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Burning issues: statistical analyses of global fire data to inform assessments of environmental change

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Global pyrogeographic study is necessary to inform climate change impact assessments used for management and decision-making. Climate is a strong driver of spatial and temporal patterns of fire such that ongoing climate change is expected to alter global fire activity. A growing number of statistical–correlative analyses examine environmental drivers of current patterns of global fire occurrence or burned area, but few studies ask important "what if" questions about the potential future of fire under scenarios of a changing climate. Accordingly, our goal is to engage the broader statistical community in analysis of global fire data products to spur further understanding of fire regimes and the complex links they demonstrate between the biosphere and atmosphere. We provide an overview of constraints over fire regimes and the role of fire in the biosphere–atmosphere, describe general approaches being used for global fire–climate assessment, summarize opportunities and pitfalls in the public-access global fire datasets, and highlight thinking on next steps for analysis of global fire and fire regime data. Copyright © 2014 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Our understanding of global patterns in modern fire activity has greatly increased over the last decade because of data from the growing archive of spatially and temporally explicit, satellite-based remotely sensed fire observations. Analysis and visualizations based on archived global fire data have revealed the broad gradient in fire's footprint (Figure 1) from fire-free to highly fire-prone ecosystems, seasonal and annual trends in area burned, and multifaceted regimes generated by interactions of biophysical processes and human culture (e.g., Le Page *et al*. 2008; Chuvieco *et al*., 2008; Krawchuk *et al*., 2009; Aldersley *et al*., 2011; Moritz *et al*., 2012; Archibald *et al*., 2013; Bistinas *et al*., 2013). Climate is a strong driver of spatial and temporal patterns of fire, and ongoing climate change is expected to alter global fire activity (Scholze *et al*., 2006; Gonzalez *et al*., 2010; Pechony and Shindell, 2010; Moritz *et al*., 2012). Statistical–correlative and process-based studies have examined global fire–climate relationships with the goal of quantifying specific drivers of variability in modern fire activity, yet there is still much more we need to learn from these data to understand the current and future role of fire in biosphere–atmosphere systems.

Pyrogeography refers to research on spatial patterns of fire. Use of the term pyrogeography is on the rise (Figure 2), with the earliest published example apparently by Sannikov (1994) and then by Pyne (1995) and Yool (1999). Early use was largely descriptive and as an "undefined" noun in the context of plant ecology and human fire relations, with spatial patterns of fires or the act of mapping them as a primary focus. The term has now become a more clearly defined field of inquiry emphasizing an understanding of drivers contributing to fire dynamics and the resulting effects on both human and natural systems. Use of the term pyrogeography in the context of identifying drivers underlying spatial and temporal patterns of fire (Moritz and Krawchuk, 2008; Krawchuk *et al*., 2009; Moritz *et al*., 2010) forged clear parallels to the established field of biogeography, for example, understanding the distribution of species and ecosystems in space and time (Parisien and Moritz, 2009) and links to the "pattern and process" emphasis of landscape ecology (Turner, 1989). Several related definitions have subsequently been proposed (e.g., Medler, 2010; Yool, 2010; Bowman and Murphy, 2011), with possibly the most expansive including the "synthesis of academic disciplines from biological sciences, physical sciences, and social sciences" (Bowman *et al*., 2013). We take this opportunity to suggest that pyrogeography further includes a synthesis contributed by the statistical and mathematical sciences.

Despite advances in global pyrogeography and the increasing availability of global fire data, its use in model development to project potential patterns of global fire into the future is still relatively rare. Here, with a goal of engaging the broader statistical community in deeper analysis of global fire data products to inform assessments of climate change impacts and environmental change, we (i) provide an overview on theory of biophysical constraints over fire and fire "regimes" and the role of fire in the biosphere–atmosphere; then (ii) describe general approaches being used for modern-era global fire–climate assessment; (iii) summarize opportunities and pitfalls in the public-access global fire datasets; (iv) demonstrate data used as explanatory variables; and (v) conclude to highlight thinking on next steps for analysis of global fire data in the context of global change.

