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Fire in the Earth System: A Paleoperspective

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In recent decades, fire activity has increased dramatically in many parts of the world, raising concerns about future fire regimes with global warming. The image above shows a recent (2009) bush fire in northern Australia (photo: www.morgueFile.com/). Fire is recognized as an essential, natural process in most ecosystems but to fully appreciate fire's role in the Earth System requires an examination of its causes and consequences over multiple temporal and spatial scales. This newsletter highlights recent research efforts that seek to gain this broader perspective.

Inside PAGES

New PAGES Communications Officer

PAGES has a new Project and Communications Manager! Anand Chandrasekhar (anand.chandrasekhar@pages.unibe.ch) lived and studied in India and the UK and has now joined PAGES International Project Office team in Switzerland. Anand has a forestry and conservation biology background and specializes in environment communications, advocacy and policy. At PAGES, Anand will be further developing the PAGES communication strategy, in particular revamping the PAGES website to make it more dynamic and user-friendly and establishing new pathways of communication, such as PAGES on Facebook (become a fan!).

New PAGES publications

The Integrated History and Future of People on Earth (IHOPE) Research Plan is now completed and available for download from the PAGES website (under resources>products). IHOPE seeks to better understand the dynamic interactions between all aspects of human behavior and the environment by connecting the histories of humans, climate and environment at multiple temporal scales (millennial, centennial, decadal and future scenarios). For more information on their pretty, new website: http://www.stockholmresilience.org/ihope.

PAGES has also recently published an article, essentially providing a condensed version of the recent science plan (*Current Opinion in Environmental Sustainability*, in press). For more information visit http://www.pages-igbp.org/cgi-bin/WebObjects/products.woa/wa/type?id=11

A number of articles from PAGES initiatives and Working Groups have been published. Two review papers from Focus 4 Working Groups highlight research results and future goals. One paper, coming out of the LUCIFS (Land Use and Climate Impact on Fluvial Systems) Working Group, was led by T. Hoffmann and reviews the interaction of people with rivers over the Holocene (*Global and Planetary Change*, 72: 87-98). The other paper, led by M.-J. Gaillard, reviews approaches and data sets of land-cover reconstructions, under the umbrella of Focus 4 Land Cover Theme (*Climate of the Past*, 6: 483-499).

Two milestone articles uncovering the climatic history of the Southern Hemisphere have also been published. These provide spatial, temporal and seasonal temperature (Neukom et al., *Climate Dynamics*, DOI: 10.1007/s00382-010-0793-3) and precipitation (Neukom et al., *Geophysical Research Letters*, DOI: 0.1029/2010GL043680) reconstructions over the last centuries from southern South America. The papers synthesize work done by the PAGES-LOTRED-SA (Long-Term climate Reconstruction and Dynamics of southern South America) Working Group.

Finally, the special issue resulting from the PAGES Open Science Meeting 2009, to be published in the open access journal *Climate of the Past*, is progressing with 6 articles readily published and 4 more under review. All articles can be accessed from http://www.pages-igbp.org/cgi-bin/WebObjects/products.woa/wa/type?id=3

Recent SSC meeting

At its annual meeting, PAGES Scientific Steering Committee (SSC) surveyed the status of its science plan. The structure and progress of the scientific building blocks (Themes, Working Groups, endorsed projects) was reviewed and old and new links with other organizations were discussed. Beyond this day-to-day business, the SSC also initiated a process to look further ahead and develop concepts for how PAGES and paleoscience coordination in general could evolve over the next decade.

Ideas discussed included past-to-present time-continuous coordination of the physical basis of global change, continuing to provide the historical perspective to global change science, and expanding Focus 4 type research with humans as part of the Earth System. Minutes of SSC meetings are available on http://www.pages-igbp.org/people/sscmembers/meetingminutes.html

PAGES support for meetings

PAGES Executive Committee (EXCOM) recently met to deliberate on workshop proposals submitted to the first call in 2010. A total of 10 meetings were awarded financial support. Two proposals to the "open call" from external groups were approved, one for a workshop in Tanzania of the INQUA-Eastern African regional group, and one for a Symposium in Portugal that will dissect the Medieval Warm Period idea. Two educational-type workshops received support, one on Paleochronology Building held in Mexico, and one on Paleoclimate and Paleoecology in South American held in Chile. PAGES Working Groups that were allocated support for their workshops include Past Interglacials (PIGS), Human Impacts on Terrestrial Ecosystems (HITE), Paleo–ocean Acidification, and the Asian, Arctic and European-Mediterranean groups of the 2000-year regional climate reconstruction ("2k") Network.

The next deadline for meeting support proposals is the 22 Nov 2010, for consideration by the EXCOM in mid-December.

More information on specific workshops is available on the PAGES website (calendar>PAGES supported)

Call to host PAGES OSM/YSM in 2013

PAGES invites applications by groups interested in hosting the 4th PAGES Open Science Meeting (OSM) and the associated 2nd Young Scientists Meeting (YSM). The meetings will be held in the first half of 2013. The OSM and YSM are PAGES flagship events and are much anticipated fixtures on the paleoscience calendar. Interested groups are requested to send a completed application form (see http://www.pages-osm.org/) to PAGES by 29 October 2010.

IPCC AR5 authors

Of the approximately 3000 nominations that were received from around the world, 831 scientists have been selected to prepare the IPCC Fifth Assessment Report (AR5). Three current PAGES SSC members will contribute to the "Paleoclimate Archives" chapter of IPCC Working Group 1. Michael Schulz as a Coordinating Lead Author, Bette Otto-Bliesner as a Lead Author, Heinz Wanner as a Review Editor, and other authors involved with PAGES will help to communicate results from PAGES activities to IPCC. Lists of authors of all IPCC WGs are available at http://www.ipcc.ch/

Next newsletter issue

The planned special section of the 3rd 2010 issue of *PAGES news* will be on PAGES and International Geosphere-Biosphere Programme (IGBP) science. Paired topical articles will provide different perspectives on global change questions that are addressed in PAGES and our IGBP sister-projects. If you have ideas for contributions to this issue please let us know! Ninad Bondre, Science Editor at IGBP, will be guest-editor for this special section. In addition, the newsletter will have the usual open (i.e., general) section for your research articles, program news and workshop reports. Deadline for any contributions is 4 October. Guidelines for contributions can be found online (http://www.pages-igbp.org/products/newsletters/instructions.html).

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-

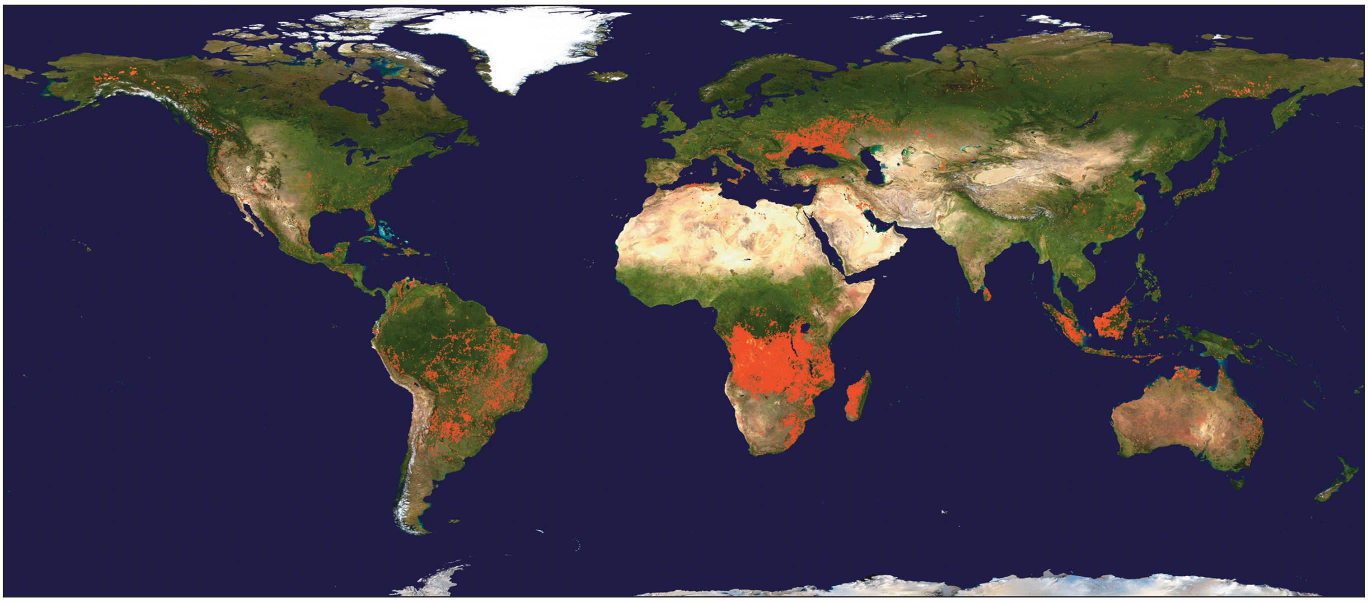

Figure 1: Global distribution of fires (red dots) in July 2009 highlighting the importance of fire as an ecosystem process. Fire maps by J. Descloitres, MODIS Rapid Response System (http://rapidfire.sci.gsfc.nasa.gov/) at NASA/GSFC, using detection algorithm by L. Giglio. Background map by Blue Marble (R. Stokli).

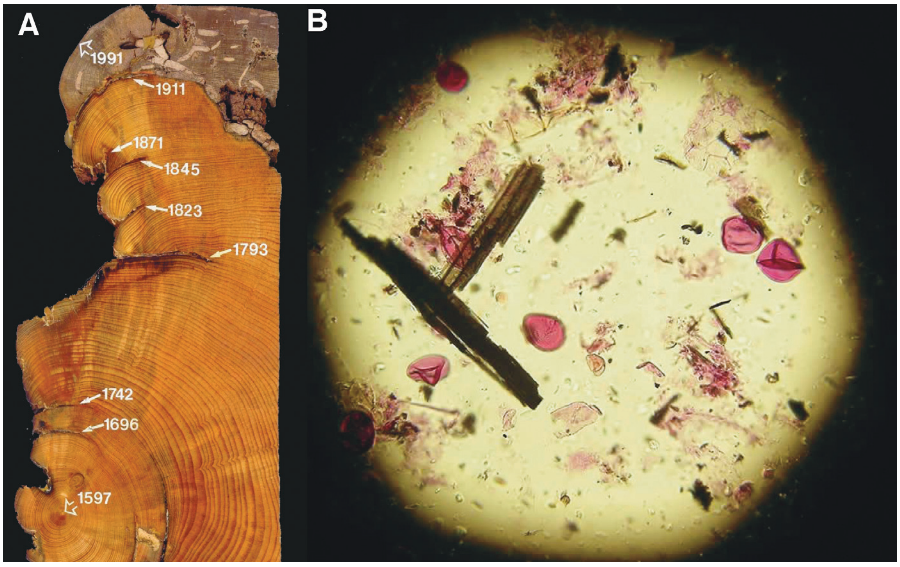

*Figure 2: Tree ring and charcoal studies that describe fire history provide critical information on the long-term role of humans, climate and vegetation in natural fire regimes. **A**) Cross-dated fire-scarred* Pinus ponderosa *sample recording numerous fire events (Photo: P. Brown, Rocky Mountain Tree-Ring 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 conditions. 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.

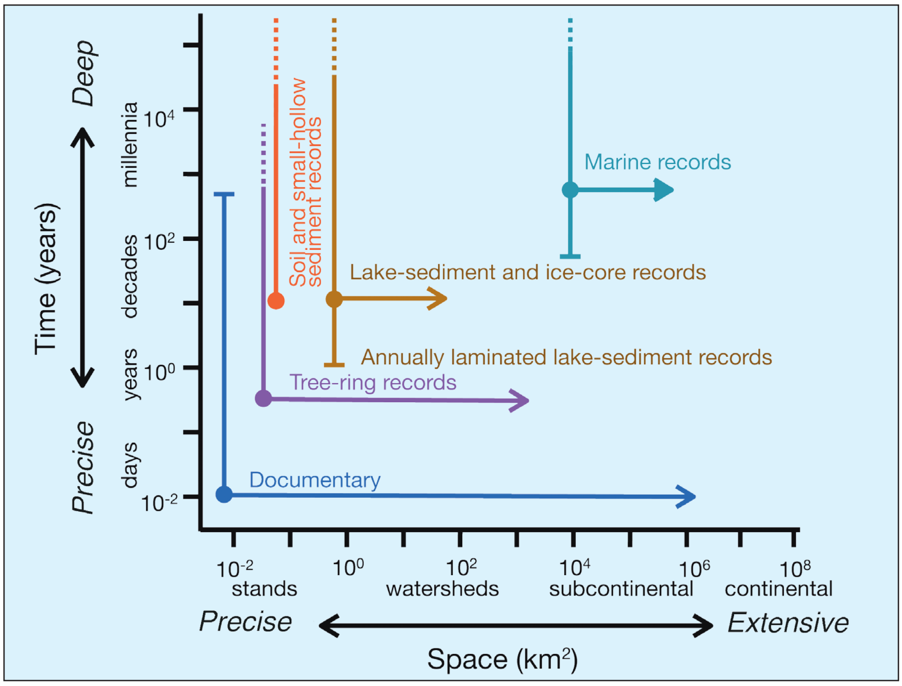

Figure 3: Paleofire science seeks to better understand fire's role in the Earth System by examining the causes and consequences of biomass burning on a variety of temporal and spatial scales, and is available from an array of archives that register fire at different scales and resolutions (modified from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

References

Bowman, D.M.J.S., et al., 2009: Fire in the Earth System, *Science*, **324**: 481-484.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A.F. and Krebs, P., 2009: Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation, *Quaternary Science Reviews*, **28**: 555-576.

Flannigan, M.D., Krawchuck, M.A., de Groot, W.J., Wotton, B.M. and Gowman, L.M., 2009: Implications of changing climate for global wildland fire, *International Journal of Wildland Fire*, **18**: 483-507

Gavin, D.G., Hallett, D.J., Hu, F.S., Lertzman, K.P., Prichard, S.J., Brown, K.J., Lynch, J.A., Bartlein, P. and Peterson, D.L., 2007: Forest fire and climate change in western North America: insights from sediment charcoal records, *Frontiers in Ecology and the Environment*, **5**: 499-506.

Whitlock, C., Higuera, P.E, McWethy, D.M. and Briles, C.E., 2010: Paleoperspectives on fire ecology: revisiting the fire regime concept, *The Open Ecology Journal*, **3**, 6-23.

For full references please consult:

http://www.pages-igbp.org/products/newsletters/ref2010_2.html

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.

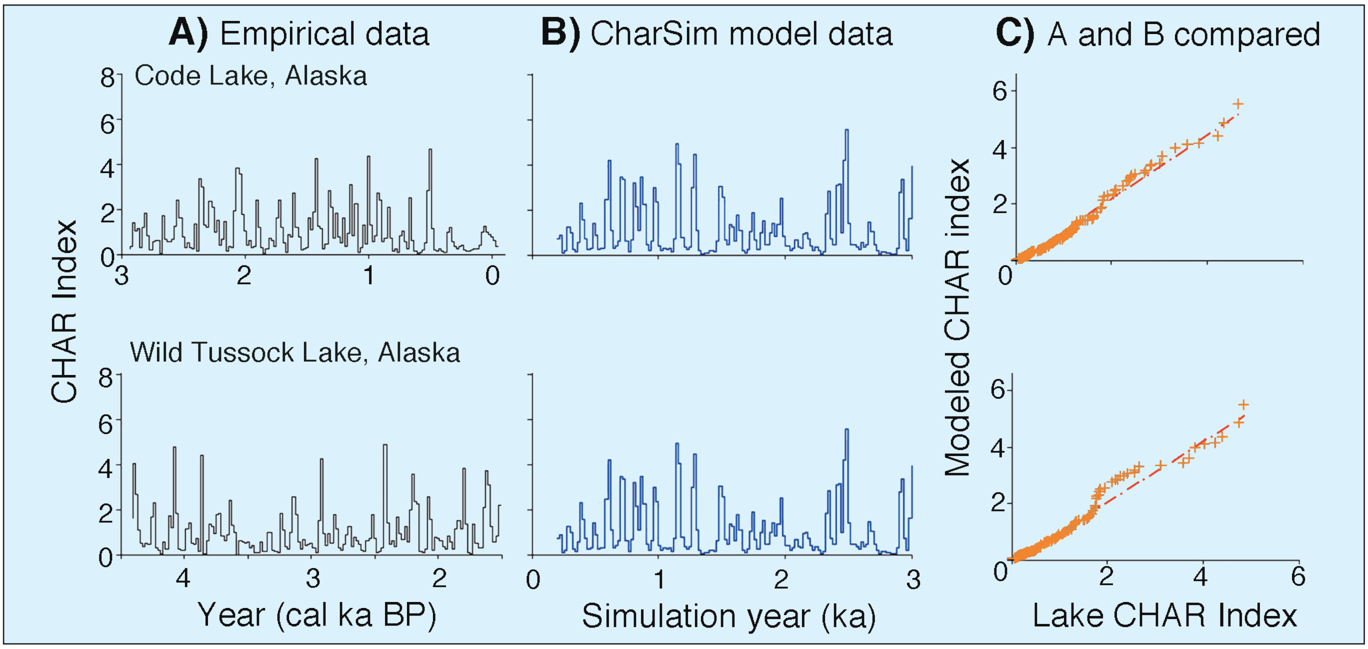

*Figure 1: Comparison between (**A**) empirical charcoal records and (**B**) a simulated charcoal record from the CharSim model (modified from Higuera et al., 2007) for Code Lake (top row) and Wild Tussock Lake (bottom row), in Alaska. Charcoal accumulation rates (pieces cm^{-2} a^{-1}) in empirical 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).*

Analysis of a series of simulated records suggests that charcoal source areas for macroscopic charcoal (>100 µm diameter) are likely larger than previously inferred from experimental data but in agreement with observations during or after fires (within several to 10s of km; e.g., Tinner et al., 2006). Distinct charcoal peaks in simulated records also reflect fire events within relatively short distances of a 1-ha simulated lake (i.e., with 500-1000 m; Higuera et al., 2007). This link between charcoal peaks and fire events emerges from the combined effects of charcoal dispersal and the landscape pattern of fire. When fires are large relative to the charcoal source area, distinct peaks are created when fires burn near a lake. These inferences provide important theoretical support for existing and recently developed statistical techniques for analyzing sediment-charcoal records.

Statistical analysis of sediment-charcoal records

Macroscopic sediment-charcoal records have been analyzed in three distinct ways: interpreting fire episodes from peaks identified in individual records, compositing multiple records to reveal a regional trend, and comparing records to identify the drivers of fire regimes. A common goal with high-resolution macroscopic charcoal stratigraphies is to identify charcoal peaks and interpret them as series of fire episodes occurring near the lake. This task of "peak detection" is accomplished by applying a threshold to the charcoal time series.

Recent advances in peak detection (reviewed in Higuera et al., in press a) include (1) determining whether a macroscopic charcoal stratigraphy is suitable for peak detection in the first place by using a signal-to-noise index (e.g., Kelly et al., 2010); (2) identifying the noise-related variance in a charcoal record as distinct from variance related to fire events; and (3) setting a threshold based on an estimate of noise-related variance. Although the statistics of peak identification have progressed, it remains important that researchers validate the recent portion of the record with independent evidence of fire.

The proliferation of charcoal records in recent decades motivates the development of regional series by compositing multiple records, akin to the goal of compositing climate reconstructions. Unlike climate proxies, which are calibrated to temperature before compositing, methods for calibrating charcoal records to biomass or area burned are just now being developed (e.g., Higuera et al., in press b). Therefore, compositing requires standardization to a common unitless scale before averaging (Marlon et al., 2008, 2009; Power et al., 2008). The resulting charcoal index of inferred biomass burning shows patterns that can be compared with independent proxies of potential fire-regime drivers (e.g., humans, vegetation, and climate; Marlon et al., 2008).

Finally, a careful comparison of closely-spaced charcoal records is a simple means of examining regional controls of fire regimes, thus helping to distinguish between regional drivers (e.g., climate, vegetation and humans) and local, more variable drivers of fire history (e.g., lightning ignitions, fuel loads and weather; Swetnam et al., 1993). Gavin et al. (2006) used this rationale to compare two fire records spanning the past 5 ka located 11 km apart. Although this period contains only a fraction of the climatic variability of the Holocene, the records showed a long-term, synchronous trend over the past 2 ka (Fig. 2).

Data-model comparisons

Our improved understanding of sediment-charcoal records and our ability to extract quantitative fire-history metrics have allowed comparisons between charcoal records and landscape models with complementary spatial and temporal scales.

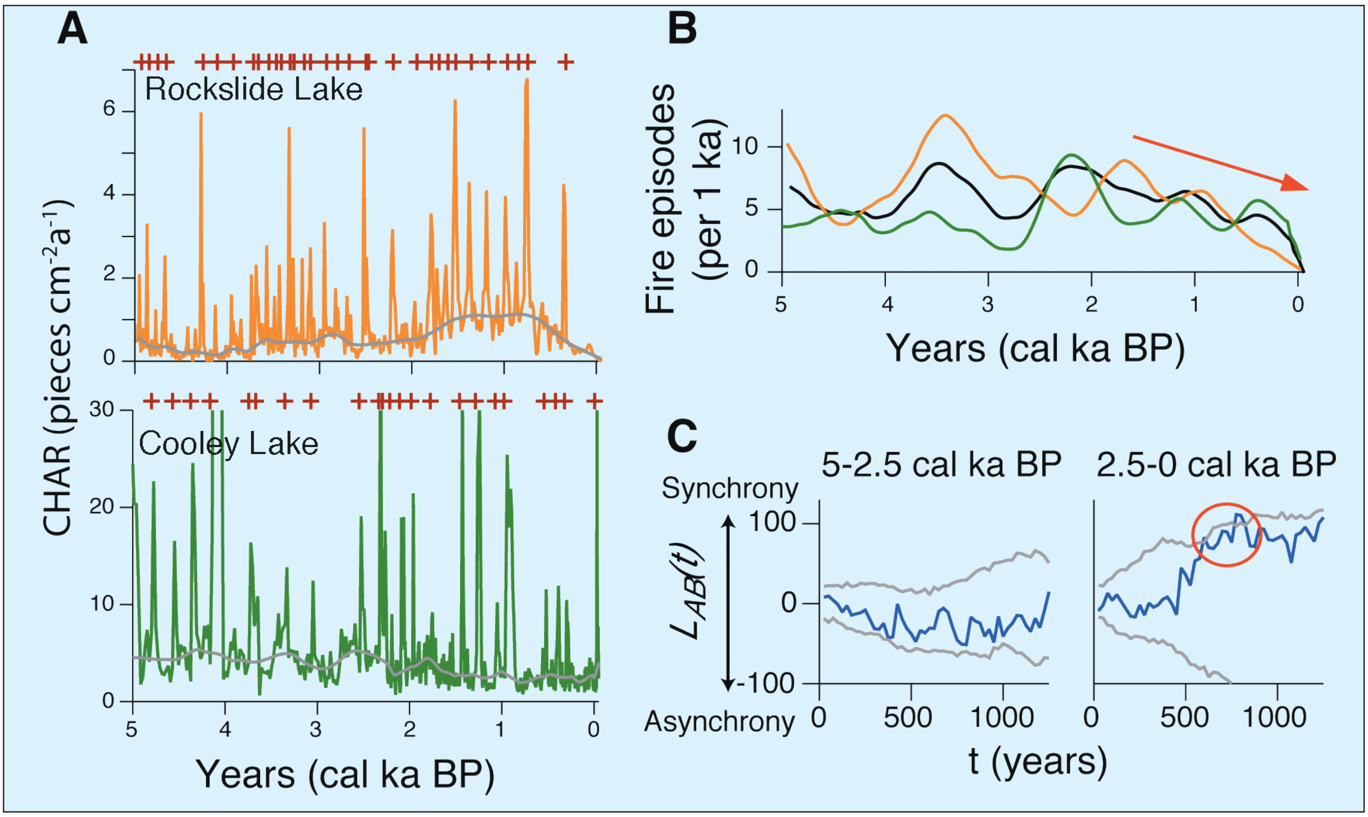

*Figure 2: Analysis of charcoal stratigraphies from two lakes 11 km apart in southeastern British Columbia (from Gavin et al., 2006). **A**) Charcoal accumulation rate (CHAR) for the past 5 ka in Rockslide Lake (orange) and Cooley Lake (green). Gray line = "background" level from which peak heights are determined. Red crosses indicate inferred fire episodes. **B**) Smoothed fire frequency (with a 500-a window) shows diverging trends before 2.5 cal ka BP but similar decreasing trends since then. Black line = composite of the Cooley (green) and Rockslide (orange) lake records. Despite the proximity of the two sites, fire-return intervals increased at Rockslide Lake but decreased at Cooley Lake between the two periods. Intervals since 2.5 cal ka BP were similar at each site (red arrow). **C**) Synchrony analysis of the inferred fire episodes based on the Ripley K function (represented by $L_{AB}(t)$) for two 2.5 ka-long periods. Gray lines are the 95% confidence envelope based on 1000 randomizations of shifting the records relative to each other. This analysis shows the temporal scales at which two (or more) records show temporal dependence ("synchrony"). The significance found at scales of 0.6 to 0.8 ka (red circle) is consistent with the timescale of the decreasing trend over this period. The dissimilar fire history from 5-2.5 cal ka BP may represent a less important role for climate during that period.*

Pairing high-resolution charcoal records with landscape models helps overcome an important limitation common to paleorecords: patterns of past change can be reconstructed, but the causal mechanisms responsible are difficult to determine.

Ecological modeling offers the distinct advantage of being able to isolate the interactive influences of climate, vegetation and/or human activity on fire regimes. Statistically comparing simulation output with reconstructed fire history then helps to evaluate competing hypotheses explaining past fire-regime dynamics. Brubaker et al. (2009) employed this approach to suggest that the impact of shifting vegetation was more influential on regional fire regimes in Alaska than the direct effects of climate change. Specifically, in a statistical comparison of charcoal-inferred and simulated fire regimes, a reconstructed increase in fire frequency at ca. 5.5 cal ka BP only matched simulations that combined the addition of highly-flammable black spruce with the fire-dampening effects of decreased temperature or increased precipitation.

Data-model comparisons are also instructive when evaluating human impacts on past fire regimes. Using a dynamic landscape vegetation model, Colombaroli et al. (in review) found that ignition frequency overrode climatic influences in determining area burned near the treeline in the Swiss Alps. Thus, an increase in the impact of fire on treeline vegetation during the last 4 ka was attributed to Bronze Age land-use intensification.

Conclusions and future directions

An improved understanding of sediment-charcoal records through process modeling has helped advance analytical techniques for inferring fire history over thousands of years. In conjunction with a proliferation of high-resolution charcoal records developed over the past several decades, paleofire records are increasingly used to untangle complex interactions between multiple drivers of historic fire regimes. Data-model comparisons in particular have and will continue to play an important role in these efforts. Although we focused here on how these comparisons help improve interpretations of sediment-charcoal records, the benefits of this integration are equally important to model development. Ultimately, landscape and larger-scale models can be validated using sediment records and thus more confidently applied to project fire regimes under anticipated future conditions.

Data

The empirical charcoal records reported in figures 1-2 are publicly available through the International Multiproxy Paleofire Database: http://www.ncdc.noaa.gov/paleo/impd/paleofire.html.

References

Brubaker, L.B., Higuera, P.E., Rupp, T.S., Olson, M., Anderson, P.M. and Hu, F.S., 2009: Linking sediment-charcoal records and ecological modeling to understand causes of fire-regime change in boreal forests, *Ecology*, **90**: 1788-1801.

Colombaroli, D., Henne, P.D., Gobet, E., Kaltenreider, P. and Tinner, W., in review: Species responses to fire, climate, and human impact at tree-line in the Alps as evidenced by paleo-environmental records and dynamic simulation approaches, *Journal of Ecology*.

Gavin, D.G., Hu, F.S., Lertzman, K. and Corbett, P., 2006: Weak climatic control of stand-scale fire history during the late Holocene, *Ecology*, **87**: 1722-1732.

Higuera, P.E., Peters, M.E., Brubaker, L.B. and Gavin, D.G., 2007: Understanding the origin and analysis of sediment-charcoal records with a simulation model, *Quaternary Science Reviews*, **26**: 1790-1809.

Kelly, R.F., Higuera, P.E., Barrett, C.M. and Hu, F.S., in press: A signal-to-noise index to quantify the potential for peak detection in sediment-charcoal records, *Quaternary Research*.

For full references please consult:
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Specific molecular markers in ice cores provide large-scale patterns in biomass burning

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Flammable vegetation releases distinct organic markers associated with smoke particles, and the presence of these compounds in ice cores across the globe provide information on changes in fire regimes through time.

International efforts to retrieve ice cores from both poles and every possible continent have resulted in a wealth of high-resolution climatic and environmental records. Methodological advances in measuring past atmospheric chemistry are revealing aerosols from both natural and anthropogenic biomass burning. Chemical markers in ice cores can measure past fire regimes including changes in spatial distribution, timing and fuel type (Conedera et al., 2009). Low-latitude ice cores primarily reflect regional fire and climate parameters, while polar ice cores reflect a global signal. The reconstruction of past wildfire occurrence through molecular markers in ice cores is a new field, one that requires further investigation; nonetheless, the global array of archived ice cores allows for future research into one of the least known aspects of the climate system.

Fire activity has varied in the past in response to climate, vegetation change and human land use. Recent aerosol emissions are a combination of anthropogenic particle emissions (e.g., oils, soot, synthetics) and vegetation burning (Simoneit, 2002). Biomass burning causes carbon dioxide emissions equal to 50% of those from fossil-fuel combustion and so is also highly likely to influence future climate change (Solomon et al., 2007). Here, we discuss four chemical groups that can be used as proxies for fire-history reconstruction from ice cores: (1) monosaccharide anhydrides (MA), (2) light carbolic acids, (3) polycyclic aromatic hydrocarbons (PAH), and (4) lignin burning products. Combining measurements of these four chemical groups can help determine the relative contributions of natural and anthropogenic emissions on regional and global scales.

Specific molecular tracers in smoke (MA)

Biomass burning injects particles with distinct signatures of organic matter into smoke and the global atmosphere (Simoneit, 2002). Important compounds from biomass burning include monosaccharide anhydrides (MA), where the most important tracer compound among them is levoglucosan and to a lesser degree galactosan and mannosan. These are specific molecular tracers because they can only be generated by combusting woody tissue at temperatures greater than 300°C (Simoneit, 2002). Among MA, levoglucosan has been considered an excellent tracer choice because it is emitted in large quantities and is globally pervasive. Levoglucosan is transported in smoke plumes and returns to the surface by wet and dry deposition. The presence of levoglucosan in ice cores

can therefore be used as a smoke emission tracer (Simoneit, 2002). The University of Venice has pioneered a technique for the determination of levoglucosan flux in ice cores (Gambaro et al., 2008) and has measured past biomass burning tracers in ice from both Greenland and Antarctic (Fig. 1).

Global and regional burning (light carbolic acids)

Fresh smoke particles contain up to 1% organic acids, including formate, acetate and oxalate, which have been measured in polar snow and ice as a proxy for global and regional biomass burning (Barbante et al., 2003; Reid et al., 2005 and references within). Figure 2 depicts oxalate concentrations and the annual cycle (Na^+) in sixty-eight snow pit samples from Summit, Greenland (72°20'N; 38°45'W, 3270 m asl). Atmospheric oxalate can be formed through both biomass burning and vehicle emissions. The summer 1994 oxalate peak highlights a Canadian forest fire (Barbante et al., 2003). However, in areas with one snow accumulation season, such as the Himalaya, or in areas near a constant influx of vehicle emissions, such as the Alps, it may be more difficult to determine if oxalate is from natural or anthropogenic sources. Preliminary results conducted at the University of Venice show that levoglucosan flux replicates the oxalate measurements in the Summit Greenland snow samples. This reproduction of biomass burning proxies can be used to validate the two types of measurements as levoglucosan can only be produced by biomass burning (Gambaro et al., 2008).

Anthropogenic activity (PAH)

Polycyclic aromatic hydrocarbons (PAH) are ubiquitous pollutants from fossil fuel or biomass incomplete combustive processes. Approximately 90% of recent PAH emissions are estimated to be anthropogenic (Yunker et al., 2002). Polar ice caps and mountain glaciers depict the historical environmental burden of PAH as a consequence of human activities. The low preindustrial quantities of these compounds have rarely been measured, but are present in ice cores because PAH can be transported over global distances by wind systems (Gabrieli et al., 2010). Wildfires comprise the largest PAH input from natural combustion but the compounds are not source specific. Once the presence of biomass burning versus hydrocarbon combustion PAH in ice cores has been established, greater specificity regarding the organic materials being burned can be obtained through analyzing vegetation sources.

