Editorial: Fire in the Earth System

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Fire as an Earth System process

Satellite images showing the broad extent of biomass burning, especially in the tropics and subtropics, bear testimony to fire's significance as an Earth System process (Fig. 1). Modern observations of fire, however, describe only part of its dynamics, particularly in biomes where fire reoccurs on timescales of decades or centuries, or is highly variable (e.g., in the boreal forest, tropical rainforests and temperate hardwood forests). Gaining information about these regions requires fire archives that span longer timescales (centuries to millennia), such as tree rings, sediments and ice cores (Fig. 2). This issue of *PAGES news* highlights current research that examines past fire activity, its consequences and its relevance for the future. The articles feature a small sample of fire-history research currently underway and give special attention to new insights that have come from records that span millennia.

Advances in paleofire sciences

Paleofire research began in the early 20th century with the analysis of fire-scarred tree rings in the American West (Clements, 1910; Leopold, 1924) and the identification of charcoal particles in wetland sediments in Europe (Iversen, 1941). The application of these methods in subsequent studies led to the concept of a fire regime (e.g., Heinselman, 1973), which used modern and historical information to describe fire characteristics (e.g., fire frequency, size, seasonality, intensity and severity) within particular ecosystems and better addressed issues of fire management (Conedera et al., 2009). Tree-ring and charcoal records remain primary sources of fire-history information, but other disciplines and technologies, including biogeochemistry, remote sensing, atmospheric physics and environmental modeling, have recently contributed significantly to the field of paleofire research.

Fire science, and particularly paleofire science, has experienced a renaissance in the last twenty years, motivated by the need to understand recent large and seemingly unprecedented fires in many parts of the world, as well as by projections that fire activity will soon exceed 20th century levels (Bowman et al., 2009; Flannigan et al., 2009). Advances have come in several forms, as described in this special issue and references therein. Networks of tree-ring records identify interannual-to-multidecadal modes of climate variability (e.g., ENSO, the Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation) as synchronizers of fire activity across regions (Kitzberger et al., 2007; Falk et al., this issue; Moreno et al., this issue). Tree-ring data also disclose the consequences of fire suppression policies and deliberate burning on vegetation, the alarming increase in disturbance interactions between fire, insect and pathogen outbreaks, and the spread of non-native plants in many forests around the world (Raffa et al., 2008).

High-resolution charcoal records from sediment cores offer information about the long-term trends in fire occurrence and area burned associated with major reorganizations of vegetation and climate. Charcoal time series are now routinely calibrated against historic tree ring and documentary data (see Whitlock and Larsen, 2001), and interpretations have become more sophisticated with the development of new process-based modeling approaches (Higuera et al., this issue). The combination of multiple proxy, empirical and modeling approaches, and an improved ability to document spatial and temporal patterns, show that natural fire regimes have long dynamic histories (Whitlock et al., 2010). These insights have guided land-management planning, as well as increased our understanding of fire as a keystone process in shaping the structure and function of ecosystems.