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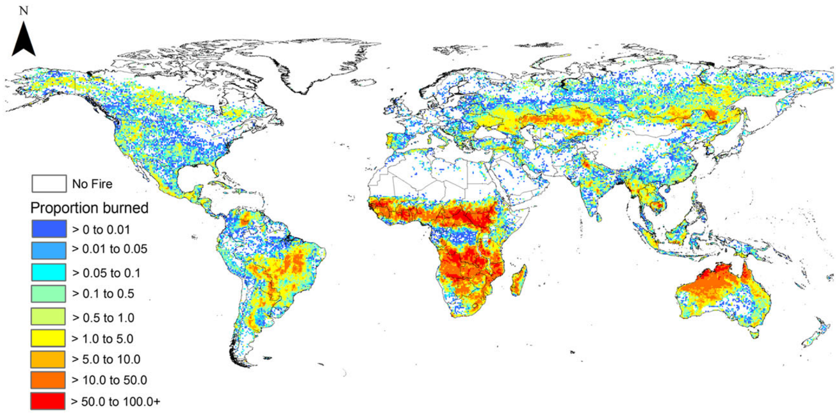

Figure 1. Global area burned illustrated as proportion of terrestrial area burned over the period 1996 to 2009 based on the GFED database (http://www.globalfiredata.org/). Proportion burned is burned area (ha) per 0.5° cell divided by terrestrial area of each cell; terrestrial area was calculated based on the Mollweide equal area projection. The white and dark blue areas of the globe indicate areas with less than 1% burned, with dark blue representing a proportion burned >0 to 0.01. Values over 100 indicate parts of the cell burned more than once during the interval of record

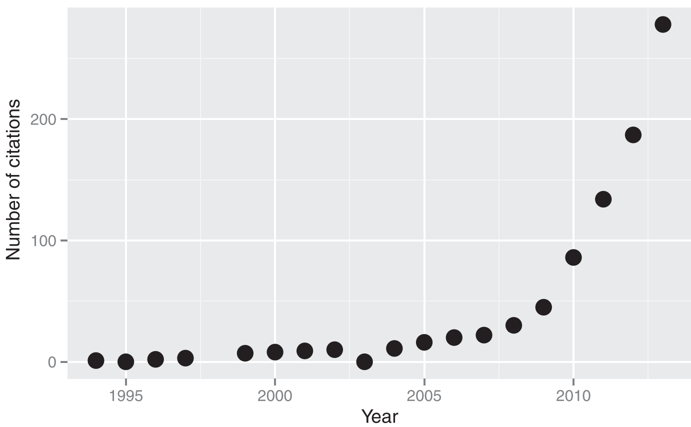

Figure 2. The appearance and exponential increase of the term "pyrogeography" in the literature, according to a Google Scholar search from 1994 to 2013

2. CONSTRAINTS ON FIRE REGIMES, AND FIRE AS A BIOSPHERE–ATMOSPHERE PROCESS

A simple conceptual model of fire activity can be characterized as fire requiring vegetative resources to burn, dry season conditions that increase fuel flammability and support the combustion process, and a coinciding ignition agent (Figure 3). Together, these three components comprise the basic constraints on patterns of burning at broad scales of space and time, forming the "fire regime triangle" of controls (Moritz *et al*., 2005; Krawchuk *et al*., 2009; Parisien and Moritz, 2009; Whitlock *et al*., 2010). The fire regime of an ecosystem (e.g., Gill, 1975) emerges from the fire regime triangle of controls and is traditionally characterized by metrics of fire frequency, size and/or area burned, seasonality, and intensity (i.e., heat released); some definitions include fire type (ie., surface and crown fire) or post-fire ecological effects as severity. Ideally, the characterization of fire regime for an area would entail a quantitative description of these metrics, which should include the statistical distribution of each and how they covary. Modeling the three families of controls on global patterns of fire and their expressions as parts of the fire regime poses major analytical challenges in pyrogeographic analysis.

