EOS®

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

IN THIS ISSUE:

VOLUME 94 NUMBER 46 12 NOVEMBER 2013

Fire Research: Linking Past, Present, and Future Data

Increased levels of burning in the past 40 years are raising public and scientific concern about the relative importance of rising temperatures, climate variability, and human actions including management practices in initiating and supporting recent conflagrations. Enormous fires in Australia, North America, Europe, and Russia since 2000 have resulted in billions of dollars in property damage, loss of life, and threats to human and ecological health. Levels of fire activity are expected to increase in the coming decades in many regions as temperatures continue to rise and droughts intensify [*Moritz et al.*, 2012]. Linked disturbances such as bark beetle infestations, nonnative plant invasions, and mass-wasting events have also exacerbated the effects of fire in many ecosystems.

Understanding the role of biomass burning in the Earth system and its interactions with human activity requires examining its drivers and consequences over multiple temporal and spatial scales. Given the evidence that biomass burning is increasing [*Moritz et al.*, 2012], several disciplines have joined forces to provide a broader understanding of past fire-climate-human linkages under a range of climate conditions and human population densities. As a result of these efforts, scientists now have the capacity to examine the spatial and temporal changes in biomass burning from local to global and seasonal to millennial scales.

Sources of Data Spanning Multiple Time Scales

Past fire information comes from a variety of sources, each with its own spatial and temporal domain (Figure 1). On hourly to monthly time scales, remotely sensed observations collected from aircraft and satellites document changes in the highly heterogeneous patterns of burning across the globe. Records from fire-scarred tree rings may offer annually resolved information on changing fire-climate teleconnections over the last few centuries as well as the sustained effects of fire management in particular forests.

Sedimentary charcoal time series from lakes and natural wetlands offer multidecadal resolution and watershed- to regional-scale information on fire patterns during the Holocene (the past ~12,000 years). Regionally composited charcoal records enable examination of changing fire activity in relation to long-term shifts in fuel biomass, climate, and human population size.

On centennial to multimillennial temporal scales, black carbon, oxidation-resistant elemental carbon, and microcharcoal from marine cores offer regional and subcontinental descriptions of biomass burning. Black carbon, charcoal, and chemical tracers of fires preserved in ice cores provide the opportunity to study regional fires over millennia from polar and high-altitude settings.

New Discoveries in Fire Science From Remote Sensing and Emissions

Fires are a source of greenhouse gases–such as methane, carbon dioxide, and nitrous oxide– and are one of the most important aerosol sources. The first global maps of fire occurrence were developed in the 1990s based on fires that burned during the satellite overpass time. These maps revealed frequently burning savannas, incidental fires in temperate and boreal regions, and tropical deforestation fires. Recently, however, the focus has switched from simply detecting fires to measuring fire extent and producing global-scale maps of area burned with 500 meter spatial resolution [e.g., *Giglio et al.*, 2009].

To estimate fire emissions, burned areas are usually aggregated to match the coarser resolution of biogeochemical models that estimate fuel loads and other relevant fire parameters [e.g., *van der Werf et al.*, 2010]. Current emission estimates from biomass burning are roughly 2 petagrams of carbon per year. Although fire emissions equal about 20% of global fossil fuel carbon emissions, a substantial part may be sequestered when vegetation regrows after a fire. Regions with increasing fire activity over the past decades include Indonesia [*Field et al.*, 2009] and boreal regions [*Kasischke et al.*, 2010].

Insight From Fire Modeling

Modeling approaches incorporate basic fire ignition and behavior processes to estimate the consequences of fire on vegetation and the release of trace gases and aerosols under different climate scenarios.

Specifically, scientists can use dynamic global vegetation models (DGVMs), which simulate fire-relevant biomass properties including fuel amount and quality (separating vegetation litter from soil carbon), fuel flammability (moisture and volatile content), and vegetation structure. Wildfire models embedded in DGVMs simulate the effect of fire on carbon fluxes, which in turn allows prediction of fire-related trace gas and aerosol emissions as well as the fraction of area burned. These fire models account for natural ignitions associated with lightning as well as ignitions usually associated with human population density [*Thonicke et al.*, 2010], which is especially important in regions such as the European Mediterranean, where most fires are currently caused by human activity.