Fire science intersects all of the PAGES research foci, for biomass burning serves as a climate forcing, a component of regional climate dynamics, a feedback to global Earth System dynamics, and a key link in human-climate-ecosystem interactions. Tree ring and charcoal data from around the world are now available through the NOAA International Multiproxy Palaeofire Database (http://www.ncdc.noaa.gov/paleo/impd/paleofire.html) and the Global Palaeofire Working Group (http://www.gpwg.org/), part of the IGBP Cross-Project Initiative on Fire supported by the IGBP core projects PAGES, AIMES, and iLEAPS. The Global Charcoal Database contains over 750 charcoal records from lakes, wet-
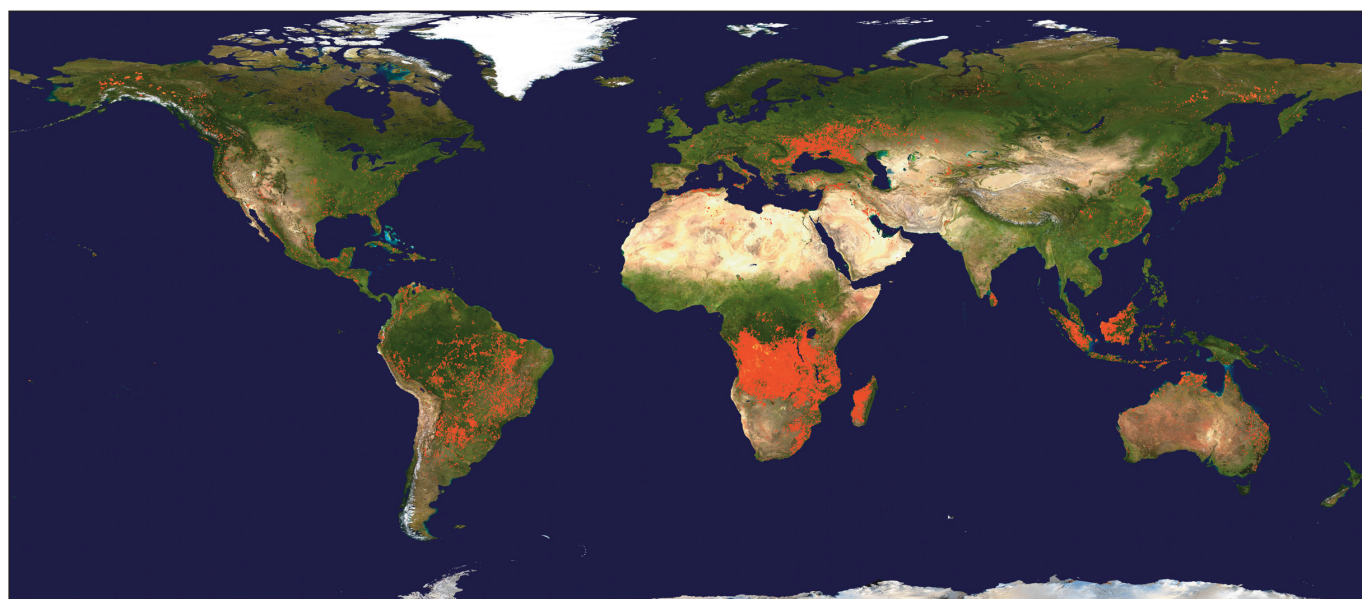

Figure 1: Global distribution of fires (red dots) in July 2009 highlighting the importance of fire as an ecosystem process. Fire maps by J. Descloitres, MODIS Rapid Response System (http://rapidfire.sci.gsfc.nasa.gov/) at NASA/GSFC, using detection algorithm by L. Giglio. Background map by Blue Marble (R. Stokli).
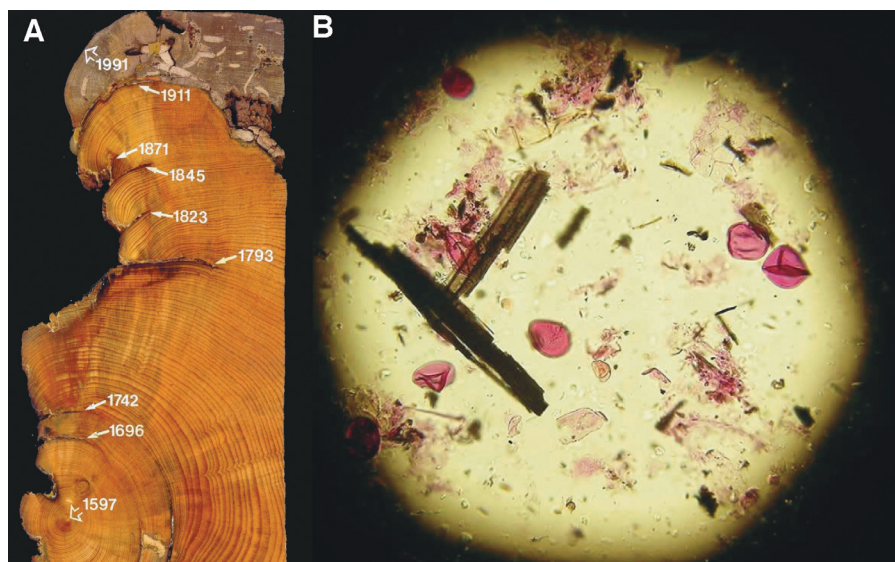
Figure 2: Tree ring and charcoal studies that describe fire history provide critical information on the long-term role of humans, climate and vegetation in natural fire regimes. **A**) *Cross-dated fire-scarred* Pinus ponderosa *sample recording numerous fire events (Photo: P. Brown, Rocky Mountain Tree-Ring Research).* **B**) *Charcoal particles in sediments from a deforestation period in New Zealand, Bracken Fern spores are also evident (pink) (Photo: J. Wilmshurst, Landcare Research, NZ).*