Fire regimes participate in the global environment through a relationship between the biosphere and atmosphere. Fire is part of the global carbon system as a form of fast respiration through combustion of plant matter that releases CO_2 and other greenhouse gases (e.g., N_20 and CH_4), photochemically reactive compounds (e.g., CO and NO_x), and particulate matter (PM) to the atmosphere (Urbanski *et al*., 2009). In most regions of the world, the carbon released by fire is resequestered through photosynthesis of regenerating plants, leading to accumulation of biomass. But where fire contributes to long-term land cover change such as in the Amazonian forest, or burning of long-sequestered biomass such as in high-latitude or tropical peatlands, there can be a net positive flux of CO_2 from the biosphere (van der Werf *et al*., 2010). Whether as a net increase or as transient pulses of CO_2, CH_4, and so on, the contribution of fire to atmospheric chemistry links it to global climate (Page *et al*., 2002; Urbanski *et al*., 2009). Climate, in turn, dictates where and when burning is possible through its control over periods of dry and warm weather, and ideally wind, as well as gradients in the availability of biomass to burn. Ignition sources, some but not all of which are also linked to climate, including lightning, human causes, and occasionally volcanoes, act as "switches" *sensu* Bradstock (2010) to turn available resources and conditions into a vegetation fire. Patterns of biogeography, climatology, and human settlement therefore contribute to spatial and temporal variability in the fire environment, which ultimately shapes the geography of the fire footprint we see today.

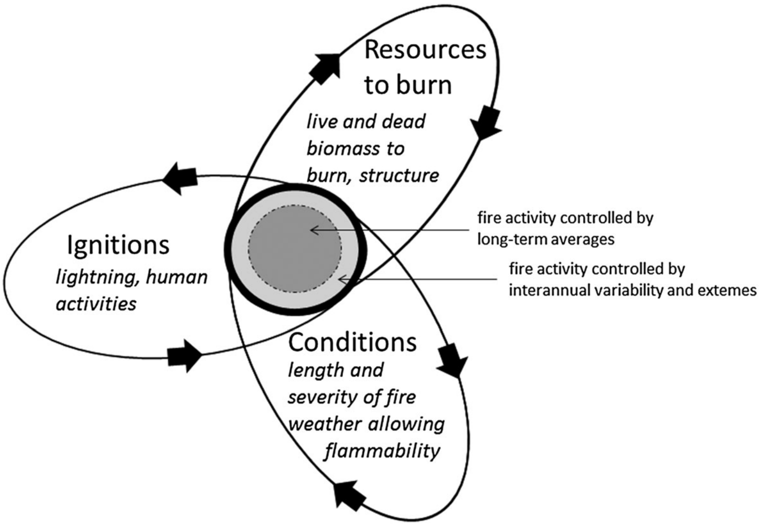

Figure 3. A conceptual model of the biophysical controls over fire activity, expressed as a fire regime "triangle." The three main contributing factors include resources to burn, conditions for burning, and an ignition agent. Moritz *et al*. (2012) propose a core of chronic, predictable fire activity controlled by long-term environmental norms complemented by additional variability controlled by inter-annual environmental fluctuations. (After Krawchuk and Moritz, 2011)

