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One thousand years of fires: Integrating proxy and model data

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Abstract:
The current fires raging across Indonesia are emitting more carbon than the annual fossil fuel emissions of Germany or Japan, and the fires are still consuming vast tracts of rainforest and

peatlands. The National Interagency Fire Center (www.nifc.gov) notes that 2015 is one worst fire years on record in the U.S., where more than 9 million acres burned -- equivalent to the combined size of Massachusetts and New Jersey. The U.S. and Indonesian fires have already displaced tens of thousands of people, and their impacts on ecosystems are still unclear. In the case of Indonesia, the burning peat is destroying much of the existing soil, with unknown implications for the type of vegetation regrowth. Such large fires result from a combination of fire management practices, increasing anthropogenic land use, and a changing climate.

The expected increase in fire activity in the upcoming decades has led to a surge in research trying to understand their causes, the factors that may have influenced similar times of fire activity in the past, and the implications of such fire activity in the future. Multiple types of complementary data provide information on the impacts of current fires and the extent of past fires. The wide array of data encompasses different spatial and temporal resolutions (Figure 1) and includes fire proxy information such as charcoal and tree ring fire scars, observational records, satellite products, modern emissions data, fire models within global land cover and vegetation models, and sociodemographic data for modeling past human land use and ignition frequency. Any single data type is more powerful when combined with another source of information. Merging model and proxy data enables analyses of how fire activity modifies vegetation distribution, air and water quality, and proximity to cities; these analyses in turn support land management decisions relating to conservation and development.

opinion

One thousand years of fires: Integrating proxy and model data

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Abstract. The current fires raging across Indonesia are emitting more carbon than the annual fossil fuel emissions of Germany or Japan, and the fires are still consuming vast tracts of rainforest and peatlands. The National Interagency Fire Center (www.nifc.gov) notes that 2015 is one worst fire years on record in the U.S., where more than 9 million acres burned -- equivalent to the combined size of Massachusetts and New Jersey. The U.S. and Indonesian fires have already displaced tens of thousands of people, and their impacts on ecosystems are still unclear. In the case of Indonesia, the burning peat is destroying much of the existing soil, with unknown implications for the type of vegetation regrowth. Such large fires result from a combination of fire management practices, increasing anthropogenic land use, and a changing climate. The expected increase in fire activity in the upcoming decades has led to a surge in research trying to understand their causes, the factors that may have influenced similar times of fire activity in the past, and the implications of such fire activity in the future. Multiple types of complementary data provide information on the impacts of current fires and the extent of past fires. The wide array of data encompasses different spatial and temporal resolutions (Figure 1) and includes fire proxy information such as charcoal and tree ring fire scars, observational records, satellite products, modern emissions data, fire models within global land cover and vegetation models, and sociodemographic data for modeling past human land use and ignition frequency. Any single data type is more powerful when combined with another source of information. Merging model and proxy data enables analyses of how fire activity modifies vegetation distribution, air and water quality, and proximity to cities; these analyses in turn support land management decisions relating to conservation and development.

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Landscape fires

The fires that raged across Indonesia in late 2015 emitted more carbon than the annual fossil fuel emissions of Germany or Japan (~1.75 billion metric tons of CO_2 equivalents as determined form the Global Fire Emissions Database), and consumed vast tracts of rainforest and peatlands. The National Interagency Fire Center[1] notes that 2015 was one worst fire years on record in the U.S., where more than 4 million hectares burned – equivalent to the combined size of Massachusetts and New Jersey. The U.S. and Indonesian fires have already displaced tens of thousands of people, and their impacts on ecosystems are still unclear. In the case of Indonesia, the burning peat is scorching much of the existing soil, with unknown

1 www.nifc.gov, last accessed 26 April 2016.