When projected into the past, these coupled fire-vegetation models can help estimate past anthropogenic burning behavior. Modelers can first separate human populations into three groups: foragers, farmers, and pastoralists, each with different subsistence strategies and levels of fire use [*Pfeiffer and Kaplan*, 2012]. Foragers rely on fire to open landscapes to improve hunting opportunities and therefore cause more fire per capita compared to the other groups. Comparisons with archeological and other paleoecological records test the sensitivity of different model assumptions about the changing human relationship with fire.

Recent fire models are capable of incorporating other human influences, including land use and fire management approaches [*Kloster et al.*, 2010]. Incorporating anthropogenic influences into fire models demonstrates that 8% of global fire carbon emission contributions (1997–2004) are from deliberate agricultural biomass burning and 24% are from deforestation [*Li et al.*, 2013].

In addition, coupled fire-vegetation models suggest that future fire activity might increase depending on the climate model used. Nonetheless, the combined effects of land use change, human demography, and fire suppression lead to counterbalancing effects at the regional scale [*Kloster et al., 2012*].

The key challenges remain in comparing fire model output with paleofire proxy reconstructions. First, the scale of observations does not usually match the modeled output—many proxy records record local fire events, whereas models simulate changes over regional to continental scales. It is also often difficult to determine the appropriate metric for comparison—for example, paleofire proxies describe fire occurrence or trends in biomass burning, whereas models simulate area burned and emissions.

Biomass Burning Reconstructions From Charcoal Records

The Global Charcoal Database v2 (gpwg.org) consists of 679 charcoal records from five continents [*Daniau et al.*, 2012]. This collaborative resource provides a tool for examining the factors that drove variability in past fire regimes across ecosystems through time. For example, hemispheric syntheses of charcoal data indicate that biomass burning levels closely track millennial-scale temperature variations during the last glacial-interglacial transition [*Daniau et al.*, 2012].

Such results demonstrate that previous model-based analyses of carbon isotopic ratios in methane which suggested that global biomass burning levels remained stable during the last glacial-interglacial transition [*Fischer et al.*, 2008], do not match observations. In fact, the magnitude of changes in biomass burning levels during the transition was larger than at any other time in the past 22,000 years.

Composite charcoal records from populated regions of Australasia, Europe, North America, and Central and South America indicate that humans played a relatively small role in causing these fires, a trend that lasted until the late Holocene [*Marlon et al.*, 2013, and references within]. Analyses of charcoal, climate, and archaeological data during the late Holocene further indicate that the global decline in biomass burning during the Little Ice Age was primarily driven by climate but may have been amplified by dramatic changes in population density following the arrival of European explorers to the Western Hemisphere [*Power et al.*, 2013].

Recent Developments in Ice Core Science

The high accumulation rates in many ice core sites offer the opportunity to reconstruct detailed histories that link with satellite, tree ring, and lake sediment records. Sampling techniques applied to tiny pieces of ice cores now allow analysis of multiple fire proxies within the same core. These small sample sizes permit the development of multiple new proxies that build upon the conventional use of ammonium and potassium as biomass burning markers and that provide complementary information to create a suite of fire information.

For example, comparing black carbon, a marker produced from both biomass and fossil fuel burning [*McConnell*, 2010], with levoglucosan, a specific biomarker only produced by cellulose burning [*Simoneit*, 2002], may help separate the contribution

Fire Research cont. on page 422

By N. M. Kehrwald, C. Whitlock, C. Barbante, V. Brovkin, A.-L. Daniau, J. O. Kaplan, J. R. Marlon, M. J. Power, K. Thonicke, G. R. van der Werf