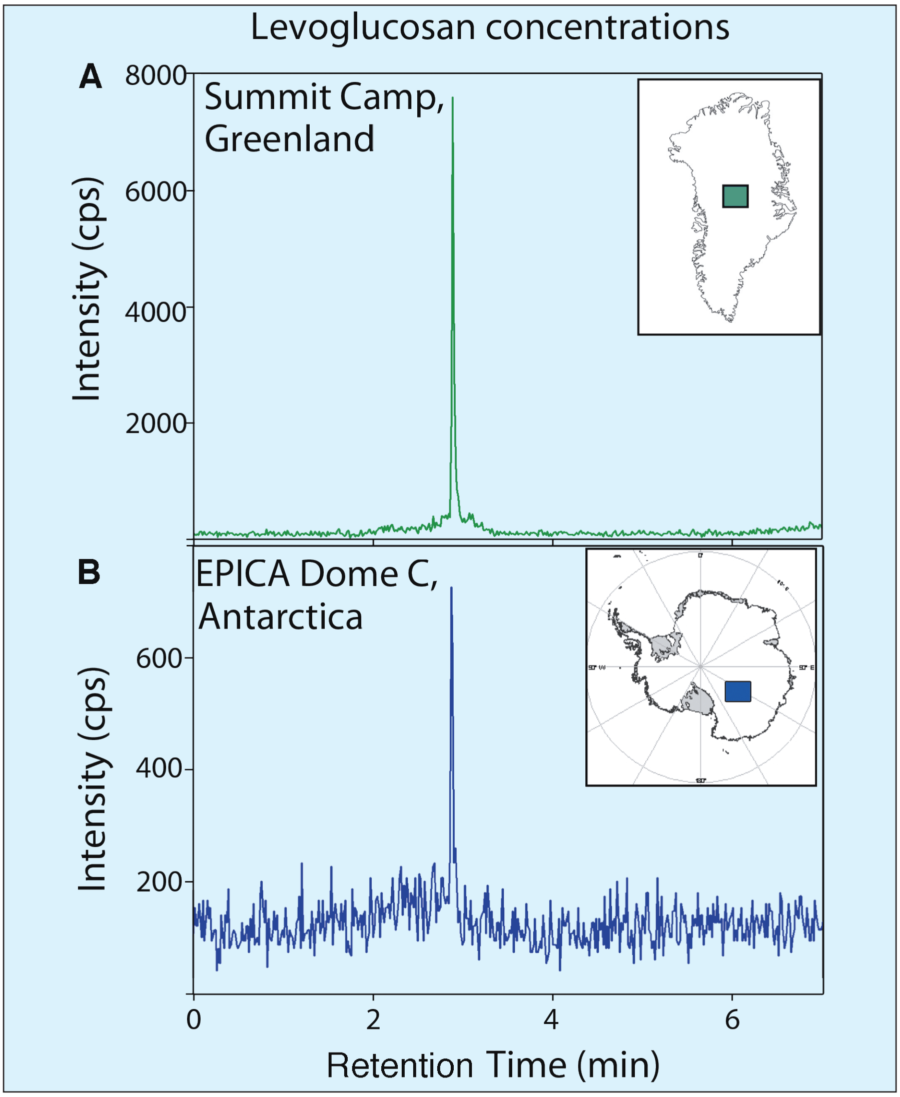

Figure 1: Chromatograms of levoglucosan (counts per second, cps) in ***A****) Greenland Summit Camp snow and* ***B****) the European Project for Ice Coring in Antarctica (EPICA) Dome C ice core (2682.9 m; 420.7 ka BP on EDC3 chronology, Parrenin et al., 2007). Levoglucosan is a monosaccharide anhydride produced by combustion of woody tissue at high temperatures (Simoneit, 2002) and can be used as a tracer of past biomass burning. The difference in levoglucosan concentrations in Greenland and Antarctica may reflect relative distance from smoke emission between the two sites. Figure modified from Zangrando, 2008.*

Vegetation sources (aromatic alcohols + degradation products)

Recent advances in methodology now allow the determination of the major species of vegetation that were burned in the past, and current investigations are examining vegetation sources as recorded in ice cores (Condera et al., 2009). Source specific molecular tracers not only show that fires occurred in the past but also provide a chemical fingerprint that can be used to identify vegetation species or regional vegetation cover (Simoneit, 2002). Woody tissue contains three major aromatic alcohols that are present in differing proportions among the major plant classes. Grasses are enriched in p-coumaryl alcohol, softwoods contain primarily coniferyl alcohol and hardwoods include a high proportion of siapyl alcohol. When these three aromatic alcohols are burned, they produce degradation products that are emitted in different proportions based on different types of biomass (Fine et al., 2004). For example, resin acids were found in emissions from pine needle fires and *Sequoia* forest. Similarly, research shows that syringaldehyde is abundant in emissions from sagebrush, whereas vanillic acid is a conifer-specific biomass burning tracer (Fine et al., 2004).

Softwoods are the easiest plant class to determine through investigating molecular markers in smoke because the aromatic alcohols and degradation products are injected into smoke plumes in relatively large quantities. The proportion of oxygenated compounds from aromatic alcohols is less prominent in hardwood smoke and almost undetectable in grass smoke (Simoneit, 2002). Grass smoke can be defined through the ratios of the detectable aromatic alcohols and degradation products with levoglucosan. The presence of levoglucosan confirms biomass burning, and the determination of aromatic alcohols and their degradation products provides more specific insight into the type of vegetation burned.

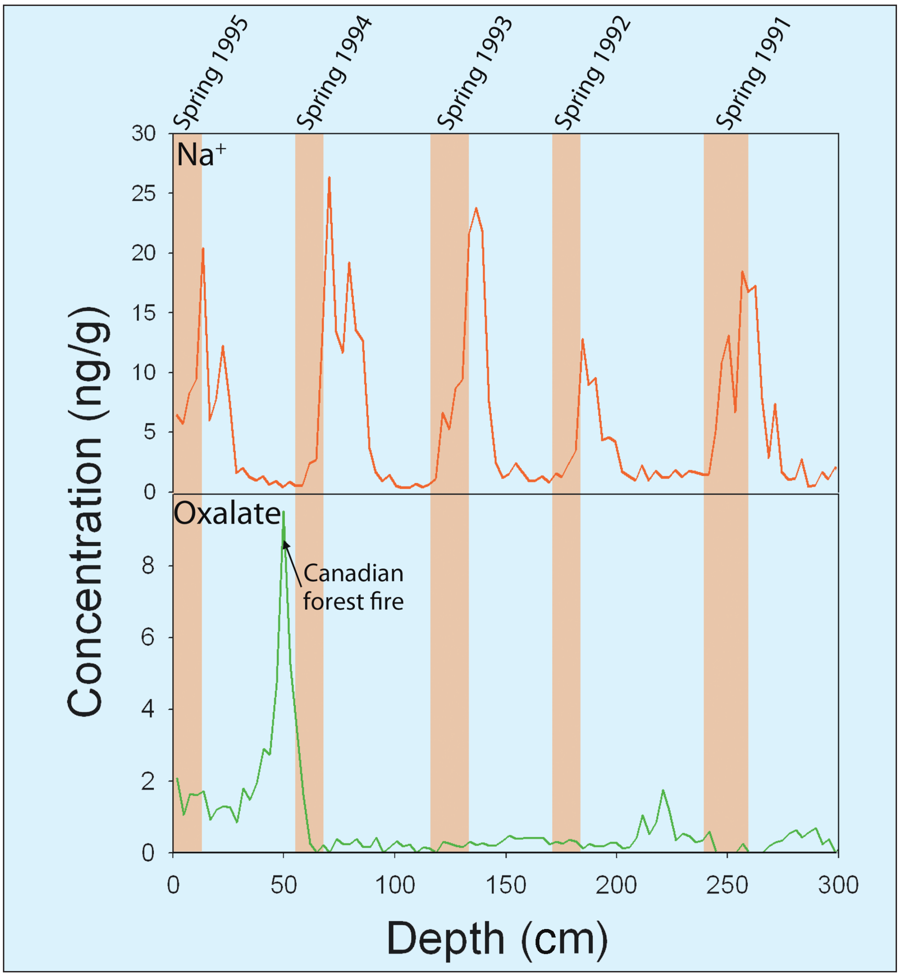

*Figure 2: Changes in Na^+ (**orange**) and oxalate concentration (**green**; ng g^{-1}) averaged from 68 central Greenland snow-pit samples, from the surface (June 1995) to 2.7 m (1991). Peaks in Na^+ are associated with boreal winters as increased cyclogenesis in the North Atlantic deposits greater concentrations of sea salts on the Greenland Ice Sheet. **Orange bars** indicate the position of spring snow accumulation. Figure modified from Barbante et al., 2003.*

Conclusion

Glaciers and ice sheets incorporate tracers of biomass burning into their ice layers resulting in a multitude of paleoenvironmental data within a single matrix. Molecular markers in ice cores provide insight into past fire occurrence, the type of material burned and the impacts of human activity. The global array of ice cores supplies high-resolution Quaternary proxy records that encompass six continents. The study of molecular markers of past fires in ice cores is still in its infancy and future work should also incorporate studies into the stability, durability and degradation mechanisms that may affect molecular markers under different conditions. Even with these caveats, the investigation of organic atmospheric tracers is expanding the limits of proxy information gleaned from ice cores and creates the possibility to couple fire activity, climate oscillations and human activity.

Data

The data from Figure 1 is available from Roberta Zangrandp (Rozangra@unive.it). Data presented in Figure 2 is available from Carlo Barbante (Barbante@unive.it).

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References

Barbante, C., Boutron, C., Morel, C., Ferrari, C., Jaffrezo, J.G., Cozzi, G., Gaspari, V. and Cescon, P., 2003: Seasonal variations of heavy metals in central Greenland snow deposited from 1991 to 1995, *Journal of Environmental Monitoring*, **5**: 328-335.

Conedera, M., Tinner, W., Neff, C., Meurer, M. and Dickens, A., 2009: Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation, *Quaternary Science Reviews*, **28**: 555-576.

Gabrieli, J., et al., 2010: Post 17th-Century Changes of European PAH Emissions Recorded in High-Altitude Alpine Snow and Ice, *Environmental Science and Technology*, **44**: 3260-3266.

Gambaro, A., Zangrando, R., Gabrielli, P., Barbante, C. and Cescon, P., 2008: Direct determination of levoglucosan at the picogram per milliliter level in Antarctic ice by high-performance liquid chromatography/electrospray ionization triple quadrupole mass spectrometry, *Analytical Chemistry*, **80**: 1659-1699.

Simoneit, B.R., 2002: Biomass burning – A review of organic tracers for smoke from incomplete combustion, *Applied Geochemistry*, **17**: 129-162.

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Global patterns of biomass burning during the last glacial period

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Sedimentary charcoal records covering the last glacial period provide information on the response of global biomass burning to rapid climate changes, such as those occurring during Dansgaard-Oeschger cycles.

The Global Palaeofire Working Group (http://www.gpwg.org/) has updated a database of over 700 individual sedimentary charcoal records worldwide (GCD_V2: Daniau et al., in prep). This database provides a powerful tool for studying changes of biomass burning at global and regional scale (Power et al., 2008; Power et al., 2010). A focused study of fire records covering the last glacial period (73.5-14.7 ka) allows examination of the response of biomass burning to the rapid climate changes (within 10-200 years) of large magnitude that occurred during Dansgaard-Oeschger (D-O) cycles (Steffensen et al., 2008). D-O cycles are characterized in Greenland ice-core records by a marked warming followed by a cooling. Herein, D-O warming events refer to the initial rapid warming (Sánchez-Goñi and Harrison, in press), Greenland Interstadials (GI) correspond with the D-O warm phase followed by the initial slow phase of cooling, D-O cooling events refer to the precipitous cooling at the end of GI, and Greenland Stadials (GS) correspond with the final cool phase.

Methodology

Sixty-seven sites (11 marine and 56 terrestrial; Fig. 1) that have records for some part of the last glacial period were extracted from the database and used to analyze changes in global biomass burning (Daniau et al., in press). These records were developed using a broad range of quantification methods and units. For the majority, charcoal counts were converted to charcoal concentration (number of particles cm^{-3} or per g of sediment), charcoal influx (number of particles cm^{-2} a^{-1}) or charcoal

area measurements made directly on pollen slides or using image analysis. A few records also used chemical assay, such as total organic fraction and black carbon concentration, or were expressed as Charcoal/Pollen ratio and percentage dry weight. The data were therefore standardized to facilitate comparisons between sites and through time. Original charcoal data (abundance or concentration) were transformed and rescaled to obtain a common mean and variance for all sites, and detrended to remove orbital timescale variability. Superposed Epoch Analysis (SEA) was performed on the detrended charcoal data to examine the pattern of fire around the time of key events, aligning the charcoal deviations on the ages of the D-O warming and D-O cooling events (Fig. 2). When the SEA summary curves fall outside a confidence band determined by Monte Carlo methods, a significant or systematic response of the variable to some externally determined event is inferred.

Fire and temperature

Figure 2 illustrates SEAs for the NGRIP oxygen-isotope data and the global composite-curve of charcoal data. These illustrate the nature of the abrupt temperature changes and the response of global biomass burning to the abrupt warming at the beginning of the GI and the most rapid interval of cooling that delimits the beginning of GS. A general increase in charcoal levels during warming (Fig. 2a, b) and a decrease in charcoal levels during cooling (Fig. 2c, d) suggest a strong correlation between biomass burning and temperature. Biomass burning increases rapidly during D-O warming events and reaches a peak at nearly the same time as temperature. In contrast, biomass burning decreases significantly at the onset of the GS and then returns to "background" levels, even though temperatures remain low (Figs. 2c, d). The response of biomass burning to the warming events is not the simple inverse of the response to cooling, suggesting a nonlinear relationship between biomass burning and climate. The association between rapid warming and increases in biomass burning seen during the glacial period has also been observed during the last deglaciation at the termination of the Younger Dryas chronozone (Marlon et al., 2009).

Fire regime and fuel

Changes in charcoal concentration have been described from two marine records off the European margin and interpreted as changes in biomass burning caused by variations in fuel availability during D-O

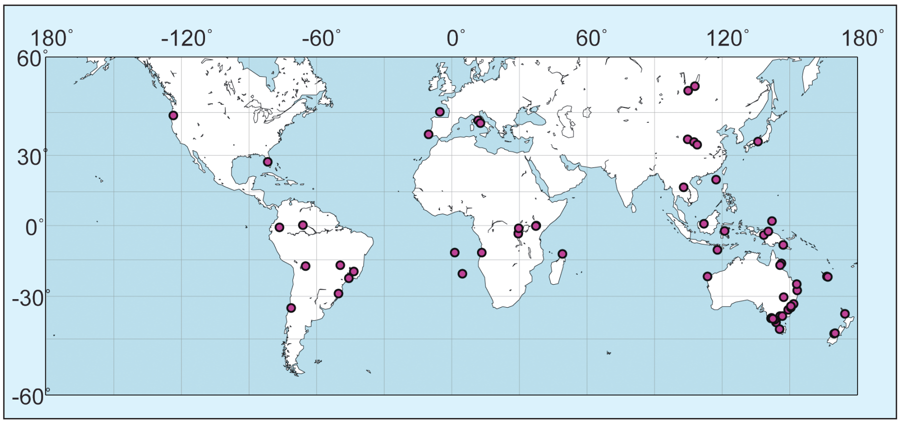

Figure 1: Location of marine and terrestrial sites with charcoal records covering all or part of the last glacial period. Figure modified from Daniau et al., in press.

cycles (Daniau et al., 2007; Daniau et al., 2009). Recent syntheses of the glacial vegetation history of Europe, Japan and adjacent parts of the Asian mainland, North America and the tropical regions of South America and Africa (Fletcher et al., in press; Takahara et al., in press; Jiménez-Moreno et al., in press; Hessler et al., in press) suggest that these rapid climate changes had an impact on vegetation globally. D-O warming events are generally accompanied by shifts from open vegetation to forest or increases in tree abundance. The similarity of variations in global levels of fire and regional vegetation patterns suggest that climate-driven changes in vegetation and biomass productivity (fuel) determined the level of global biomass burning during the last glacial period. During D-O warming events and GI, increased productivity led to increased fuel availability and promoted fire. Conversely, decreased fire in response to rapid cooling was a consequence of reduced fuel loads from lower productivity. An increase in biomass burning during the remaining GS, to levels similar to pre-cooling fire regimes may be caused by temperature-driven forest die-back, which would create conditions for increased fire.

Conclusion and outlook

This effort to synthesize charcoal records from the last glacial period allows us to

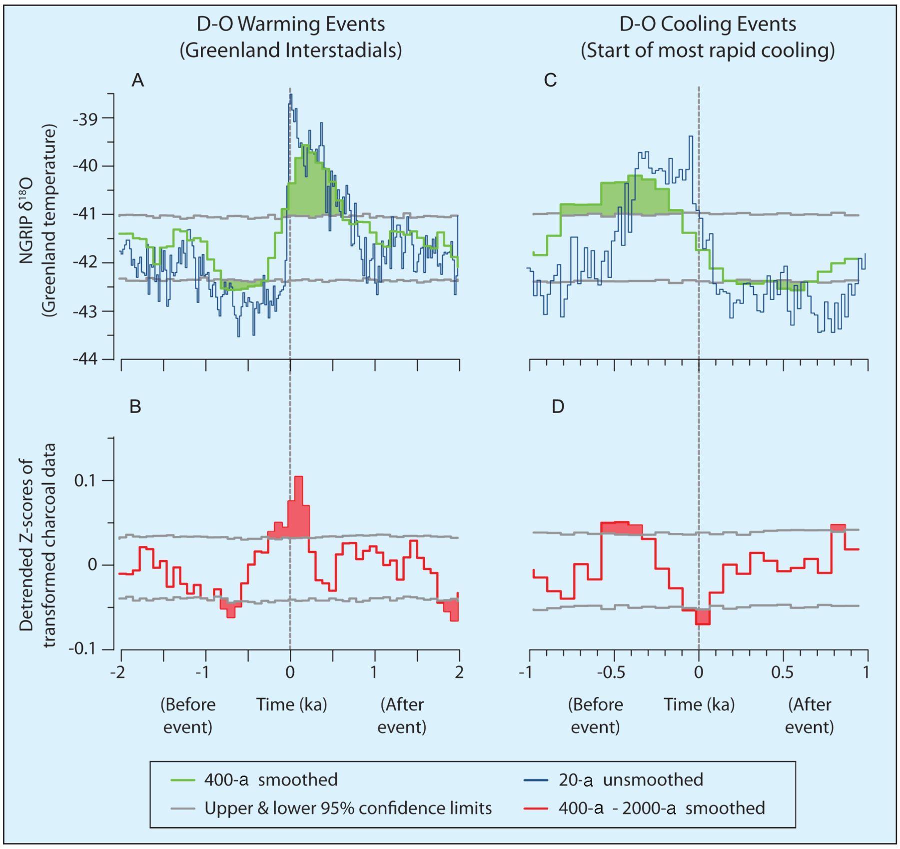

*Figure 2: Superposed Epoch Analysis (SEA) composites illustrating changes in biomass burning associated with D-O warming events (**A** and **B**) and D-O cooling events (**C** and **D**). The NGRIP $\delta^{18}O$ SEA composite record for the D-O cycles is shown for comparison. The NGRIP oxygen-isotope data (Wolff et al., in press) were integrated over 20-a-wide bins (the resolution of the data; blue lines), and over 80-a-wide bins (same resolution as the charcoal data, green lines), for comparison with the SEA of the charcoal data. The confidence intervals are given by a Monte-Carlo simulation using the timing of the 20 D-O warming events and 19 D-O cooling events. Figure modified from Daniau et al., in press.*

explore changes in global fire regimes during a period of high millennial-scale climate variability. Biomass burning at the global scale apparently responded rapidly to variations in temperature, as recorded in the Greenland ice core. Increases in biomass burning were synchronous with warming, whereas cooling was accompanied by decreases in burning followed by a return of fire to previous levels. Changes in vegetation productivity and fuel availability may explain the inferred variations in biomass burning during D-O cycles.

Additional paleofire records are still needed to derive statistically robust results at a regional scale and to better examine fire and climate interactions. Global biomass burning responds to past temperature variations, but we also seek to explore the importance of seasonality of temperature and precipitation on fire, which play a role in shaping the vegetation (type of biomes, abundance of fuel) and the flammability of fuel. We intend to extend the database by adding worldwide long and high-resolution marine and terrestrial charcoal records, in particular from poorly documented areas of North America, Africa and Eurasia. There is a great potential for long marine records to document regional fire activity where terrestrial records are not available. Characterization of the role of temperature and precipitation on fire would also benefit from the close comparison between fire and well-documented high-resolution changes in vegetation during D-O climate shifts, for example, in Europe where these rapid changes led to an alternation between open and forested biomes.

Data

The data presented herein will be available in the version 2 of the Global Charcoal Database when it is released (see http://www.gpwg.org/).

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References

Daniau, A.-L., Harrison, S.P. and Bartlein, P.J., in press: Fire regimes during the Last Glacial, *Quaternary Science Reviews*, doi:10.1016/j.quascirev.2009.11.008.

Marlon, J.R., et al., 2009. Wildfire responses to abrupt climate change in North America, *Proceedings of the National Academy of Sciences*, **106**(8): 2519-2524 doi: 10.1073/ pnas.0808212106.

Power, M.J., Marlon, J.R., Bartlein, P.J. and Harrison, S.P., 2010: Fire History and the Global Charcoal Database: a new tool for hypothesis testing and data exploration, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **291**(1-2): 52-59.

Sánchez-Goñi, M.F. and Harrison, S.P., in press: Millennial-scale climate variability and vegetation changes during the last glacial: concepts and terminology, *Quaternary Science Reviews*, doi:10.1016/j.quascirev.2009.11.014.

Wolff, E.W., Chappellaz, J., Blunier, T., Rasmussen, S.O. and Svensson, A., in press: Millennial-scale variability during the last glacial: The ice core record, *Quaternary Science Reviews*, doi:10.1016/j.quascirev.2009.10.013.

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A fire paradox in ecosystems around the Mediterranean

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Multi-proxy sedimentary charcoal records show that, despite evidence of early human-induced fire, the regional-scale switch from climate-regulated to human-dominated biomass burning occurred only between 4 and 2 ka in the Mediterranean region, coinciding with a late-Holocene expansion of fire-adapted ecosystems.

Wildfires in Mediterranean countries are a regular agent of disturbance for ecosystems and are generally attributed to a combination of extreme summer drought, strong winds and heat-waves along with accidental—or sometimes deliberate—ignition by human hands (e.g., Pausas, 2004). While these factors are certainly among the contemporary causes, the ultimate causes operating over multi-decadal and longer timescales are far from fully understood. What does the past tell us about the respective roles of climate and human actions in determining long-term Mediterranean fire regimes? Compared with other Mediterranean-like ecosystems in the world (e.g., chaparral in California), the Mediterranean basin has experienced a long history of human occupation, with human fire use recorded as far back as 0.8 Ma in eastern Mediterranean regions (Alperson-Afil, 2008). The spread of agriculture in the Mediterranean started more than 11 ka ago and Neolithic populations were present in the whole region from ca. 7 cal ka BP (Bocquet-Appel et al., 2009). Thus, disentangling climate and human causes is often difficult in the Mediterranean area because these drivers may operate synergistically. Well-dated sedimentary archives help us to understand when fire regimes switched from being climate- to human-dominated across the region. In recent years, multi-proxy studies and regional- to global-reconstructions of biomass burning have greatly improved our knowledge about fire-climate-human interactions in the past. Here we discuss how Holocene fire-ecosystem-climate-human linkages can be inferred from paleoecological studies in the Mediterranean area.

Fire-vegetation-climate relationships

Recent charcoal-based studies from well-dated lake sediments show that fire frequency in the Mediterranean region varied significantly throughout the last 11.6 ka (Holocene). Fire has played a contrasting role in the history of circum-Mediterranean landscape ecosystems; sometimes positive (e.g., increasing biodiversity) and at other times negatively affecting ecosystems (e.g., disrupting forest stands; Vannière et al., 2008). For instance, paleoecological records show that late-summer grassland burning delayed the early postglacial re-advance of woodland across interior areas of southwest Asia by up to 3 ka (Turner et al., 2010). In Sicily (Gorgo Basso; Fig. 1A), higher fire frequency before 8 cal ka BP probably restricted broadleaved evergreen stands (Tinner et al., 2009). Similarly, and in contrast to commonly held ecological assumptions, high-resolution pollen and charcoal time series from different sites in the central Mediterranean show that evergreen forest ecosystems (e.g., with *Quercus ilex*) were disadvantaged or even irretrievably destroyed by fire (Colombaroli et al., 2009; Fig. 1B). Thus, increasing drought and/or fire activity in the future could strongly endanger relict stands of *Q. ilex* in southern parts of the Mediterranean region and favor the expansion of drought-adapted maquis vegetation.

Multi-proxy approaches have provided additional insights. For example, Turner et al. (2008) compared proxies for fire activity (microscopic charcoal data, particles <180 µm in diameter), land use and vegetation (pollen data) and climate (oxygen isotope data) from Eski Acıgöl crater record (Central Turkey; Fig. 2A). Landscape burning coincided with periods of wetter climate at centennial- to millennial-

timescales, implying that wildfires were fuel-limited in this oak-grass parkland ecosystem. Only in the late Holocene did climate and fire activity become decoupled in terms of timing. These data imply that, for most of the Holocene, wet-dry oscillations in climate acted as the pacemaker for biomass burning intensity, and that the switch from a climate- to a human-regulated fire regime took place only during the last 2 to 3 millennia.

A high-resolution sedimentary charcoal record from Lago dell'Accesa (Tuscany, Italy) reveals a mean Holocene fire interval of ca. 150 years, which is very close to present values of quasi-natural fire frequency in Mediterranean ecosystem, according to historical and modern ecological studies (Vannière et al., 2008). High-resolution pollen data from Lago dell'Accesa show that the area around the lake was occupied by Neolithic settlements ca. 8 ka, and that fire was the primary tool used to create open environments for agricultural and grazing purposes (Colombaroli et al., 2008). Nonetheless, long-term trends in fire return intervals compared with reconstructed lake-level trends (Magny et al., 2007; Vannière et al., 2008; Fig. 2B) suggest that, for the major part of the record, the amplitude and rhythms of hydrological and fire frequencies followed the same trend. Specifically, high fire frequency periods were triggered by drier climatic conditions and especially a dry summer season that promoted ignition and biomass burning. From ca. 4 cal ka BP the signals became decoupled, which is likely related to interferences with human activities. Demographic increase coupled with changing agricultural practices strongly modified vegetation cover (fuel), and fire frequency was enhanced by deliberate burning for woodland clearance and fields/pasture management.

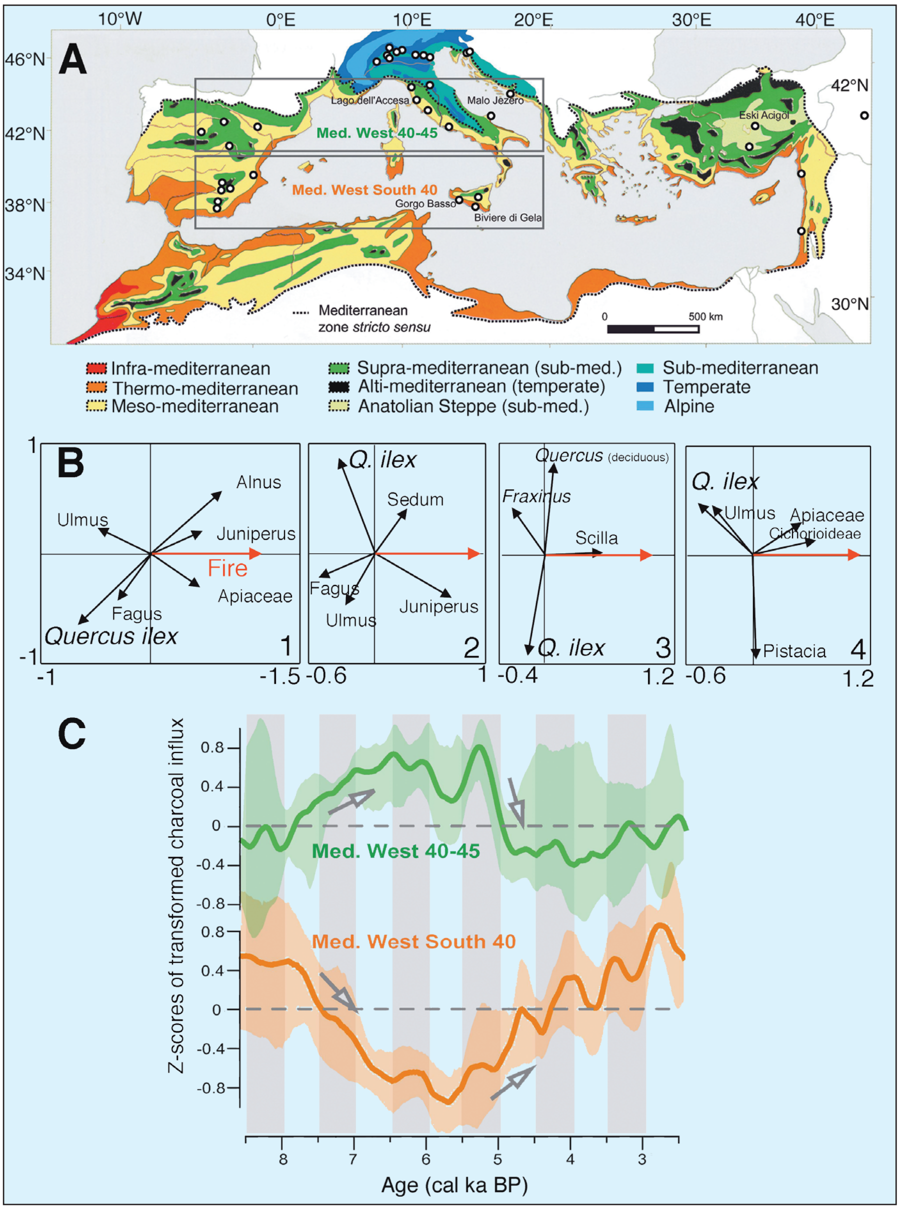

*Figure 1: **A**) Mediterranean bioclimates (modified from Ozenda and Borel, 2000; Quézel and Médail, 2003) and the limit of the Mediterranean zone stricto sensu (Quézel and Médail, 2003). White circles mark the location of charcoal records of the Mediterranean fire synthesis by Vannière et al. (in press) and cited in this paper. The two boxes delimit the groups of sites used in panel C; **B**) Redundancy analysis biplot showing species response to fire at four Mediterranean sites: 1) Lago di Massaciuccoli (Tuscany, Italy) 2) Malo Jezero (Croatia) 3) Lago dell'Accesa (Tuscany, Italy) 4) Biviere di Gela (Sicily, Italy). Arrow direction indicates the association among species and the environmental variable (fire); arrows pointing in the same direction indicate a positive correlation (modified from Colombaroli et al., 2009); **C**) Regional Z-scores of transformed charcoal influx (particles cm^{-2} a^{-1}) from the western Mediterranean (250-a smoothing window/1000-a bootstrap): averaging sites between 40-45°N ("Med. West 40-45") and sites south of 40°N ("Med. West South 40") (modified from Vannière et al., in press). Envelopes represent the upper and lower confidence intervals from the bootstrap analysis. Dashed lines correspond to the mean values of the base period: 21 to 0.02 cal ka BP.*

Regional fire synthesis

Many examples highlight site-specific fire responses to climate change depending on fuel availability and indicate a switch from climate- to human-regulated burning regimes between 4 and 2 cal ka BP. To what extent is this also evident in aggregated multi-site syntheses?

Analysis of regional fire activity based on 36 sedimentary charcoal records by Vannière et al. (in press; Fig. 1A) shows spatial coherency within, but differences between, areas of the Mediterranean. During the mid-Holocene Thermal Maximum (approx. 9-5 ka BP), charcoal records from the northern Mediterranean suggest the region was fire prone, while records from the southern Mediterranean indicate a decrease in fire activity from early Holocene levels, closely associated with wetter-than-present summers. In the central and western Mediterranean, there is a north-south partition around 40-43°N. Relatively rapid changes in fire regime at ca. 5.5-5 cal ka BP may have been tied to a weakening of Asian and African monsoon strength, which indirectly influences Mediterranean climate mechanisms and results from the orbitally induced summer cooling trend (Tinner et al., 2009; Vannière et al., in press). These records attest to important changes in seasonal climate around the Mediterranean during the Holocene, in contrast to previous notions of gradual aridification of the entire region or a series of short-term events occurring in a chaotic manner across space and time (Beaulieu et al., 2005; Sadori et al., 2008; Jalut et al., 2009; Fig. 1C). Although fire activity decreased after 5.5-5 cal ka BP in northern Mediterranean regions, the southern part of the Mediterranean generally experienced increased fire activity associated with drier summer conditions. During the late Holocene, starting from 4-3.5 cal ka BP, paleoecological evidence shows that fire-tolerant Mediterranean ecosystems expanded together with large-scale land-use conversion by Bronze Age and later cultures, and this permanently changed biomass availability and burning activity

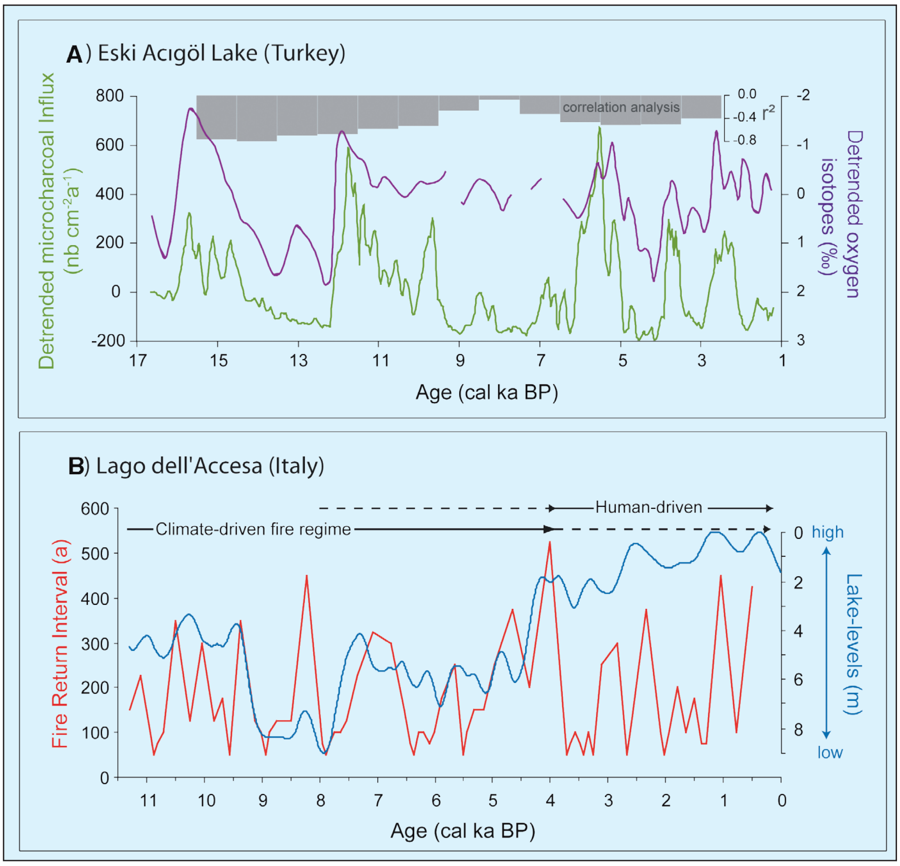

*Figure 2: **A**) Detrended microscopic charcoal (green line) and oxygen isotope record (purple line) for Eski Acıgöl Lake (Turkey). Correlation analysis (gray bars) shows statistically significant correlations between microscopic charcoal influx (particles cm^{-2} a^{-1}) and $\delta^{18}O$ (‰) for most of the record (modified from Turner et al., 2008); **B**) Lago dell'Accesa (Tuscany, Italy) lake-level fluctuations (blue line; modified from Magny et al., 2007) and the fire-return interval (red line) reconstructed from fire-event detection based on sedimentary macroscopic charcoal (modified from Vannière et al., 2008). Peaks in the fire-return interval curve correspond with high lake-level stands before 4 cal ka BP.*

across the Mediterranean (Carrión et al., 2003, 2007; Sadori et al., 2008).

