridge, or whether the eventual spread of populations from Beringia across the American continents were delayed by thousands of years.

Vachula et al. (2019) found that elevated levels of PAHs from 19-32kyr were coincident with coprostanol levels consistent with human presence. Coprostanol:stigmastanol ratios have been used to distinguish human and ruminant herbivore fecal inputs to lake sediments in Norway (D'Anjou et al., 2012), and given the known coprolite sterol compositions of mammoth, which comprised about half the glacial animal biomass of northern Alaska (Mann et al., 2013), these data suggest increased burning during the glacial period in Beringia may have been due to human activities. Whether the fire and sterol data provide evidence of temporary or permanent residence in the area is unclear, but multiple spikes in the coprostanol:stigmastanol ratio during the interval from 32–19ka suggest that human populations may have inhabited Beringia much earlier than conventionally thought.

Matching fecal biomarkers with the timing of human presence and charcoal was used as evidence for human-lit fires in New Zealand at c. AD 1350, confirming the role of humans as the cause of dramatic deforestation at that time (Argiriadis et al., 2018). Other research by Brittingham et al. (2019) exploits the differences in the types of PAHs found in widely-dispersed wildfire emissions versus those found in particulate emissions of burned wood from Lusakert Cave in Armenia. The authors use their data to argue that Middle Paleolithic hominins (ca. 300,000 to 35,000 years ago) were able to control fire and utilize it regardless of the variability of fires in the environment, providing support for the intentional creation and control of fire by hominins independent of exploitation of wildfires in Eurasia. Such studies illustrate the potential for progress in advancing our understanding of how humans have shaped fire history and environmental change through time as our fire proxy repertoire expands.

LESSONS FROM PALEOFIRE RESEARCH

Fire regimes track climate changes

Fire regimes not only track climate—they are finely tuned to them. On the broadest scales of Earth history, a warmer planet means a more fire-prone planet. About sixty-five million years ago, during the Paleocene-Eocene thermal maximum, global temperatures increased more than 5–8°C. The interval of warming was associated with a massive release of carbon to the atmosphere from volcanism, which lasted tens of thousands of years. The warming was associated with major increases in global biomass burning (Collinson et al., 2007; Marynowski and Simoneit, 2009). In contrast, the cold climate conditions that characterized the Last Glacial Maximum, when temperatures were about 6.0°C colder than today and 25% of the land surface was covered with ice, are associated with reduced biomass burning at the global scale (Power et al., 2008).

Paleofire literature is replete with examples of how fire regimes have responded to the powerful, mostly gradual effects of the hierarchical controls that drive Earth's climate system (Bartlein et al., 2014). The paleoecological record from Cygnet Lake in Yellowstone National Park in the United States exemplifies the effects of gradual insolation changes on forest fires. Consistently surrounded by lodgepole pine forest for more than 11,000 years, the detailed environmental reconstruction shows how fire increased in direct response to increased summer warmth and dryness during the peak of northern mid-latitude summer insolation in the early Holocene (Millspaugh et al., 2000). As the Holocene progressed, summer insolation declined and fires gradually became less frequent.

Cygnet Lake's setting is unique, which made it possible to link fire directly to climate. The vegetation on the plateau where the lake sits reflects the influence of infertile rhyolite soils, which limit the establishment and growth of most other conifer species. This unique physical constraint limited the ability of vegetation around the lake to respond to climate changes (Whitlock, 1993). In most places, vegetation change is also highly responsive to climate changes, interacting with fire regime characteristics including size, frequency, and timing, to catalyze additional change and ecosystem reorganization (Colombaroli et al., 2008).

A 170,000-year marine sediment core off the coast of Namibia in southern Africa reveals the interaction of fire and fuels synchronized by orbital variations in insolation (Daniau et al., 2013). Six fire cycles occurred during the long record that correspond both in timing and magnitude to the precessional forcing of north–south shifts in the Intertropical Convergence Zone. Fire increased with wetter and cooler climate conditions owing to a shift in rainfall amount and seasonality. The increased fire thus occurred in response to an increase in biomass produced by reliable rains and coupled with regular dry intervals that increased grass flammability, revealed through measurements of the elongation (length/width ratio) of microcharcoal particles.

Two syntheses of paleofire records from the GCD further demonstrate the sensitivity of fire regimes to temperature and precipitation over long time scales. In the first, 67 sites paleofire records from the Last Glacial Maximum showed that fire was consistently lower during the glacial period than during the Eemian and Holocene (Daniau et al., 2010). Most records, particularly from the northern extra-tropics, show millennial-scale variability in fire regimes corresponding to the rapid climate changes associated with Dansgaard–Oeschger (D-O) cycles. Fire increased during D-O warming events and decreased during intervals of rapid cooling. A high-resolution wildfire record from Greenland ice cores shows similar results (Fischer et al., 2015). The paleofire records indicate that strong climatic variability evident during the glacial period resulted in substantial changes in fire regimes even though biomass burning was less than today. A second synthesis using 679 paleofire records from the GCD show that the changes in fire regime over the past 21,000 years are predictable from changes in regional climates (Daniau et al., 2012). Fire increases monotonically with changes in temperature and peaks at intermediate moisture levels, and temperature is the most important driver of changes in biomass burning over the past 21,000 years. Increasing fire with increasing temperature and peak fire activity at intermediate moisture levels is also evident in modern remotely-sensed area burned data (Daniau et al., 2012; Bistinas et al., 2014).