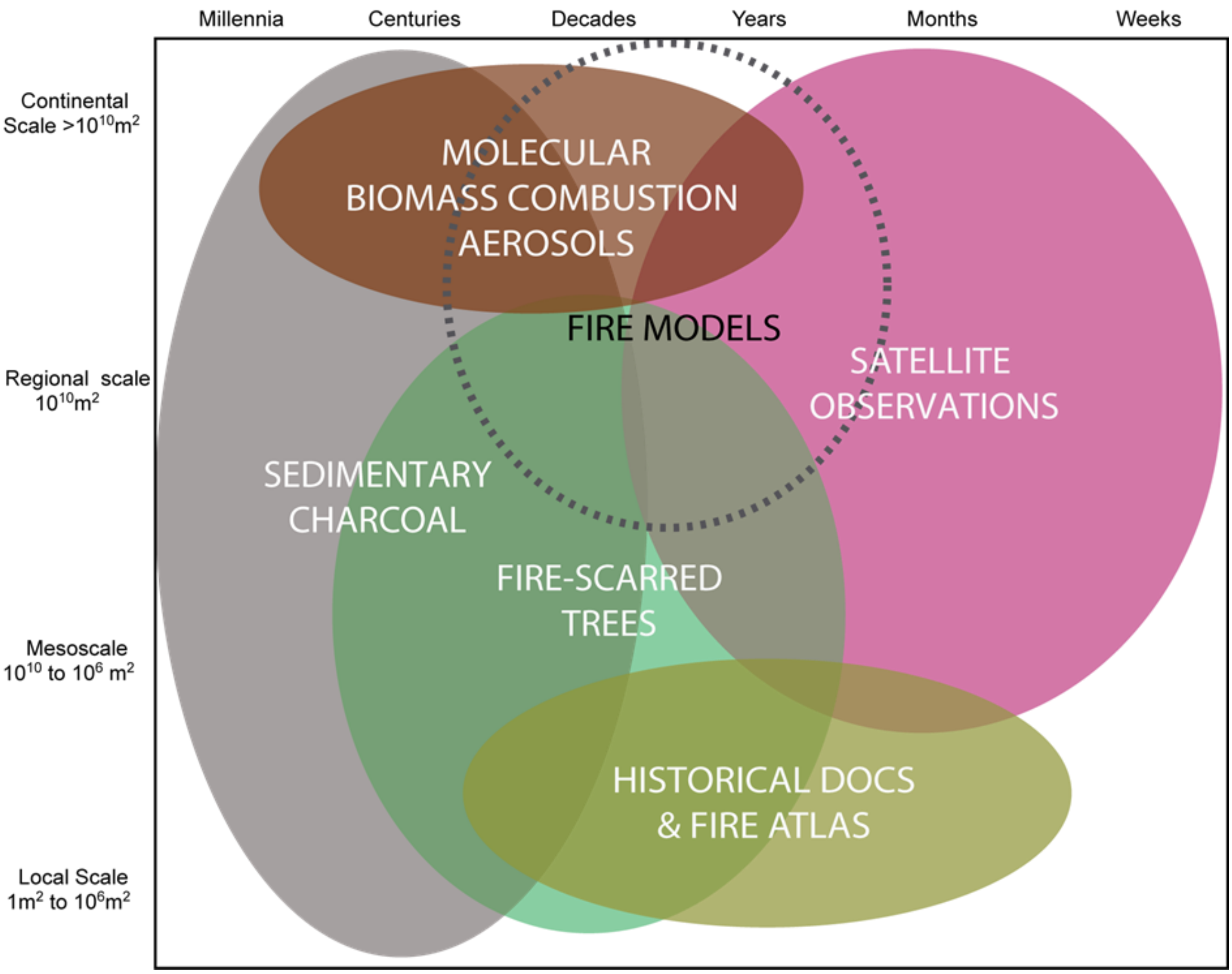

Figure 1. The temporal and spatial scales of fire history proxies, ranging from sedimentary charcoal-based reconstructions on long time scales and across multiple spatial scales, to satellite observations from daily to decadal time scales.

implications for forest regeneration or future land use. These current fire crises differ in many specifics, but both reflect a history of land use (such as forest clearance in Indonesia or past fire suppression in the U.S.), regional climate variability (such as droughts affected by El Niño in Indonesia, or the sustained drought in the Western U.S.), and global climate change.

Integrated approach

The expected increase in fire activity in the upcoming decades has led to a surge in research trying to understand their causes, the factors that may have influenced similar times of fire activity in the past, and the implications of such fire activity in the future (e.g. Marlon et al., 2012, Scheffer et al., 2012 and references therin). Multiple types of complementary data provide information on the impacts of current fires and the extent of past fires. The wide array of data encompasses different spatial and temporal resolutions (Fig. 1) and includes information such as charcoal and tree-ring fire scar records of past fires, observational records, satellite products, modern emissions data, fire models within global land cover and vegetation models, and sociodemographic data for modeling past human land use and ignition frequency. Any single data type is more powerful when combined with other sources of information. Merging model and observational data enables analyses of how fire activity modifies vegetation distribution, air and water quality, and proximity to cities; these analyses in turn support land-management decisions relating to conservation and development.

On September 29 to October 2, 2015, researchers from Africa, Asia, Europe and North America met at the ‘Paleofire Data–Model Comparisons for the Past Millennium Workshop' in Harvard Forest, Massachusetts, USA, to explore how knowledge about past fire activity can provide insights into the data and model strengths and weaknesses. The workshop aimed to leverage proxy and observational data about fire activity over time scales ranging from decades to millennia, and to develop testable hypotheses about fire interactions with climate, ecology, and humans using both the data and models. We addressed the following ideas: What are ways to combine data-based and model-based methods to understand fire? What types of research questions can best be addressed by combining these approaches, particularly in areas where multiple proxies and models overlap in time and space? How can we apply these data in the future to ecological, climate change and/or land use problems? What is the role of humans in fire activity over the last thousand years?

Case studies

The initial workshop ideas created a series of objectives with practical applications. Here, we present case studies of our ongoing efforts to integrate model and proxy data. For example, the need to calibrate modern charcoal data with model data served as the impetus to create a modern Global Charcoal Database (mGCD) comprising fire proxy data from the past ~100 years, strengthening the temporal overlap of sedimentary charcoal and satellite data. The goal of the mGCD is to have researchers and citizen scientists collect surface sediments by promoting a community-based data collection and dissemination approach to link recent patterns of emissions, land cover change, and fire history data. The differences in source area sizes affect the spatial utility of proxy records in models (paleo records record local events while models simulate regions/continents). A wider spatial array of modern charcoal can help with comparing models and data over the past century.