3. THREE GENERAL APPROACHES USED FOR ASSESSING MODERN GLOBAL FIRE–CLIMATE RELATIONSHIPS

3.1. Fire weather index models

Global patterns in current and potential future fire environments have been quantified through indices that integrate daily weather data using a base set of calculations to estimate fuel dryness and burning conditions. Examples of these "fire weather indices" address only one of the three controls over fire regimes, that is, flammability conditions, and include the Canadian Fire Weather Index System (Van Wagner, 1987), the US National Fire Danger Rating System (Bradshaw *et al*., 1978), and Australia's Forest Fire Danger Index (McArthur, 1967; Noble *et al*., 1980). These indices were initially developed for fire suppression and management, contributing to fire behavior estimates and public fire rating systems. The daily indices can be aggregated to quantify weekly, monthly, or seasonal variability in fire weather, and projections of future fire weather can be obtained based on manipulated output from Global Circulation Models (GCMs). For example, the metrics have been used to project future changes in fire weather severity and duration of the fire season under global climate change (e.g., Flannigan *et al*., 2013; see Figures 4–6 in Scholes and Settele, 2014), assuming that fire activity will increase in step with fire weather indices. While valuable, a strong caveat of future projections of fire based on the meteorological, fire weather index approach alone is an absence of explicit accounting for changes in the distribution of fuel for burning or global patterns of potential fire initiation.

3.2. Statistical–correlative fire models

Statistical–correlative models of empirical data provide a rigorous method to examine environmental characteristics that explain spatial and temporal patterns of global fire. Some of the earliest research on global patterns of fire was based on remotely sensed satellite data of global burned area (Chuvieco and Martin, 1994), and numerous studies have since focused on simple characterization of spatial and temporal patterns of either burned area or active fire hotspots (e.g., Carmona-Moreno *et al*., 2005; Le Page *et al*., 2008), see Section 4 in the succeeding texts for an introduction to data types. As a complement to fire pattern analysis, research expanded to fire–climate relationships based on data visualization and bivariate analysis. In one of the first analyses of this ilk, a single year of global (AVHRR satellite sensor) burned area data demonstrated the importance of precipitation, moisture deficit, and biotemperature underlying variability in fire activity (Dwyer *et al*., 2000). Further work has shown, for example, correlations between fire and lightning seasonality, precipitation, metrics of conditions suitable for burning (e.g., Le Page *et al*., 2008), and global population patterns (e.g., Aldersley *et al*., 2011; Bistinas *et al*., 2013; Knorr *et al*., 2013).

The development of multiple regression statistical models provides an opportunity to test the relative influence of numerous explanatory variables corresponding to the three conceptual arms of the fire regime triangle. Such an examination of the "niche" of fire (Moritz and Krawchuk, 2008; Moritz *et al*., 2010) was undertaken globally by Krawchuk *et al*. (2009) using multiple logistic regression analysis and a multiyear dataset to characterize recent historical fire occurrence. The fire occurrence model generated intuitive relationships between resources to burn, conditions promoting flammability, and initiation potential based on explanatory variables including a gradient in net primary productivity (NPP), climatological normals, lightning flash rate, and the human footprint. In particular, Krawchuk *et al*. (2009) demonstrated a fundamental relationship between fire occurrence and NPP as a global, unimodal, hump-shaped curve, which was originally hypothesized by Ryan (1991). The hump-shaped relationship is interpreted as an integration of two constraints over burning: availability of resources/fuel at low values of NPP and by availability of conditions for burning at high values of NPP. This global finding of Krawchuk *et al*. (2009) complements subsequent work on the four switch model (Bradstock, 2010), provided the core gradient underpinning the varying constraints hypothesis (Krawchuk and Moritz, 2011), and has been revisited in recent work focused on the intermediate fire-productivity relationship (e.g., Pausas and Ribeiro, 2013; Bowman *et al*. 2014). It is worth noting that intermediate fire-productivity relationships have also been described in other contexts or spatial scales (e.g., Bond and van Wilgen, 1996; Pausas and Bradstock, 2007; van der Werf *et al*., 2008). The emerging pedigree of this basic pyrogeographic concept demonstrates the strength of statistical–correlative methods.