In areas where fuels are limiting, wet/dry cycles are more closely associated with high fire activity than temperature, whether those cycles occur on a monthly basis or a millennial basis. Hao et al. (2020) examined a 32,000-year sediment core from Qinghai Lake, the largest in China, and found that more wildfires occurred during the cold-dry late glacial period (32.8-11.7 ka), and fewer wildfires during the warm-humid Holocene. The study points to drought as the primary control of fire regimes on orbital time-scales in the region when lack of fuel biomass and continuity limited fire spread.

Not all climate changes, of course, are gradual. Evidence of the sensitivity of fire regimes to rapid shifts in temperature and precipitation is found even since the late glacial period. Fire across North America increased at both the beginning and end of the Younger Dryas Chronozone, for example (Marlon et al., 2012). Fire regimes and vegetation in Europe also show a swift response to the 8.2 event (Davis and Stevensen, 2007; Tinner et al., 2009). Regionally-specific rapid climate shifts are evidenced by paleofire records from central Europe (Finsinger and Tinner, 2007) and fire-prone communities of the Mediterranean (Linstädter and Zielhofer, 2010), from the tropical savannas of Africa (Colombaroli et al., 2018), the shifting steppe-forest ecotone of southern South America (Iglesias et al., 2014) and elsewhere. In the late Holocene, hundreds of paleofire studies show evidence of increased burning during the Medieval Climate Anomaly and decreased burning during the Little Ice Age, reflected in global and regional compilations of paleofire records (Marlon et al., 2008; Marlon et al., 2012; Power et al., 2013; Calder et al., 2019).

The strong evidence for climatic controls of fire regimes during Earth's geological past and throughout the Holocene is not mutually exclusive of strong human impacts on fire regimes in the more recent past. Debates over the relative importance of these two powerful (now interacting) forces center on when, at what scale, and to what degree each has shaped local and regional flora and fire. Paleofire records, particularly when examined in conjunction with pollen, climate, archaeological, and other data, have provided compelling evidence of cases with intense human impacts regardless of climate (e.g., McWethy et al., 2010) as well as limited human impacts in comparison with those forced by climate (e.g., Oswald et al., 2020). The fact that both vegetation and fire respond to climate, however, often makes it difficult to disentangle the two. More natural experiments, like Cygnet Lake, where the confounding effects of one or another of climate, vegetation and fire can be controlled, would help. To date, however, fossil charcoal and pollen-based records of intensive human impacts emerge at the global scale only during the industrial era (Marlon et al., 2008; Brugger et al., 2019; Osmont et al., 2019).

"Slow" (interannual- to decadal-scale) socioecological processes are essential for predicting the future of wildfire and carbon emissions

While long-term climate dynamics set the stage for variations in wildfire on millennial and longer time scales, the interannual and decadal-scale coupling between fire, climate, vegetation, and human activities is more important for understanding our current challenges. Such intermediate-scale socioecological processes are what produce many of the landscape- to regional-scale changes in fire regimes that will unfold in the coming decades (Trouet et al., 2009). Insight into the effects of El Nino Southern Oscillation (ENSO) on fires in the tropics can be gained through analysis of satellite data (van der Werf et al., 2004). But analyses of how global warming may additionally impact Australian bushfires, for example, would benefit greatly from historical and paleo data on fire activity and synoptic-scale atmosphere-ocean interactions beyond interannual scales. Disentangling the effects of anthropogenic climate change from this natural climate variability could reduce large uncertainties in expected fire occurrence in many parts of the world over the coming years and decades (Wittenberg, 2009; Eden et al., 2020). Examination of feedbacks between fires and extreme climate conditions in Amazonia, for example, is needed to understand the likelihood that forests will reach "dieback" tipping points—knowledge essential for informing land management strategies (Brando et al., 2014). Likewise, identifying demographic trends, such as urbanization, rural abandonment, agricultural expansion, and development in the wildland-urban interface, in different regions can reveal how land-cover changes have and will continue to shape fuels and fire in the coming decades (Foster, 2002; d'Amour et al., 2017). Development in the Wildland Urban Interface and migration away from coasts, as well as cultural changes that affect agriculture and land-use, have major implications not only for fuels and ignitions that affect fire regime trends, but also for the exposure of new populations to fire regardless of fire-regime shifts (Knorr et al., 2016). Sociodemographic changes can also influence fire attitudes and policy relating to hazard mitigation and fire suppression (e.g., Guyette et al., 2002; Pausas and Fernández-Muñoz 2012; Bühler et al., 2013; Wu et al., 2015).