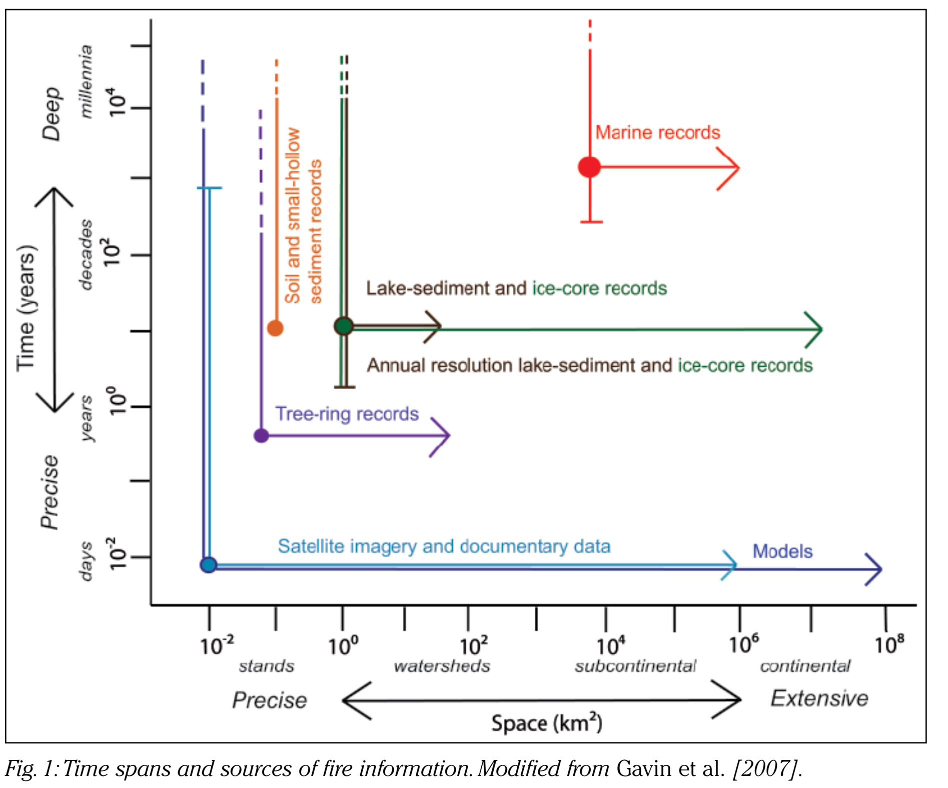

Fig. 1: Time spans and sources of fire information. Modified from Gavin et al. *[2007].*

EOS

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION
The Newspaper of the Earth and Space Sciences

Eos, Transactions, American Geophysical Union (ISSN 0096-3941) is published weekly except the last week of December by the American Geophysical Union, 2000 Florida Ave., NW, Washington, DC 20009, USA. Periodical Class postage paid at Washington, D. C., and at additional mailing offices. POSTMASTER: Send address changes to Member Service Center, 2000 Florida Ave., NW, Washington, DC 20009, USA. *Member Service Center:* 8:00 A.M.–6:00 P.M. Eastern time; Tel: +1-202-462-6900; Fax: +1-202-328-0566; Tel. orders in U.S.: 1-800-966-2481; E-mail: service@agu.org. Information on institutional subscriptions is available from the Wiley institutional sales team (onlinelibrarysales@wiley.com). Use AGU's Geophysical Electronic Manuscript Submissions system to submit a manuscript: http://eos-submit.agu.org.

Fire Research

cont. from page 421

of biomass versus fossil fuel burning in ice core records. Additionally, organic acids provide a more specific idea of the combusted vegetation types [*Makou et al.*, 2009].

The variety of data preserved in ice cores combines climate and fire data across long time scales and provides multiple opportunities to link with sediment records and model output. Specifically, pollen and charcoal records from lake sediments can readily link with analyses of organic acids and charcoal preserved in ice cores [*Eichler et al.*, 2011] to enhance regional fire reconstructions. Globally dispersed greenhouse gases and their sample isotopes trapped in ice cores can help demonstrate the effect of climate on fire variability, especially during the preindustrial era [*Wang et al.*, 2010].

Areas for Future Research

For those studying fire, the challenges ahead center on achieving common fire metrics for multiproxy and data-model comparisons and linking past and modern observations. Global fuel maps, better detection of small/understory fires, and better estimates of combustion completeness, emission ratios, landscape effects, and the influence of humans are needed for the past as well as the present. For example, paleofire estimates are often compared with human population density, which oversimplifies anthropogenic use of fire in many regions and does not account for different vegetation, land use, and agricultural practices. Refining landscape-scale process models and modeling approaches based on specific fire agents as well as linking them with DGVMs also holds promise for understanding human influences on fire across different spatial and temporal scales.

The diversity of paleofire data sets also provides an opportunity for calibrating modern observations and models with information spanning decadal to millennial time scales. Paleofire studies point to the importance of interannual climate variability and long-term insolation trends, but we still know little about the suite of climate conditions that support biomass burning on different time scales. Comparisons of proxy data with model scenarios will help clarify climate drivers of vegetation and fire change as well as feedbacks to the climate system in terms of trace gas emissions and aerosols.

Interdisciplinary research that draws on real-time observations, paleoperspectives, and modeling tools is the scientific community's best opportunity to project fire's role in the future. With such collaboration, scientists will be able to better understand the interplay among rising carbon dioxide levels, changing climate, and land use as drivers of fire activity.