Two additional calibration initiatives evolved during the workshop. In collaboration with the Paleoecological Observatory Network (PalEON[2]), we discussed a statistical process model that relates charcoal accumulation rates to independent records of area burned (e.g., from fire-scar records) to better understand how changes in fire location, extent, and other fire-regime characteristics are registered by charcoal in sediment. A process model will allow us to quantify past burning and the uncertainties within those reconstructions, providing robust comparisons of data and models (Tipton et al. 2016), and potential opportunities for data assimilation into models. A second calibration project estimates baseline levels of biomass burning emissions just prior to the industrial era. Historical estimates currently extend back 100 years (Mouillot and Field 2005), but extensive land-use change during the past century requires longer term knowledge of how burning varied prior to this time, for initializing models (Kelly et al. 2015) and for understanding climate–fire interactions (van der Werf et al. 2013).

Long-term vegetation and fire data can also be used to test ecological hypotheses about the mechanisms that influence biome distributions worldwide. Indeed, recent global analyses of remotely sensed data (Hirota et al. 2011, Staver et al. 2011b, Scheffer et al. 2012), supported by modeling work (Bond et al. 2005, Staver et al. 2011a, Staver and Levin 2012) suggest that current biome distributions are, in some areas, maintained by positive feedbacks between vegetation and fire. These positive feedbacks potentially create the conditions for alternative ecological states (Beckage and Ellingwood 2008), such that the same environmental conditions can support multiple stable states. Bistable systems are thus characterized by long temporal periods of equilibrium punctuated by abrupt changes in response to a gradual change in the environmental conditions (e.g., climate change) or to disturbances (e.g., land use, fire regime modifications) (Scheffer et al. 2001, Scheffer and Carpenter 2003). Because vegetation dynamics are slow, testing the existence of catastrophic regime shifts on modern time scales, such as using fire suppression or prescription experiments (e.g., Moreira 2000), is not sufficient. Paleoecological data provide information on fire regime and vegetation change from century to

2 www3.nd.edu/~paleolab/paleonproject/, last accessed 26 April 2016.

millennial scales. Such data permit testing whether ecological transitions between flammable and non-flammable biomes really exhibit these unique regime shifts (Gavin et al. 2013).

Another workshop focus was the challenge of determining the antiquity, scale, and extent of human influences on fire activity. The intensity and biogeographical implications of fire management and landscape modification have varied through time and across space. For example, in Europe, humans have substantially altered vegetation distribution through biomass burning for at least the past three thousand years (Tinner 1999, Vanniere et al. 2008, Galop et al. 2013). Recent agricultural abandonment, cessation of traditional burning practices, and climate change have increased the hazard of severe fires that threaten landscape conversion (Pausas and Fernández-Muñoz 2012, Valese et al. 2014). In North America, the arrival of Europeans in the last 500 years provides a natural experiment to evaluate the role of fire activity following the Native American demographic collapse (Power et al. 2012), followed by several centuries of increasing Euro-American agriculture and land conversion, resource extraction, and human-caused ignitions. These activities significantly impacted fire activity and biogeography, variously increasing or decreasing fire frequency and severity, depending on the region and time period. The late 19th century introduction of industrial land use and fire management in the western United States, for example, initially resulted in decreased fire activity, but subsequently contributed to the recent increase in occurrence and severity of large fires (Marlon et al. 2012). Yet, at fine scales, the onset and chronology of significant human modifications to fire regimes is poorly resolved for the last few millennia across much of the globe. Paleoenvironmental and archaeological evidence can currently determine the presence of humans in an area, but cannot yet determine the relative importance of humans versus natural sources of ignition. As a consequence, not only do we lack ecological baselines for setting fire management goals, we also lack understanding of the impacts that particular management strategies will have on land-cover trajectories.

Conclusions

Fire is a terrestrial phenomenon that links vegetation, atmospheric chemistry, human activities, and climate across local to global scales. Scientists are actively investigating each of these aspects of the fire system, but often this research is isolated within individual disciplines. Each discipline faces separate challenges, but often the data or approaches of other disciplines can help address these obstacles. For example, integrating observational, paleoenvironmental, and model-output data can help to investigate important ecological questions, such as the possibility of catastrophic regime shifts between biomes (e.g., in tropical and boreal areas) with ongoing global change and fire-regime modifications. A unified approach can also help determine whether regional warming and increased aridity associated with climate change may amplify fire frequency and intensity in specific regions of the globe. A statistical process model relating charcoal accumulation rates to the environmental characteristics surrounding each charcoal site will also increase our understanding of taphonomic processes and how to better integrate them into past fire-regime reconstructions. Combining model output and proxy data thus provides a fuller analysis of past and modern fire activity, and promises a variety of opportunities for advances in our understanding of fire ecology, human–environment interactions, and climate change.

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