Conclusion

The paleofire record from the Mediterranean is paradoxical. Climatic variations have certainly acted as one of the main pacemakers of fire regimes, particularly in the first half of the Holocene. Under different climate conditions (e.g., seasonality of precipitation), the southern and northern Mediterranean may have been differentially impacted by fire. Similarly, human actions (e.g., directly via ignition or indirectly via fuel management) have both increased and decreased fire activity during the Holocene. Increased sedimentary charcoal influx is often associated with pre- and proto-historic forest clearance but in the late Holocene, wildfire frequency often reached a maximum during phases of land abandonment and secondary scrub-woodland development, e.g., during the last century in much of Mediterranean Europe. Even apparently well-established relationships, such as evergreen oaks being favored by fire, turn out to be wrong when viewed over decadal to centennial timescales. These complex long-term responses are significant in the context of increasing aridity and warming, as well as major regional land-use changes linked to agricultural and tourism development around the Mediterranean Sea. Understanding them will help us to better manage and preserve one of the most fire-prone regions of the world, characterized by extraordinary plant diversity.

Data

The data are submitted to the Global Palaeofire Working Group Database (http://www.gpwg.org) and are available by contacting B. Vannière (boris.vanniere@univ-fcomte.fr)

Acknowledgements

We are greatly indebted to M. Magny, M. Power, W. Tinner and R. Turner who have contributed to these results and for enriching discussions about paleofire. Many thanks also to all contributors to the Mediterranean part of the Global Charcoal Database.

References

Colombaroli, D., Tinner, W., van Leeuwen, J.F.N., Noti, R., Vescovi, E., Vannière, B., Magny, M., Schmidt, R. and Bugmann, H., 2009: Response of broad-leaved evergreen Mediterranean forest vegetation to fire disturbance during the Holocene: insights from the peri-Adriatic region, *Journal of Biogeography*, **36**: 314-326.

Colombaroli, D., Vannière, B., Chapron, E., Magny, M. and Tinner, W., 2008: Fire-vegetation interactions during the Mesolithic-Neolithic transition at Lago dell'Accesa, Tuscany, Italy, *The Holocene*, **18**: 679-692.

Turner, R., Roberts, N. and Jones, M.D., 2008: Climatic pacing of Mediterranean fire histories from lake sedimentary microcharcoal, *Global and Planetary Change*, **63**: 317-324.

Vannière, B., et al., in press: Circum-Mediterranean fire activity and climate changes during the mid Holocene environmental transition (8500-2500 cal yr BP), *The Holocene*.

Vannière, B., Colombaroli, D., Chapron, E., Leroux, A., Tinner, W. and Magny, M., 2008: Climate versus human-driven fire regimes in Mediterranean landscapes: the Holocene record of Lago dell'Accesa (Tuscany, Italy), *Quaternary Science Reviews*, **27**: 1181-1196.

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Tropical fire ecology across the African continent: A paleoecological perspective

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High-resolution charcoal records from African lake sediments provide new insights for longstanding research questions on fire-climate-human interactions in tropical and subtropical ecosystems.

Every year, the tropics experience more fire than any other region in the world (Fig. 1). Tropical grassland (savannah) fires are the dominant source of carbon from biomass burning and provide more than 60% of the global total (Mouillot and Field, 2005). However, much of what is known about tropical fire ecology is based on monitoring programs started within the last decade, with highly fragmentary historical data extending only to the early 20th century. These data do not allow us to assess whether recent trends in fire frequency and magnitude are unusual in the context of natural long-term ecosystem dynamics (Gillson and Willis, 2004).

Natural or anthropogenic fire regime?

Seventy percent of tropical and subtropical areas worldwide are considered to have ecologically degraded fire regimes (Shlisky et al., 2007). In Africa, the recent increase in fire frequency is attributed to human ecosystem disturbance associated

with intensifying agriculture (Fig. 2; Davidson et al., 2003). For instance, in the lowland rainforests of West Africa and in moist montane forests at higher elevations in East Africa, natural fire is uncommon (Goldammer, 1990). Yet widespread clearance of natural vegetation has converted large, formerly forested areas into highly flammable grasslands (Roberts, 2000; Goldewijk, 2001). Studies of global-scale patterns in historical land use (e.g., Archibald et al., 2005) tend to assume that human impact on tropical African ecosystems was limited before 1700 AD because population densities of indigenous people were low (Goldewijk, 2001; Ramankutty and Foley, 1999). This perspective contrasts with archeological and paleoecological evidence that indicates that anthropogenic forest clearance in parts of East Africa started at least 2.5 ka ago, in association with the introduction of iron smelting technology (Robertshaw and Taylor, 2000). Other authors suggest that humans have altered African forest ecosystems over a longer time (Willis et al., 2004). If increasing fire activity during the Holocene was indeed related to intensifying human impact (Lejju et al., 2005; Ryner et al., 2008), the timing and extent to which humans altered local ecosystems varied regionally and among ecosystems. For instance, recent studies indicate that deforestation associated with sedentary agriculture started only ~0.35 ka ago in the moist highlands of central Kenya (Lamb et al., 2003) but at least ~0.8–1 ka ago in sub-humid western Uganda (Ssemmanda et al., 2005; Russell et al., 2009). In drier environments, agricultural activity often began ~0.12 ka ago, during colonial times, yet landscapes may have been significantly modified by pastoralist cultures well before then. Detailed charcoal studies with adequate spatial coverage are needed to determine whether current fire regimes are within the range of historic variability (Willis and Birks, 2006), or whether fire frequency has increased in response to the different types and intensities of human impact associated with pastoralist and agriculturalist societies.

Fire regime response & feedback to past climate variability

High-resolution charcoal studies have shown how fire can be a "catalyst" for climate-change effects on vegetation. For instance, moist conditions limit fire to spread in present tropical forests, but during drier periods in the past wildfire was likely more common, causing changes in ecosystem structure and degradation (e.g., Willis and Birks, 2006; Bush et al., 2008; Fig. 2). Climate-proxy information from the sediments of East African lakes document major variations in moisture balance. For example, in the late 18th century, an episode of severe drought completely desiccated all but one lake in the Eastern Rift Valley of Kenya, south of Lake Turkana (Verschuren, 2004; Bessems et al., 2008). In the last few millennia, century-long periods of both significantly drier and wetter conditions than today have occurred over most of equatorial East Africa. There have also been periods (e.g., from ~1500 to 1750 AD) when climate was unusually dry in the normally sub-humid western parts of the region while remaining unusually wet in semi-arid regions further east (Verschuren et al., 2000; Russell and Johnson, 2007). Research documenting the response of terrestrial ecosystems to this climate variability reveals the high sensitivity of vegetation transition zones, such as the forest/savannah ecotone, to even modest decadal-scale variations in rainfall (Lamb et al., 2003; Ngomanda et al., 2007). Additional charcoal records of high temporal resolution are needed to show how fire regimes have responded to contrasting climate trends at the regional scale (Fig. 1b).

Tropical ecosystems resilience to fire

In the seasonally dry climate regime prevailing throughout most of East Africa, fire is the dominant direct control on vegetation distribution (Bond et al., 2005; Gillson and Duffin, 2007) but natural fire frequency decreases from semi-arid central and eastern Kenya to sub-humid western Uganda. How does fire control the landscape-scale ecotone between savannah and forest? Recent studies postulate that tropical rainforests and grass savannah may exist as "stable states" in which a grass-dominated ecosystem is maintained by frequent fires while a tree-dominated ecosystem helps create a wet microclimate and low ground cover/fuel load that limits fire (Sankaran et al., 2005; Gillson and Duffin, 2007; Gillson, 2008). A shift from small patchy fires set by indigenous peoples to the larger fires characteristic of European land management has strongly altered the savannah-forest ecotone, by favoring highly flammable annual grasses. Thus, by increasing the flammability of grass communities, this historical change in fire management may have caused a positive feedback with fire (Cochrane, 2009). This hypothesis needs to be rigorously tested

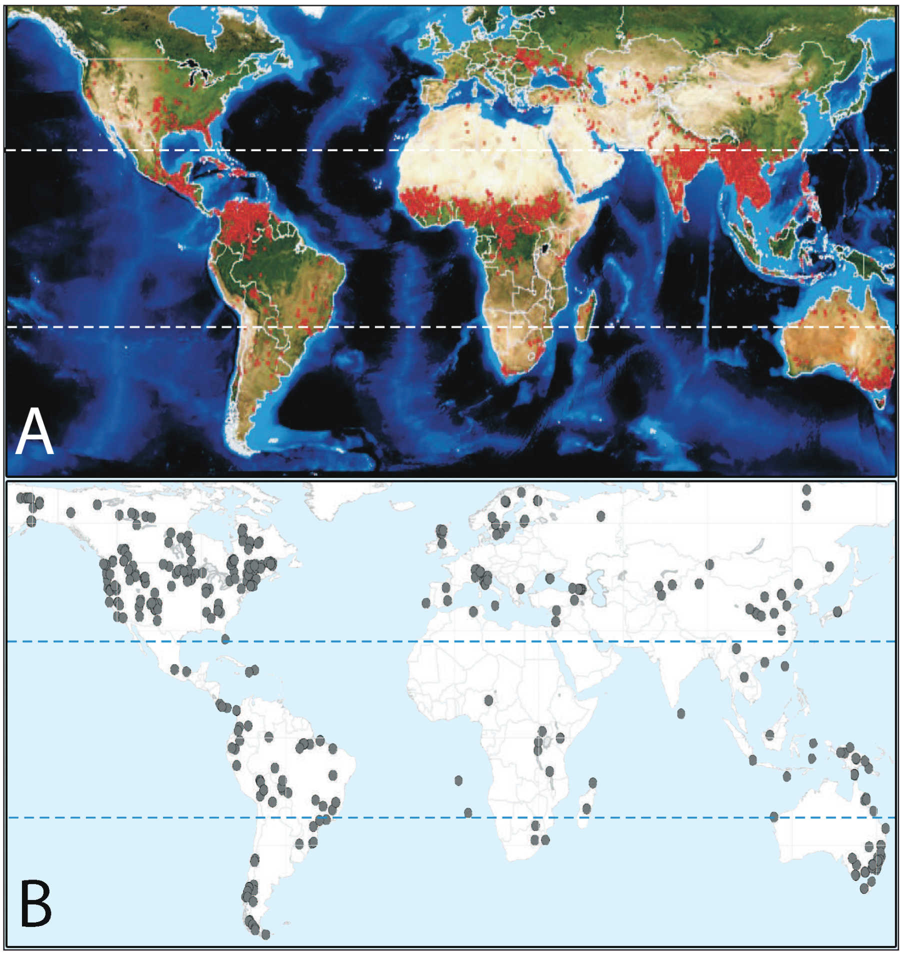

*Figure 1: **A**) Satellite image of world fire activity detected by MODIS in the early spring of 2010 (red dots, data from Fire Information for Resource Management System FIRMS, http://maps.geog.umd.edu/firms). **B**) Worldwide geographical distribution of paleoecological fire-regime records currently in the Global Charcoal Database (modified from Power et al., 2008). Despite the great fire activity in tropical and subtropical ecosystems, few paleofire records are available from regions such as Africa. Dashed lines delimit the tropical region, bounded by latitudes 23.5°N and S.*

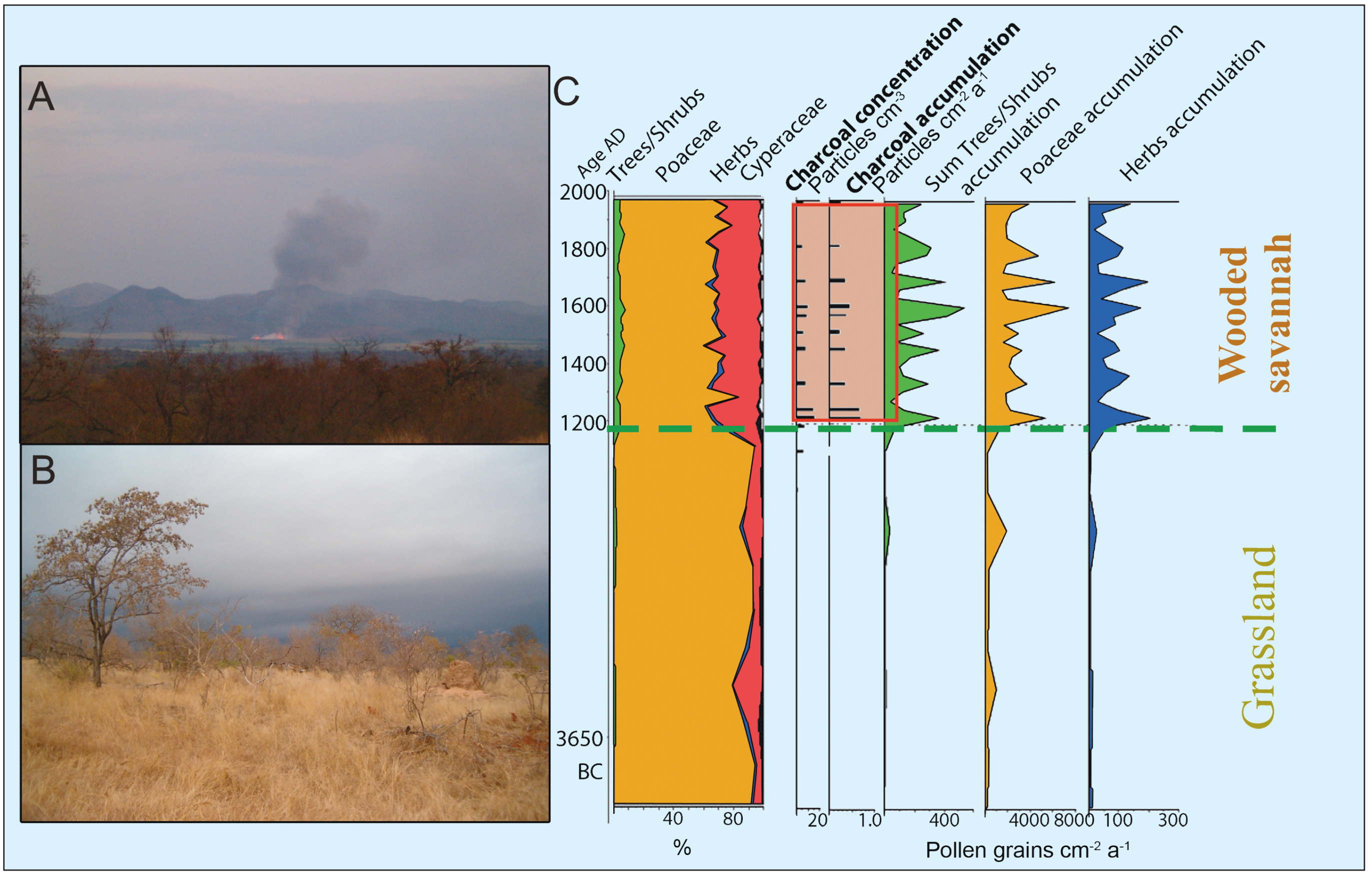

Figure 2: ***A****) Human-set fire in a rural area close to Mozambique border. Here, fire is used to clear land for agriculture and livestock ranching.* ***B****) Wooded savannah stand in Kruger National Park (South Africa). During the dry season (Apr-Oct), most of the biomass dries, increasing the fire hazard. (Photos by D. Colombaroli).* ***C****) Pollen and charcoal record from Malahlapanga Lake (Kruger National Park) showing the transition from grassland to a fire-maintained wooded savannah after 1100 AD (modified from Gillson and Ekblom, 2009). The authors suggested that increased regional rainfall promoted biomass production (i.e., wooded savannah), allowing fire activity to increase.*

on long timescales and in multiple regions to determine whether this feedback is characteristic of presently highly disturbed conditions, or whether it also occurred during natural cycles of long-term hydrological change. Paleoinformation on the resilience of tropical moist forests to occasional fire and, specifically, the rate at which rainforests recover from destructive fire would also be highly instructive for future conservation (Cochrane, 2003). New reconstructions of past fire regimes based on fossil charcoal analysis that quantify the local frequency of fire (e.g., Whitlock and Larsen, 2001; Gavin et al., 2006; Higuera et al., 2008), combined with modern calibration studies (Duffin et al., 2008), should reveal how African ecosystems respond to fire variability at decadal to century timescales.

Research outlook

Coupled atmosphere/ocean/biosphere climate models project future temperatures across tropical Africa to increase from 0.2 to 0.5°C per decade, and precipitation in East Africa to increase during the short rainy season (Northern Hemisphere winter) and decrease during the main rainy season (Northern Hemisphere spring) (Hulme et al., 2001; IPCC, 2007). In addition, changes in the teleconnected El Niño/Southern Oscillation (ENSO) are projected to cause pronounced drought in some regions and increased risk of flooding in others (Wara et al., 2005). If mean annual precipitation over East Africa does increase (IPCC, 2007), its beneficial effect on forest ecosystems will likely be lost in areas with frequent anthropogenic fires and increasing demographic pressure. Insights into how Africa's forest and savannah ecosystems will respond to the multiple stressors of future global climate change requires an understanding of past ecosystem responses to large-magnitude environmental changes. Currently still very rare in Africa and elsewhere in the tropics, high-resolution paleoecological records of (pre-)historical human impact, fire and vegetation can provide such holistic information.

Acknowledgements

We thank Lindsey Gillson for useful comments and Mitchell J. Power for the global map of sites in the Global Charcoal Database. The project "Fire, climate change and human impact in tropical ecosystems: paleoecological insights from the East African region" is funded by the Swiss National Science Foundation (FNS "Ambizione" Project no. PZ00P2_126573).

References

Cochrane, M.A., 2003: Fire science for rainforests, *Nature*, **421**: 913-919.

Duffin, K.I., Gillson, L. and Willis, K.J., 2008: Testing the sensitivity of charcoal as an indicator of fire events in savanna environments: quantitative predictions of fire proximity, area and intensity, *The Holocene*, **18**: 279-291.

Gillson, L. and Ekblom, A., 2009: Resilience and thresholds in savannas: nitrogen and fire as drivers and responders of vegetation transition, *Ecosystems*, **12**: 1189-1203.

Sankaran, M., Hanan, N. and Scholes, R., 2005: Determinants of woody cover in African savannah, *Nature*, **438**: 846-849.

Willis, K.J., Gillson, L. and Brncic, T.M., 2004: How "virgin" is virgin rainforest? *Science*, **304**: 402-403.

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Holocene fires in eastern Canada: Towards a forest management perspective in light of future global changes

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Studies on the Holocene fire history in eastern Canada at local and regional scales decipher the relationships between climate and vegetation, which are used to simulate future fire risk.

In eastern boreal Canada, interest in fire-related studies has increased with the emergence of a new forest management paradigm based on the emulation of natural disturbance regimes (e.g., Gauthier et al., 2008). A key need is to improve understanding of the variability of past disturbances and their linkage with climate and ecosystems during the Holocene (11.7-0 ka). Research conducted over the last 15 years has focused on: (i) reconstruction of natural ranges of fire variability (frequency, size, severity), (ii) analysis of fire-climate dynamics, and (iii) modeling of future regimes.

Local reconstructions of fire regimes

Reconstructions of long-term fire regimes in eastern Canada first attempted to document past changes in fire frequency and fire return intervals (FRI), a component deduced from both dendroecological data (e.g., age structure, fire-scars; Bergeron et al., 2004; Bouchard et al., 2008; Le Goff et al., 2008) and sedimentary charcoal data (Carcaillet et al., 2001; Ali et al., 2009). For example, sediments from seven lakes were sampled in the transition region between two vegetation zones; a mixed needleleaf/broadleaf vegetation (dominated by fire-intolerant species) and the northern boreal forest—a closed-crown needleleaf vegetation dominated by fire-prone *Picea mariana* (Black Spruce). Charcoal time series were broken down into background and peak components, providing millennial-scale series of FRI (Carcaillet et al., 2001; Ali et al., 2009). The two vegetation zones yielded different temporal patterns of FRI, with maximum fire frequency between 5.8 to 2.4 cal ka BP in the north, and after 2.5 cal ka BP in the south. These different fire histories from within the same region raised questions about the long-term relationships between fire and climate in explaining vegetation distribution. In the north, the mean FRI during the Holocene indicated a higher fire frequency than in the south, consistent with the observation that the dominant species, Black Spruce, is fire-prone. Additionally,

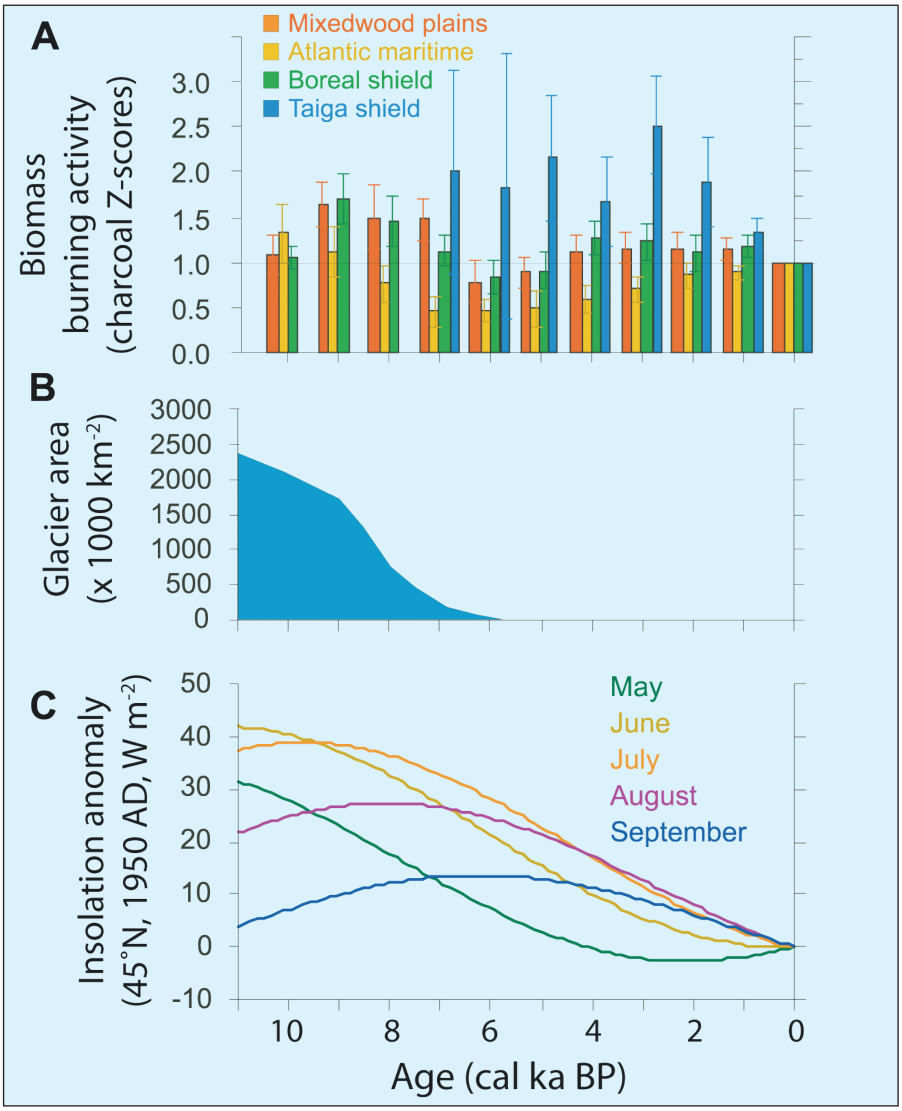

*Figure 1: **A**) Biomass burning activity (z-scores = anomalies calculated to the present-day) assessed from sedimentary charcoal from eastern Canada (modified from Bremond et al. in press). The colors correspond to the Canadian ecozones (SISCan, 2008). **B**) Termination of the Laurentide ice cover inferred from a reconstruction of ice-sheet areas (Dyke et al., 2003). **C**) Insolation computed at 45°N (Berger and Loutre, 1991).*

fires in both zones were synchronous from 8 to 4 cal ka BP, suggesting that the main driver was climate, with longer or drier fire seasons creating large fires (Ali et al., 2009). After 4 cal ka BP, the independence of fire histories among sites suggests that local features controlled fire occurrence. A progressive rise in regional water tables in Ontario and Québec beginning ~4 cal ka BP (e.g., Muller et al., 2003; Moos et al., 2009) may have modified fuel moisture and landscape connectivity and resulted in more small-size fires (Ali et al., 2009). This role of landscape on fire is well illustrated by fire-history studies on islands compared with those from mainland regions (Bergeron, 1991), and by present-day fire modeling (Hély et al., in press).

But how can we define the natural range of fire variability in a changing climate? A key issue is to disentangle natural internal processes that control forest dynamics from external processes, such as those controlled by the climate. Even if natural fire and vegetation histories were perfectly known, past conditions might not be relevant for understanding present and future fire conditions. For example, ice

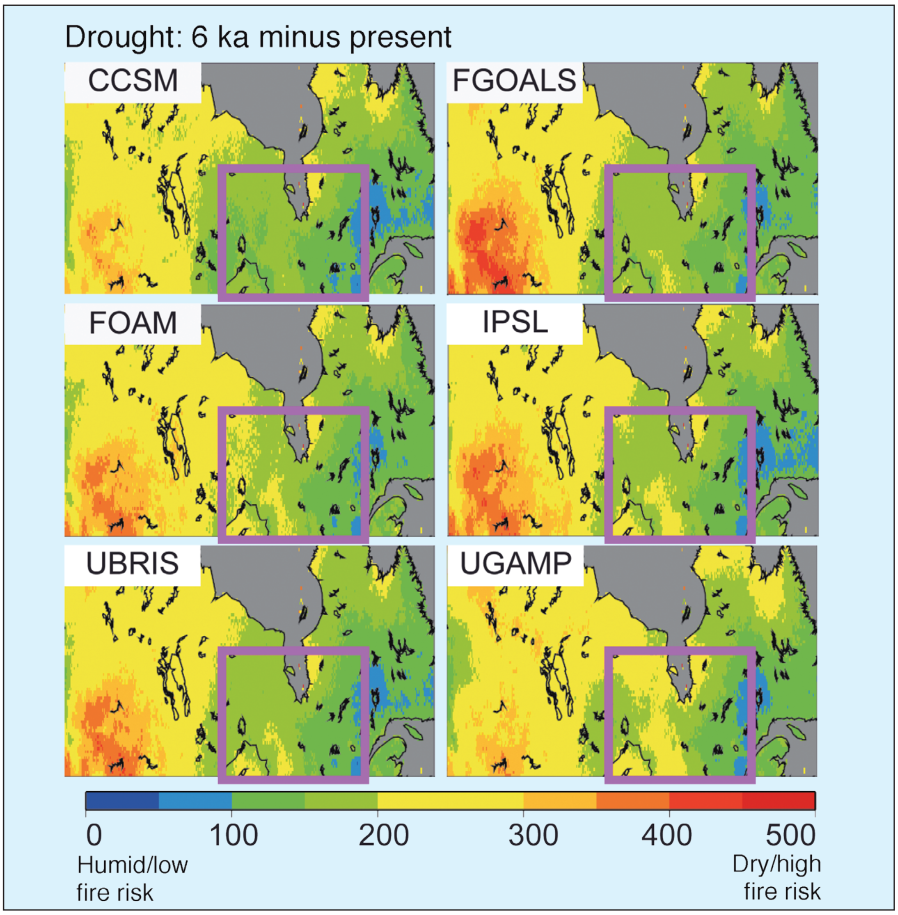

Figure 2: Spatial distribution of the mean Drought Code (DC, unitless). The values are for July at 6 cal ka BP versus present-day conditions simulated by general circulation models (GCMs: CCSM3 (Collins et al., 2006); FGOALS (Yu et al., 2002); FOAM (Jacob et al., 2001); IPSL (Marti et al., 2005); UGAMP (Slingo et al., 1994)). The DC is an indicator of fire danger potential, part of the Canadian Forest Fire Weather Index used to predict the risk of fire ignition based on weather conditions (van Wagner, 1987; De Groot et al., 2007). The GCM simulations were compared based on the mean values for the region in the rectangle (90-70°W and 47-55°N). No significant difference was highlighted among GCMs (one-way ANOVA, $F = 1.851$, $df = 153$, $p > 0.05$).

cover before ~6 cal ka BP in north-central Quebec (Fig. 1) maintained periglacial conditions, whereas climate was warmer than present before 8 cal ka BP in Alaska and northwest Canada (Kaufman et al., 2004).

Sub-continental reconstructions: Fire-vegetation-climate linkages

Sub-continental fire reconstructions have been developed from regional charcoal datasets for eastern Canada (Carcaillet and Richard, 2000; Carcaillet et al., 2002). Based on data downloaded from the Global Charcoal Database (see data information below; Power et al., 2008), Bremond et al. (in press) highlighted the south-north variability of Holocene biomass burning and linked it with the main ecozones and regional climate, which was influenced by both ice cover and insolation (Fig. 1). Biomass burning in the southern ecozones of eastern Canada (Mixedwood Plains, Atlantic Maritime, Boreal Shield East) occurred as soon as the ice sheet collapsed between 10-7 cal ka BP (Fig. 1b), whereas fire activity was lower from 7-5 cal ka BP when climate was drier according to lake-level reconstructions (Hély et al., 2010). Conversely, the moister late Holocene experienced higher fire activity in these southern ecozones. This reconstruction supports evidence of annually colder and drier climate conditions during the early Holocene (Muller et al., 2003; Viau et al., 2006) promoting fires. Annually drier and warmer conditions followed in the middle Holocene with lower fire activity, in contrast with the late Holocene when biomass burned under an annually wetter climate. This pattern suggests that fires activity does not depend on annual precipitation but rather on summer conditions, which were likely wetter on average during the middle Holocene and drier since 4 cal ka BP (Carcaillet and Richard, 2000). The Taiga Shield East (northern forest ecozone) displayed higher-than-present fire activity from 7 to 1 cal ka BP, with fires likely being important sources of carbon emissions during that time (Bremond et al., in press). This reconstruction matches well with data from the adjacent northern boreal forest (Ali et al., 2009) that display a different temporal pattern of fire from that of the southern boreal ecozones. The fire histories thus suggest that the northern Quebec-Labrador Peninsula displayed two fire-climate systems, a northern one under the influence of Arctic air masses, and a southern one under the influence of the Caribbean and the Pacific air masses.

Modeling past and future fires

The ultimate objective of fire-history research is to improve our ability to simulate future fire regimes through numerical models. Several modeling approaches have been used. First, the Fire Weather Index (an estimation of the risk of wildfire) has been simulated under scenarios of 1 x CO_2 and 2 x CO_2 greenhouse gas emissions using outputs from general circulation models (GCMs) in order to provide estimates of present and future fire risks (Flannigan et al., 2001). Second, the Drought Code (DC), an index of moisture content of deep organic matter (e.g., Girardin et al., 2009; Girardin and Wotton, 2009), has been computed using an ensemble of GCMs for 6 ka (Fig. 2), a period considered to have had minimal temporal and regional variability in fire activity. The area south of Hudson Bay (rectangle; Fig. 2) has high-quality and abundant paleodata to test past DC simulations. Multiple-comparison tests showed no difference among the six GCMs (Fig. 2), allowing us to use the UK Universities Global Atmospheric Modelling Program (UGAMP) GCM—the sole GCM providing climate data at each millennium—to simulate the DC over the entire Holocene for eastern Canada (Hély et al., 2010). The seasonal cycle of insolation was important for past fire activity as it modified the fuel dryness necessary for ignition and fire spread. Variations in monthly insolation curves during the Holocene (Fig. 1c) match well with the fire reconstruction and the simulated fire season, both in length and magnitude (Hély et al., 2010). The long-term diminishing trend toward present-day low fire activity in eastern Canada is attributed to the reduction of summer insolation from 6 cal ka BP to present. Predicted changes in temperature and precipitation over the next decades, as a consequence of increasing concentration of atmospheric CO_2, could reverse this downward trend in fire activity. Indeed, estimates suggest that future fire risk will reach values similar to the most severe values of the Holocene (Bergeron et al., in press).

Conclusion

Information on the long-term variability in mean FRI obtained from charcoal-based fire history reconstructions is relevant for sound boreal-forest management. Paleofire records encompass a long history of varying ecological conditions and document the resilience of the boreal forest to changes in disturbance regime. In this

context, the cumulative impacts of fire and timber harvesting are worrying. It has already been shown that clear-cut harvesting has considerably altered the age-class representation of forests at the landscape level by diminishing the number of stands older than the length of a typical harvest rotation (Bergeron et al., 2006; Cyr et al., 2009). Excessive use of even-aged management, therefore, erodes ecological resilience by reducing ecosystem variability in time and space (Drever et al., 2006), and this erosion will be exacerbated by the predicted increase in fire with future climate warming (Bergeron et al., in press).

Data

Charcoal data is available from the Global Charcoal Database http://www.bridge.bris.ac.uk/projects/QUEST_IGBP_Global_Palaeofire_WG/index.html

References

Ali, A.A., Carcaillet, C. and Bergeron, Y., 2009: Long-term fire frequency variability in the eastern Canadian boreal forest: the influences of climate vs. local factors, *Global Change Biology*, **15**: 1230-1241.

Bergeron, Y., Cyr, D., Girardin, M.P. and Carcaillet, C., in press: Will climate change drive 21st century burn rates in Canadian boreal forests outside of natural variability: collating global climate model experiments with sedimentary charcoal data, *International Journal of Wildland Fire*.

Cyr, D., Gauthier, S., Bergeron, Y. and Carcaillet, C., 2009: Forest management is driving the eastern part of North American boreal forest outside its natural range of fire-interval variability, *Frontiers in Ecology and the Environment*, **7**: 519-524.

Girardin, M.P., Ali, A.A., Carcaillet, C., Mudelsee, M., Drobyshev, I., Hély, C. and Bergeron Y., 2009: Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s, *Global Change Biology*, **15**: 2751-2769.