References

Daniau, A.-L., et al. (2012), Predictability of biomass burning in response to climate changes, *Global Biogeochem. Cycles*, *26*, GB4007, doi:10.1029/2011GB004249.

Eichler, A., W. Tinner, S. Brusch, S. Olivier, T. Papina, and M. Schwikowski (2011), An ice-core based history of Siberian forest fires since AD 1250, *Quat. Sci. Rev.*, *30*(9–10), 1027–1034, doi:10.1016/j.quascirev.2011.02.007.

Field, R. D., G. R. van der Werf, and S. S. P. She (2009), Human amplification of drought-induced biomass burning in Indonesia since 1960, *Nat. Geosci.*, *2*, 185–188.

Fischer, H., et al. (2008), Changing boreal methane sources and constant biomass burning during the last termination, *Nature*, *452*, 864–867.

Gavin, D. G., D. Hallett, F. S. Hu, K. Lertzman, S. J. Prichard, K. J. Brown, J. A. Lynch, P. Bartlein, and D. L. Peterson (2007), Forest fire and climate change: Insights from sediment charcoal records, *Front. Ecol. Environ.*, *5*, 499–506.

Giglio, L., T. Loboda, D. P. Roy, B. Quayle, and C. O. Justice (2009), An active-fire based burned area mapping algorithm for the MODIS sensor, *Remote Sens. Environ.*, *113*(2), 408–420, doi:10.1016/j.rse.2008.10.006.

Kasischke, E. S., et al. (2010), Alaska's changing fire regime—Implications for the vulnerability of its boreal forests, *Can. J. For. Res.*, *40*(7), 1313–1324, doi:10.1139/X10-098.

Kloster, S., N. M. Mahowald, J. T. Randerson, P. E. Thornton, F. M. Hoffman, S. Levis, P. J. Lawrence, J. J. Feddema, K. W. Oleson, and D. M. Lawrence (2010), Fire dynamics during the 20th century, *Biogeosciences*, *7*(6), 1877–1902, doi:10.5194/bg-7-1877-2010.

Kloster, S., N. M. Mahowald, J. T. Rangerson, and P. J. Lawrence (2012), The impacts of climate, land use, and demography on fires during the 21st century simulated by CLM-CN, *Biogeosciences*, *9*, 509–525, doi:10.5194/bg-9-509-2012.

Li, F., S. Levis, and D. S. Ward (2013), Quantifying the role of fire in the Earth system—Part 1: Improved global fire modeling in the Community Earth System Model (CESM1), *Biogeosciences*, *10*, 2293–2314, doi:10.5194/bg-10-2293-2013.

Makou, M. C., L. G. Thompson, D. B. Montlucon, and T. I. Eglinton (2009), High-sensitivity measurement of diverse vascular plant-derived biomarkers in high-altitude ice cores, *Geophys. Res. Lett.*, *36*, L13501, doi:10.1029/2009GL037643.

Marlon, J. R., P. J. Bartlein, A.-L. Daniau, S. P. Harrison, M. J. Power, W. Tinner, and S. Tracy (2013), Global biomass burning: A synthesis and review of Holocene paleofire records and their controls, *Quat. Sci. Rev.*, *65*, 5–25, doi:10.1016/j.quascirev.2012.11.029.

McConnell, J. R. (2010), New directions: Historical black carbon and other ice core aerosol records in the Arctic for GCM evaluation, *Atmos. Environ.*, *44*(21–22), 2665–2666, doi:10.1016/j.atmosenv.2010.04.004.

Moritz, M. A., M.-A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe (2012), Climate change and disruptions to global fire activity, *Ecosphere*, *3*, Article 49, doi:10.1890/ES11-00345.1.

Pfeiffer, M., and J. O. Kaplan (2012), SPITFIRE-2: An improved fire module for Dynamic Global Vegetation Models, *Geosci. Model Dev. Discuss.*, *5*, 2347–2443, doi:10.5194/gmdd-5-2347-2012.

Power, M. J., et al. (2013), Climatic control of the biomass-burning decline in the Americas after AD 1500, *Holocene*, *23*, 3–13, doi:10.1177/0959683612450196.

Simoneit, B. R. T. (2002), Biomass burning—A review of organic tracers for smoke from incomplete combustion, *Appl. Geochem.*, *17*, 129–162, doi:10.1016/S0883-2927(01)00061-0.