Long-term fire-history data from both dendrochronological and paleoecological records, particularly when they overlap in space and time, can improve projections of changing fire activity and its effects on vegetation, climate, and populations beyond seasonal time frames. Indeed, without a better understanding of the key mechanisms driving these "slow" processes or even the ability to identify gaps in our awareness of which processes are most important in driving decadal-scale fire behavior, reducing uncertainty in estimates of future fire and associated carbon emissions will be exceedingly difficult (Kloster et al., 2012). A focus on intermediate (interannual to centennial-scale) ecosystem processes requires the compilation and integration of diverse data sources (Fig. 2; after Gavin et al., 2007). In the western U.S. or southeastern Australia, some of these data are available and abundant if not stored together and in comparable formats (Mooney et al., 2011; Marlon et al., 2012; Williams et al., 2015), whereas in other areas, such as Africa and Siberia, fire as well as other relevant data (e.g., paleoclimate records) are sparse. In most cases, substantial data exist for one or two key components (e.g., fire or climate) but not all (e.g., fire, vegetation, human activities, climate). In northeastern North America, for instance, paleofire and archaeological data are relatively abundant but paleoclimate data are sparse (Oswald et al., 2020; Marlon et al., 2017). In parts of Asia, such as in Japan, rich historical documents complement archaeological and paleoecological evidence (Sasaki and Takahara, 2011). In much of Europe, historical, archaeological and paleoecological data are abundant and provide rich local evidence for long-term environmental change (e.g., Turner et al., 2010; Roberts et al., 2018).

The integration of historical, dendrochronological, and lake-sediment-based paleofire data in the western US during the past 3000 years provides an example of how dramatically climate and human activities can shift fire regimes over several decades (Marlon et al., 2012). Fire frequency and biomass burned here were both driven largely by temperature and drought until the 21st century, when climate and fire became completely decoupled due to increasing human activities that reduced or fragmented fuels and excluded or suppressed fire. A "fire deficit" or gap thus ensued between the amount of fire expected given warmer climate conditions versus the amount of fire actually allowed to burn in the West. This "deficit" helps explain the current surge in fire activity in the West as fuels have accumulated and temperatures continue to warm, extending the fire season and drying out fuels for longer periods each year (Westerling et al., 2006; Williams et al., 2019).

Strong decadal to centennial trends in fire associated with changing human activities, land-use, and demographic patterns are a common feature of paleofire records around the world. Not only are clear increases in burning often evident at the establishment of cultivation as mentioned previously, but examples of subsequent shifts in the intensity and type of fire use are also abundant. Such data provide evidence that charcoal records can detect fine-scale changes in fire caused by human activities. Declines in fire and land-use intensity coupled with forest regeneration are documented, for example, by decreases in charcoal abundance and increases in maize and other pollen types associated with cultivation from sediment cores in Costa Rica in the late Holocene (Clement and Horn, 2001). Also during the late Holocene in northwestern China, peaks in charcoal coincide with declines in arboreal pollen, while gradual increases in the abundance of pollen types indicating human activity, including *Herba taraxaci* and *Radix asteris*, are also observed (Zhang et al., 2015). In Europe, mid- to late-Holocene

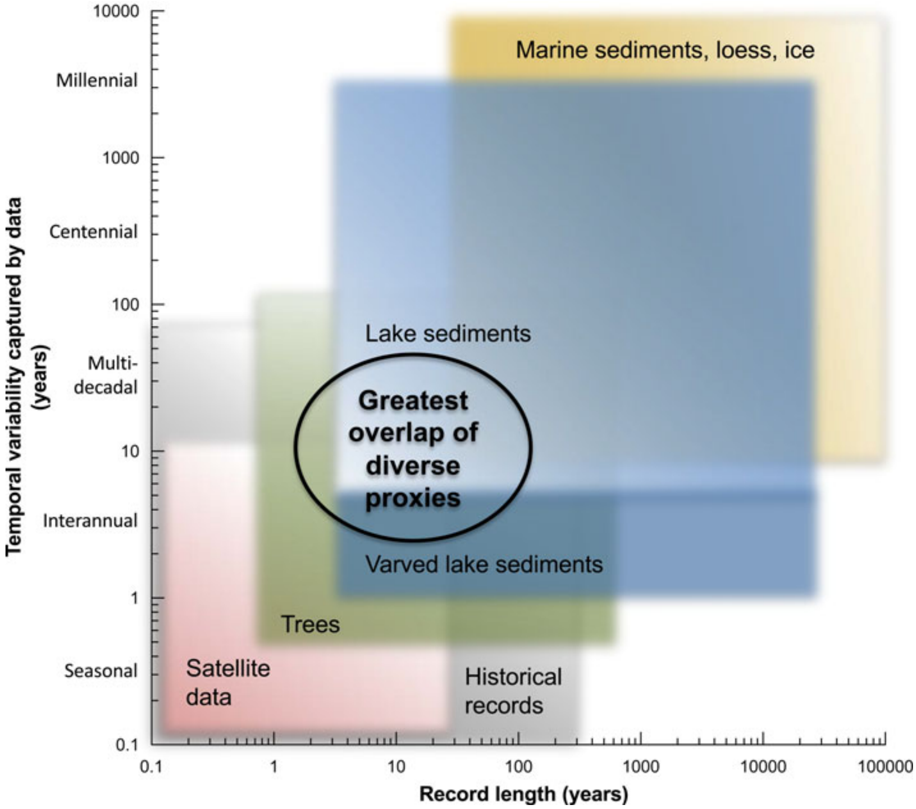

Figure 2. Temporal distribution of record lengths and scales of variability captured by different fire proxies (after Gavin et al., 2007). Many proxy types can capture interannual to decadal scale variability to some extent, but such information is often pushing the limits of sediment proxies in terms of their data availability and accuracy. Nevertheless, many critical research questions lie at this intersection, making multi-proxy data synthesis and integration increasingly imperative.

charcoal increases at Lago dell'Accesa in Tuscany, Italy, are synchronous with the development of settlements in the region, slash-and-burn agriculture, animal husbandry, and mineral exploitation. Human-caused burning in turn triggered significant changes in vegetational communities (e.g. temporal declines of *Quercus ilex* forests and expansion of shrublands and macchia) (Vannière et al., 2008). In east Africa, pollen, charcoal, and archeological data document the cumulative effects of climate and land-use change and how they have continuously shaped fire regimes over the past 6000 years (Marchant et al., 2018).