Hély, C., Girardin, M.P., Ali, A.A., Carcaillet, C., Brewer, S. and Bergeron, Y., 2010. Eastern boreal North American wildfire risk of the past 7000 years: a model-data comparison, *Geophysical Research Letters*, **37**: L14709, doi:10.1029/2010GL043706.

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Fire and climate variation in western North America from fire-scar and tree-ring networks

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Multi-scale fire-scar networks in western North America open new lines of inquiry into fire as an ecosystem process and reveal interactions of top-down and bottom-up regulatory factors across scales of space and time.

Fire regimes (i.e., the pattern, frequency and intensity of fire in a region) reflect a complex interplay of bottom-up and top-down controls (Lertzman et al., 1998; Mc Kenzie et al., in press). Bottom-up controls include local variations in topographic, fuel and weather factors at the time of a burn (e.g., fuel moisture and continuity, ignition density and local wind and humidity patterns). Bottom-up regulation is manifest as fine-scale spatial and temporal heterogeneity in fire behavior and effects within landscapes subject to the same general climate. Examples include variation in fuel consumption, tree mortality and soil effects, which create complex burn severity legacies that can influence subsequent fires (Collins and Stephens, 2008; Scholl and Taylor, 2010).

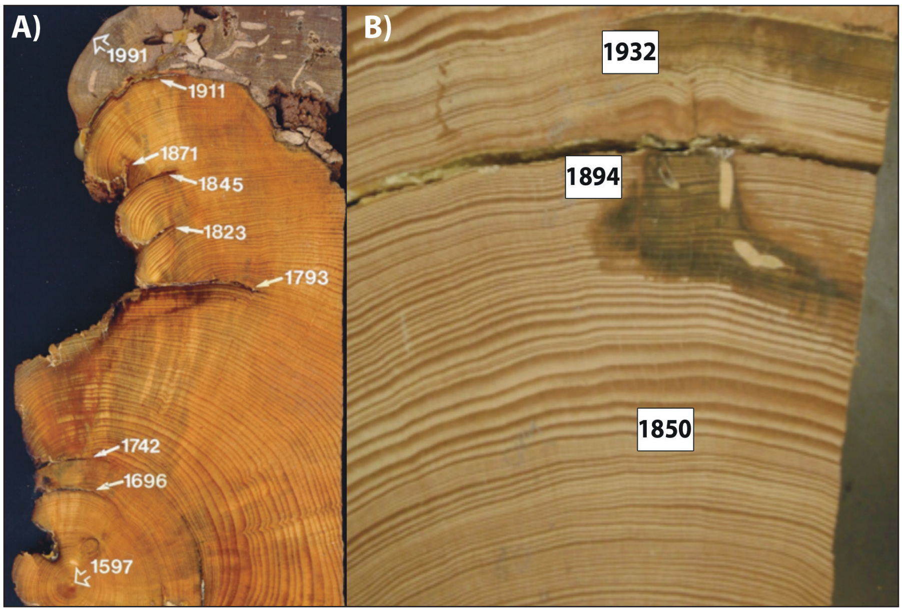

Figure 1: Tree-ring evidence of fires includes cross-dated fire scars and abrupt increases or decreases in ring width. ***A****) Cross-dated* Pinus ponderosa *fire-scarred sample (Photo: P. Brown, Rocky Mountain Tree-Ring Research).* ***B****) Bigcone Douglas-fir (*Pseudotsuga macrocarpa*) sample from Los Padres National Forest, USA, exhibiting growth anomalies following an 1850 wildfire, a buried fire scar dated to an 1894 wildfire, and both a fire scar and growth change from the 1932 Matilija Fire (Photo: K. Lombardo, Laboratory of Tree-Ring Research, University of Arizona).*

Climate is the primary top-down control of fire regimes, acting largely through interannual regulation of biomass production, fuel moisture and regional ignition patterns, and control of the geographic distribution of biomes. Top-down regulation leads to spatial and temporal synchrony in fire occurrence beyond scales at which individual fires are likely to spread.

Recent scientific publications and interest in fire climatology on centennial to multimillenial timescales has expanded our understanding of the interplay of bottom-up and top-down regulation of forest fire regimes (Falk et al., 2007; Swetnam and Anderson, 2008; Conedera et al., 2009; Whitlock et al., 2010). New understanding of broad-scale ocean-atmosphere oscillations (e.g., El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO)) and their influence on regional climate, has clarified the mechanisms that synchronize fires across regions (Schoennagel et al., 2005; Kitzberger et al., 2007; Heyerdahl et al., 2008; Trouet et al., 2010).

Contemporary human influences on fire regimes (including fire suppression, forest management, altered landscape configurations and the spread of non-native species) complicate the analysis of what drives fire regimes. Modern data cover a limited time frame and thus cannot capture longer-term variation in fire regimes driven by climate variability and ecosystem succession. Paleoecological data are essential to understand interactions of

vegetation, climate and people in past and current ecosystems; to create a multiscale "pyrogeography" for coupled natural-human systems.

Development of the North American fire history network

Fire regimes can be reconstructed from fire scars evident in tree rings, abrupt changes in tree-ring width, tree recruitment and mortality (from tree-age data), historical records and landscape analysis of forest structure (Fig. 1). Fire scars have been used since the 1930s to provide local fire chronologies but in the last 20 years the temporal and spatial coverage of the fire-scar record has expanded dramatically. In western North America, it now includes networks of 100s to 1000s of trees sampled across 100s to 10,000s of hectares, spanning centuries to millennia.

New insights from fire history networks

The extensive North American fire-history network yields new avenues for understanding past fire dynamics across multiple scales. Spatial patterns of annual fire occurrence are now being mapped at multiple scales (Swetnam et al., in press). At fine scales, patterns of historical fire occurrence are reconstructed using spatially-distributed sampling designs (Fig. 2). Such studies encompass fire perimeters and thus estimate fire size, as well as reveal the landscape heterogeneity and interactions between successive fires that are characteristic of bottom-up regulation (Heyerdahl et al., 2001; Hessl et al., 2007; Farris et al., 2010; Scholl and Taylor, 2010).

At larger spatial and temporal scales, synchronous fire occurrence captured in networks of fire-history chronologies reveals the entrainment of fire regimes by droughts, pluvials and other expressions of regional climate variability (Fig. 3). Fire-history networks, for example, have revealed the signature of interannual to multidecadal climate modes (especially ENSO, PDO and AMO) in regional fire regimes across western North America (Kitzberger et al., 2007; Morgan et al., 2008; Trouet et al., 2010).

Recent studies also incorporate annually resolved tree demographic data (recruitment and mortality) to infer spatial variability in fire behavior (e.g., crown vs. surface fire) and show how patterns have varied between historical and current forests (Brown et al., 2008). For example, tree-age data from a 240-a study on southern Colorado ponderosa pine (*Pinus ponderosa*) found that episodic recruitment occurred largely during periods

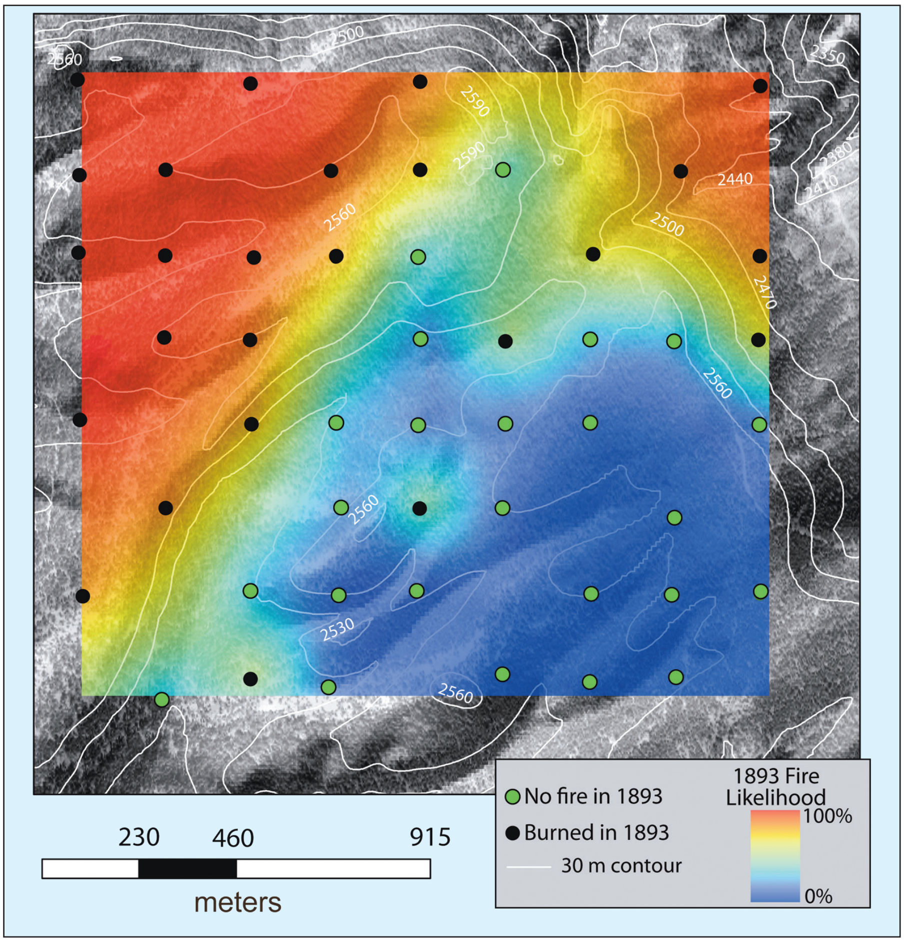

*Figure 2: Spatial pattern in fire occurrence at Monument Canyon Research Natural Area, USA, reconstructed from AD 1893 fire scar data using a 200 m gridded sampling design (Swetnam et al., in press). **Circles** indicate the locations of fire scar sample plots with multiple trees sampled over a 0.5-ha area. Inverse-distance weighting was used to spatially interpolate occurrence of fire in AD 1893 using the nearest neighbors of each plot. **Red areas** indicates a high (>89%) probability of fire occurrence based on presence of fire at surrounding plots; **green - blue areas** indicate low probability (<20%) of fire occurrence in that year. Spatial reconstruction can reveal bottom-up fire controls that modify fire spread, and leave a complex post-fire legacy. Data from Falk and Swetnam, 2003; Map by T.L. Swetnam.*

when regional climate was less favorable to fire, permitting higher survivorship of seedlings (Brown and Wu, 2005). Combined with demographic data, fire-history networks elucidate the complex environment/climate/vegetation interactions that regulate both fire regimes and ecosystem responses at multiple scales of space and time (Brown, 2006; Margolis and Balmat, 2009).

Fire scar networks and research in Canada and Mexico

The complex fire regimes of western Canada require multi-proxy approaches to reconstructing fire history, including fire-scar chronologies, charcoal in lake sediment cores, post-fire vegetation cohorts and land-surface models. Investigators have used synchronous patterns of post-fire tree recruitment to reconstruct high-severity fire regimes in coastal temperate rainforest, boreal forest, and subalpine forests in British Columbia and Alberta; however, less is known about the history of low- and mixed-severity fire regimes. Recent research funded by the National Science and Engineering Research Council (NSERC) promises to improve this situation. For example, a network of 30 sites in the southern Rocky Mountain Trench shows highly variable fire-return intervals, some synchrony with regional fires in adjacent US states, and evidence of fire suppression over the 20th century (Heyerdahl et al., 2008). Other research is developing regionally intensive networks of sediment cores, cohort data and fire scars in southeastern British Columbia.

In Mexico, the fire-history network includes over 25 georeferenced, cross-dated studies in northern Mexico (Fulé et al., 1997, 1999; Heyerdahl and Alvarado, 2003; Stephens et al., 2003). Many forests have experienced fire exclusion only recently or not at all, which allows for comparisons with adjacent US forests where fire has been suppressed for over a century (Stephens et al., 2008). Presence of 20th century fire scars also allows for analysis of controls on fire occurrence using modern instrumental weather data and new insights into the influence of climate variation on fire, such as variation in ENSO teleconnections in space and time across the region (Yocom et al., 2010).

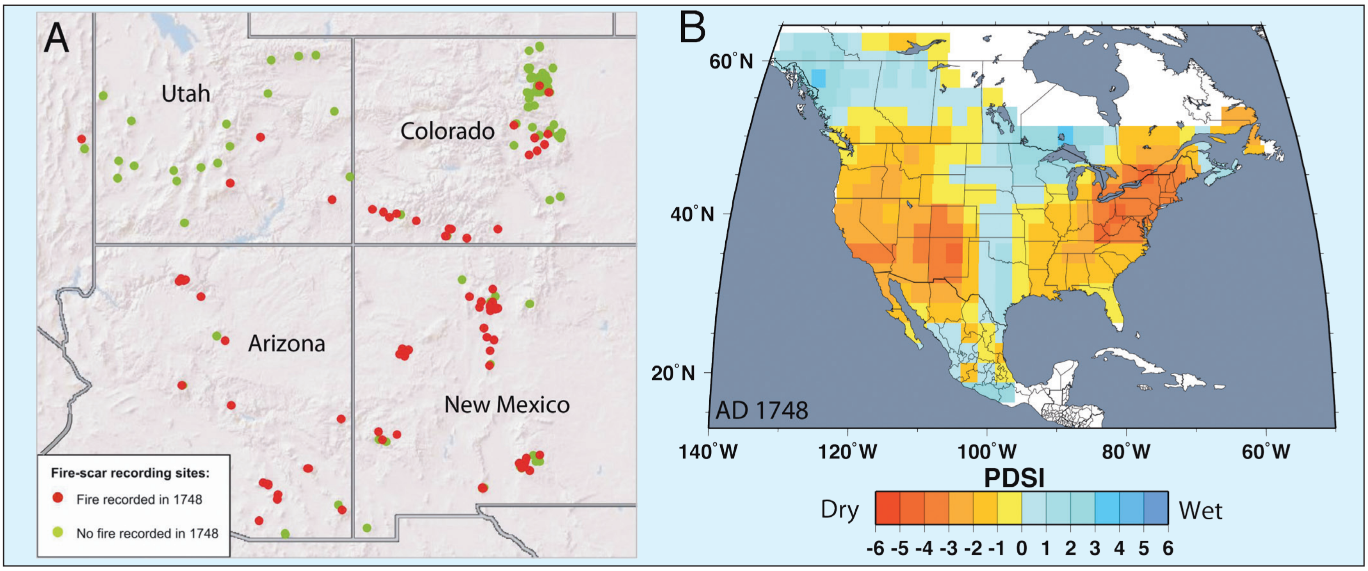

Figure 3: Synchronous fire occurrence captured in fire history networks can provide information on top-down fire controls. ***A****) Regional fire patterns in AD 1748 across southwestern North America, a year of widespread fires in the region. Data from the International Multiproxy Paleofire Database (see Data section of text) and individual research studies. Map by E. Bigio, University of Arizona.* ***B****) Values in the Palmer Drought Severity Index (PDSI) for AD 1748 reconstructed from tree-ring width data (from Cook and Krusic, 2004).*

New directions

The US Forest Service Global Change Research Program and the Joint Fire Science Program (JFSP) are supporting a new collaborative project, "Fire and Climate Synthesis" (FACS) to quantitatively synthesize fire climatology in western North America. Analogous efforts are underway in northern Mexico (National Science Foundation) and Canada (NSERC). We are employing multivariate similarity and cluster analysis techniques to create self-organizing maps of coherent fire-climate regions with persistent patterns of similarity in past fire. Regression and association tests (e.g., superposed epoch analyses) are used to infer the mechanisms of climate control of fire, including lagged climate effects. FACS emphasizes the role of annual-to-decadal climate variation that complement analyses of potential future climate variations on fire regimes (Brown et al., 2004; Flanigan et al., 2009).

Girardin et al., (2006) recently demonstrated an approach that enables the development of dendrochronological fire histories in regions or ecosystems lacking fire scars. Exploiting the strong control of climate on fire, they infer historical area burned in Canada using regression models built from modern climate-sensitive ring-width chronologies and 20th and 21st century observations of area burned. This approach has significant potential because tree-ring chronologies remain more numerous and more widely distributed than the fire-scar data per se. Multi-proxy and modern fire history cross-calibrations, using combinations of ring-width, fire scar and area burned time series, offer the potential for centuries-long calibration and verification with independent records (Westerling and Swetnam, 2006). Enhanced multi-proxy and modern fire-history networks help reconstruct long-term estimates of area burned, biomass consumed and fire-carbon relationships (Hurteau et al., 2008) and provide a comparison with decadal- to centennial-resolution charcoal time series (e.g., Marlon et al., 2008). Fire-scar networks are also developing in Scandinavia, Russia, Mongolia and temperate South America, and combined with other proxies, will clarify the past, present and future role of fire in those regions.

Data

More than 480 fire-scar chronologies are archived in the International Multiproxy Paleofire Database (http://www.ncdc.noaa.gov/paleo/impd/paleofire.html) with an additional 500 chronologies yet to be archived (Falk et al., unpublished). Tree-ring data is available from the The International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html), and Palmer Drought Severity Index data is available at The North American Drought Atlas website http://iridl.ldeo.columbia.edu/SOURCES/.LDEO/.TRL/.NADA2004/.pdsi-atlas.html

References

Brown, P.M. and Wu, R., 2005: Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine forest, *Ecology*, **86**:3030-3038.

Girardin M.P., Bergeron, Y., Tardif, J.C., Gauthier, S., Flannigan, M.D. and Mudelsee, M., 2006: A 229-year dendroclimatic-inferred record of forest fire activity for the Boreal Shield of Canada, *International Journal of Wildland Fire*, **15**: 375-388.

Heyerdahl, E.K., McKenzie, D., Daniels, L.D., Hessl, A.E., Littell, J.S. and Mantua, N.J., 2008: Climate drivers of regionally synchronous fires in the inland northwest (1651-1900), *International Journal of Wildland Fire*, **17**: 40-49.

Kitzberger T., Brown, P.M., Heyerdahl, E.K., Veblen, T.T. and Swetnam, T.W., 2007: Contingent Pacific–Atlantic Ocean influence on multi-century fire synchrony over western North America, *Proceedings of the National Academy of Sciences USA*, **104**: 543–548.

Yocom, L., Fulé, P.Z., Brown, P.M., Cerano, J., Villanueva-Díaz, J., Falk, D.A. and Cornejo-Oviedo, E., 2010: El Niño-Southern Oscillation effect on a fire regime in northeastern Mexico has shifted over time, *Ecology*, **91**: 1660-1671.

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Paleofire activity in tropical America during the last 21 ka: A regional synthesis based on sedimentary charcoal

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Fire in most Neotropical systems has generally occurred during periods of reduced precipitation, and fire activity, at times, has been shown to be anti-phased between the northern and southern regions.

Understanding the linkages between past climate change and forest dynamics in the Neotropics (an area of North, South, Central America and the Caribbean from 30°N to 30°S) is a major international research challenge because of the importance of tropical biomes to global climate change. Global climate models suggest that much of Amazonia will experience increased drought and hence susceptibility to burning in the 21st century (Malhi and Phillips, 2004). Yet, large uncertainties remain for understanding the relationship between Amazonian moisture balances and future fire regimes (Cochrane and Barber, 2008). The global implications of accelerating tropical burning in the near future and the potential feedbacks between tropical deforestation and climate, makes understanding Neotropical ecosystem responses to past fire activity an important research focus.

Little is known about the frequency and spatial extent of past fires in the Neotropics since the Last Glacial Maximum (LGM; ca. 21 cal ka BP). A compilation of 56 charcoal records allowed us to compare the patterns of fire during the last 21 ka in northern (0°–30°N) and southern (0°–30°S) latitudes and to identify potential drivers of past biomass burning (Fig. 1). Published charcoal records from the Neotropics were combined to examine regional trends in biomass burning during the past 21 ka. Nearly half the records came from the tropical evergreen and semi-evergreen broadleaf biomes (48%); others were from the tropical deciduous broadleaf forests and woodlands (18%), the warm temperate evergreen broadleaf and mixed biome (16%), and savannas (7%). Individual charcoal records were transformed and rescaled as Z-scores of charcoal influx values and composited together. Published age-depth models were used when calibrated ages were available; otherwise, radiocarbon ages were converted to calendar kiloyears before present (cal ka BP) using the calibration curve of Fairbanks et al. (2005) and new age models were created using median calibrated radiocarbon ages and a "best fit" model (see Power et al., 2008). Site-specific fire histories were also examined within the region.

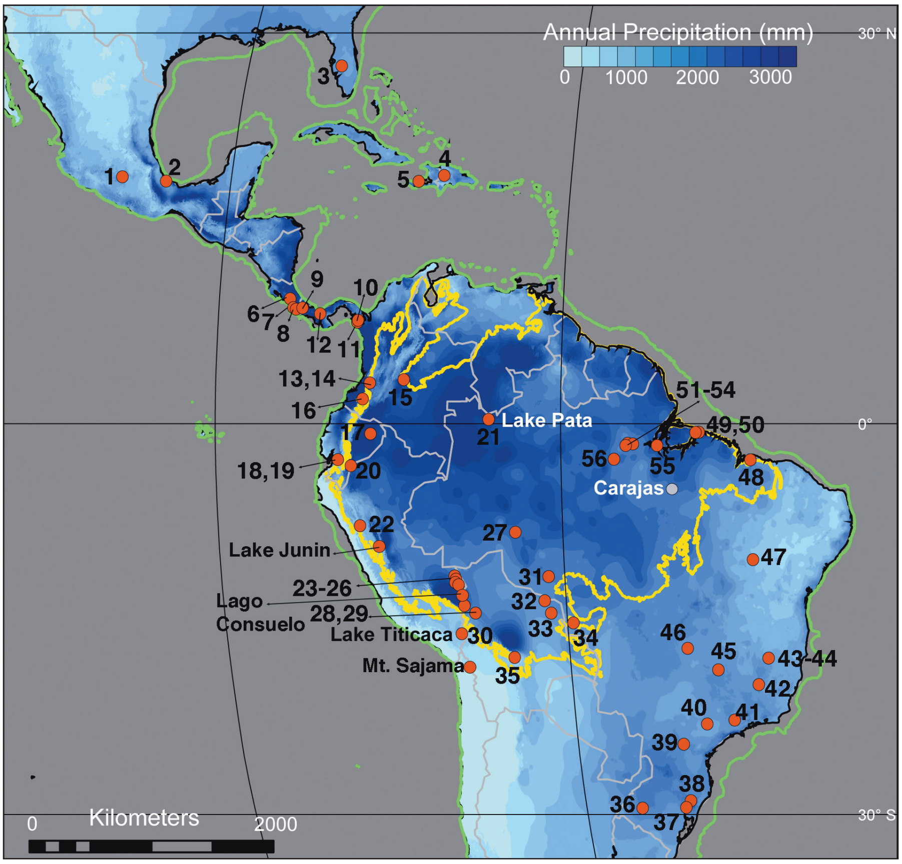

*Figure 1: A regional map of tropical and subtropical America and the Caribbean showing annual average precipitation and sites mentioned in the text and figure 2 (Hijmans et al., 2005). **Yellow line** delineates the Amazon Basin, which encompasses both humid evergreen rainforests in the lowland basin and Guyana Shield, semi-deciduous Chiquitano dry forests in the south, and all forest types on the eastern flank of the Andes. **Green line** indicates Last Glacial Maximum (LGM) coastline reconstructions (Peltier, 2004); **red circles** indicate the location of charcoal records obtained from the Global Charcoal Database. A list of the oldest and youngest sample charcoal ages (following Power et al., 2008) and number of charcoal samples from each record are available at http://www.pages-igbp.org/products/newsletters/ref2010_2.html*

Results and Discussion

Drier-than-present late-glacial climates resulting from lower-than-present sea-surface temperatures, CO_2 and sea level, resulted in decreased biomass burning across the Neotropics during the LGM (Power et al., 2008). During the late-glacial period (ca. 19 - 14 cal ka BP), most charcoal records indicate infrequent fires (Fig. 2). Late-glacial pollen, charcoal and $\delta^{13}C$ evidence from Lake Titicaca (Paduano et al., 2003) suggest fires became more important as available moisture and fuel production around 15–20°S gradually increased after 17.7 cal ka BP. Regional charcoal summaries (Fig. 2) suggest fire activity in the northern Neotropics decreased to the lowest levels of the last 21 ka by 14 cal ka BP. During the early Holocene, the precessional component of insolation increased summer warmth and seasonality in the northern tropics (and reduced them in the south) and through atmospheric circulation responses, also influenced seasonal moisture and drought patterns. In both the southern and northern Neotropics, fire activity increased after ca. 14 cal ka BP and again after 11 cal ka BP, as orbital precession lengthened and intensified the dry season (Berger and Loutre, 1991). More-severe seasonal droughts were particularly evident in the northern Neotropics, with charcoal records from the Yucatan, for example, showing highest fire activity of the last 84 ka between ca. 17 and 14 cal ka BP (Bush et al., 2009).

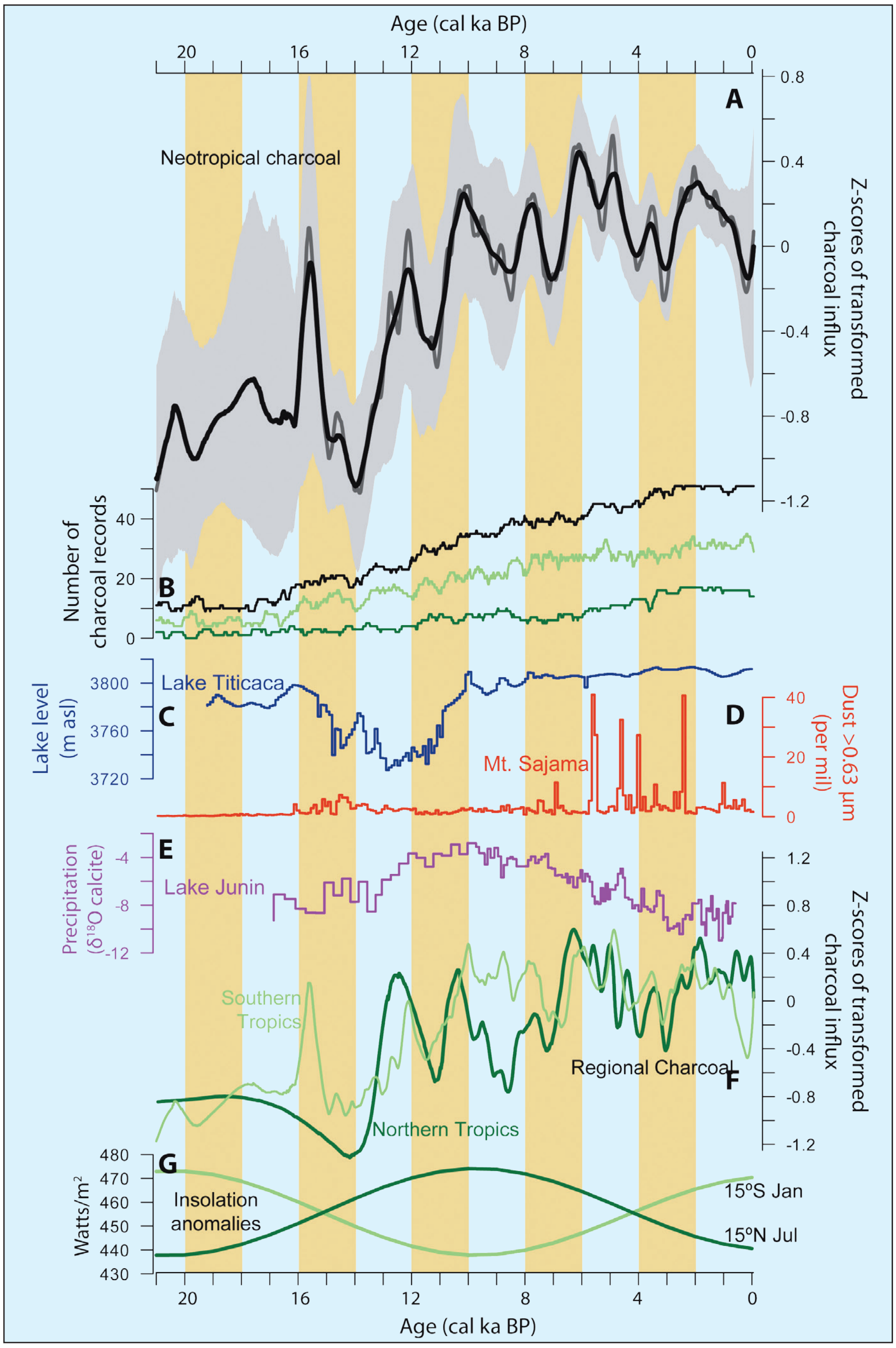

*Figure 2: **A**) 21 ka composite time series from all Neotropical records (between 30°N and 30°S) of 250-a (black) and 100-a (gray) smoothed Z-score charcoal anomalies. The upper and lower 95% confidence limits from bootstrap analysis are shown in light gray. The composite charcoal curve was produced from 56 records from the Global Charcoal Database version1, including lakes, bogs and in few instances, soil charcoal. **B**) The number of charcoal records contributing to each composite curve for Neotropics (black), northern Neotropics (0°-30°N; dark green), and southern Neotropics (0°-30°S; light green). Paleomoisture proxies are shown from selected tropical records, including (**C**) Lake Titicaca elevation (m asl) inferred from $\delta^{13}C$ (Abbott et al., 2003), (**D**) Mt. Sajama dust particles larger than 0.63 µm from ice cores (Thompson et al., 1998), and (**E**) $\delta^{18}O$ of calcite at Lake Junin, proxy for precipitation (Seltzer et al., 2000). **F**) Northern and southern tropics composite charcoal time series using a 250-a smoothing window. The composite approach normalizes individual records in order to stabilize the variance and standardize results (Power et al., 2008, 2010). The charcoal time series was smoothed by fitting a lowess curve (Cleveland and Devlin, 1988), which prevents high-resolution records from affecting regional signals and avoids introducing, by interpolation, data into lower-resolution records. **G**) Mid-month insolation anomalies for June at 15°N and January at 15°S (Berger and Loutre, 1991). Yellow vertical bars represent 2 ka intervals.*

As summer insolation decreased from 10 to 8.5 cal ka BP in the Northern Hemisphere, charcoal records from the northern Neotropics suggest decreased fire activity. Fire activity remained higher-than-present in the southern Neotropics during this time. From 8 to 6 cal ka BP, orbital-scale controls of tropical fire activity weakened. As summer insolation decreased in the Northern Hemisphere, drought intensity and biomass burning generally decreased from 6 cal ka BP to present (Fig. 2). Increasing summer insolation in the Southern Hemisphere may have promoted more droughts and biomass burning ca. 5 cal ka BP, but both the northern and southern tropics show similar millennial-scale trends of decreasing biomass burning thereafter.

Reconstructions of tropical moisture between 6 and 3 cal ka BP suggest wetter-than-present conditions in the northern Neotropics (Hodell et al., 2000; Horn, 2007), while records from the southern Neotropics, including the tropical Andes and Amazonia, suggest drier-than-present climates. High climate variability also characterized this period, as evidenced by peak dust concentrations and snow accumulation in Andean ice cores (Thompson et al., 1998), oxygen isotope ratios from lake-sediment calcite analysis (Seltzer et al., 2000), and evidence of lake-level low stands in Lake Titicaca (Baker et al., 2001) (Fig. 2). Centennial-scale intervals of high and low biomass burning were embedded within millennial-scale trends of decreasing fire across the Neotropics. The temporal variability in biomass burning may be related to changes in Atlantic sea surface temperatures, characterized by the Atlantic thermal dipole (Hillyer et al., 2009), which reflects the seasonal and interannual changes in the position of the ITCZ and thermal equator in the tropical Atlantic Ocean (Bush et al., 2007).

Soil-charcoal records provide paleofire information in neotropical regions where suitable lakes and bogs are absent (Sanford and Horn, 2000). Most tropical soil charcoal records are younger than 3 cal ka BP and fire occurrence is generally considered anthropogenic in origin. Intensification of human land-use in the Neotropics during the last three millennia undoubtedly changed the geographic pattern and frequency of fire (Cochrane and Barber, 2008). In addition, radiocarbon dates on soil charcoal suggest that high fire activity in Amazonia coincided with sun-spot minima during the last 2.5 cal ka BP (Bush et al., 2008). These solar minima are possibly linked to drought events, which may have facilitated the spread of human-set fires.

Conclusions

Charcoal records from the Neotropics suggest fire activity is associated with periods of high climate variability, including changes in moisture budgets and the intensification of seasonal droughts. The direct effects of summer insolation likely explains periods of higher-than-present fire activity in the Neotropics at ca. 10 cal ka BP. Drier-than-present climates likely promoted more fires during this period, either directly by reducing humidity, lowering fuel moisture and drying soils, or indirectly by favoring more flammable vegetation. From ca. 10 to 8.5 cal ka BP, fire activity is anti-phased in the northern versus southern Neotropics. After ca. 6 cal ka

BP, biomass burning generally decreased to present across the Neotropics, with multi-centennial periods of high fire activity (e.g., 6 to 5 cal ka BP and ca. 2 cal ka BP) embedded in these long-term trends. Remarkably, records from the wettest regions of Amazonia (e.g., Lake Pata and Consuelo; Fig. 1) have no charcoal, suggesting that they remained fire-free over the last 21 ka. In contrast, Neotropical regions with high seasonality (e.g., Carajas, Brazil; Fig. 1) experienced more fires in the early to middle Holocene, when savanna replaced evergreen forest (Absy et al., 1991).

Neotropical ecosystems have experienced significant variability in biomass burning since the LGM but additional high-resolution charcoal records are needed to better establish regional fire-frequency trends. Simulating past changes in fire regimes with global and regional Earth System models will help assess the ability of these models to predict future changes in Neotropical fire regimes. Furthermore, studies of fire history from the tropics are highly relevant to issues of climate change and biodiversity conservation and can contribute to the development of appropriate fire-management policies (Horn and Kappelle, 2009).

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References
Baker, P.A., Seltzer, G.O., Fritz, S.C., Dunbar, R.B., Grove, M.J., Tapia, P.M., Cross, S.L., Rowe, H.D. and Broda, J.P., 2001: The history of South American tropical precipitation for the past 25,000 years, *Science*, **291**: 640–643.