lands, soils and marine deposits. Members of the Global Palaeofire Working Group have used the database to describe global patterns of biomass burning since the Last Glacial Maximum (Power et al., 2008), the role of abrupt climate events (Marlon et al., 2009; Daniau, this issue), and patterns of anthropogenic burning and land-cover change (Marlon et al., this issue). Biochemical signatures of fire in ice cores also hold promise for inferring regional and hemispheric patterns of burning (Kehrwald et al., this issue), and statistical and dynamical models help predict future changes in fire regimes as well as clarify the role of fire as a catalyst between climate and ecosystem change (Carcaillet et al., this issue; Moritz et al., this issue).

Important Insights and New Directions

The paleofire community is international and brings together researchers with paleoecologic, paleoclimatic, archeological, modeling and land management backgrounds. Their findings show that fire regimes are complex and change in response to variations in fuel conditions and climate, and humans are seen as both fire starters and fire eliminators in the past. Fire history delivers surprises that could not otherwise have been gleaned. For example, present-day fire-vegetation associations do not easily explain some fire-regime changes in the past when different fuel and climate configurations prevailed (Vannière et al., this issue; Higuera et al., 2008). Moreover, even the wettest forests of the planet have experienced and sometimes been transformed by fire (Gavin et al., 2003; Power et al., this issue; Haberle et al., this issue), and most regions have experienced periods

of burning that were more extreme than the recent centuries (Falk et al., this issue; Colombaroli and Verschuren, this issue; Moreno et al., this issue).

Future research should be directed towards further improving our understanding of the drivers and consequences of biomass burning. We need to increase our knowledge of regional fire history, particularly as large areas of the world, such as Russia and Africa, still have too few records for reconstructing past fire patterns. Multiproxy studies can greatly increase our understanding of fire-prone (e.g., Mediterranean) and fire-sensitive (e.g., rainforest, tundra) ecosystems through time and thus provide useful information to preserve biodiversity under global-change condi-

tions. We also must further explore paleofire records to disentangle the respective roles of climate, vegetation and humans in shaping fire activity at different spatial and temporal scales. This task requires developing hypotheses that can be tested at the local, continental and global scales and engaging new interdisciplinary approaches. Improved interpretation of paleofire datasets will require rigorous proxy calibration and new modeling approaches to increase our precision in reconstructing critical fire-regime metrics. Finally, we need to understand how biomass burning has served as a feedback to the climate system through biogeochemical cycling over Earth's history (e.g., Fischer et al., 2008).