Analysis of relatively slow processes only evident in long-term reconstructions can also yield insights into the importance of physical processes not considered in typical studies based solely on modern datasets. Calder et al. (2019), for example, identified landscape patterns of climate-fire-vegetation interactions in subalpine ecosystems of Colorado involving “ribbon forests.” These high-elevation bands of forest became separated by meadows, evidenced by coincident increases in sagebrush (*Artemisia*) and other meadow taxa, and decreases in conifers, especially spruce (*Picea*). The vegetation changes occurred during an interval of warming about 1000 years ago, yet were also associated with decreased wildfire frequency as the high-elevation meadows served as novel fuel breaks.

The lack of integration of decadal to centennial trends in fire and fire emissions modeling is evident in simulations produced by dynamic global vegetation models (DGVMs) and in historical reconstructions of fire emissions based largely on paleoclimate and Earth system model output (van Marle et al., 2017). Despite integration of some paleoecological data, such simulations show essentially no multidecadal variability in global fire activity prior to the most recent decade or two. The results stand in remarkable contrast to most paleofire records, including those from the tropics and subtropics, where most burning occurs (e.g., Bush et al., 2005; Colombaroli et al., 2014; Rucina et al., 2009; Wick et al., 2003). Another example of the vital need to incorporate paleodata into modeling comes from Kelly et al. (2016), who demonstrate the importance of accurately estimating baseline levels of burning before trying to model boreal carbon emissions in the coming century. Informing an ecosystem model with paleofire data resulted in predictions showing that forests serve as a carbon source rather than a carbon sink, which they had initially indicated when not informed by paleofire data. Further work integrating diverse fire proxies, especially at decadal to centennial scales, is needed to improve fire modeling and prediction under rapidly changing climate conditions (Rabin et al., 2017).

Progress has been made towards compiling and standardizing data within proxy types, promoted by the Past Global Changes Organization (PAGES) and its many initiatives around climate, land-cover, and fire, for example, but multi-

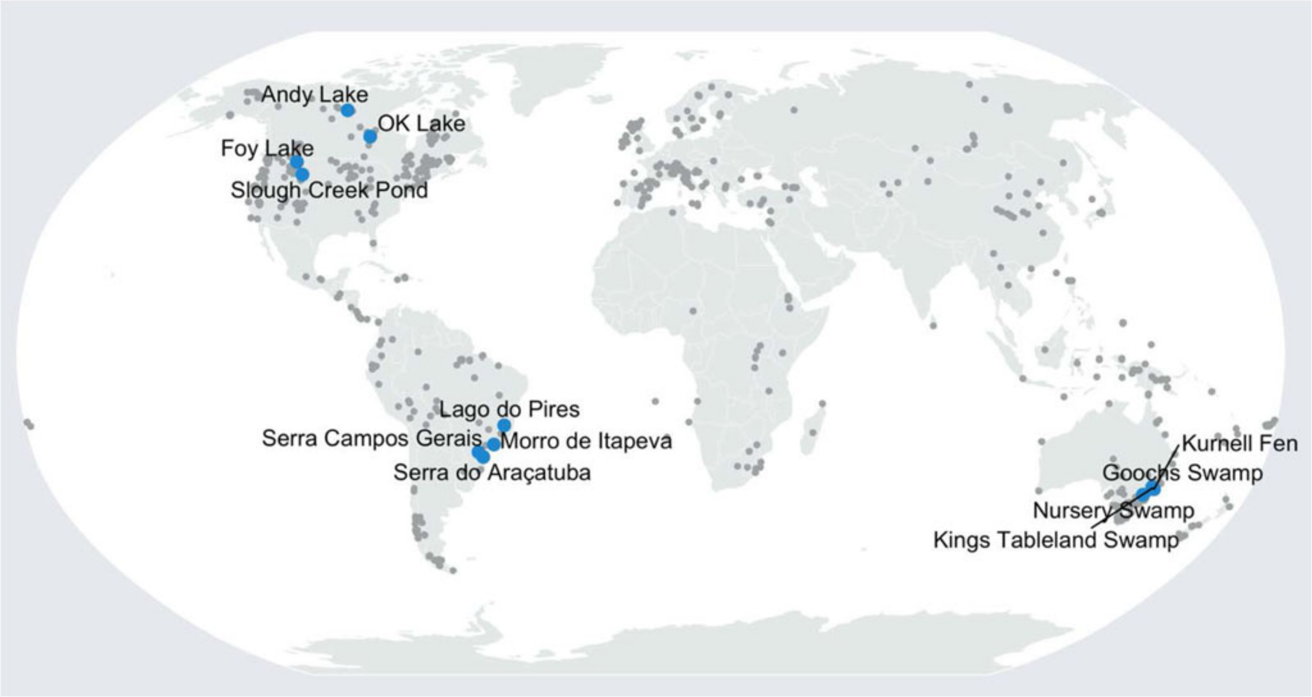

Figure 3. Locations of 12 paleoecological sites (blue) that show unusually high rates of charcoal accumulation during recent decades as compared with Holocene levels. All sites are from the Global Charcoal Database version 3 (Marlon et al., 2016) are shown in gray. Selected sites in blue were selected because they have unprecedented rates of recent charcoal accumulation, but many other sites with similar patterns exist in the database.