Bush, M.B., Correa-Metrio, A., Hodell, D.A., Brenner, M., Ariztegui, D., Anselmetti, D., Gilli, A., Burton C. and Muller A.D., 2009: The Last Glacial Maximum: Central America. In: Vimeux, F., et al., (Eds), *Past climate variability from the Last Glacial Maximum to the Holocene in South America and surrounding regions*, Springer, Paris.

Cochrane, M.A. and Barber, C.P., 2008: Climate change, human land use and future fires in the Amazon, *Global Change Biology*, **15**(3): 601–612.

Horn, S.P. and Kappelle, M., 2009: Fire in the páramo ecosystems of Central and South America. In: Cochrane, M. (Ed.), *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics*, Berlin, Springer, 505–539.

Power, M.J., Marlon, J.R., Bartlein, P.J. and Harrison, S., 2010: Fire history and the global charcoal database: a new tool for hypothesis testing and data exploration, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **291**: 52-59.

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Paleofires in southern South America since the Last Glacial Maximum

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Southern South American charcoal- and tree-ring-based fire histories suggest strong linkages between climate variability and regional fire regimes, with human influences having a more localized impact on fire occurrence.

The diverse physiography, climate and biota of southern South America (SSA; 30-55°S) offer the possibility of examining the pattern and causes of paleoclimate change and paleofire activity from subtropical to subantarctic environments, including the region of maximum surface wind speeds and frontal precipitation (48-50°S) delivered by the Southern Westerly Winds (SWW). The southern Andes establishes an effective barrier to the advection of moist air masses across SSA and isolates Pacific and Atlantic moisture sources. An array of fire-history records along latitudinal and longitudinal gradients through SSA identifies the sensitivity and vulnerability of vegetation to past fire occurrence and the underlying climate and vegetation drivers of fire operating at different spatial and temporal scales.

At present, natural fire occurrence in SSA is driven primarily by tropical and extra-tropical influences on the SWW, as demonstrated by the correspondence of fires with synoptic patterns associated with El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). These modes of variability are captured by such indices as the Multivariate ENSO Index and the Antarctic Oscillation Index (Garreaud et al., 2009; Villalba, 2007) (Fig. 1). During the positive (or warm) phase of ENSO, the southeastern Pacific subtropical high-pressure system weakens, allowing an equatorward deflection of the SWW to ~30°S. In conjunction with the development of an anomalously warm pool in the southeastern Pacific, this induces warm dry conditions in the mid latitudes (40-50°S) of western Patagonia, which promotes fire. During the positive phase of SAM, a low atmospheric pressure anomaly develops over Antarctica shifting the circumpolar vortex and subtropical high-pressure system south and deflecting the SWW to 50-60°S. The result is dry conditions conducive for fires between 35-43°S. In addition, a positive SAM is correlated with a warm South Atlantic sea-surface pool that further enhances positive temperature anomalies over the mid-latitude eastern flanks of the Andes. The varying strength of these relationships in space (the correlation indices decline north and south along the Pacific side of the Andes) and time (the relationship remains significant only for the post-1977 warm phase of the Pacific Decadal Oscillation in the 1938-2004 record from northern Patagonia) suggests modulation of signals by nonstationarities and lower-frequency climatic (Enfield et al., 2001) and fire controls (Kitzberger et al., 2007). The complexity of climate drivers at different spatial and temporal scales argues for the need for a dense network of high-resolution paleofire reconstructions on both Andean flanks between 38-55°S.

Charcoal records
The first charcoal-based fire histories in SSA were described by Calvin Heusser in Chile (Heusser, 1983) and Vera Markgraf in Argentina (Markgraf, 1983). Since then, fire history has been studied in many regions and most researchers suggest strong linkages between fire and climate, with human influences being more localized (e.g., Markgraf, 1993; Heusser, 1994; Heusser et al., 1999; Moreno, 2000; Huber and Markgraf, 2003; Haberle and Bennett, 2004; Whitlock et al., 2006; Markgraf et al., 2007; Abarzúa and Moreno, 2008). Regional syntheses of charcoal records have identified conspicuous multi-millennial trends in paleofire activity (Fig. 2) with low abundance of charcoal prior to 14 cal ka BP, an increase

to prominent charcoal maxima from 12-11.5 to 10.5-8 cal ka BP, followed by a persistent decline between 8 and 3.5 ka and a steady increase toward preindustrial values (Power et al., 2008). A spatio-temporal analysis of paleofire activity south of 35°S revealed widespread high fire activity between 12-9.5 cal ka BP, followed by latitudinal differentiation of fire activity between 9.5-6 cal ka BP and a heterogeneous fire pattern after 6 cal ka BP (Whitlock et al., 2007). These broad patterns suggest that insolation-driven changes in atmospheric circulation (i.e., variations in strength of the SWW and the southeastern Pacific subtropical high-pressure system) and the onset and strengthening of ENSO (Fig. 2) were drivers of regional paleofire activity, as well as vegetation change and renewed glaciation in the southern Andes (Moy et al., 2002; Huber et al., 2004; Moreno, 2004; Whitlock et al., 2006; Moreno et al., 2010).

Comparisons of high-resolution charcoal records provide insights into decadal and longer variations in fire activity, including a separation of local fire events from regional fire activity. Figure 2 shows three Holocene charcoal records from the lake districts of southern Chile and Argentina (Abarzúa and Moreno, 2008; Whitlock et al., 2006). At multi-millennial scales, the records from Lago Melli (Chile) and Lago Mosquito (Argentina), show high fire activity in the early Holocene, in keeping with the SSA pattern for sites south of 35°S. In contrast, Lago el Trébol (Argentina) records highest fire activity after 6 cal ka BP. A shift from canopy fires to surface fires (inferred by increasing grass charcoal %) is noted east of the Andes at ~7.8 cal ka BP (Lago Mosquito) and 6.8 cal ka BP (Lago el Trébol), suggesting wetter conditions. This change in fire regime coincides with lower fire activity (Lago Melli) and a multi-millennial expansion of cold-resistant North Patagonian trees on the Pacific side of the Andes (e.g., the *Eucryphia-Caldcluvia*/Podocarpaceae Index (ECPI) from Lago Condorito; Moreno, 2004). The regional patterns and individual site-based reconstructions suggest a shift to increased fires after 3.5 cal ka BP at many sites as well as more spatial heterogeneity in the occurrence of fire. The onset and subsequent intensification of ENSO at ~6 and ~3 cal ka BP, may explain these fire patterns. In addition, charcoal records suggest that fire activity peaked during the Medieval Climate Anomaly (1-0.8 cal ka BP) and then declined, in concert with a weakening of ENSO activity after ~1 cal ka BP (Fig. 2b).

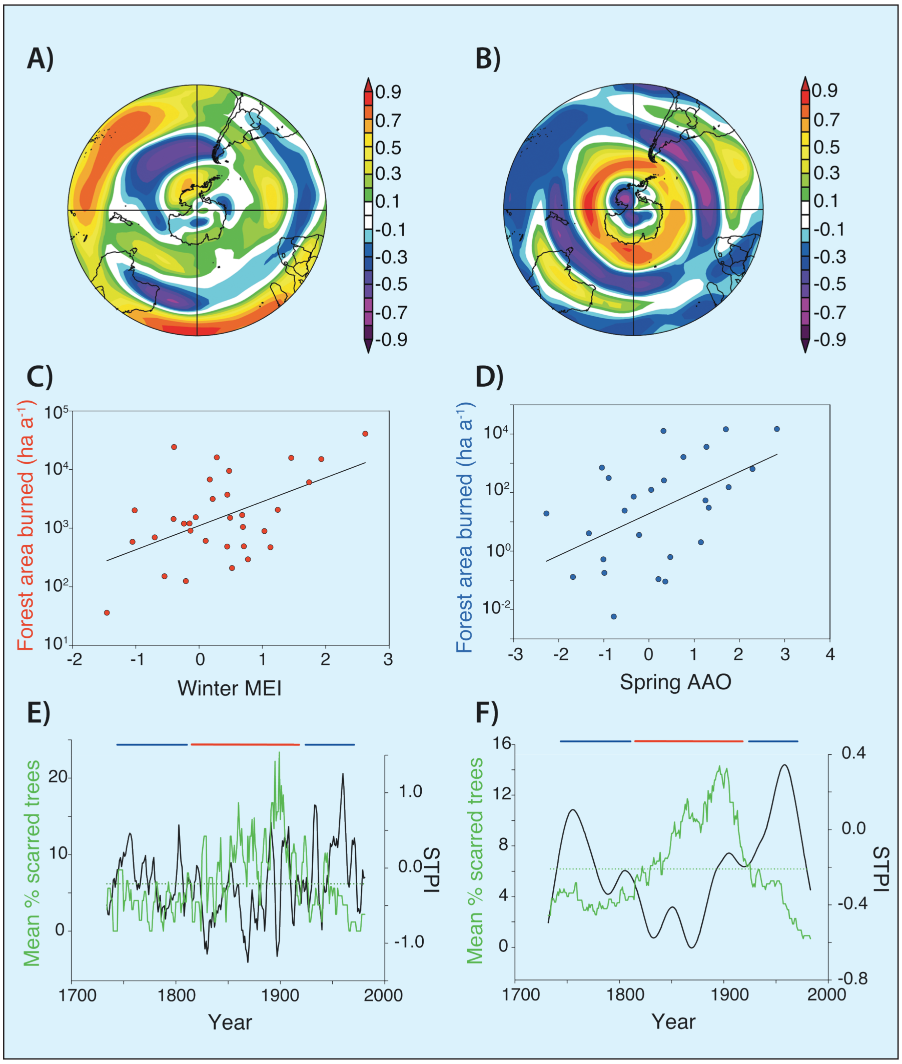

*Figure 1: Correlation fields between (**A**) spring-summer Multivariate El Niño Southern Oscillation Index (MEI) and (**B**) Antarctic Oscillation Index (AAOI) with the 300 hPa zonal wind (NCEP Reanalysis). Blue-violet fields indicate reduction (enhancement of westerly flow) during positive (negative) phases of the indices and vice versa for orange-red fields. **C**) Annual forest area burned in the Chilean Lake and River Districts (39-43°S; 1972-2005, CONAF, 2010) in relation to winter MEI. **D**) annual forest area burned in the Argentinean Lake District (39-43°S, 1978-2004; Administración de Parques Nacionales, unpublished data) and spring AAO (r=0.52 and r=051, respectively, P<0.01). Yearly % of scarred trees in the Lake District of Argentina (green) and the tree-ring reconstructed Summer Trans- Polar Index (STPI, black), expressed as (**E**) 5-a and (**F**) 49-a moving averages (modified from Veblen et al., 1999; Villalba et al., 1997). Horizontal blue and red bars illustrate multi-decadal to century-long periods of low and high fire, respectively.*

Fire scar records

On shorter timescales, tree-ring-based fire-history networks from the Lake District of Argentina suggest widespread fire occurrence in the last 2-4 centuries as a result of human activity, and tropical and high-latitude climate drivers (Kitzberger and Veblen, 1997; Veblen et al., 1999). For example, large/synchronous fire events are related to winter-spring droughts of the late stages of strong La Niña events or hot summers following late-developing El Niño events. In the *Araucaria-Nothofagus* forests of the western Andes (~39°S), positive ENSO phases are followed by warm dry summers and years of high fire activity (González and Veblen, 2006). Multidecadal variations of the Summer Trans-Polar Index, a measure of the circumpolar vortex strength and eccentricity (Villalba et al., 1997), influence long-term variations in fire occurrence (Fig. 1). Fire histories from 42-48°S, based on the long-lived conifer *Pilgerodendron uviferum*, document the pervasive role of both ENSO and SAM in this cool-maritime hyperhumid sector of SSA (Holz, 2009; Holz and Veblen, 2009). Fire-history research is currently focused on coastal areas (49-55°S) using *P. uviferum*, and along the eastern Andean flank using *Nothofagus pumilio* and *Austrocedrus chilensis* (43-52°S), and *Araucaria araucana* (38-40°S).

Outlook

Large gaps in our understanding of paleofires in SSA during and since the LGM suggest four directions for future investigation: (i) better calibration and cross-validation of fire-scarred tree-ring records, high-resolution charcoal data, and documentary information; (ii) geographic expansion of the high-resolution paleofire network (charcoal and fire scars) in the region; (iii) time series analysis on multiple high-resolution charcoal records to enable reconstruction of centennial-scale climate

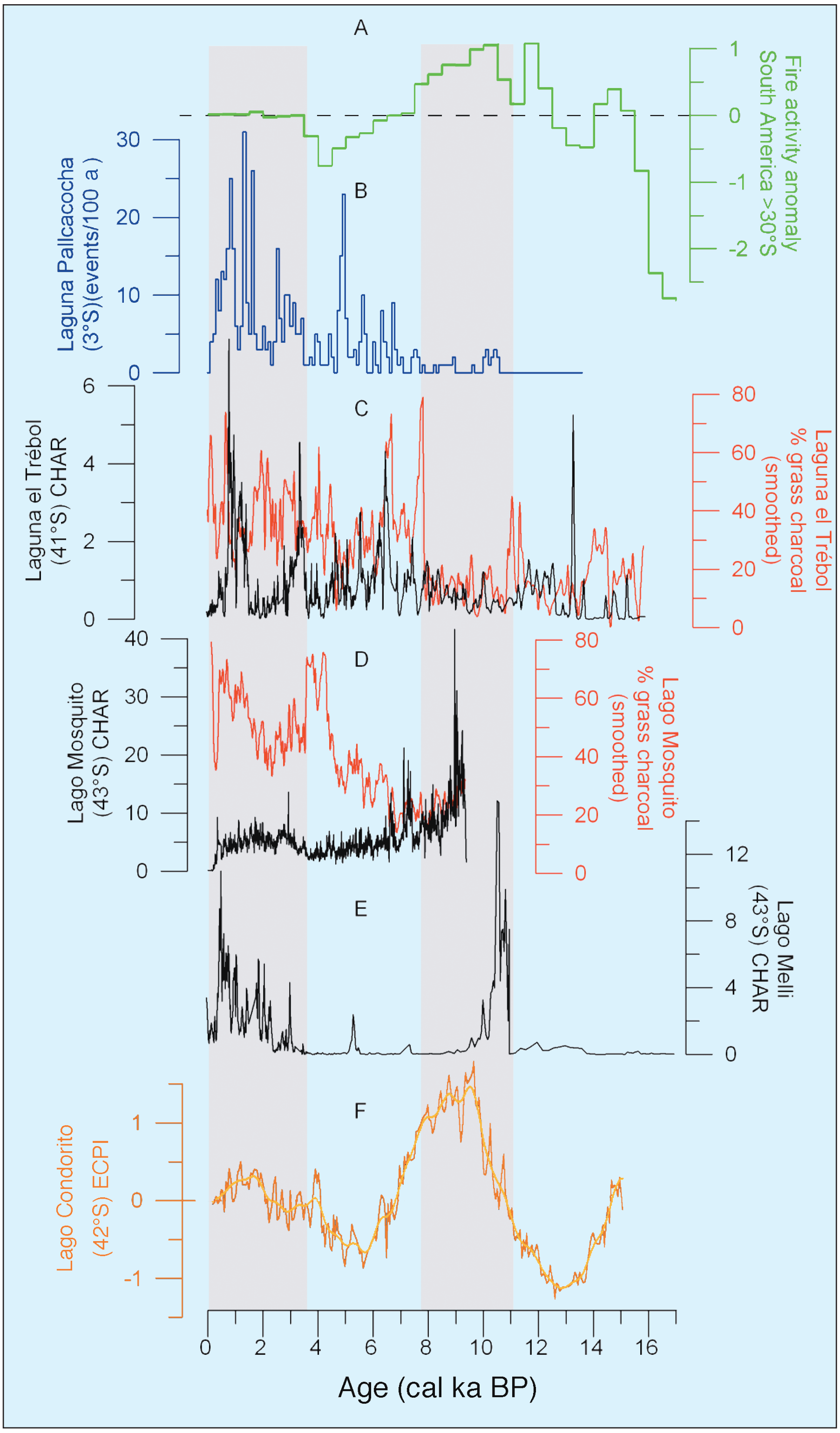

*Figure 2: From top to bottom: **A**) normalized and transformed charcoal data averaged at 500-a time steps over southern South America (>30°S) (modified from Power et al., 2008); **B**) number of El Niño events/100-a inferred from the Lago Pallcacocha record (Ecuador) (modified from Moy et al., 2002); macroscopic CHAR (charcoal accumulation rates in particles cm^{-2} a^{-1}; black lines) from (**C**) Laguna el Trébol (Whitlock et al., 2006), (**D**) Lago Mosquito (Whitlock et al., 2006), and (**E**) Lago Melli (Abarzúa and Moreno, 2008). Percentage of grass charcoal particles (red lines) at Lago el Trébol and Lago Mosquito shows the increase in surface fires in the mid Holocene (Whitlock et al., 2006); and (**F**) the Lago Condorito palynological index (ECPI; orange line), which indicates multi-millennial timescale variations in precipitation of westerly origin since 14 cal ka BP. Positive anomalies indicate predominance of thermophilous (warmth-loving), drought-resistant Valdivian trees and relatively dry conditions and reduced influence of the Southern Westerly Winds (SWW). Negative anomalies represent the prevalence of North Patagonian rainforest taxa under cooler wetter conditions, implying stronger SWW influence. The vertical gray panels indicate the duration of a multi-millennial "dry" interval during the early Holocene (10.5-7.8 cal ka BP) and the period of high fire activity during the last 3.5 ka.*

and fire variability at the landscape level; and (iv) studies of the climatic and non-climatic interactions that lead to fire-regime changes under different climatic and land-use scenarios.

Data

The charcoal and tree-ring derived fire history data has been submitted to the International Multiproxy Paleofire Database (NOAA, NCDC; http://www.ncdc.noaa.gov/paleo/impd/paleofire.html)

References

Abarzúa, A.M. and Moreno, P.I., 2008: Changing fire regimes in the temperate rainforest region of southern Chile over the last 16,000 yr, *Quaternary Research*, **69**: 62-71.

Kitzberger, T. and Veblen, T.T., 1997: Influences of humans and ENSO on fire history of *Austrocedrus chilensis* woodlands in northern Patagonia, Argentina, *Ecoscience*, **4**: 508-520.

Moreno, P.I., 2004: Millennial-scale climate variability in northwest Patagonia over the last 15000 yr, *Journal of Quaternary Science*, **19**: 35-47.

Whitlock, C., Bianchi, M.M., Bartlein, P.J., Markgraf, V., Marlon, J., Walsh, M. and McCoy, N., 2006: Postglacial vegetation, climate, and fire history along the east side of the Andes (lat 41–42.5°S), Argentina, *Quaternary Research*, **66**: 187-201.

Whitlock, C., Moreno, P.I. and Bartlein, P., 2007: Climatic controls of Holocene fire patterns in southern South America, *Quaternary Research*, **68**: 28-36.

For full references please consult:
http://www.pages-igbp.org/products/newsletters/ref2010_2.html

Paleofire in the wet tropics of northeast Queensland, Australia

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New approaches to fire history reconstructions in Australia provide insights into climate, human and ecosystem influences on fire regimes of the past.

Fire in wet tropical environments is often associated with deforestation and degradation of diverse and "pristine" habitats. These notions have been exacerbated by mega-fire events associated with El Niño-related droughts in Southeast Asia and New Guinea. Forest loss in Indonesia after the intense El Niño of 1997-98 is estimated at more than 5 million hectares (Glover and Jessop, 1999) and the carbon released as a result of these fires is thought to have been equivalent to 40% of the mean annual global carbon emissions from fossil fuels for that year (Page et al., 2002). These events led to fears that repeated large fires in the future may lead to large changes in the distribution of rainforest and sclerophyll (trees and shrubs with hard leaves adapted mainly to dry climate) communities in northern Australia. There is growing recognition that a greater understanding of the role of fire in the environment is needed, and can be gained through the study of the frequency and impact of past fire events (Lynch et al., 2007; Bowman et al., 2009).

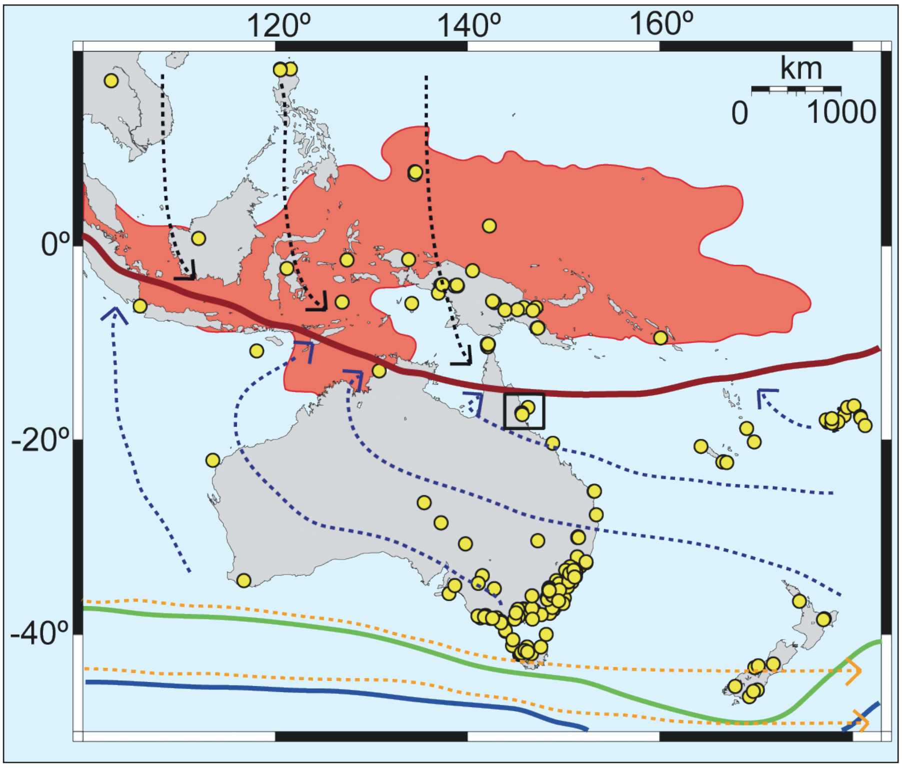

*Figure 1: Location of Atherton Tablelands (**black box**) and paleoecological sites in Australasia that have charcoal data (**yellow circles**, data from databases mentioned in Data section of text). The principal atmospheric circulation affecting the Atherton Tablelands region during the austral summer, and mean annual location of oceanic water masses are also shown: **Red line** = Inter-Tropical Convergence Zone, **green line** = Sub-Tropical Front, **blue line** = Sub-Antarctic Front, **red shaded area** = western Pacific warm pool, **orange dashed arrows** = westerlies, **black dashed arrows** = Asian monsoon, **blue dashed arrows** = Southeast Trade winds.*

Fire and Australian Rainforests

The Wet Tropics of Far North Queensland, Australia, contain a complex and biodiverse vegetation that covers approx. 1.8 million hectares, from sea level to cool humid mountains over 1600 m asl. On the Atherton Tableland (see Fig. 1), a fragmented band of sub-montane rainforest is interspersed with fire-prone sclerophyll vegetation (including grasslands, open woodlands and eucalypt forests) (Hopkins et al., 1993; Hilbert et al., 2001). The boundary between rainforest and fire-prone sclerophyll vegetation is buffered by wet sclerophyll forests, characterized by a sclerophyll overstorey with a rainforest and pyrophytic (fire tolerant) species underneath. The arrival of European settlers in the 1880s heralded a period of rapid rainforest clearance and burning for forestry, pastoral and agricultural purposes. Prior to this, human-lit fires were associated with Aboriginal occupation, and exploitation of the fire-prone sclerophyll vegetation began as early as 30,000 years ago, although human occupation of rainforests is evident only with the period of postglacial expansion of rainforest after 8 cal ka BP (Cosgrove et al., 2007). Lightning strikes may also have been an ignition source leading to large wildfires during severe drought conditions. Whatever the source of ignition, extended droughts coupled with dry seasons strongly increased the likelihood and consequences of fire in otherwise fire-resistant rainforests of the Atherton Tableland (Marrinan et al., 2005).

Today the dominant source of precipitation in the Atherton Tableland is the Southeast Trades and occasional northwesterly monsoonal flows. Associated tropical cyclones bring high but infrequent rainfall events during the austral summer months when the intertropical convergence zone (ITCZ) is at its most southerly extent (Fig. 1). During El Niño episodes, a northward movement of the ITCZ and a northeastward migration of the South Pacific Convergence Zone result in a significant decrease in summer precipitation (typically 150–300 mm below seasonal average) over the region. This can create conditions suitable for fires to penetrate otherwise "impenetrable" or pyrophobic rainforest habitats.

Records show that fires have long been a factor in rainforest dynamics on the Atherton Tablelands (Haberle, 2005; Kershaw et al., 2007). Charcoal identified to rainforest species (*Halfordia* sp. and *Pouteria* sp.) have been dated to 0.4-0.25 cal ka BP within soil under "pristine" rainforest vegetation (Cosgrove, 2005) suggesting that some fire events are destructive to rainforest and that rainforest species can recolonize if fire return intervals are long (multi-century). Frequent fires have led to

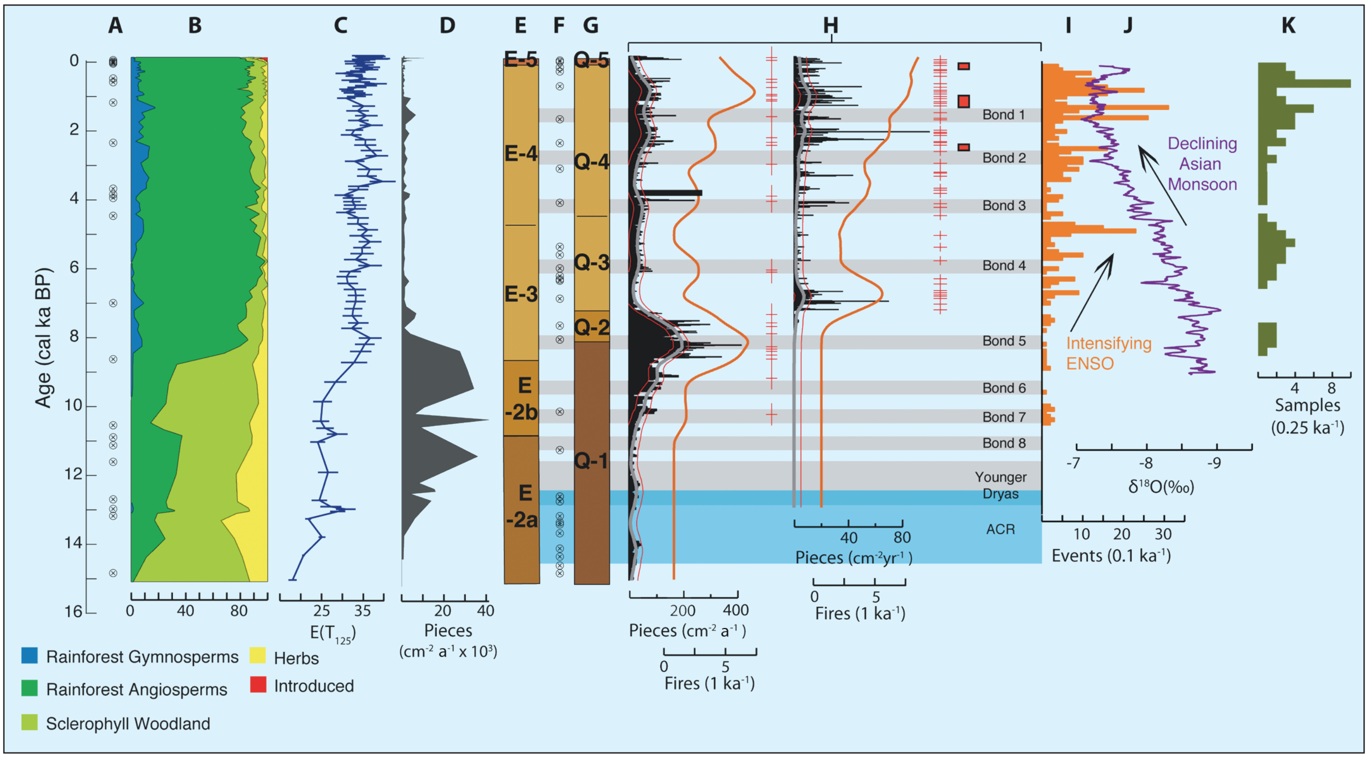

Figure 2: Selected pollen and charcoal data for Lake Euramoo and Quincan Crater. ***A****) and* ***F****) Euramoo and Quincan* [14]*C samples, respectively.* ***B****) Euramoo pollen diagrams and (****C****) Euramoo palynological richness ($E(T_{125})$ = standardized pollen sum) plotted using Psimpoll (© Kieth Bennett).* ***D****) Euramoo microcharcoal (<125 µm) reflecting burning of low plant biomass during the glacial period.* ***E****) Euramoo and (****G****) Quincan pollen zones representing past vegetation (Kershaw, 1971; Haberle, 2005; unpublished data): Q-1 = Dry sclerophyll woodland: E-2a = Wet sclerophyll woodland (>* Eucalyptus *and grass) with marginal rainforest; Q-2 and E-2b = Wet sclerophyll woodland (>* Casuarina*) with marginal rainforest; Q-3 and E-3 = Lower montane rainforest dominated by Cunoniaceae and Urticaceae/Moraceae; Q-4 and E-4 = Sub-montane rainforest dominated by Elaeocarpaceae; Q-5 and E-5 = degraded sub-montane rainforest with European introductions.* ***H****) Fire event reconstruction from Euramoo (left) and Quincan (right) based on raw charcoal accumulation rate (black plots) over interpolated 7-a intervals with the background signal (Lowess smoothing, gray line) and global threshold (mean Gaussian model, thin red lines). Also shown are the detected peak fire events (red +), simulated fire frequency (orange line) over 1 ka intervals (CharAnalysis, © Philip Higuera, see Higuera et al. 2009), synchronous peak fire events (red boxes), Northern Hemisphere multi-centennial paleoclimate events (gray shaded bars; Bond et al., 2001) and the Antarctic Cold Reversal (ACR; blue shading; Blunier et al., 1997). For interpretation of possible drivers, regional climate records are shown for comparison including* ***I****) total number of strong El Niño events per century interpreted from flood deposits in Laguna Pallcacocha, Ecuador (orange bars; Moy et al., 2002),* ***J****) Past precipitation in China from the Dongge Cave speleothem $\delta^{18}O$ record (purple line; Wang et al., 2005), and* ***K****) Radiocarbon dates associated with archaeological sites in the Wet Tropics region (number of* [14]*C dates/250-a windows) from Cosgrove et al., 2007).*

long-term changes in rainforest communities, which may take hundreds of years to recover, or result in a rapid transition to an alternative stable state (Warman and Moles, 2009). Pollen records from Lake Euramoo (718 m asl, 17°09'30"S, 145°37'46"E) and Lynch's Crater (760 m asl, 17°21'56"S, 145°41'10"E) suggest that shifts from rainforest to sclerophyll and vice versa occurred in only a few centuries as exemplified by major shifts between dominance of sclerophyll to rainforest vegetation approximately 8 cal ka BP, 38 cal ka BP, 132 ka and 222 ka; each shift is accompanied by increased charcoal just prior to rainforest dominance (Haberle, 2005; Kershaw et al., 2007).

Two decadal charcoal records from Lake Euramoo and Quincan Crater (16 km to the southwest of Lake Euramoo at 790 m asl, 17°18'07"S, 145°34'53"E), provide a better understanding of fire's on the Atherton Tablelands. Charcoal particle concentration per unit volume was determined following methods of Whitlock and Larson (2001). The size fraction of charcoal analyzed here was of sufficient size to provide an indicator of local burning (assumed to be within ~200 m of the sites). This is in contrast to microscopic charcoal particles counted on pollen slides that may be derived from many kilometers from the sampling site, and thus a good indicator for regional fire activity.

The Lake Euramoo record shows that past fire-event frequencies in rainforest environments fluctuated between 2-5 events per 1 ka (Fig. 2). Macroscopic charcoal preservation was poor in glacial clayey sediments and statistically reliable charcoal concentrations only occurred after 15 cal ka BP at Lake Euramoo and 10 cal ka BP at Quincan Crater. Micro-charcoal was preserved and in much higher concentration during the glacial period compared to the Holocene, perhaps reflecting continued burning of low plant biomass (open sclerophyll woodland dominated by *Casuarina* and *Eucalyptus* with a grass understorey). Peak fire-event frequency at ca. 8 cal ka BP was associated with a rapid transition from sclerophyll to rainforest. Increasing plant biomass produced greater quantities of charcoal as rainforest species invaded *Eucalyptus* (particularly *E. intermedia* comp.) woodland and thus high fire-event frequencies, typical of the fire prone wet sclerophyll forests of today, occurred. Despite rising fire-event frequencies in the late Holocene (from 2 to 5 events per 1 ka), the biodiversity of rainforest at Lake Euramoo has remained relatively stable for the last 8 ka.

Fire Frequency Change

What are the drivers for changes in fire-event frequency in the wet tropics of northern Australia? The new core from Quincan Crater (Fig. 2) shows the post-glacial rapid expansion of rainforest approximately 1.5 ka later, at 7 cal ka BP (Kershaw, 1971 and unpublished data) than at Lake Euramoo (Haberle, 2005). This difference represents a rate of rainforest expansion of about 3 m/a, which is three times greater than that recorded in modern rainforest expansion surveys under conditions of reduced burning and increased atmospheric CO_2 (~1 m/a; Adam, 1992). The delayed nature of the transition from a mosaic of sclerophyll and rainforest to rainforest dominance at Lake Euramoo (15-8.7 cal ka BP) compared with Quincan Crater (~7.2-6.8 cal ka BP) may relate to the proximity of Lake Euramoo to glacial rainforest refugia and the relatively rapid spread of rainforest eastward across the Atherton Tableland after 8.7 cal ka BP.

Low fire-event frequencies characterize the mid-Holocene period when warm

temperate rainforest covered the region. A combination of low inter-annual climate variability (ENSO-related), declining strength of the Asian monsoon, and low intensity of Aboriginal occupation in the rainforests likely caused low charcoal quantities and fire-event frequencies. It was not until around 4 cal ka BP that charcoal quantities and fire-event frequencies rose across the region, peaking in the last 2 ka. Holocene El Niño activity has been highest in the last 2 ka and may have been a significant cause of drought and greater potential fire ignition over this time. This period also coincides with evidence for increased Aboriginal site occupation and the adoption of more complex food-extraction strategies and intensive use of rainforest resources (Turney and Hobbs, 2006; Cosgrove et al., 2007).