The success in development and interpretation of statistical–correlative models of global fire suggests they provide a robust top-down, macroscaled understanding of mechanisms controlling the fire process and could be useful for asking "what if?" questions of projecting the potential future of fire. A multiple regression model built with climate normals supports statistical prediction of future fire occurrence using model parameter estimates and simulated climate normal data from GCMs to advance our understanding of potential changes in global fire with altered climate. For example, the global fire occurrence model developed by Krawchuk *et al*. (2009) based on output from one GCM showed that through changes in both resources and conditions for fire, climate change may lead to increases in fire in some parts of the world but decreases in others; the latter attributed to the effect of increasing temperatures leading to moisture stress, decreases in plant productivity, and ergo fire occurrence. Further development by Moritz *et al*. (2012) highlighted uncertainty generated by projections from an ensemble of 16 different GCMs, including areas of consistency and disagreement in future projections of fire but an overall increase in global burning expected over the coming decades.

A significant challenge to any statistical–correlative formulation of future fire is that climate acts on different aspects of the fire environment at different rates. For example, we know that past changes in climate have altered the distribution of vegetation, or resources to burn, as well as fire itself (e.g., Higuera *et al*., 2009). Two general methods in existing statistical frameworks have been used to capture climate-driven changes in availability of biomass to burn alongside changes in conditions for burning. The first method develops a regression model that includes climate covariates representing spatial variation in resources/biomass to burn and conditions for burning and assumes that retreat and advance of vegetation, in other words plant die-back, dispersal and establishment capacity, under future climate conditions is unlimited and rapid, and will track changes in climate variables directly. The second method makes simple assumptions about the rate of fire-relevant shifts in resources to burn, and develops regression models for near-future projections where resource-related variables (e.g., a metric of NPP or land cover type) are kept constant and climate variables change, and develop a second set of models for distant-future that allow vegetation to vary directly with climate, as in method one. These ideas are demonstrated by Krawchuk *et al*. (2009). Both methods are rough proxies, and further development is required to refine the approach. Although it is difficult to formally include vegetation–climate relationships in statistical fire models, their effects may be approximated or even assumed to be second-order effects for example, if conditions supporting fire are changing faster than vegetation and/or projections are made for near-future forecasts.

Statistical–correlative studies that go beyond examination and projection of fire occurrence, and move toward a more holistic quantification of future fire regimes, are urgently needed. Statistical characterization based on aggregation techniques for a suite of regime metrics provides us with preliminary understanding of multifaceted patterns of fire, using characteristics that we can currently map (e.g., Chuvieco *et al*., 2008; Archibald *et al*., 2013). However, identifying climatic drivers of a fire regime requires further analysis, either through research into the regime "types" themselves (e.g., Boulanger *et al*., 2013) or through the particular metrics of regime. For example, development of statistical models for each individual regime metric (occurrence, burned area, seasonality, and intensity), projection of potential future changes in that metric from environmental change, followed by a method for clustering into discrete future regime types, could provide a preliminary examination in a statistical framework. It should be noted, however, that all of these metrics likely vary/covary continuously, and identification of discrete entities or types is a function of our own need to classify a process that more realistically is a gradient, and the outcome may be somewhat arbitrary or transient. Existing statistical projections at the global scale (Krawchuk *et al*., 2009; Moritz *et al*., 2012) have focused only on fire occurrence/probability, leaving obvious open questions about the future of fire from the perspective of a more comprehensive, multifaceted fire regime.

3.3. Fire process models

Process-based fire models are often considered bottom-up and mechanistic, in that they characterize particular aspects of fire initiation, growth, effect, and "death" in response to variability in soil, vegetation, climate, or weather. The parameters of fire process models can come from statistical models of empirical data (e.g., Cumming, 2001; Krawchuk and Cumming, 2011) but often include idealized deterministic relationships (Prentice *et al*., 2011). These bottom-up models are attractive in that fire effects emerge from the constituent processes of the model. Most process-based global models operate at coarse spatial resolutions constrained by data availability, but constituent modules often support daily, monthly, or annual estimates. In the context of climate change, different facets of fire regime can be analyzed from process models for change in their distribution in response to altered climate fed by GCM projections. For example, Pechony and Shindell (2010) demonstrate changes in fire activity through a process-based fire model based on climate data from GCMs, data indices representing fire initiation and suppression behavior, and vegetation data that vary through time though are not linked dynamically. One step further, Dynamic Global Vegetation Models (DGVMs) that include fire models (or modules) provide the opportunity to explicitly integrate shifts in vegetation, fire conditions, and initiation in response to climate over time and can characterize multiple facets of the fire regime depending on their structure and spatio-temporal resolution. The potential to capture the feedbacks in the fire–vegetation–climate response is another important advantage of DGVMs.