proxy initiatives are more nascent. The increasingly availability of data and open-source tools make integration increasingly tractable, at least at regional scales, however. New data collection specifically targeting areas of interest remains critical, so that sites can be carefully selected to maximize the temporal and spatial areas overlap between multiple proxies that yield unique information about ecosystem responses to climate, disturbance, and other changes (Nolan, 2019). Such efforts are challenging given the different areas of expertise and traditions of different subdisciplines, but moving more quickly towards integrating diverse scientific approaches as well as proxies is essential to make progress on ecological challenges that don't fit neatly into disciplinary domains (Buma et al., 2019).

Current fire regime changes are unprecedented

Attributing individual weather events such as hurricanes and heat waves to anthropogenic climate change has been challenging. Attributing fire *regime* changes to global warming can be more even more difficult because of the history of land-use legacies and fire management policy that affect fuels. Yet evidence continues to build that increasing global temperatures are leading to extreme heat and drought that are in turn driving changes in patterns of fire activity (Partain et al., 2015; Abatzoglou and Williams, 2016; Kirchmeier-Young et al., 2019). Defining a specific event as "unprecedented," however, remains contentious, especially in the context of an issue as politically-divisive as global warming in the U.S. Some have argued, for instance, that recent extreme weather events were not unusual because of their physical characteristics or causes, but rather because of their skyrocketing costs, which they attribute to population growth and development in vulnerable areas (Pielke and Landsea, 1998; Crompton et al., 2010). Such arguments, which attempted to temper concern about climate change and its effects on weather, fail to hold up, however, as intense flood events unfold in inland areas, water shortages accompany extreme drought in rural and urban areas alike, and unusually large and severe wildfires spread through wildlands, rural, suburban and urban areas regardless of community or ecosystem type, region, or even continent (Mutch et al., 2011; Burls et al., 2019; Boer et al., 2020).

Paleofire records provide a unique opportunity to assess the rapid emergence of seemingly novel and unusually severe wildfires over very long time periods and in diverse and widely-separated regions (Fig. 3). Individual paleofire records that capture charcoal from tens of kilometers or more around a site can provide long-term context for changes at local scales (Clark, 1988; Tinner et al., 2006), while broad-scale syntheses allow comparisons across regions that reveal patterns shaped by regional and global processes (Marlon et al., 2009; Marlon et al., 2013). Here, examples of paleofire records that show "unprecedented" recent charcoal accumulation rates (influx, measured using diverse methods) are identified where unusually severe wildfires have occurred in the recent past: western North America, the Brazilian Atlantic Coast, and southeastern Australia (Fig. 4).

Fires in western North America have been increasing for the past forty years. Abatzoglou and Williams (2016) find