Concluding remarks

The comparison of charcoal records with climate and human impact proxies in the Wet Tropics of Australia reveals the complexity inherent in fire dynamics through time. There are corresponding peaks in fire-event frequencies and millennial-scale climate changes in the North Atlantic (Bond et al., 2001; Turney et al., 2005) and regional climate drivers (El Niño activity) that may have influenced fire ignition in the wet tropic rainforests of Australia through the Holocene. However, no single driver can explain past fire patterns and many events may be the result of multiple drivers (climate-vegetation-people) interacting on differing temporal and spatial scales. It also remains unclear whether or not Northern Hemisphere millennial-scale climate changes had an impact on the Australian tropics (Turney et al., 2004). In Australia, current severe drought and plant mortality are increasing fire hazard and raising concerns about the trajectory of post-fire vegetation change and future fire regimes (Lynch et al., 2007; Bowman et al., 2009). Understanding the interaction between multiple drivers of fire and fire-events from the past will be critical information for managing fire regimes in Australia in the future.

Data

The Lake Euramoo and Quincan Crater data are available upon request from the first author. Data shown in Figure 1 are from the Indo-Pacific Pollen Database http://palaeoworks.anu.edu.au/databases.html and the Global Palaeofire Database http://www.bridge.bris.ac.uk/projects/ QUEST_IGBP_Global_Palaeofire_WG/index.html).

Acknowledgements

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References

Cosgrove, R., Field, J. and Ferrier, A., 2007: The archaeology of Australia's tropical rainforests, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **251**: 150-173.

Haberle, S.G., 2005: A 23,000-yr pollen record from Lake Euramoo, Wet Tropics of NE Queensland, Australia, *Quaternary Research*, **64**: 343-356.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S. and Brown, T.A., 2009: Vegetation mediated the impacts of postglacial climatic change on fire regimes in the south-central Brooks Range, Alaska, *Ecological Monographs*, **79**: 201-219.

Kershaw, A.P., Bretherton, S.C. and van der Kaars, S., 2007: A complete pollen record of the last 230 ka from Lynch's Crater, north-eastern Australia, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **251**: 23-45.

Lynch, A.H., Beringer, J., Kershaw, A.P., Marshall, A., Mooney, S., Tapper, N., Turney, C. and Van Der Kaars, S., 2007: Using the paleorecord to evaluate climate and fire interactions in Australia, *Annual Review of Earth and Planetary Sciences*, **35**: 215–39.

For full references please consult:

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Humans and fire: Consequences of anthropogenic burning during the past 2 ka

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Holocene sedimentary charcoal records document human influences on biomass burning around the world, with global-scale consequences in the past two centuries.

A global network of sedimentary charcoal records (Fig. 1a; Power et al., 2008) has shown that trends in biomass burning that were long controlled by climate (including CO_2 changes) have now come to be driven primarily by people (Fig. 2a-d; Marlon et al., 2008). Three case studies from western North America, New Zealand and Europe demonstrate the spatiotemporal variability of human impacts on fire regimes and vegetation and illustrate why local impacts do not aggregate to distinct broad-scale signals until the very recent past.

Western North America

In the Pacific Northwest, paleoecological records illustrate a wide range of climatic and human influences on fire regimes during the past 2 ka. For example, at Battle Ground Lake (conifer forest; Washington State), fire occurrence tracked climatic changes prior to Euro-American settlement (ca. AD 1830), most notably showing high fire activity during the Medieval Climate Anomaly (MCA; ca. AD 950-1250) and almost no fires during the Little Ice Age (LIA; ca. AD 1450-1850) (Fig. 1b; Walsh et al., 2008)—a pattern characteristic of many other sites in western North America (Marlon et al., 2006). These shifts seemingly occurred in the absence of major vegetation changes, suggesting little association with Native American land-use (fire was used to create more open and resource-rich landscapes). Following Euro-American settlement, fire occurrence was more clearly influenced by human activity, with a large-magnitude fire event in AD 1902 and little to no fire in the last 100 years. In contrast, fire activity at Lake Oswego (oak woodland; Oregon) was likely the result of anthropogenic burning modulated by regional climate variability. Fire activity generally increased ca. AD 0-1000 despite cooling summer temperatures, suggesting land-use intensification by Native Americans (Fig. 1c) (Walsh et al., in press). By approximately AD 1000, higher fire activity, possibly aided by warmer drier conditions during the MCA, forced a sharp decline in forest cover near the site and an increase in grasses and other disturbance-tolerant taxa. Frequent burning continued until the onset of the LIA (ca. AD 1450), at which time fires decreased and forest cover subsequently increased. The timing of this regime shift could be associated with the collapse of Native American populations following Euro-American contact (Boyd, 1999) or reduced ignitions and fire-conducive weather during the LIA. Little to no fire activity has occurred at Lake Oswego in the last 300 years. Thus, the extent of human impacts on fire regimes in the Pacific Northwest appears closely linked to the spatial configuration of vegetation

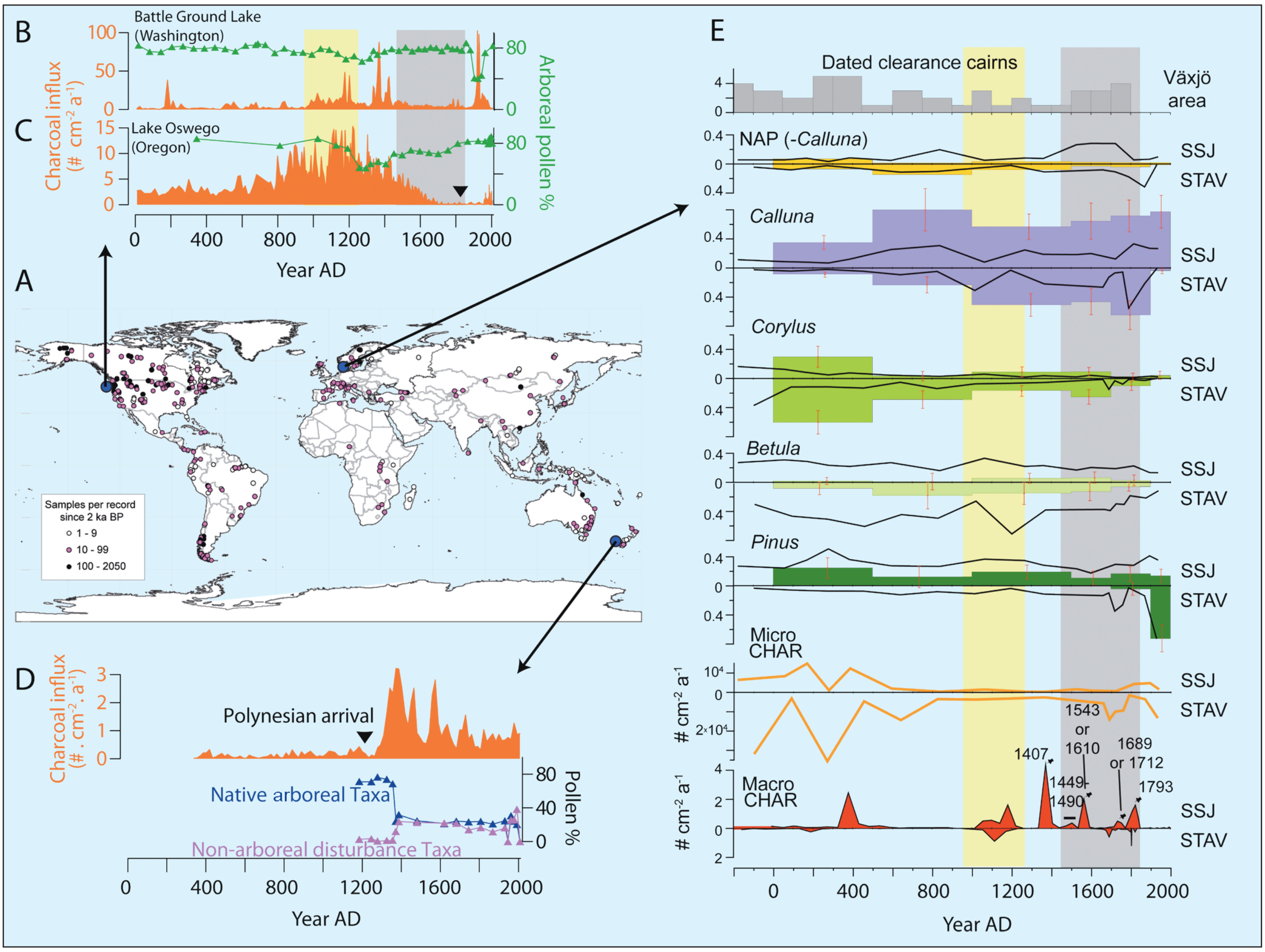

*Figure 1: **A**) Sites of paleofire reconstructions in the Global Charcoal Database (Marlon et al., 2008; Power et al., 2008); Macrocharcoal influx (CHAR; orange) and changes in % arboreal pollen (green) from (**B**) Battle Ground Lake and (**C**) Lake Oswego. Black triangle indicates timing of Euro-American arrival (~AD 1830), yellow shading on all plots indicates timing of Medieval Climate Anomaly, gray shading indicates timing of the Little Ice Age; **D**) Diamond Lake (New Zealand) CHAR (orange) and changes in pollen % of arboreal taxa (blue), primarily beech and podocarps, and non arboreal pollen (NAP) taxa (violet), primarily grasses and bracken fern associated with Polynesian arrival and increased CHAR during the initial burning period ca. 1300-1600 AD; **E**) records of CHAR (red) and microscopic charcoal (orange; counted in pollen slides) from Stavsåkra (STAV) and Storasjö (SSJ), and model-derived estimates of local abundance (in proportion to cover of vegetation) of main tree taxa (3 x green) and NAP (purple and yellow) within the relevant source area of pollen (RSAP; Sugita, 1994), 750-1500 m radius in the case of these two sites during the last 2 ka. The model used was the LOVE (LOcal Vegetation Estimates) model (Sugita, 2007a; 2007b), which estimates plant cover within the RSAP of small basins (lakes or bogs) from pollen records. Estimates were calculated for 500-a intervals except in the recent time, AD 1500-1700, AD 1700-1900, and AD 1900-2000 and are overlain by pollen % (thin black lines). A tentative correlation between the CHAR peaks and fire events dated by dendrochronological analysis of fire scars at Storasjö (Wäglind, 2004) is proposed. The top gray plot shows frequency of dated clearing cairns per 100-a interval in the Växjö region (Skoglund, 2005), documenting extensive forest clearing by burning.*

communities and human land-use intensity within those ecosystems.

New Zealand

In contrast to Australia where natural fires are common and the influence of humans on patterns of fire is complex (Lynch et al., 2007), New Zealand presents a unique example where deliberate and repeated burning by a relatively small human population overwhelmed strong climatic constraints limiting fire (occurring only once every 1-2 millennia; Ogden et al., 1998) and enacted large-scale deforestation of closed-canopy forests. Paleoecological data from New Zealand indicate widespread deforestation of native forests soon after the first known presence of Polynesians (Māori), ca. AD 1280 (McGlone and Wilmshurst, 1999; Wilmshurst et al., 2008). Charcoal and pollen data from lake-sediment cores throughout central South Island show a prominent period of initial burning that consists of one to three fire episodes (i.e., several fire events occurring within a few years) within 100 years (Fig. 1d; McWethy et al., 2009). This initial burning period is associated with a major decline in forest taxa, increased erosion, and elevated levels of grass and bracken (ferns). By the time Europeans arrived in the 18th century, over 40% of the South Island was deforested and native closed-canopy forests were replaced by open vegetation (Fig. 1e; McGlone, 1983; Fig. 2e, Mark and McLennan, 2005). Contrary to examples of deforestation linked to intensive human population pressure (Heckenberger et al., 2007), populations on South Island were estimated to be small, with founding numbers at approximately 100-200 individuals (Murray-McIntosh et al., 1998). Paleoclimatic data from tree-ring and speleothem archives suggest that abrupt deforestation occurred in the absence of climate change (Lorrey et al., 2008). Hence, the transformation of large landscapes was apparently achieved by the concerted burning efforts of small transient populations acting largely as hunter-gatherers.

Europe and southern Sweden

Many paleoecological studies have demonstrated anthropogenic influences on fire regimes of central and southern Europe since Neolithic time (e.g., Tinner et al., 2005, 2009; Vannière et al., 2008; Carcaillet et al., 2009). Climate impacts on fire regimes were prominent during the early and mid Holocene but became increasingly masked by the human use of fire during the late Holocene (e.g., Vannière et al., 2008; Kaltenrieder et al., 2010). Conversely, in parts of southern Europe (e.g., Northern Italy), widespread arboriculture (e.g.,

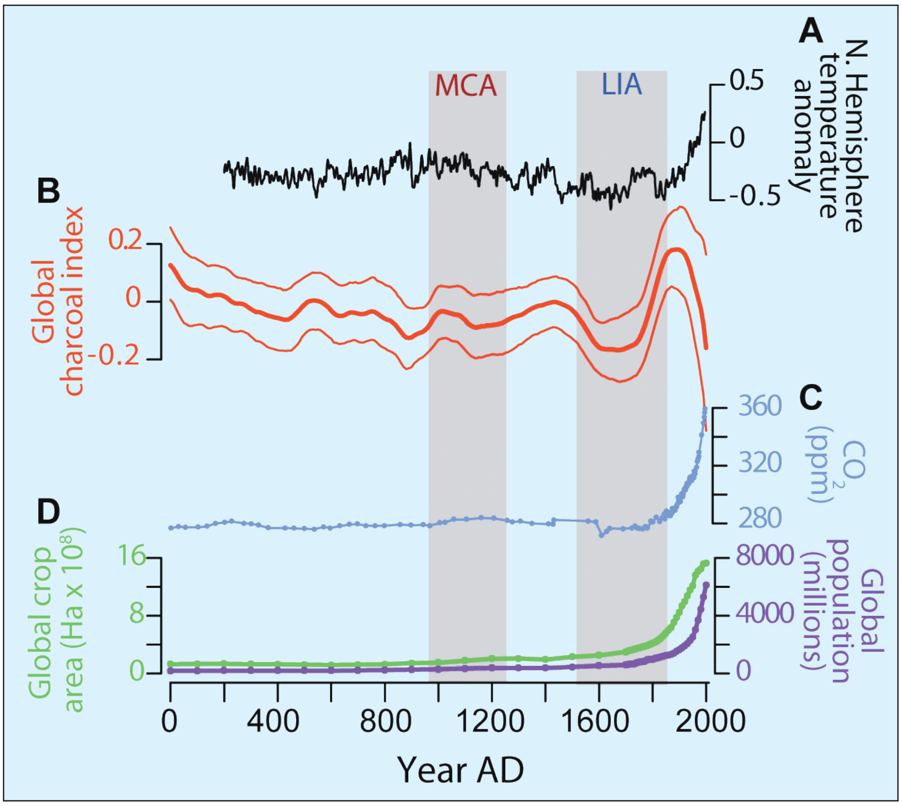

*Figure 2: Reconstructions of (**A**) Northern Hemisphere temperature anomalies (black; Jones and Mann, 2004), (**B**) global biomass burning with confidence intervals based on bootstrap resampling by site (red; Marlon et al., 2008), (**C**) atmospheric CO_2 concentration (blue; Meure et al., 2006), which was likely responsible for the peak in fire prior to 1850, and (**D**) global population (purple) and agricultural land cover (green) from the HYDE 3.1 database (Klein Goldewijk et al., 2010). The Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) are represented by the gray bars. This figure shows that global biomass burning and Northern Hemisphere temperatures both generally declined during the past 2 ka despite increasing human populations; human influences on global biomass burning are readily apparent during the past two centuries when agriculture, grazing and other human influences expanded rapidly.*

the cultivation/management of *Castanea sativa*) required fire suppression during the past 2 ka (Conedera et al., 2004). The strong decline of land use in marginal areas of southern Europe has caused an expansion of shrublands and forests and increasing fires after the 1950s (Moreno et al., 1998) mirrored in sedimentary charcoal content (e.g., Tinner et al., 1998). In northwestern Europe, climate may have acted as a primary control on fire activity during the early and mid Holocene (Carcaillet et al., 2007; Greisman and Gaillard, 2009), whereas human impacts were as (or more) important during the late Holocene (e.g., Lindbladh et al., 2003; Olsson et al., 2010). Two Holocene charcoal records from bogs (Storasjö and Stavsåkra) in southern Sweden indicate that fire activity was mainly related to human land use during the past 2 ka (Fig. 1e; Greisman and Gaillard, 2009; Olsson et al., 2010; Olsson and Lemdahl, 2009; 2010). Species composition of the forest was also an important influence; e.g., the continuous presence of pine at Storasjö explains why there was more fire during the mid-Holocene than at Stavsåkra where pine was rare. Pine was the dominant tree at Storasjö from AD 500, while it was absent or rare at Stavsåkra until planted in the 20th century (Fig. 1e). High macroscopic charcoal values ca. AD 1000-1200 may be related to the MCA. The data also indicate that the area was characterized by grazed *Calluna* (heather) heaths that were maintained by fire from 750 BC until the 18th century (Fig. 1e; Olsson et al., 2010; Olsson and Lemdahl, 2009, 2010). Dates from clearance cairns (Mounds of stones usually created by clearance of stones from fields for agricultural purposes) in the Stavsåkra region from 2000 BC to AD 1800 (Fig. 1e) document extensive forest clearing by burning (Skoglund, 2005). At Storasjö, macroscopic charcoal (Fig. 1e) correlates with dated fire scars on pine attributed to human-caused burning during the last 0.6 ka (Wäglind, 2004). The change from very frequent to no fires in the 18th-19th centuries in Sweden coincides with fire suppression (e.g., Niklasson et al., 2002; Lindbladh et al., 2003). Hence, human activities appear to have strongly shaped patterns of fire in parts of southern Sweden and northwestern Europe during the late Holocene.

Conclusions

The case studies here illustrate how the timing and consequences of anthropogenic interventions in natural fire regimes vary greatly across space and depend heavily on local ecological context; they also demonstrate why the cumulative global effects of anthropogenic impacts on fire regimes have been difficult to detect until the past two centuries (Fig. 2). Increasing efforts to synthesize existing paleoecological records (Power et al., 2009), and combine multiproxy evidence of paleoenvironmental changes with archeological data and modeling promise valuable advancements in our understanding of coupled human-natural systems in the past.

Data

All charcoal data discussed herein are available from the Global Charcoal Database (http://www.ncdc.noaa.gov/paleo/impd/gcd.html)

Acknowledgements

We thank the Global Palaeofire Working Group (GPWG) for their contributions to the Global Charcoal Database – this research would not be possible without their efforts.

References

Marlon, J.R., Bartlein, P., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J. and Prentice, C.I., 2008: Climate and human influences on global biomass burning over the past two millennia, *Nature Geoscience*, **1**: 697-701.

McWethy, D.B., Whitlock, C., Wilmshurst, J.M., McGlone, M.S., and Li, X., 2009: Rapid deforestation of South Island, New Zealand by early Polynesian fires, *The Holocene*, **19**: 883-897.

Olsson, F., Gaillard, M.-J., Lemdahl, G. Greisman, A., Lanos, P., Marguerie, D., Marcoux, N, Skoglund, P. and Wäglind, J., 2010: A continuous record of fire covering the last 10,500 calendar years from southern Sweden — The role of climate and human activities, *Palaeogeography, Palaeoclimatology, Palaeoecology*, **291**: 128-141.

Walsh, M.K., Whitlock, C. and Bartlein, P.J., in press: 1200 years of fire and vegetation history in the Willamette Valley, Oregon and Washington, reconstructed using high-resolution macroscopic charcoal and pollen analysis, *Palaeogeography, Palaeoclimatology, Palaeoecology*.

Walsh, M.K., Whitlock, C. and Bartlein, P.J., 2008: A 14,300-year-long record of fire-vegetation-climate linkages at Battle Ground Lake, southwestern Washington, *Quaternary Research*, **70**: 251-264.

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Pyrogeography: Understanding the ecological niche of fire

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With insights into the controls of past, current and potential future fire patterns, there is great potential to integrate a modern understanding of pyrogeography with paleoecological studies.

Given the impact of fire on ecosystem processes, human well-being and global carbon cycling, there is growing interest in studying fire-environment interactions across various scales of space and time. To this end, the concept of pyrogeography—the study of the distribution of fire—has been put forward as a general framework for evaluating the environmental controls of fire (Krawchuk et al., 2009; Parisien and Moritz, 2009). Pyrogeography, which is inherently spatial, attempts to quantify observed variability in fire activity as a function of the complex interplay of environmental factors. As such, it can be likened to ecological niche concepts that have been applied to species and biological communities. Like biota, fire appears to have an optimal response to environmental gradients and, conversely, tends to avoid its extremes (e.g., deserts, rainforests, tundra).

Environmental factors that generate different fire regimes across the world fall into three basic categories: consumable resources (vegetation), atmospheric (weather) conditions conducive to combustion, and ignitions (Fig. 1). One method of pyrogeographical research is through spatial distribution modeling, which incorporates mapped fire and biophysical data into a statistical framework. Key strengths of these models include an ability to quantify the contribution of various environmental factors controlling fire's distribution and the use of parameters from statistical models to produce spatially explicit fire activity expected in new regions or under new conditions.

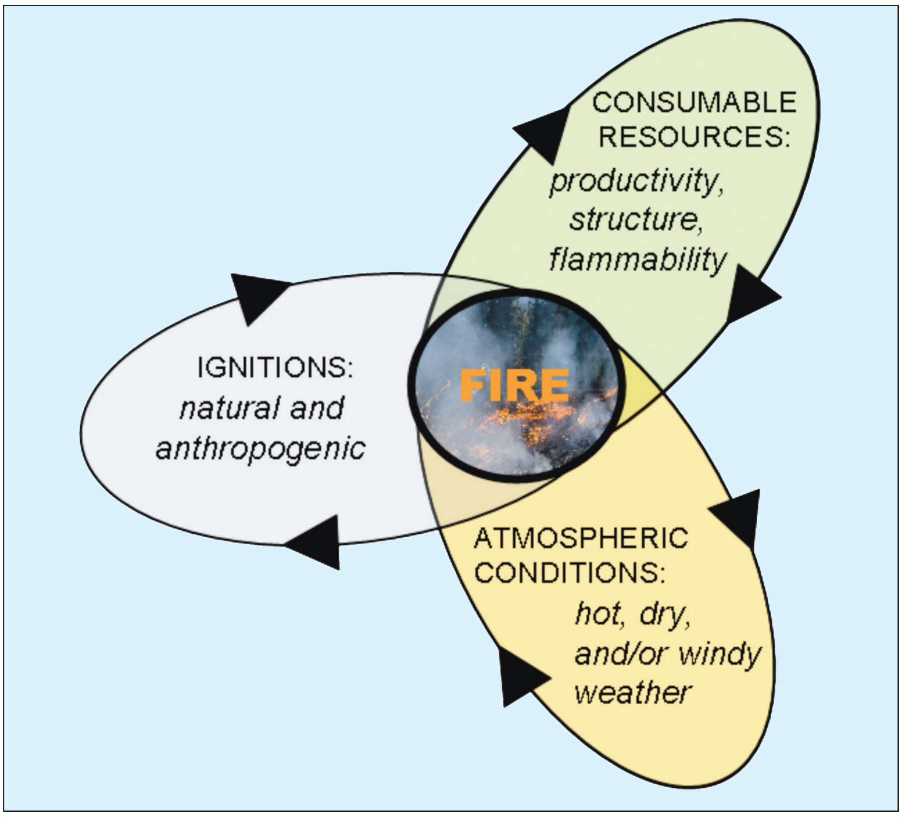

Figure 1: The pyrogeography framework includes vegetation resources to consume, atmospheric conditions, and ignition agents. Each of these components is spatially and temporally variable, as illustrated by arrows, and it is their coincidence that results in fire activity. Variation in their coincidence generates different fire regime types (e.g., frequent low-intensity surface fire versus infrequent high-intensity crown fire).

Methodology

Spatial distribution models describing empirical fire-environment relationships can take many forms and may be estimated using a number of statistical methods. The approach takes advantage of an ever-growing collection of spatial data (e.g., Westerling and Bryant, 2008; Krawchuk and Moritz, 2009; Krawchuk et al., 2009; Parisien and Moritz, 2009). Mapped fire observations (the dependent variable; Fig. 2a) are used in conjunction with spatial environmental gradients (independent variables) to produce statistical models of fire probability (Fig. 2b). Data used to build models and assess hypotheses concerning the distribution of fire can come from many sources, and recent work has shown the importance of variables such as primary productivity, annual precipitation, temperatures in the warmest and/or wettest months of the year, high winds, drought, and monthly soil moisture. The resulting models produce mapped surfaces, as in Figure 2c.

Applications

Fire distribution models have a host of applications. In climate change science, they have been used to evaluate the current and projected future likelihood of fire at various spatial extents, using projected climate surfaces from global circulation models (e.g., Krawchuk et al., 2009; Westerling and Bryant, 2008). Although the interpretation of future estimates should be evaluated carefully, salient trends may highlight the potential for drastic changes in fire regimes. For example, there is reason to believe that the Tibetan Plateau, a currently fairly cool and moist area, may experience substantial changes in fire likelihood and potentially create a cascade of change (Krawchuk et al., 2009). This is even more worrisome when considering the rapid increase of human access to the area, as a result of infrastructure expansion and population pressures. Accordingly, measurements of uncertainty as a function of differences in projections from these global circulation models (Moritz et al., in review), alongside statistical model uncertainty, are important caveats with such modeling applications.

Fire distribution modeling is also relevant to land management. The technique is currently being used to evaluate large-scale land management practices, such as the placement of fuel treatments in the western United States, due to its ability to provide spatially explicit estimates of fire probability. Estimates of current fire probability also offer an opportunity to asses where fire has likely been "extirpated" to

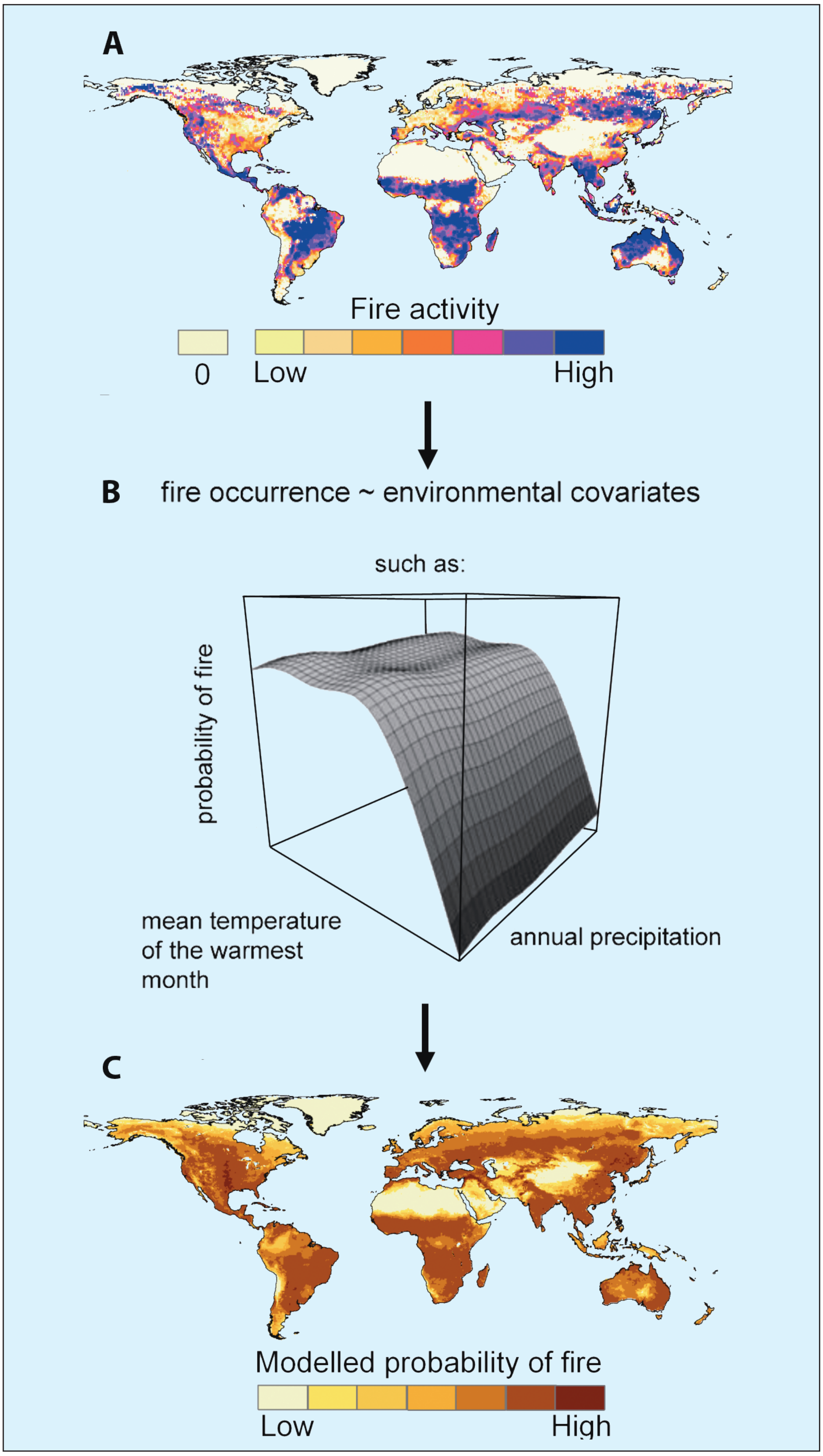

*Figure 2: **A**) Cumulative global fire activity detected by ATSR sensors onboard Earth-orbiting satellites between 1996 and 2006; **B**) Fire activity is translated to occurrence, then a distribution model relating fire to a suite of environmental covariates representing resources, conditions and ignitions necessary for fire); **C**) The model is then used to produce a mapped surface demonstrating the modeled probability of fire. Figure based on Krawchuk et al., 2009.*

inform on-going natural restoration efforts. For example, in the northern Central Valley of California, where fire has been excluded for well over a century because of extensive conversion to agriculture, models suggest that fire may have been fairly frequent given the biophysical space of the region (Parisien and Moritz, 2009).

A key advantage of spatial distribution modeling techniques is their ability to extract relevant information from scarce, incomplete, or geographically biased observations, a situation that fire modelers often confront. Once a certain degree of model reliability has been ascertained, these models can then be useful to project fire likelihood to data-deficient areas. For example, in many parts of the world, we have remotely sensed data of recent fire activity due to the growing datasets collected by satellite but we may know little or nothing of longer term fire history (e.g., the last 200+ years). Krawchuk and Moritz (2009) mapped potential fire regimes in China based on fire-climate relationships and analogues in climate with the United States, a region for which we have a more thorough understanding of fire over recent centuries. These models provide initial estimates of potential fire regimes, yet further studies are needed to help validate these predictions.

Potential integration with paleoecology

Paleoecological studies based on numerous environmental proxies are providing new insights into relationships between climate and/or dominant vegetation and fire activity over regional and global extents (e.g., Clark, 1990; Millspaugh et al., 2000; Power et al., 2008; Vannière et al., 2008; Conedera et al., 2009; Genries et al., 2009; Higuera et al., 2009; Marlon et al., 2009). Although most of these studies are spatially constrained, they provide empirical records of fire-climate dynamics over longer time horizons than is available through instrumental data records. In a complementary way, the fire distribution models described here provide an excellent opportunity to identify complex relationships between fire and its environmental controls in a spatially complete and coherent manner. Understanding the interplay of controls over recent historical fire activity could thus aid in interpreting fire-environment relationships in paleorecords. An attractive idea for future synthesis of paleofire studies with the fire distribution modeling framework would also be to use back-casted climate data to provide spatial estimates of fire activity under past climatic conditions. Of course, scale issues as well as assumptions about the role of humans (e.g. a source of ignitions) and the couplings between climate and vegetation would need to be carefully incorporated in such an exercise, but the potential for new insights from such studies appears high.

Future outlook

Environmental changes will cause direct alterations to both vegetation and fire likelihood; however, these two factors are not independent of each other, as changes in one will likely—and sometimes drastically—affect the other. Distribution models of biota could thus be combined with those of fire to paint a clearer picture of fire-climate-vegetation dynamics, which could shed more light on complex feedback mechanisms (Higuera et al., 2009). It could be possible with this approach to map the potential "invasiveness"

of fire in areas that are undergoing substantial land-use changes or are subject to widespread biological invasions (e.g., cheatgrass in the Great Basin of the United States).

Currently, the spatial distribution models of fire activity described here have primarily been used to explore the occurrence of fires, yet other fire regime elements will be important to include in future work. Fire seasonality, intensity, area burned, and frequency are all elements of a fire regime, and all of these characteristics could be expected to shift under past or future climates. Overall, the pyrogeography framework provides a foundation for quantifying the causes and effects of fire regimes, which is critical to understanding fire-related ecosystem function, carbon dynamics and atmospheric chemistry.

References

Higuera, P., Brubaker, L., Anderson, P., Hu F. and Brown, T., 2009: Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska, *Ecological Monographs*, **79**: 201–219.

Krawchuk, M.A. and Moritz, M.A., 2009: Fire regimes of China: inference from statistical comparison with the United States, *Global Ecology and Biogeography*, **18**: 626–639.

Krawchuk, M.A., Moritz, M.A., Parisien, M.-A., Van Dorn, J. and Hayhoe, K., 2009: Global pyrogeography: the current and future distribution of wildfire, *PLoS ONE*, **4**: e5102.

Parisien, M.-A. and Moritz, M.A., 2009: Environmental controls on the distribution of wildfire at multiple spatial scales, *Ecological Monographs*, **79**: 127–154.

Westerling, A. and Bryant, B., 2008: Climate change and wildfire in California, *Climatic Change*, **87**: 231–249.

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Emerging proxy evidence for coherent failures of the summer monsoons of Asia during the last millennium

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New high resolution speleothem and tree ring records show evidence for spatially widespread Asian monsoon megadroughts during the last millennium.