Thonicke, K., A. Spessa, I. C. Prentice, S. P. Harrison, L. Dong, and C. Carmona-Moreno (2010), The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: Results from a process-based model, *Biogeosciences*, *7*(6), 1991–2011, doi:10.5194/bg-7-1991-2010.

van der Werf, G. R., J. T. Randerson, L. Giglio, G. J. Collatz, M. Mu, P. S. Kasibhatla, D. C. Morton, R. S. DeFries, Y. Jin, and T. T. van Leeuwen (2010), Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), *Atmos. Chem. Phys.*, *10*(23), 11,707–11,735, doi:10.5194/acp-10-11707-2010.

Wang, Z., J. Chappellaz, K. Park, and J. E. Mak (2010), Large variations in Southern Hemisphere biomass burning during the last 650 years, *Science*, *330*, 1663–1666, doi:10.1126/science.1197257.

Author Information

NATALIE M. KEHRWALD, Department of Environmental Sciences, Informatics and Statistics, University of Venice, Italy; email: kehrwald@unive.it; CATHY WHITLOCK, Montana Institute on Ecosystems and Department of Earth Sciences, Montana State University, Bozeman; CARLO BARBANTE, Department of Environmental Sciences, Informatics and Statistics, University of Venice, Italy; and Institute for the Dynamics of Environmental Processes, Italian National Research Council, Venice, Italy; VICTOR BROVKIN, Max Plank Institute for Meteorology, Hamburg, Germany; ANNE-LAURE DANIAU, University of Bordeaux, Centre National de la Recherche Scientifique; JED O. KAPLAN, Atmosphere Regolith Vegetation Group, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland; JENNIFER R. MARLON, School of Forestry and Environmental Studies, Yale University, New Haven, Conn.; MITCHELL J. POWER, Department of Geography, Natural History Museum of Utah, University of Utah, Salt Lake City; KIRSTEN THONICKE, Potsdam Institute for Climate Impact Research, Potsdam, Germany; and GUIDO R. VAN DER WERF, Department of Earth and Life Sciences, Earth and Climate Cluster, Vrije Universiteit, Amsterdam, Netherlands

NEWS

Natural Hazards Experts Learn First Hand from the Colorado Storm and Flood

The mid-September deluge of parts of central Colorado—which broke many precipitation records and devastated communities—also personally affected a number of natural hazards experts who live there.

"It was very dramatic. I study floods. I've written about floods. Over 20 years, I've never been a flood victim. This is a totally different experience. It's really quite a remarkable thing to see the object of your study come after you," Robert Brakenridge, a flood remote sensing expert, told *Eos*. Brakenridge, director of the Dartmouth Flood Observatory at the University of Colorado Boulder, was at the annual meeting of the Geological Society of America (GSA) in Denver, listening to a 29 October panel discussion about the flood and its impacts.

Brakenridge lives in Lyons, north of Boulder along Colorado's Front Range, where 232 households were damaged. During the evening of 14 September, he and other town residents were evacuated following several days of downpours and flooding after persistent rumors that the nearby Button Rock Dam was going to fail.

That evening, Brakenridge, whose own house sits on high ground and was not flooded, drove his Toyota Corolla along an improvised dirt road through a farmer's muddy lot. He was part of a convoy of about 400 subdivision residents headed to Main Street and away from flooded areas along the normally peaceful North and South St. Vrain creeks.

Driving out of Lyons, he saw the blacked-out town, the devastation where houses were destroyed, military vehicles, and a checkpoint warning residents that they could not return for a while.

Brakenridge, who also is senior research scientist with the Institute of Arctic and Alpine Research at the University of Colorado, Boulder, said, "I guess the lesson is, if you want to really understand this phenomenon, you need to go at peak flow and stand next to the monster and see it for yourself."

He told *Eos* that he doesn't understand why people were so underprepared and overwhelmed by the event. "We have historic records. The same thing happened in 1894, it happened in 1941. The same thing. The same parts of town were destroyed. It's not a 1000-year event, it's not even a 100-year event. But it's beyond the memory of 99.9% of the people" in Lyons.

Brakenridge said that he is still trying to come to grips with the flood professionally but that the event "changes things" for him. "It just makes me recommit to the work that I've been doing, but with a different trajectory." Brakenridge said that geologists and other experts "have to do a better job at getting the reality of these past events incorporated into flood risk." He noted, for instance, that this information needs to get

Photo courtesy FEMA via Colorado Civil Air Command.

Flooding along South St. Vrain Creek, Lyons, Colo.

News cont. on next page