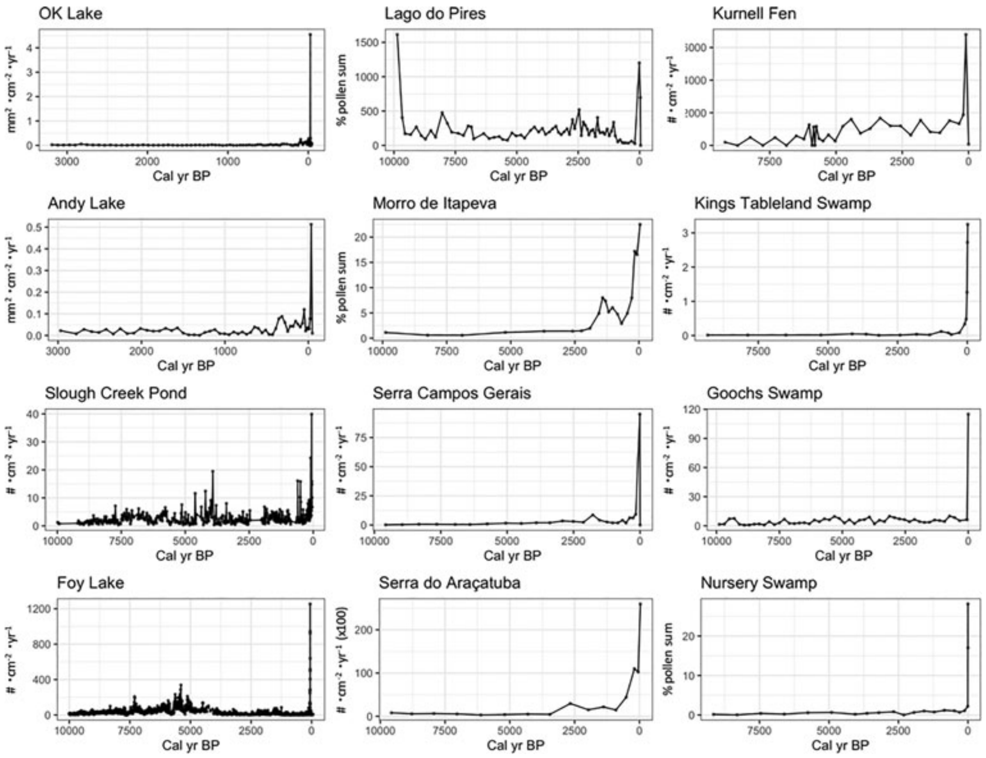

Figure 4. Examples of 12 paleoecological sites showing unusually high rates of charcoal accumulation during recent centuries as compared with Holocene levels in North America (OK Lake, Manitoba; Andy Lake, Northwest Territories; Slough Creek Pond, USA; Foy Lake, USA), in Brazil (Lago do Pires; Morro de Itapeva; Serra Campos Gerais; and Serra do Araçatuba); and Australia (Kurnell Fen, Kings Tableland Swamp, Goochs Swamp, and Nursery Swamp).

that over half (~55%) of the observed increases in fuel aridity across western US forests during this time are attributable to human-caused climate change. Despite a doubling of area burned since the early 1980s, however, some argue that current fire activity levels are only unusual in the context of the past few decades. Stephens et al. (2007), for instance, estimate that approximately 1.8 million ha burned annually in California alone prehistorically (pre-1800). They further estimate that prehistoric annual area burned in California was 88% of the total annual wildfire area in the entire U.S. from 1994–2004. The authors suggest that characterizing two million ha burning annually in California as extreme is a uniquely 20th or 21st century perspective, and that smoky skies must have been characteristic of the summer and fall in California during the prehistoric period.

Indeed, historical, dendrochronological, and paleofire evidence from the western U.S. are highly consistent with the characterization of 20th century burning as extremely low compared with most of the past 3000 years (Marlon et al., 2012). Thus, increases in area burned in and of themselves are not necessarily unprecedented. However, in the two centuries prior to Euro-American settlement of the West, burning was also extremely low due to cool climate conditions and limited drought during the Little Ice Age (Marlon et al., 2012). The causes of pre- and post-settlement fire regime changes are completely different, however. The rates of change in burning and the spatiotemporal variability of changes are also unique in recent times, and not only due to the clustering of modern fires along road networks and coincidence of modern fire outbreaks with summer holidays (Bartlein et al., 2008). Change in charcoal accumulation in lakes across North America during the Industrial Era are visibly anomalous in the past 1000 years, and in some cases the past 5000 or even 10,000 years (Delcourt et al., 1998; Toney and Anderson, 2006; Lynch et al., 2006; Walsh et al., 2010). Examples of this exist in Manitoba at Andy Lake, which had a fire in its watershed in 1994, and in the Northwest Territories at OK Lake, which had a fire in its watershed in 1980 (Lynch et al., 2004). The large wildfires in Yellowstone National Park that burned in 1988, evident in the record from Slough Creek Pond (Whitlock et al., 2008), and fire(s) that registered at Foy Lake in Montana with unknown dates (Power et al., 2011) appear unique at least at the local scale (Fig. 4).

Prior to the 1800s, variations in burning in the Western U.S. resulted from gradual changes in both lightning and human-caused ignitions. Today the additional influences of suppression as well as anthropogenically-induced climate changes that are extending the fire season, producing more extreme high temperatures, and shifting hydroclimatic patterns are becoming evident (Westerling et al., 2006; Abatzoglou and Williams, 2016). The combined effects of climate change with those in land-cover, development, aggressive fire suppression, the spread of invasive species, and other factors have fundamentally altered fire activity in recent decades not only in terms of area burned, but also in terms of timing, severity, location, and other characteristics (Westerling et al., 2006; Lentile et al., 2007, Bartlein et al., 2008; Fusco et al., 2019). The paleofire record captures the anomalous activity of the past two centuries in their long-term context, and as new cores are collected and analyzed, fire activity at regional scales during the most recent decades will be better contextualized as well. In Alaska, the anomalous nature of regional fire regimes is clear. Fire frequency and biomass burning is increasing now more rapidly than at any time in the past 10,000 years based on 14 paleofire records from the Yukon Flats, and this is an area that has been largely unaffected by land-use changes (Kelly et al., 2013). Thus, while it is accurate to say that burning was more widespread in the West prior to the 1800s than it is today, it is *also* accurate to say that at least some of the recent fires in the West are unprecedented in the paleofire record.