No annually recurring weather phenomena on Earth influence the lives of as many people as the regional summer monsoons of Asia. Agricultural output and consequently food security across Asia is largely dependent on the timely arrival and adequate amounts of monsoon rainfall. Groundwater resources are often the only safeguard against monsoon failure and their rapid depletion signifies an increased vulnerability to monsoon deviations (Rodell et al., 2009). To a first order, the poleward march of the inter-tropical convergence zone during the boreal summer leads to a large amount of rainfall across the "Monsoon Asia". However, in years when the monsoon circulation and precipitation amount departs from its "normal" spatiotemporal patterns, it can have significant adverse societal impacts. Our current understanding of the variability of the regional summer monsoons of Asia is primarily gleaned from the instrumental record, which is too short to confidently assess the potential end-member hydroclimate scenarios of the monsoon system. Some of the longest instrumental records (starting ca. 1850s AD) from India show that, barring a few sporadic occurrences of monsoon failure (defined by the Indian Meteorology Department as JJAS rainfall >20% below the mean), year-to-year variations in the Indian monsoon rainfall have remained generally within 10% of its long-term climatological mean. However, historic documentary evidences from the region point to the occurrence of extended spells of substantially reduced monsoon rainfall before the instrumental record began (Maharatna, 1996).

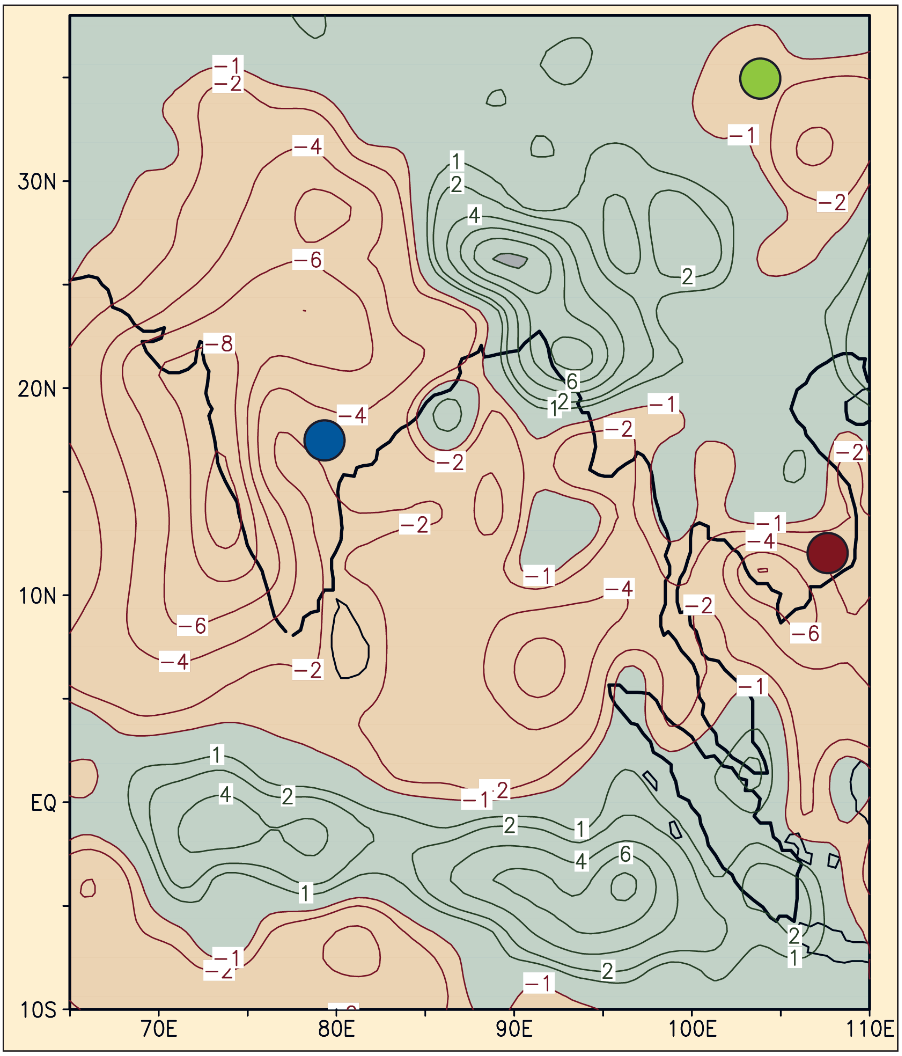

*Figure 1: Map showing locations of sites mentioned in the text and Figure 2; **Green circle** = Wanxiang, **blue circle** = Dandak, **brown circle** = Bidoup Nui Ba National Park. Contours and shading indicate July and August precipitation anomalies (mm/day) with respect to 1971-2000 interval (**red** = drier, **blue** = wetter) during the major monsoon break spells in 2002 and 2004. Rainfall data are from the Climate Prediction Center Merged Analysis of Precipitation.*

The present day water resource infrastructure and the contingency planning in Monsoon Asia, as informed by instrumental observations, does not take into account the possibility of protracted

failures of the monsoon. A longer-term assessment of monsoon variability is crucial to identify the full frequency spectrum of monsoon behavior. This should be developed from a spatially expansive network of precipitation, circulation, and drought sensitive proxy records, spanning the last several centuries to millennia, at resolutions comparable to the instrumental record. In this text, we highlight how an emerging network of proxy records from Asia is unraveling previously unknown aspects of monsoon behavior during the last millennium. Manifested in these proxy records is an evolving picture of monsoon's natural variability, including the repeated tendency to get locked in extended dry and wet phases.

Recent proxy records of Asian summer monsoons

Speleothem-based oxygen isotopic ($\delta^{18}O$) records have previously yielded a remarkably coherent depiction of how the monsoon systems of Asia have varied on orbital and millennial timescales (Wang et al., 2008). In monsoonal regions, the empirical inverse relationship between the $\delta^{18}O$ of precipitation and precipitation amount (the amount effect) forms the basis of these reconstructions. This approach however, has not been rigorously applied to the reconstruction of monsoon variability over the last 1-2 millennia. This is due in part, to the notion that the amplitude of late Holocene climate-related $\delta^{18}O$ change in the speleothem would be too small to be discernible from the "noise" produced from local karst and non-climate related processes.

A sub-annually resolved speleothem $\delta^{18}O$ record from Dandak Cave in central India serves as a test of this approach (Fig. 1). This site, by virtue of its location, is characterized by a strong amount effect and the local monsoon precipitation is strongly correlated with the area-averaged precipitation over much of India (Sinha et al., 2007). The near millennial-length $\delta^{18}O$ record (AD 600 and 1500) reveals prominent multi-decadal scale variability in the Indian summer monsoon precipitation with a ~90 year period comparable to that inferred from the instrumental record (Berkelhammer et al., 2010). The $\delta^{18}O$ record also provides evidence for years to decades-long intervals of substantially reduced monsoon rainfall, such as during portions of the 7th, 9th, 11th, 13th, 14th and early 15th centuries (Fig. 2). The observed amount effect relationship for this region suggests that some of these droughts were marked by a reduction in monsoon rainfall amount (relative to the 20th century climatological mean) of up to 20 to 30 %, and at least one drought during the latter half of the 14th century may have lasted as long as 30 years (Sinha et al., 2007). These inferred monsoon failures, most of which are independently corroborated with historical accounts of famine in India, have no analog in the instrumental record.

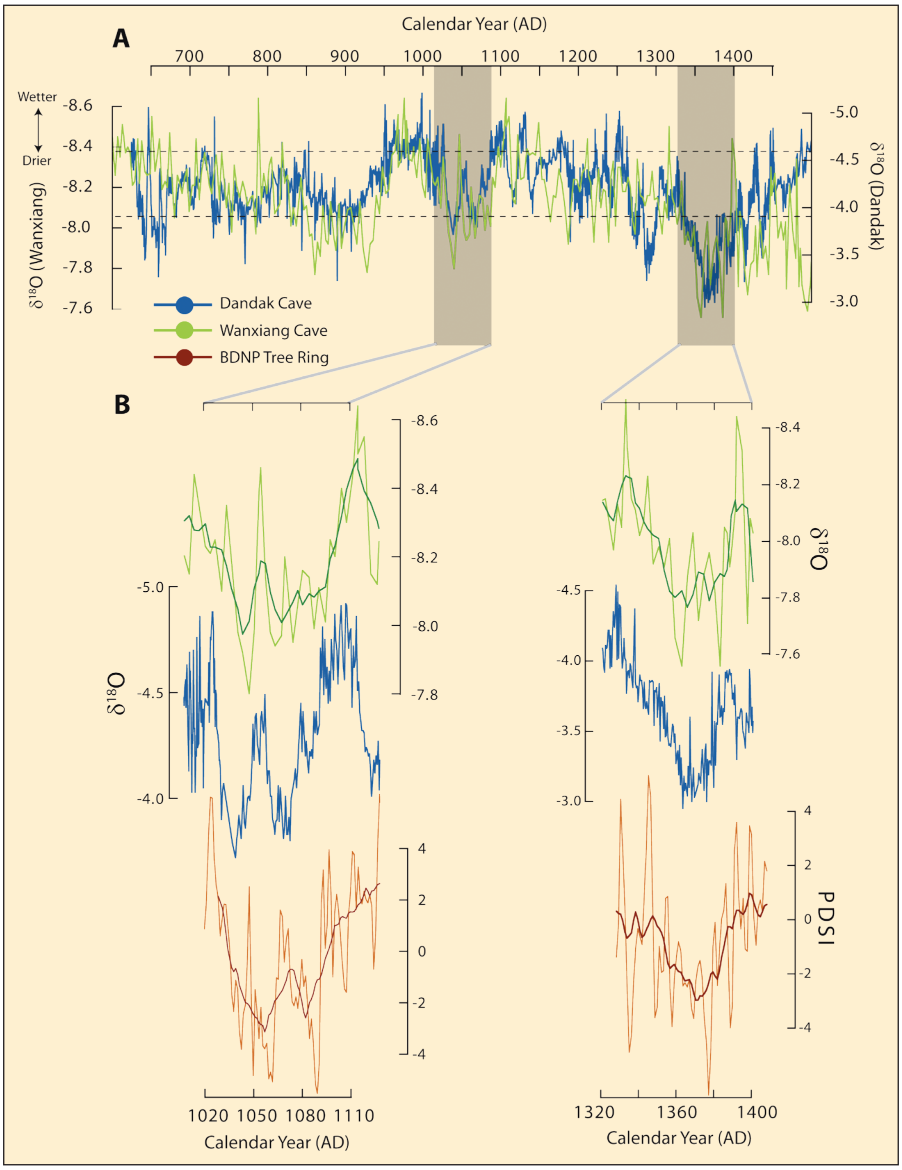

*Figure 2: Recent proxy records from monsoon Asia. **A**) Comparison of Dandak Cave $\delta^{18}O$ record with the overlapping portion of the Wanxiang Cave $\delta^{18}O$ record. The range of modern $\delta^{18}O$ values of calcite in Dandak Cave is shown by two dashed lines. The $\delta^{18}O$ values higher than -3.8 ‰ delineate intervals of inferred drought and imply more than 10% decrease in monsoon months (JJAS) rainfall. Gray bars indicate two extended periods of inferred drought. **B**) Comparison between the speleothem $\delta^{18}O$ records and Vietnam's Bidoup Nui Ba National Park (BDNP) tree-ring Palmer Drought Severity Index (PDSI) (March-May) reconstruction for the two extended intervals of drought. Dark lines show running mean averages.*

A high-resolution speleothem $\delta^{18}O$ record from the Wanxiang Cave in central China (Fig. 1), which reveals broad-scale changes in the East Asian summer monsoon during the past two millennia (Zhang et al., 2008), bears a striking resemblance with the $\delta^{18}O$ record from India (Fig. 2). Together, these two speleothem records provide not only assurance of the timing and magnitude of drought events but also suggest that these extended intervals of weaker monsoon were in fact synchronous across a large region of Asia. This assertion is strongly supported by a new tree ring-width based Palmer Drought Severity Index (PDSI) record from Bidoup Nui Ba National Park (BDNP) in southern Vietnam (Fig. 1; Buckley et al., 2010). This PDSI record, reflecting the SE Asian monsoon variability during the last millennium, is notable because thus far, comprehensive dendroclimatology has rarely been applied in the core monsoon regions of Asia due, in part, to the notion that trees in these regions lack clear annual rings, and also poor understanding of phenology and physiology of the tree species, and large-scale deforestation in the region (Buckley et al., 2007).

The comparison of overlapping portions of the PDSI and speleothem $\delta^{18}O$ records highlights two extended intervals of region-wide weaker monsoon during the 11th and mid 14th/early 15th centuries (Fig. 2). In particular, the latter interval stands out as one marked by significant societal

change across monsoon Asia, which included famines and significant political reorganization within India (Sinha et al., 2007), the collapse of the Yuan dynasty in China (Zhang et al, 2008); and the Khmer civilization of Angkor Wat fame in Cambodia (Buckley et al., 2010). Although the relationship between climate and societal change is complex and not necessarily deterministic, the close temporal association between droughts and widespread societal changes across monsoon Asia at that time strongly suggests that monsoon droughts may have played a major role in shaping these societal changes.

Conclusion

The case for synchronous droughts in recent monsoon reconstructions across widely separated regions is compelling and suggests that the monsoon circulation in Asia can "lock" into a drought-prone mode that may last for years to decades. Understanding the ocean-atmosphere dynamics that trigger such droughts is important in order to anticipate the likelihood of their reoccurrence today. The spatiotemporal patterns of monsoon rainfall over Asia are complex and vary from year to year (Fig. 1). This complexity stems from interactions between rain-bearing synoptic-scale systems, which are propagated from the oceans onto the land, mid-latitude weather systems, ocean-atmosphere dynamics over the Equatorial Indian Ocean, and the Walker circulation in the tropical Pacific. Periodic perturbations in coupled modes of ocean-atmosphere variability, such as the El Niño Southern Oscillation, and/or dynamical processes intrinsic to the monsoon system such as quasi-periodic episodes of intense ("Active") and reduced ("Break") monsoon rainfall, are key processes that are known to orchestrate substantial precipitation anomalies over large parts of Asia. The societal implications of these new findings suggest that the narrow view of the monsoon taken from the instrumental data alone may lull us into a false sense of security. Thus a longer term and a fuller range of monsoon variability, as documented in the recent proxy records, should be urgently incorporated into future drought management and mitigation planning.

References

Berkelhammer, M., Sinha, A., Mudelsee, M., Cheng, H., Edwards, L. and Cannariato, K. G., 2010: Persistent Multidecadal Power in the Indian Summer Monsoon, *Earth and Planetary Science Letters*, **290**: 166–172.

Buckley, B.M., Palakit, K., Duangsathaporn, K., Sanguantham, P. and Prasomsin, P., 2007: Decadal scale droughts over northwestern Thailand over the past 448 years: links to the tropical Pacific and Indian Ocean sectors, *Climate Dynamics*, **29**: 63–71.

Buckley, B.M., Anchukaitis, K.J., Penny, D., Fletcher, R., Cook, E.R., Sano, M., Nam, L.C., Wichienkeeo, A., Minh, T.T. and Hong, T.M., 2010: Climate as a contributing factor in the demise of Angkor, Cambodia, *Proceedings of the National Academy of Science*, doi: 10.1073/pnas.0910827107.

Sinha, A., Cannariato, K.G., Stott, L.D., Cheng, H., Edwards, R.L., Yadava, M.G., Ramesh, R. and Singh, I.B., 2007: A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India, *Geophysical Research Letters*, **34**: L16707.

Zhang et al., 2008: A test of climate, sun, and culture relationships from an 1810-year Chinese cave record, *Science*, **322**: 940–942.

For full references please consult:
http://www.pages-igbp.org/products/newsletters/ref2010_2.html

An emerging paradigm: Process-based climate reconstructions

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Emerging techniques and concepts offer ways to improve the use of process knowledge in reconstructions of past climate, and to make more comprehensive estimates of the uncertainties associated with them.

The last few decades have seen extraordinary progress in the reconstruction of past climates using natural and human archives (Jones et al., 2009; Wanner et al., 2008). At the same time, our understanding of the climate system has deepened, strongly motivating development of new methods of integrating observations and model analyses. To continue this progress, it would be desirable to use all the climate information we can extract from natural archives. Frequently, only those aspects of the records are used that lend themselves to linear transformation into estimates of conventional climate quantities, such as mean seasonal temperatures or seasonal totals of precipitation. However, one can readily point to robust climatic information in natural archives that does not fit conveniently into a linear regression model (e.g., see Kelly et al., 1989). A way forward is offered by increased use of process-based forward models that capture the main features of the environmental control of the formation of natural archives (Fig. 1).

Focus on process

Each proxy archive represents a record of climate that was generated through physical, chemical and/or biological processes. Reconstructions of climate represent attempts to turn this around in order to get back to the climate information. Statistical solutions (most often regression) are used to identify simple, usually linear, relationships over a period covered by both proxy and instrumental climate records. This approach therefore reduces the problem to identifying a single climatic driver of the local proxy record stored in the natural archive, a driver that is assumed to be dominant at all times.

Two recent articles (Guiot et al., 2009; Hughes and Ammann, 2009) discuss converging trends in the use of modern understanding of proxy-forming processes. They point to important emerging tools and capabilities in exploring climates of the past that could help avoid the limitations of current empirical-statistical methods.

Guiot et al. (2009) focused on the Holocene and the Last Glacial Maximum, periods spanning major shifts in both forcing and the state of the climate system. Emphasizing paleovegetation records, Guiot et al. (2000) proposed a move from empirical-statistical models to the inversion of forward models of the formation of such natural archives (Fig. 1). For sediment data with relatively low accumulation rates, the current statistical solution is to use spatial data to calibrate a relationship between proxy and climate and to apply this "space-for-time" relationship to information on past vegetation so that the climate can be inferred. This approach assumes that the laws producing the natural archive remained constant throughout space and time (uniformitarian principle). However, when non-climatic factors such as atmospheric CO_2 concentration have changed during the period analyzed or with respect to the present, this assumption may have been violated. This is a major motivation for moving towards process-based models to better capture vegetation changes according to a realistic set of all major forcing variables, whether climatic or not.

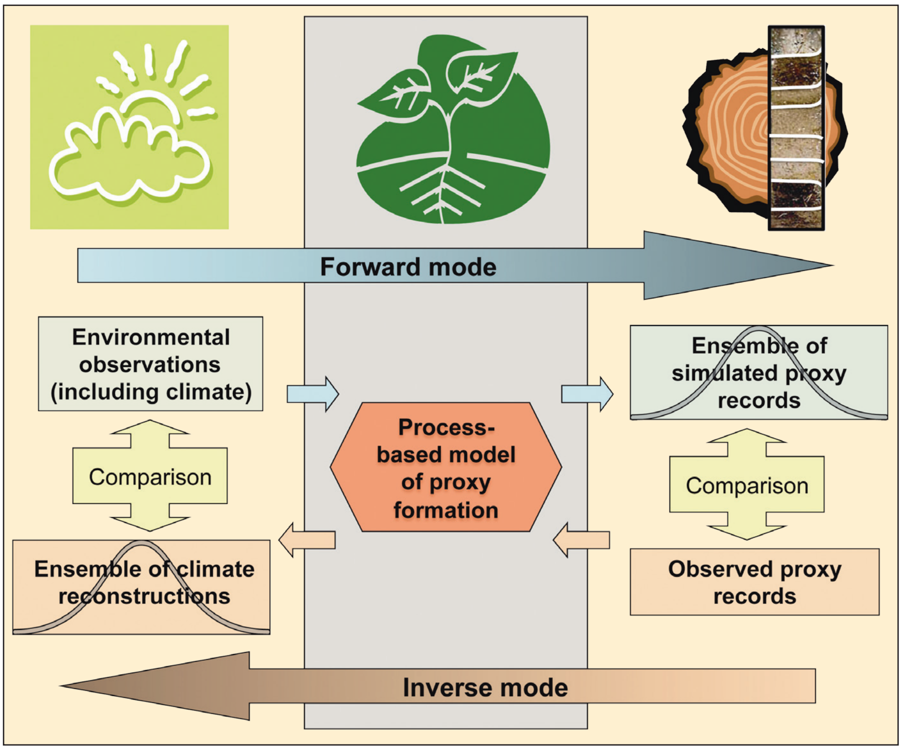

*Figure 1: Schematic view of the use of process-based forward models in climate reconstruction. In the forward mode, environmental data drive the forward model to produce an ensemble of simulated proxy records, whose distribution represents the range of variability due to known and quantified uncertainties. These are evaluated by comparison (**yellow**) with observed proxy records. In the inverse mode, observed proxy records drive the inverted process model to produce an ensemble of climate reconstructions, the distribution of which similarly represents the range of variability due to known and quantified uncertainties in the proxy data and the process model. The ensemble of climate reconstructions is in turn evaluated by comparison (**yellow**) with observed climate data. The central, gray, block represents topics in need of increased and intensified research, namely, the processes forming proxy records and the modeling of them.*

Hughes and Ammann (2009) focused on high-resolution paleoclimatology over the last few millennia, considering records such as annually layered sediments, coral growth bands, annual layers in polar and high-elevation ice, tree rings and documentary sources. They similarly propose a formalization of the combination of process knowledge (of the Earth System and of the formation of proxies) and proxy records. They argue that although calibration and verification of statistical transfer functions are frequently found to be robust, these proxy-to-climate relationships

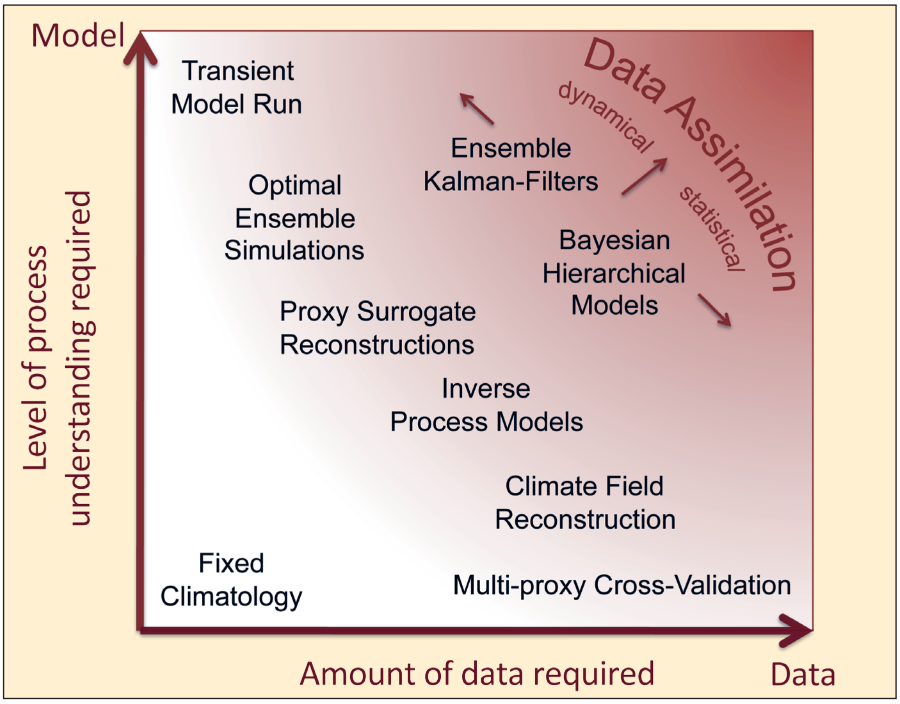

Figure 2: A schematic illustration of the relationships between methods requiring increasingly detailed process understanding (y-axis) and those depending on increasing amounts of data (x-axis). For a fuller explanation please see Hughes and Ammann (2009) from where this figure has been modified to include the inversion of process models indicated in Figure 1.

may differ in sensitivity across timescales (see also Guiot et al., 2010), and in some cases also be influenced by changes in unidentified or unmeasured factors influencing the formation of the archive. The challenge is that the instrumental period usually used for calibration of proxy records in the empirical-statistical approach overlaps with massive and widespread environmental modifications in all aspects of the Earth's surface environment. Therefore, reconstructions are likely to inspire greater confidence if they are based on models that also appropriately include important forcing factors for archive formation that may differ in instrumental and pre-instrumental times.

Towards new ways of using proxies

Consider the possibilities of a situation in which we had sufficient understanding of the formation of individual proxy records to construct "forward models" that would be driven by climate and other environmental data, and could be tested against actual observed proxy records (e.g., see Evans et al., 2006). Successful "forward models" could then be "inverted" so as to extract climate information from the proxy data (Fig. 1).

Other intriguing possibilities are emerging (Fig. 2). When coupled with forward models of proxy formation, advances in understanding of the climate system enables approaches that are very different to the existing "climate reconstruction" paradigms. For example, imagine an ensemble of forced climate model runs producing, through a proxy model, an ensemble of time series of simulated proxy fields, e.g., synthetic tree-ring records arrayed as geographic fields, or synthetic coral skeleton isotope or elemental record series. These could then be tested against existing observed natural archives for the same period. Such comparisons could be used to examine the uncertainties in both the model and the proxy data. This in turn could be used to focus attention on aspects of both data and model where it is important to make improvements (Fig. 2).

Implications for PAGES scientists

There is now a pressing need for renewed emphasis on quantitative, mechanistic understanding of how natural archives are formed. This should be given high priority in all aspects of paleoclimatology. Research on mechanisms of natural archive formation needs to be targeted to meet the needs of simple forward models of broad generality. Their parameters should

have direct physical, chemical or biological meaning in the natural world, and should be measurable quantities.

In contrast to empirical-statistical models, forward models of formation of natural archives can explicitly account for potential time-dependent biases and errors, such as diagenesis in sediment-based proxies, or changing replication and age/size trend in tree rings. Moreover, by using process models, the reconstructions can finally make use of all the known climate information contained in the proxies and thus benefit from their wider Earth System context (e.g., atmospheric composition, effects of Milankovitch variations, temperature vs. moisture influence, temperature vs. salinity effects). This extends their applicability and reduces the risk of violating the uniformitarian principle.

These forward models have another very important advantage. They can be invaluable in developing new and more complete ways of evaluating and presenting all kinds of errors associated with reconstructions of past climate. As both Guiot et al. (2009) and Hughes and Ammann (2009) point out, a number of approaches to achieve this are available or are under active development (Li et al., in press) (Fig. 2). These range from largely data-driven approaches to those that explicitly combine existing understanding of natural archive formation (that is, forward models) and of climate with treatment of multiple sources of uncertainty (e.g., Bayesian hierarchical approaches). Both providers and users of proxy climate records must be jointly engaged in the development of these techniques.

Final thoughts

We do not propose the abandonment of present methods but rather an expansion of the toolkit PAGES scientists have available. The approaches used in many parts of paleoclimatology were developed 30 or 40 years ago, and were creative and productive responses to the situation we faced then. We now have a much richer set of records, a more diverse and powerful set of tools for analyzing and using them, and benefit from great advances in knowledge of the workings of the climate system. Let's find ways to incorporate this improved understanding of how natural archives are formed into the exploration of the past, using the tools and concepts available in the 21st century!

References

Guiot, J., Wu, H.B., Garreta, V., Hatte, C. and Magny, M., 2009: A few prospective ideas on climate reconstruction: from a statistical single proxy approach towards a multi-proxy and dynamical approach, *Climate of the Past*, **5**: 571-583.

Hughes, M.K. and Ammann, C.M., 2009: The Future of the Past-an Earth System Framework for High Resolution Paleoclimatology: Editorial Essay, *Climatic Change*, **94**: 247-259.

Li, B., Nychka, D.W. and Ammann, C.M., in press: The value of multi-proxy reconstruction of past climate, *The Journal of the American Statistical Association, Case Studies Section*.

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http://www.pages-igbp.org/products/newsletters/ref2010_2.html

Workshop on modeling Holocene climate evolution

Bremen, Germany, 16 June 2010

Gerrit Lohmann and workshop participants

Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; Gerrit.Lohmann@awi.de

The major objective of this workshop was to investigate the spatio-temporal pattern of Holocene climate changes as derived from transient integrations with climate models of different complexity; from comprehensive global climate models to models of intermediate complexity and statistical-conceptual models. For the 23 participants from Germany, The Netherlands, Switzerland and Norway, this was the first step in comparing data with models and may develop into a benchmark for models used in the assessment of future climate change. The Priority Research Program "Integrated analysis of interglacial climate dynamics" (INTERDYNAMIC; www.interdynamik.de; funded by the German Research Foundation; Schulz and Paul, 2009) formed the framework for the workshop. INTERDYNAMIC is based on an integrated approach in paleoclimate research, in which all available paleoclimate archives are combined with results from Earth System models to gain insights into the dynamics of climate variations during interglacials.

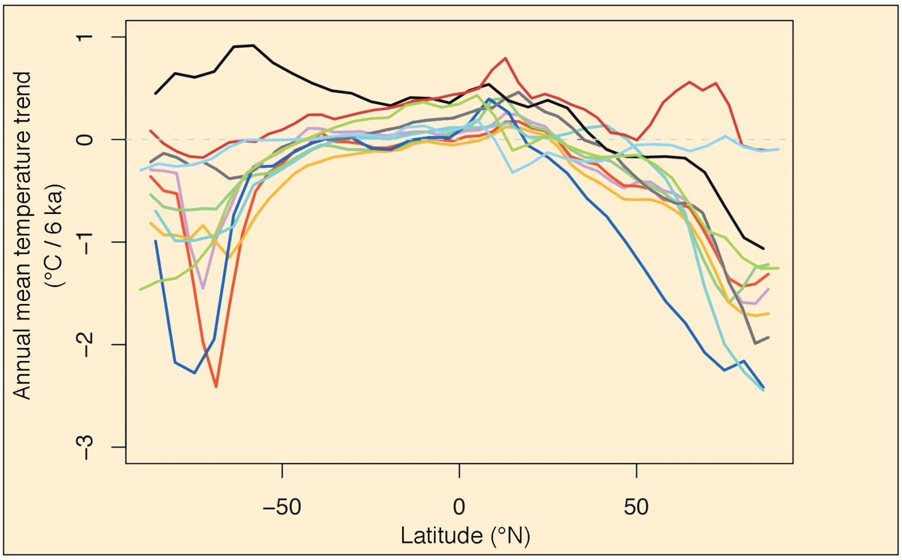

Figure 1: Zonal mean temperature trend from 6 ka BP to the pre-industrial climate as obtained from different climate simulations, forced by Earth's orbital parameters and fixed levels of greenhouse gas concentrations. Most models show a high latitude cooling and low latitude warming. In an upcoming manuscript, it will be disclosed which model shows which temperature trends.

For the paleomodel intercomparison, we compared the results from scenarios with identical forcing for the mid- to late-Holocene period: varying Earth's orbital parameters, fixed level of greenhouse gas concentrations, fixed land-sea mask and orography. All major paleoclimate modeling groups in Germany are involved in this initiative, as well as some European groups working on transient Holocene simulations. Members of the Paleoclimate Dynamics Group at the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven created a data set for the available transient simulations. Posters were prepared in advance, allowing for comparison of the results with common analyses programs and discussions on the results. In addition to participation by the paleoclimate modeling community, some colleagues from the data reconstruction side were also involved. One major issue, affecting both the modeling and reconstruction side, is the quantification of uncertainties and the evaluation of trend and variability patterns beyond a single proxy and beyond a single model simulation. The goal is now to obtain robust results of

trend patterns, seasonality changes, and transitions on a regional scale.

Currently, nine different model simulations are available (and will be made publically available through the PANGAEA database at http://www.pangaea.de/). A preliminary analysis shows common patterns of temperature changes (Fig. 2). More analysis is necessary to clarify the model differences in response to orbital forcing. Using statistical analysis of the model results, variability modes and their amplitude during the Holocene are identified in the model experiments. Our analyses reveal heterogeneity in temperature and precipitation trends and yield a quantification of robust features in the models. The variations in the large-scale atmosphere-ocean circulation and feedback mechanisms between the components of the climate system will be investigated in the future. Further analysis will also include the development of Southern Hemisphere wind and vegetation changes. We invite the paleoclimate community to participate in this initiative. Those that are interested are invited to email the author to obtain the required transient simulations and data information.

References

Schulz, M. and Paul, A., 2009: Integrated analysis of interglacial climate dynamics - INTERDYNAMIC Status Seminar, *PAGES news*, **17**: 84-85.

Advances in varved sediment studies during the last 10 years

1st PAGES Varves Working Group workshop, Palmse, Estonia, 7-9 April 2010

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A varve is a sequence of layers deposited in a water body within 1 year. Therefore, varved sequences have been the object of a lot of attention from the paleoscience community because they can provide the highest-resolution paleoenvironmental and paleoclimatic records with accurate chronologies independent of radiocarbon reservoir complications and because they enable one to resolve interannual trends in average and even seasonal climate. Iconic paleoclimatic records, such as the Cariaco Basin or Holzmaar in the German Eifel, are famous varved sequences.

Recently, the PAGES Varves Working Group (VWG) was established within the frame of Cross-Cutting Theme 1 (Chronology) and 2 (Proxy development, calibration, validation) to provide a further impetus for the study of varved sediments. The VWG has the objectives of reviewing what has been accomplished during the last 10 years in terms of new methodological developments and improvements in calibration of records, as well as making an inventory of varved records. Other VWG topics are detailed at http://www.pages.unibe.ch/science/varves/index.html

A group of 41 scientists from 11 countries (including 8 students and 4 young scientists) met for the first VWG workshop in the Palmse Manor House, in Lahemaa National Park Centre, Estonia. The workshop was divided into four oral and one poster sessions (for abstract volume see http://www.pages.unibe.ch/science/varves/publications.html). The first session was devoted to the study of the processes responsible for the formation (and preservation) of varves from various environments in the Canadian Arctic, Western Europe and the Middle East. The second session reviewed advances in the improvement of chronologies of varved records using independent dating techniques, such as paleomagnetic secular variation, tephra horizons and radiocarbon dating, as well as the detailed analysis of internal structures of varves (Fig. 2). The third session was devoted to technological advances in the study of varved and other laminated sediments. It focused on the increasing application of micro-XRF techniques and the development of new softwares helping scientists in the analysis of the large datasets obtained by varve counting. Environmental and climate history case studies from lacustrine and marine sites were discussed during the fourth session. During the poster session, covering all the topics mentioned above, authors briefly introduced their papers to the group.