These new directions require linking experimental, observational and satellite data on modern fires with tree-ring records that cover decadal, centennial and sometimes millennial timescales, lake-sediment and ice-core records that span multi-millennial timescales, and geologic archives that go back even farther in time (Fig. 3). Across spatial scales, our goal is to understand the factors that govern ignition and fire spread, the conditions of fuel and weather/climate conditions that affect fire behavior, and the role of vegetation and climate in determining fire patterns at subcontinental scales. Finally, fires were an important catalyst in biome formation and evolution. Accordingly, paleofire studies are critical for understanding ecosystem dynamics and Earth System interactions, on the basis of which sound land management and conservation strategies can be developed.
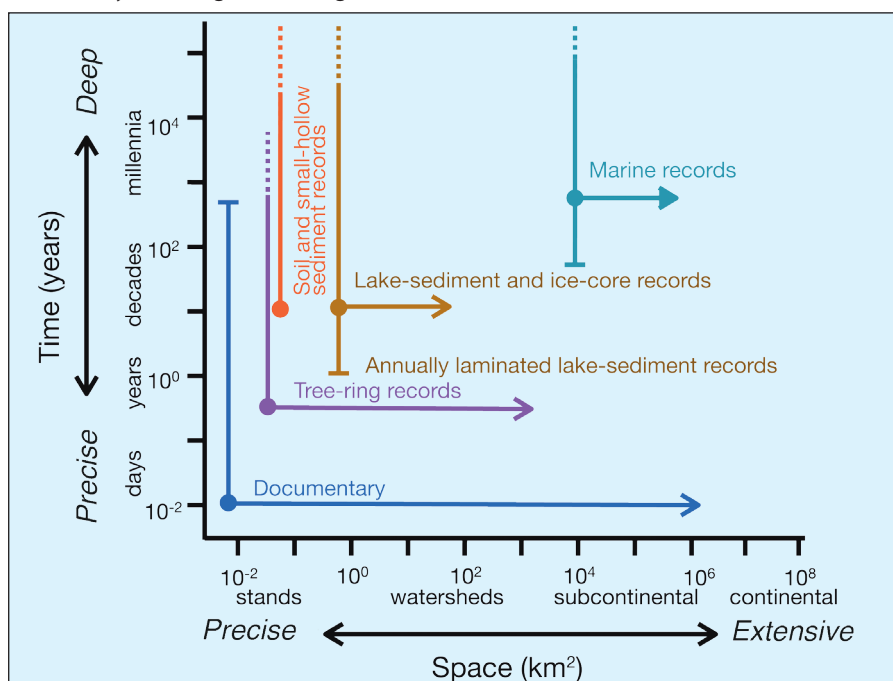

Figure 3: Paleofire science seeks to better understand fire's role in the Earth System by examining the causes and consequences of biomass burning on a variety of temporal and spatial scales, and is available from an array of archives that register fire at different scales and resolutions (modified from Gavin et al., 2007).

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Recent advances in the analysis and interpretation of sediment-charcoal records

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Numerical models and statistical analysis aid interpretation of fire history from sediment-charcoal records, allowing inferences into the causes of past fire-regime shifts through quantitative analyses and data-model comparisons.

High-resolution charcoal records from lake sediments are an increasingly important proxy for understanding the characteristics and variability of past fire regimes (e.g., Gavin et al., 2007). Recent advances in simulating sediment-charcoal records have improved our understanding of this proxy and help guide data analysis methods. With improved quantitative analyses, comparisons between fire-history records, other paleoenvironmental records and dynamic ecosystem models increasingly enable insights into the causal mechanisms controlling past fire regimes.

Modeling sediment-charcoal records

The interpretation of fire history from sediment-charcoal records has relied heavily on understanding two sets of processes: (1) Those affecting the charcoal source area, and (2) Those affecting charcoal deposition and burial (taphonomy; e.g., Clark, 1988). Questions of charcoal source area have been addressed through empirical studies (e.g., Clark, 1990; Whitlock and Millspaugh, 1996; Tinner et al., 1998; Gardner and Whitlock, 2001; Lynch et al., 2004) but ultimately assessing source areas requires an appropriate model to simulate charcoal dispersal. Peters and Higuera (2007) expanded the dispersal model used by Clark (1988) and tested its suitability for simulating charcoal dispersal by comparing predictions with data from an experimental canopy fire (Lynch et al., 2004). The dispersal model explained 67% of the variability in charcoal deposition from 0-200 m from the edge of the fire, implying that it was an appropriate tool for simulating charcoal records.