Recent burning along the Brazilian Atlantic Coast provides additional examples of unprecedented change with no comparison in the paleofire record (Fig. 4). Deforestation fires affect the livelihoods and health of nearby communities in myriad ways and have tremendous consequences for biodiversity in tropical rainforests and the global carbon cycle (Brando et al., 2020). Concerns that a tipping point may exist where rapid forest destruction becomes assured even without further human impacts increase during extreme wildfire seasons such as what occurred in 2019 when the rate of deforestation rose to its highest level in 11 years (Elassar, 2019). In a synthesis of charcoal accumulation rates in different Amazonian biomes, Cordeiro et al. (2014) found that fire associated with recent intense land-use changes had no precedent during the Holocene history of the Amazon. Similar examples can be found at many sites in Brazil, including Lago do Pires, Morro de Itapeva, Serra Campos Gerais, and Serra do Araçatuba (Behling, 1995; Behling, 1997a; Behling, 1997b, Behling, 2007), but others exist through South America, for example in Columbia (Berrío, et al., 2002), Mexico (Caballero et al., 2006), and Chile (Haberle and Bennett, 2004). While the anomalous changes are not always evident in the original publications of these paleofire records, reanalyses that convert concentration values to accumulation rates, which account for changes in sedimentation at each site, reveal the nature of recent increases in burning more clearly (Fig. 4, based on reanalyzed data from the GCDv3, Marlon et al., 2016). Accurately dating the most recent (uppermost) samples in sediment cores is very difficult, and so obtaining precise dates for recent abrupt changes in charcoal accumulations typically requires validation with independent evidence of burning. Nevertheless, examples such as those described above are not particularly rare; many records from most parts of the world show rapid and dramatic increases (often followed by equally dramatic decreases) in charcoal abundance in recent decades.

A final set of examples showing the unprecedented nature of recent fire-regime changes in their paleoecological context come from southeastern Australia, from lakes not far from where the bushfires of 2019 occurred (Fig. 3). Just south of Sydney, for example, paleofire data from a coastal wetland on the Kurnell peninsula provide a history of fire extending back more than 9000 years. Low levels of fire activity are recorded early in the record but charcoal steadily increases throughout the Holocene. Only two samples span the most recent century, with the earlier one showing extremely high fire activity relative to previous levels, and the more recent sample having almost no charcoal. About 150km to the west of Sydney in the Blue Mountains National Park, several other records show unprecedented fire activity in the most recent decades or century. At Goochs Crater, fire activity was relatively high prior to 9000 yr BP and after 6,000 years BP, when effective moisture was generally low (Black and Mooney, 2006, Black et al., 2008). A mid-Holocene interval of low charcoal accumulation is consistent with an estimated decrease in summer temperature in south-eastern Australia of about 2°C between 9000 and 8000 years BP (Goede et al., 1996), which would have shortened the fire season. Burning in the recent historic past at this site clearly occurred at a level without precedent in the previous 14,200 years. Similar findings come from Kings Tableland Swamp, (Chalson, 1991, Black, 2001), also in the Sydney Basin, and Nursery Swamp in the Australian Capital Territory (Rogers and Hope, 2006; Mooney et al., 2011). Fire activity at Kings Tableland Swamp was minimal for the past 18,000 years, with evidence of small increases in fire ca. 16,000 and 3,000 years ago. The past few decades, however, have seen an exponential increase in the amount of charcoal recorded at the site, clearly unprecedented in this case in the past 18,000 years.

The common factor associated with these examples of unusual yet seemingly unrelated fire events in distant places is human activities, especially intensive, industrialized agriculture and land clearance. The most recent syntheses showing many nearby sites with high recent charcoal accumulation rates, perhaps most evident in Alaska (Kelly et al., 2013), is now additionally reflecting the impacts of human activities on global climate, and particularly the increases in global temperatures that extend fire seasons and cause an increase in the number of very hot, dry days. Globally, satellite data show that the increase in temperatures has lengthened the fire season between 1979 and 2013 (Jolly et al., 2015). In addition to more frequent extremely hot days, nighttime temperatures are rising (Donat et al., 2012), which may lead to increases in fire duration and ultimately fire season length. New data syntheses and analyses will be needed to examine the mechanisms behind the most recent changes in fire activity (Andela et al., 2019).

Fire scientists must help the public understand the connections between global warming and wildfire

Climate scientists have been sounding the alarm about the risks of a warming planet and its effects on wildfires and many other impacts for decades. The societal response continues to fall far short of what is needed to slow global carbon emissions. For many individuals, climate change impacts have been perceived as distant in space (e.g., affecting those in other countries) as well as in time (e.g. affecting future generations). At least in the U.S., it is only over the past few years that a clear upward trend in public concern has begun to emerge (Ballew et al., 2019). In 2019, registered U.S. voters said that out of 29 issues, ranging from healthcare to international trade, global warming was the 17th most important issue in determining their vote in the 2020 presidential election. A large partisan divide was evident, however, with global warming ranking 29th out of 29 voting issues among conservative Republicans, and 23rd among liberal and moderate Republicans. Among moderate and conservative Democrats, however, it was the eighth highest priority voting issue, up eight places from a year prior. Among liberal Democrats, it was ranked third, with environmental protection ahead of it—ranking *second* as a voting priority. Overall, global warming as a national policy priority for the president and Congress has increased dramatically in the U.S. among Democrats, and somewhat for Independents, while remaining relatively unchanged among Republicans. Thus, for the first time in American electoral history, climate change has become a top tier voting issue for a major political party (Leiserowitz et al., 2019).