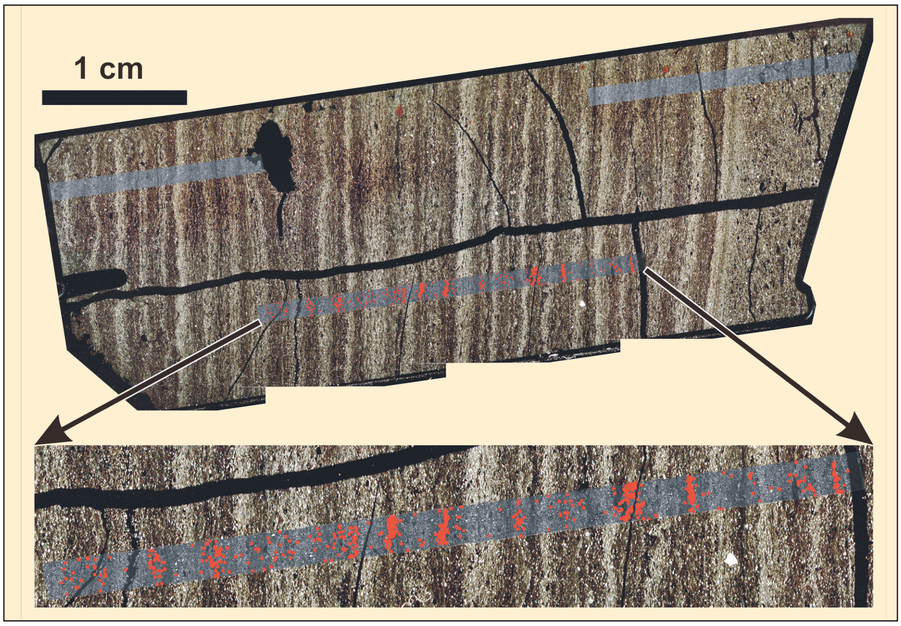

Figure 1: Microscopic view of varved sediments from Lower Mystic Lake, Massachusetts, USA in thin-section (crossed-polarized light). Superimposed ***grey bands*** *are mosaics of scanning electron microscope images acquired in backscattered mode and used to identify the individual occurrence of the diatom Cyclotella (****red dots****), which indicates spring blooms and hence confirms the annual character of these laminations. Figure from M.R. Besonen.*

The workshop participants discussed several practical topics during 3 plenary sessions. They first identified the needs of the VWG community, which included the need for advertising methodological and technical services that can be provided from within the community (e.g., making of thin-section), establishing standards for best practice, promoting systematic comparison of methods, and organization of specialized training courses (e.g., spectral analysis, Bayesian chronological correc-

tion, image analysis). It was also suggested to implement a website (to be hosted on the PAGES website) with a metadatabase of existing varved records and a database of images of varves.

Key topics to be addressed at future workshops were also discussed. The next workshop will focus on bridging the gap with other communities that deal with the study of archives of past climate with annual resolution, i.e., ice cores, tree rings, corals, and speleothems. Additionally, models and data assimilation communities will be included. This workshop will be held in the USA (exact place and time to be announced). A third and potentially fourth workshop will focus on establishing standards of best practice for the study of varved sediments, and on specific thematic themes such as events, climate variability, calibration and intersite comparisons.

Anybody interested in varves studies and the VWG can register and contribute to activities by contacting the first author.

Acknowledgements
The organizers wish to thank PAGES, the Geological Survey of Finland, Estonian Environmental Board Visitors Centre of Lahemaa National Park Centre and Emilia Kosonen for their help and support.

The 1st Australasia 2k regional workshop: Towards data synthesis

Melbourne, Australia, 31 May–2 June 2010

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Australasia spans from the tropics to the sub-Antarctic, and straddles several major oceanographic and atmospheric systems that are of global significance and potentially sensitive to anthropogenic-driven climate change. For instance, northern Australasia is influenced by the Indo–Pacific Warm Pool (Hansen et al., 2006), which is a major source of latent heat and hence drives global atmospheric and oceanic circulation. Towards higher latitudes, the Southern Ocean (south of 45°S) plays a key role in global climate (Caldeira and Duffy, 2000). Although considerable progress has been made in developing quantitative reconstructions of temperature change for the Northern Hemisphere over the past two millennia (Mann et al., 2009), significantly more work is required in Australasia (and the Southern Hemisphere as a whole) (Nicholls et al., 2006).

The first Australasia 2k (Aus2k) regional network workshop aimed to fill this critical gap in climate science by reviewing annually- to centennially-resolved climate reconstructions for Australasia for the past 2 ka, towards synthesis in the planned PAGES Regional 2k Network synthesis book. 73 scientists from around the world, representing the proxy, modeling and dynamics communities, met to present the latest datasets and interpretations from across the region.

The first day focused on short presentations and posters of single proxies from the full range of natural archives spanning ice, marine and terrestrial records of the past 2 ka. Not surprisingly, tree rings underpin the terrestrial annual resolution record for Australasia (Antarctic ice is great for teleconnections (Fig. 1) but not local variability). However, the majority of well-replicated records are less than 500 years and only Tasmania and NZ have records extending for the full 2 ka (i.e., a classic "fading record problem"). A surprise was the number of "new" species used in tree-ring reconstructions being developed from throughout the region—vital for understanding geographic variability. A good example is the Western Australian

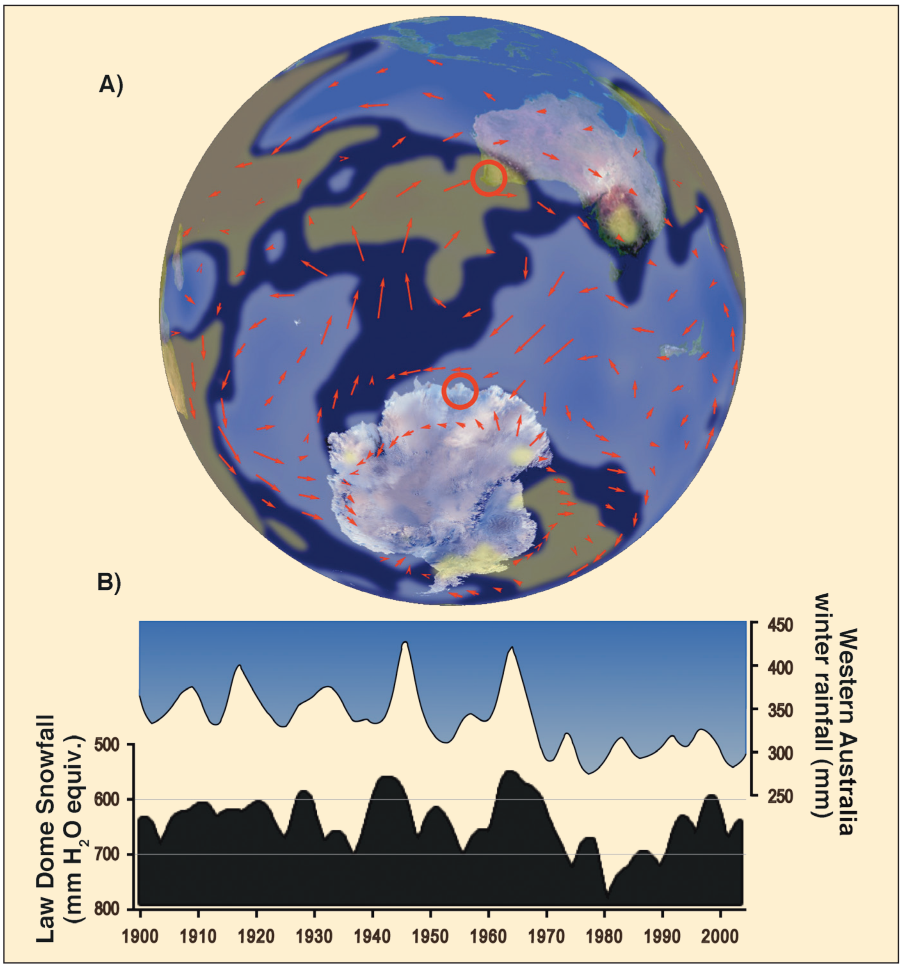

*Figure 1: **A**) Atmospheric water vapor and wind anomalies for years with high precipitation at Law Dome. Blue regions show wet anomalies; tan regions show dry anomalies, which can be seen to extend across southwest Western Australia (SWWA) (Data from NCEP/NCAR reanalysis) (Credit: Tas van Ommen). **B**) Comparison of SWWA winter rainfall (blue) and Law Dome snowfall (black) since the beginning of reliable rainfall data for WA. The two regions are connected via large-scale meridional flow (van Ommen and Morgan, 2010). The positive precipitation anomaly at Law Dome over the past four decades, corresponding to extended drought in SWWA, is the largest such anomaly in 750 years of snowfall data (Credit: Tas van Ommen/Mat Oakes, Australian Antarctic Division).*

rainfall reconstruction from *Callitris* tree-rings. After the presentations, there was an open discussion of common themes and the challenges facing the groups working in the region. Key issues raised during this session included the strategic sampling of key lake sequences before they are lost to the current drought in Australia, proposed development of sub-regional reconstructions, determining the stability of teleconnections over time, clarifying the seasonality of the signal preserved within different proxies, the challenge of calibration against contemporary climate given recent land use changes, and the extension of records both forwards and backwards in time. Furthermore, several presentations reported asynchronous temporal and spatial temperature and precipitation trends when compared to those in the Northern Hemisphere over much of the past 2 ka, raising the question of whether the use of such terms as the "Medieval Warm Period/Anomaly" and the "Little Ice Age" are appropriate when referring to the Australasian region. Further work is needed to gain a consensus on this issue. Presentations also highlighted that more effort is needed to develop proxies from this region if we are to get good enough resolution to comment on the past millennium with adequate spatial coverage.

On the second day, presentations and posters focusing on multiproxy reconstructions and modeling work across the region were given and their policy relevance discussed. A broader discussion then took place on how the data might be most effectively collected. After exploring a range of options, it was agreed that the community would collate only published (or directly publishable) data (using both raw and quantified analyses) from each of the different archives, with a full estimate of the uncertainties included and an agreement that objective criteria for the final selection of records must be developed prior to the generation of final reconstructions (in consultation with other regional 2k groups). Qualitative, lower resolution data will also be utilized as an independent check on reconstructed high resolution variability. On the third day, these issues were explored in greater detail and individuals were identified who would lead the collection of data from each proxy group by mid April 2011.

As a starting point, the group was encouraged to develop an Aus2k metadatabase hosted on the PAGES Aus2k website (http://www.pages.unibe.ch/science/2k/aus2k/index.html), to develop an inventory of records that are currently available and/or being actively developed in the Australasian region. Following the meeting, a small-scale proposal was submitted to the Australian Government to fund a research fellow, who will develop a quantitative database of the records listed on the website. This will allow all members of Aus2k to access the database and develop the suite of climate reconstructions needed for the region. Qualitative, lower resolution data will also be utilized as an independent check on reconstructed high resolution variability (Fig 1).

The second Aus2k workshop will be hosted by Pauline Grierson and take place in the first half of 2011 (most likely in Perth). This workshop will focus on combining the collated datasets to generate reconstructions of different climate variables for the Australasian region and identify future reconstruction needs to capture the full 2k period.

References

Caldeira, K. and Duffy, P.B., 2000: The role of the Southern Ocean in uptake and storage of anthropogenic carbon dioxide, *Science*, **287**: 620-622.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W. and Medina-Elizade, M., 2006: Global temperature change, *Proceedings of the National Academy of Sciences*, **103**: 14288-14293.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G. and Ni, F., 2009: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, *Science*, **326**: 1256-1260.

Nicholls, N., Collins, D., Trewin, B. and Hope, P., 2006: Historical instrumental climate data for Australia-Quality and utility for palaeoclimatic studies, *Journal of Quaternary Science*, **21**: 681-688.

van Ommen, T.D. and Morgan, V., 2010: Snowfall increase in coastal East Antarctica linked with southwest Western Australian drought, *Nature Geoscience*, **3**: 267-272.

The nitrogen cycle in the ocean, past and present

1st NICOPP Workshop, Montreal, Canada, 14-16 May 2010

Eric Galbraith[1], M. Kienast[2] and T. Kiefer[3]

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Some three decades after the first measurements of nitrogen isotopes ($\delta^{15}N$) were made in the marine environment, 27 nitrogen enthusiasts from nine nations congregated on the verdant flanks of Mount Royal, in Montreal. This meeting represented the first for the PAGES Working Group "Nitrogen cycle in the ocean, past and present" (NICOPP). Over three days, this group discussed recent findings, summarized the state of knowledge, and highlighted outstanding challenges related to the use of sedimentary $\delta^{15}N$ as a tracer of the marine nitrogen cycle. From a series of stimulating talks and enthusiastic discussions, three overarching topics emerged.

Seeing the big picture

While some areas of the ocean are dominated by either water column denitrification, nitrate utilization, or N_2 fixation (Fig. 1), overlap between these processes can produce complex spatial patterns in nitrogen isotopes, apparent in simulations with coupled ocean-biogeochemistry models. As a result, isolated sediment records can be deceiving, as any one is likely to be a time-varying amalgam of all three processes. However, when assembled, records show coherent changes over time even in complex regions, with clear relationships to their oceanographic contexts, allowing the multiple processes to be disentangled. Accordingly, it was resolved by the NICOPP Working Group to amass a global database of all available bulk sediment N isotope measurements, to help move beyond the ambiguity of isolated wiggly lines.

The devil's in the details

There has been considerable concern, over the decades, regarding just what N isotopes in marine sediments represent. The hopeful interpretation is that bulk combustible nitrogen, an easily measured quantity, represents the isotopic composition of the integrated marine organic export flux. However, isotopic alteration during sinking and burial, and contributions from terrestrial nitrogen, have been shown to modify the bulk isotope record in some environments. To account for these secondary influences, measurements are being made in a growing number of sedimentary fractions and specific compounds. These include the organic nitrogen trapped within microfossils, corals, chlorophyll and amino acids, as well as inorganic nitrogen. The results, so far, reveal new dimensions of complexity, as these individual components can vary with species assemblages, growth conditions, and trophic structures; yet, they often parallel

the bulk sediment δ15N records. These observations point to the potential of these targeted measurements to complement the bulk N isotope records: where the two agree, the story is straightforward for both (Fig. 1b). Where they don't agree, the specific measurements can reveal changes in the surface ecosystem, alteration of the bulk record, or both. The emerging picture is that bulk organic records are more representative of the export flux than was thought a few years ago. Given the relative ease of measuring bulk sediment δ15N, this is good news.

Taking inventory

A primary motivation behind sedimentary nitrogen isotope research is to understand the coupling between the marine N inventory and climate. A lot of progress has been made, most notably in developing the notion of enhanced water column denitrification and N_2 fixation during warm periods (Fig. 1). However, newly identified issues complicate the translation of sedimentary nitrogen isotope records into quantitative constraints on the marine N inventory. At the forefront of these is the anaerobic oxidation of ammonium by nitrite to yield N_2 (anammox). New measurements from culture experiments show that the anammox isotope effect is distinct from that of canonical (i.e., heterotrophic) denitrification. Problems aside, perhaps the most useful single quantity to track through time would be the isotopic composition of mean ocean nitrate. Although the availability of such a record remains elusive, efforts toward a global synthesis should prove a step in the right direction.

The second NICOPP workshop will include a broader range of nitrogen cycling processes and will be held in Halifax, Canada in 2011. In the meantime, a catalog of published bulk sediment δ15N records has been developed: http://www.pages-igbp.org/cgi-bin/WebObjects/metadb.woa/wa/map?group=nitrogen. All investigators with relevant data are encouraged to contact eric.galbraith@mcgill.ca for inclusion in the global database, which will ultimately be available as a data product in multiple formats.

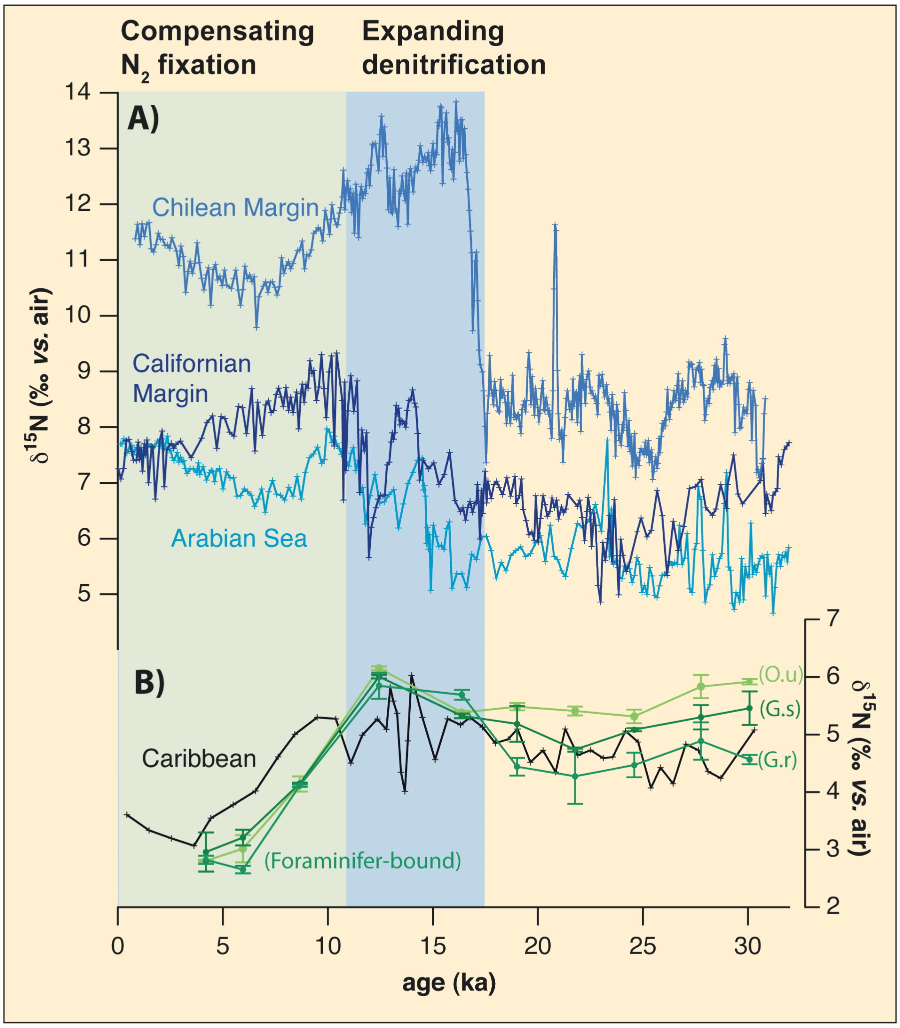

Figure 1: Sedimentary records of bulk and microfossil-bound δ15N since the last glacial maximum (after Ren et al., 2009). ***A)*** *Bulk sediment δ15N records from each of the three major oceanic denitrification zones (Chilean Margin, Californian Margin, Arabian Sea) increased between 12-18 ka, although with local nuances.* ***B)*** *Bulk sediment record (black) from the Caribbean Cariaco Basin and three foraminifera-bound δ15N records (O.u = Orbulina universa, G.s = Globigerinoides sacculifer, G.r = G. ruber) from the open Caribbean. N_2-fixation is very active in both Caribbean regions today. The bulk and microfossil-bound records of the Caribbean reveal an opposite sense of change to that of the oxygen-minimum zones in panel A, consistent with the notion that deglacial warming drove an increase of denitrification that was then compensated by a delayed increase of N_2 fixation.*

References

Ren, H., Sigman, D.M., Meckler, A.N., Plessen, B., Robinson, R.S., Rosenthal, Y. and Haug, G.H., 2009: Foraminiferal Isotope Evidence of Reduced Nitrogen Fixation in the Ice Age Atlantic Ocean, *Science*, **323**: 244-248.

The first Africa 2k regional workshop

Ghent, Belgium, 11-14 May 2010

Mohammed Umer[1] and Dirk Verschuren[2]

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[2]Limnology Unit, Department of Biology, Ghent University, Belgium

The first workshop of the PAGES Africa 2k Working Group was a small, focused workshop, hosted by Dirk Verschuren in Gent and attended by all Working Group members (see http://www.pages.unibe.ch/science/2k/africa2k/people.html). May 12 was dedicated to presentations and May 13 was for discussions. The workshop was opened by Louise Newman (PAGES IPO) who presented the PAGES Regional 2k Network, as well as issues relating to the geographical boundaries of each focal region, critical time intervals, deadlines on expected outcomes and the development of metadatasets. The first formal presentation, by Sharon Nicholson, dealt with the spatial patterns of African climate anomalies associated with important drivers of tropical climate variability. The ensuing presentations dealt with sets of paleodata currently available from various regions of sub-Saharan Africa. These included precipitation patterns from documentary and gauge station data (Sharon Nicholson); 19th century documentary evidence of precipitation variability in South Africa (David Nash); a regional synthesis of records spanning the West African monsoon domain (Tim Shanahan); anthropogenic versus climatic impacts on paleoenviron-

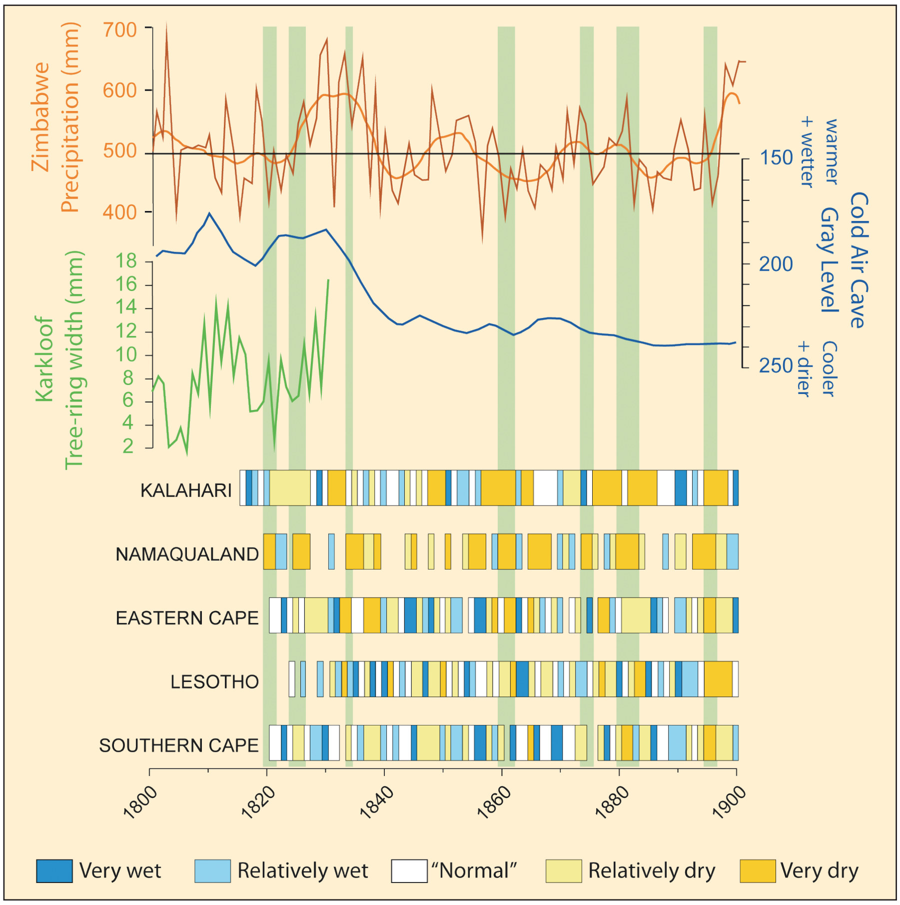

*Figure 1: Nineteenth-century climate chronologies for southern Africa, including tree-ring based rainfall reconstructions for Zimbabwe (**orange**; bold line is a 10-a running mean; Therrell et al. 2006) and Karkloof (South Africa) (**green**; Hall, 1976), the speleothem record of regional hydrology from Cold Air Cave (South Africa) (**blue**; Holmgren et al., 1999) and document-derived rainfall reconstructions from the southern Kalahari Desert (Nash and Endfield, 2002a, 2008), Namaqualand (Kelso and Vogel, 2007), the Eastern and Southern Cape (Vogel, 1989) and Lesotho (Nash and Grab, 2010). Gaps in the documentary records are unclassified years. Widespread drought (**green shading**) occurred in 1820–21, 1825–27, 1834, 1860–62, 1874–75, 1880–83 and 1894–1896 (Kelso and Vogel, 2007), with an additional dry period from the early- to mid-1840s affecting the Kalahari and Zimbabwe only (Nash and Endfield, 2002b; Therrell et al., 2006).*

ments in western Central Africa (Ilham Bentaleb); climate of the past 2 ka and impacts in Ethiopia (Mohammed Umer); decadal-scale rainfall variability in Ethiopia recorded in annually laminated Holocene-age stalagmites (Asfawossen Asrat); climate variability in central and eastern equatorial Africa over the past two millennia (Dirk Verschuren); and high-resolution palaeoenvironmental records from southern Africa (Brian Chase). This was a truly interactive workshop, with much discussion during the presentations themselves keeping both speakers and audience on their toes. Broader discussion after each block of talks focused on internal and external mechanisms of climate variability and emphasized the role of oceans, land-surface changes, and atmospheric circulation. It was stressed that the geographically complex climate of Africa requires thorough consideration of regional climate regimes and the exact timing of climate shifts. For this a reference map showing homogeneous modern climate regions will be established (by Sharon Nicholson) on which existing sites of paleodata for the last 2 ka will be plotted. This will reveal spatial gaps as well as show how patterns of regional variation at different times in the past compare to present-day regional patterns. During discussions it was also pointed out that the geographical boundary of Africa 2k should include Yemen and the Arabian Peninsula, and also the Sahara. Finally the group discussed a spreadsheet format for the compilation of available datasets holding all existing site and metadata information. Later, this will be filtered and reduced to include only those data that fit strict criteria for their dating reliability and time resolution. Brian Chase will lead this task. The data will be further structured into two partial datasets; those dealing with the last 2 ka at decadal- to century-scale resolution, and those that cover the last 200 years at annual resolution.

The next meetings of the Africa 2k Working Group will be conducted during the 3rd East African Quaternary Association meeting in Zanzibar, Tanzania, 8-13 Feb 2011, and the 18th INQUA Congress in Bern, Switzerland, 20-27 July 2011.

References

Kelso, C. and Vogel, C.H., 2007: The climate of Namaqualand in the nineteenth century, *Climate Change*, **83**: 357–380.

Nash, D.J. and Endfield, G.H., 2002a: A nineteenth century climate chronology for the Kalahari region of central southern Africa derived from missionary correspondence, *International Journal of Climatology*, **22**: 821–841.

Nash, D.J. and Endfield, G.H., 2008: 'Splendid rains have fallen': links between El Niño and rainfall variability in the Kalahari, 1840–1900, *Climate Change*, **86**: 257–290.

Nash, D.J. and Grab, S.W., 2010: "A sky of brass and burning winds": documentary evidence of rainfall variability in the Kingdom of Lesotho, Southern Africa, 1824–1900, *Climatic Change*, **101**: 617-653.

Vogel, C.H., 1989: A documentary-derived climatic chronology for southern Africa, 1820–1900, *Climate Change*, **14**: 291–306.

For full references please consult:
http://www.pages-igbp.org/products/newsletters/ref2010_2.html

PAGES regional workshop in Japan

Nagoya, Japan, 5-6 June 2010

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Due to its unique language, culture and geographical isolation, it is frequently mentioned that Japanese do not often play major roles in international societies, including political and scientific areas. In fact, the average Japanese scores of international English communication tests (e.g., Test of English for International Communication) are almost worst in the world. In addition, young Japanese scientists rarely move to foreign countries because they worry about job opportunities upon returning to Japan. Yet, Japanese people have created many industrial and academic products, some of which are very unique and have been analogized with the isolated and specialized evolution of life on the Galapagos Islands. Likewise, in Japanese paleoscience, there are also some unique research products that are rarely shared with the international paleoscience community. This PAGES Regional Workshop, held at the Noyori memorial conference hall, Nagoya University (prior to the PAGES Scientific Steering Committee (SSC) meeting), was designed to introduce the variety of Japanese paleosci-

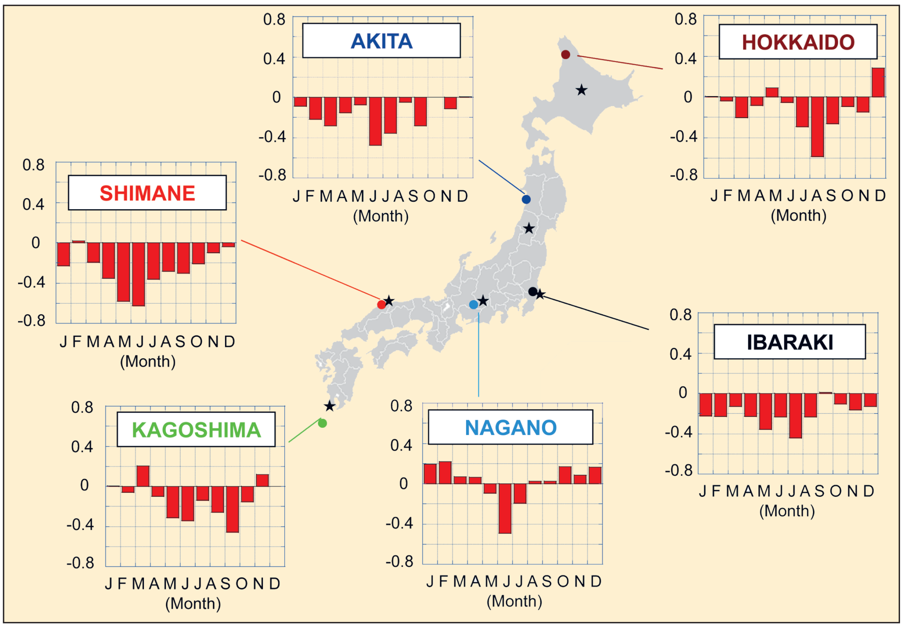

Figure 1: A new network of tree-ring cellulose oxygen isotopic ratios from Japan (Nakatsuka et al., unpublished). Correlation coefficients between the tree-ring cellulose $\delta^{18}O$ and monthly mean relative humidity observed at meteorological stations (stars) close to the sample sites during recent 50 years show that tree-ring cellulose $\delta^{18}O$ has a clear negative correlation with relative humidity during its growing season. This indicates that tree-ring $\delta^{18}O$ can be a useful proxy of summer monsoon activity in Japan. Due to reduced sensitivity of tree-ring width to moisture, it is difficult to reconstruct Japanese summer hydroclimate based on traditional dendrochronological methods. Thus tree-ring cellulose $\delta^{18}O$ provides a new option, and will be important in contributing to Japanese records for the PAGES Asia 2k reconstruction Working Group.

ence to the PAGES SSC and enhance the collaboration between the Japanese and international paleoscience communities.

84 scientists and students, including the international scientists from the PAGES SSC, attended this workshop with 21 oral and 47 poster presentations. Oral sessions consisted of keynotes by SSC members to introduce PAGES 4 scientific Foci and Cross-Cutting Themes (CCTs), followed by presentations by Japanese paleoscientists on recent research activities relating to each Focus or CCT. All fields of paleosciences were represented in this workshop, demonstrating that in Japan there is a full lineup of paleoscience research, corresponding to all of PAGES activities. After a brief introduction to PAGES science (T. Kiefer), two topics relating to Focus 4 (Human-Climate-Ecosystem Interactions: J. Dearing) were presented, highlighting the impact of preindustrial cultivation upon Asian monsoon climate (T. Yasunari) and the historical human-nature interactions in Japanese Archipelago (T. Yumoto). After lunch, several topics within Focus 2 (Regional Climate Dynamics: H. Wanner) and CCT 2 (Proxy Development, Calibration and Validation: F. Abrantes) were presented, including IMAGES research around Japan (H. Kawahata), Himalayan glaciers and ice cores (K. Fujita), NW Pacific coral records in the early 20th century (A. Suzuki), tree-ring oxygen isotopic network in Japan (T. Nakatsuka; Fig.1 shown just as an example of ongoing research in Japan), and Japanese documentary based paleoclimate studies (M. Zaiki). The next morning followed on from lively discussions between Japanese scientists and SSC members at an evening reception, with two sessions, relating to Focus 1 (Climate Forcings: B. Otto-Bliesner, C. Whitlock) and CCT 3 (Modeling: B. Otto-Bliesner). Presentations included topics of Holocene sea level changes (Y. Yokoyama), impacts of historical solar activity on climate change (H. Miyahara), and perspectives on glacial-interglacial modeling in Japan (A. Abe-Ouchi). Finally, in the afternoon, Focus 3 (Global Earth-System Dynamics: T. Kiefer) and CCT1 (Chronology: P. Francus, S. Colman, C. Turney) were covered with presentations on Dome Fuji ice core analyses (K. Kawamura), millennial-scale Asian monsoon dynamics (R. Tada), North Pacific overturning at the last glacial termination (Y. Okazaki), and *Emiliania huxleyi* blooming and global geochemical cycles (N. Harada).

Oral and poster presentations by Japanese paleoscientists not only demonstrated the high level of their academic findings but also suggested the potential for international contributions in the near future. As a result of this workshop, it was shown that Japanese paleoscience is of a high international level and efforts should be made for better integration of Japanese paleoscientists, and for Japanese young paleoscientists to enhance their international contributions, even though isolated circumstances, such as the "Galapagos Island" effect, may continue produce some unique creatures or some unique science…

PAGES Calendar 2010/2011

3rd Past Interglacials (PIGS) Workshop
20 - 22 Oct 2010 - New York, USA
http://www.pages-igbp.org/calendar/

PAGES Arctic 2k Workshop
11 - 12 Dec 2010 - San Francisco, USA
http://www.pages-igbp.org/calendar/

Land-cover reconstructions in the monsoon affected tropical world - pollen modeling approach and data synthesis
27 - 29 Jan 2011 - Puducherry, India
http://www.pages-igbp.org/calendar/

3rd EAQUA Workshop
8 - 13 Feb 2011 - Zanzibar, Tanzania
http://www.pages-igbp.org/calendar/

18th INQUA Congress
20 - 27 Jul 2011 - Bern, Switzerland
http://www.inqua2011.ch/

2nd Workshop of PAGES Regional 2k Initiative
28 July 2011 - Bern, Switzerland
http://www.pages-igbp.org/calendar/

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Call for contributions to *PAGES news*

All PAGES newsletters have an open section for general contributions. If you would like to contribute a "Science Highlight", "Workshop Report", "Program News", or an amusing "Tales from the field" story for the forthcoming December 2010 issue of *PAGES news*, please contact Louise Newman (newman@pages.unibe.ch).

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