Higuera et al. (2007) used this work to develop a numerical model simulating the charcoal deposition in a lake bottom, given dispersal from hypothetical fire histories and mechanisms affecting charcoal taphonomy. The CharSim model, when calibrated to fire regimes from Alaskan boreal forests, generates charcoal stratigraphies that are statistically similar to empirical records (Higuera et al., 2007; Fig. 1). This similarity suggests that the model represents at least one set of processes creating observed sediment-charcoal records and makes it possible to use simulated charcoal records to test conceptual models and inform data analysis methods.
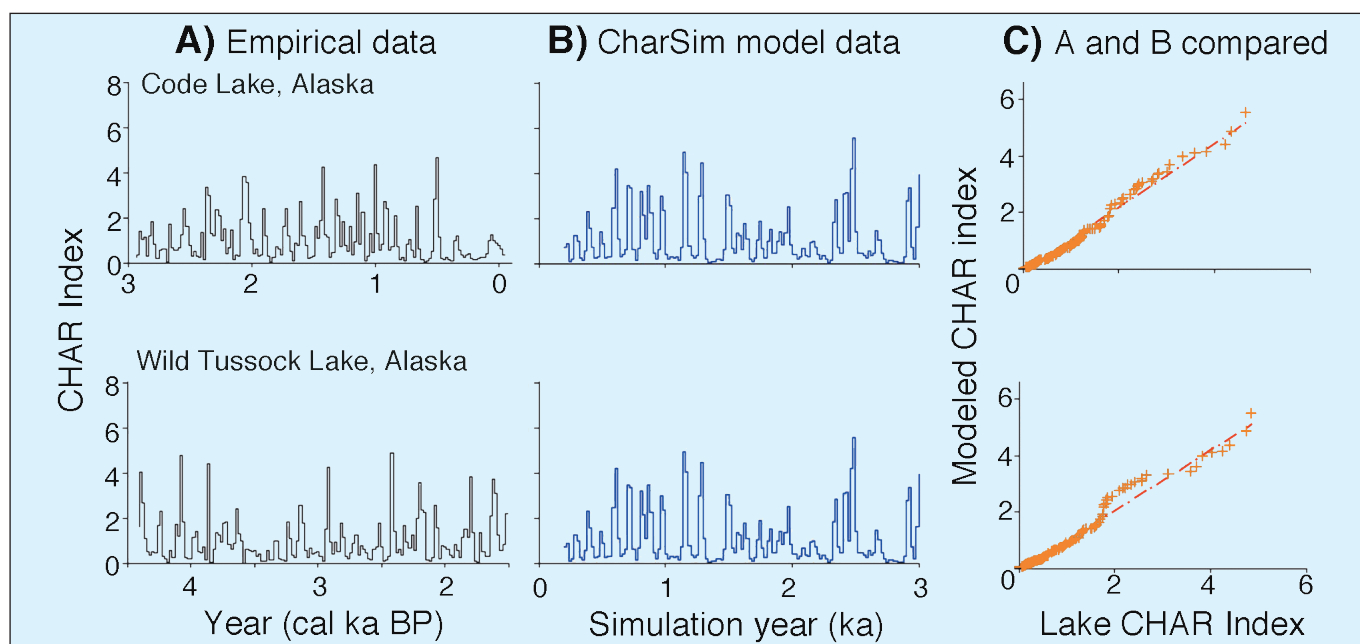

*Figure 1: Comparison between (**A**) empirical charcoal records and (**B**) a simulated charcoal record from the CharSim model (modified from Higuera et al., 2007) for Code Lake (top row) and Wild Tussock Lake (bottom row), in Alaska. Charcoal accumulation rates (pieces cm^{-2} a^{-1}) in empirical records are standardized to a mean value (CHAR index), allowing direct comparison with the simulated record. Empirical records include only periods that could satisfy the assumption of approximately constant sediment accumulation, mixing and burning rates (explicit in the simulated record). Linear quantile-quantile (Q-Q) plots (**C**) support visual inspection suggesting similar CHAR distributions between empirical and simulated records. The CharSim records were created using specific, non-varying parameters representing fire frequency, fire size, primary and secondary charcoal transport, sediment mixing, and sediment sampling. The mean fire-return interval (FRI) within 100 m of the simulated lake was 120 a. This is consistent with the mean FRIs of 135 a at Code and Wild Tussock lakes (95% CI 113-160 and 113-157, respectively) for the past 5.5 ka, inferred from peak detection methods (Higuera et al., 2009).*