Because climate change is a highly complex scientific issue, scientists have necessarily played (and continue to play) a critical role in communicating with and educating the public about its causes, consequences, and solutions. Knowledge about these complexities is extremely low among the public (Leiserowitz et al., 2010), and majorities trust climate scientists more than any other group (e.g. other scientists, television weather reporters, family and friends, or your primary care doctor) for information about this issue (Leiserowitz et al., 2015). Wildfires burning in unusual places, at unusual times, lasting longer or burning hotter than they otherwise would because of extreme heat and drought caused by global warming provide an opportunity for climate and fire scientists to approach the topic when it is already in the news. Scientists can use these extreme weather events made worse by global warming as "teachable moments"—not for those directly experiencing the impacts who need to be focus on preparedness, safety, and self-protection—but rather for those safe from the direct impacts but who are paying attention to these events and are seeking to understand why what we are seeing is unusual. It is exactly at these moments when many are most open to learning what we know from paleoecology about the true range of variability in Earth systems.

Surveys of the American public indicate that many are already making a connection a between global warming and uncontrollable wildfires (Marlon and Cheskis, 2017). Yet, it is only in states that experience wildfires that majorities believe global warming is making them worse. In California and Colorado, for example 69% and 66% of the public, respectively, believe that global warming is increasing the severity of wildfires. In Texas, 61% think that global warming is making wildfires more severe. But fewer people make this connection in states where wildfires are less common. In Ohio, 36% think wildfires are worse now due to global warming. Such differences in perception indicate that people often do not come to understand global warming's consequences until they or their local communities experience them directly, and even then, two individuals who experience the same fire can come away with remarkably different interpretations about the cause and appropriate responses (Howe et al., 2019). More efforts are needed by scientists and many others to help the public understand the seriousness of climate change, the need to act quickly, and critically, the value of acting—even if many impacts are already underway and unavoidable at this stage. Reducing the rate of warming, reducing the magnitude of change, can still have enormous benefits to current and future generations, to ecosystems, and to other species. Articulating the strong and varied connections between wildfires, human activities, and global warming presents a unique communication opportunity for paleoecologists.

Maintaining scientific integrity when discussing the relationships between wildfires and climate change is essential. While the attribution of worsening wildfires to climate change is complex, informing the public about the connections between the two does not have to be (Doerr and Santin, 2016). The public does not need to and in most cases does not want to know about the nuances of fire regimes and their causal relationships to specific components of the climate system. In the vast majority of cases, the public primarily needs to know that managed fires are a critical component of healthy ecosystems, that aggressive suppression of all fires is extremely counterproductive, and that the impacts of unconstrained fossil fuel burning are extremely serious and will continue to worsen if little is done to lower carbon emissions. The growing body of climate attribution studies now provide ample scientific evidence that human activities are increasing the impacts of most extreme weather events (e.g., Trenberth et al., 2015; Herring et al., 2016; Wang et al., 2018). New statistical learning and climate model simulations now show that even when given a single day of globally observed temperature and moisture, the fingerprint of human-caused climate change is detectable (Sippel et al., 2020). The effect of increasing carbon pollution from anthropogenic activities on global climate is thus now affecting *all* weather events. And yet, much can still be done to reduce future damages. Effective solutions are at hand—from the individual to the international level—for reducing global warming and for improving fire management (Schoennagel et al., 2017; Moritz et al., 2014).

The increasing pace of climate change and its impacts are beginning to drive concern among the public (Howe et al., 2019). Wildfires are not the only events gaining attention, but they may be one of the most powerful, visual examples of a rapidly changing climate. From the standpoint of human perception, sea level rise is too slow, too incremental, and limited to the coasts to engage most people. Drought is also a slow process and is ill-suited to the highly visual media of television and the internet. Wildfire, in contrast, has arresting imagery and stories, and unlike hurricanes or flooding, it is intuitively and viscerally consistent with the idea of "global warming." While care in any discussion of wildfire is critical to avoid describing all fire as destructive, the concrete images and strong affective associations of unusually large and severe events that *are* destructive is vital for helping people understand the *meaning* of a warmer world for our own health, our families, and our communities (Weber, 2006). Even when confronted with unmistakable evidence that climate is changing and fire is responding, people still find it difficult to understand, because it is indeed "unprecedented." Yet, by showing them that fire has always been sensitive to climate changes, that reticence to believe it's happening now might be eroded.

CONCLUSIONS

The paleofire evidence discussed here and drawn from hundreds of studies by thousands of scientists around the world point to key lessons about fire that can inform our future efforts to manage fire more sustainably. First, fire is highly sensitive to climate change, and specifically to global temperature changes. As long as there is sufficient fuel, we can expect that fires will continue to grow unusually large, severe, and uncontrollable in fire-prone environments if we do not slow global warming. Second, a better understanding of the many and varied "slow" (interannual to decadal) socioecological processes are essential for predicting the future of wildfire and carbon emissions. Research on these processes requires investment in interdisciplinary collaborations focused on data integration, synthesis, and modeling to advance our understanding of their interconnections. Third, in the context of the Holocene, current patterns of burning, especially in areas with intensive land-use change, are extremely unusual. Unprecedented rates of change are occurring in fire activity not only in limited regions, but in diverse ecosystems on multiple continents, and the only factor common to these changes are human activities and their impacts on the land, vegetation, and now climate. Taken together, these lessons point to the need for deepening engagement of the paleoecology community with other disciplines across the natural as well as social sciences, and also with the public, many of whom are still struggling to understand the nature and scope of climate change and how it will affect our lives, communities and planet in the coming years.

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