Neither process models nor statistical–correlative models perfectly capture the global fire footprint. The process models can result in poor depiction of fire when compared against observations from the global fire datasets (e.g., Scholze *et al*., 2006; Gonzalez *et al*., 2010; Prentice *et al*., 2011; Li *et al*., 2013), suggesting key constraints are not included or not represented adequately. The top-down statistical–correlative frameworks seem able to capture the observed spatial pattern of fire but do so through generalized "stochastic–mechanistic" explanatory variables. Bistinas *et al*. (2014) highlight that assumed processes contributing to fire modules in DGVMs are largely untested and provide a useful statistical test of key assumptions as guidance for future development of fire modules within DGVMs. An attempt at fusion of the information from statistical assessments of modern fire with the process elements of DGVMs to maximize the potential strength of each framework seems promising, whether at the regional or global scale. This fusion in the statistical-mechanistic and process-mechanistic frameworks requires that practitioners pro-actively aim to merge disciplinary lines that are sometimes difficult to cross.

4. GLOBAL FIRE DATA: OPPORTUNITIES AND PITFALLS

4.1. Data opportunities

The various publicly available global fire datasets are ripe for further advancement in statistical analysis. Understanding global fire–vegetation–climate relationships is crucial in supporting carbon accounting (van der Werf *et al*., 2010), ecosystem conservation (Gonzalez *et al*., 2010), changes in fire characteristics (Moritz *et al*., 2012), fire regime assessment (Archibald *et al*., 2013), and climate change impacts (Scholes and Settele, 2014). Mouillot *et al*. (2014) provide a comprehensive review of the global fire products, but here we include a brief summary of data with an eye to those with a rich temporal and spatial archive.

Data from the MODIS sensor onboard the Aqua and Terra satellites offered through the NASA program are frequently used for global fire estimates. The MODIS sensors collect a vast array of data to develop products for global assessments (MODIS Web 2014), two of which relate to fire activity and biomass burning (Justice, 2014), the active fire and burned area products. The MODIS active fire data are based on thermal anomalies of fire " hotspots," detected as strong emission of mid-infrared radiation (Justice *et al*., 2002) that can be used to estimate spatial pattern of burning and to calculate seasonality of fire. The minimum detection of fires is roughly 50 to 900 m^2, with hotspots archived at a 1-km spatial resolution. The fire radiative power signal from hotspots can be interpreted to estimate intensity of fire (Wooster, 2002). The data are available to download at a variety of temporal resolutions based on the four-time daily overpass of two satellites, including daily, 8-day, or monthly aggregations.

A second product is the MODIS burned area dataset based on a hybrid analysis of the active 1-km fire data and a 500-m reflectance product (Giglio *et al*., 2009; compare to Roy *et al*., 2008). The MODIS burned area data contribute to the GFED dataset (Global Fire [Emissions] Data (GFED) 2014) assembled to estimate monthly burned area at 0.25° or 0.5° resolution (Giglio *et al*., 2013) and estimate fire emissions to the atmosphere (van der Werf *et al*., 2010). The GFED dataset provides the longest duration of global burned area estimates (1996 to current) by integrating MODIS with other sensors available prior to MODIS (Giglio *et al*., 2009, 2013). The MODIS sensor began collection of data onboard Terra in November 2000 and onboard Aqua in July 2002, so we now have a global archive of over a decade. The MODIS active fire and burned area, and GFED burned area datasets are freely available and served online. The VIIRS active fire detection system (VIIRS active fire, 2014) onboard the Suomi satellite is beginning to contribute data to the global archive, aimed to continue the near real-time monitoring capabilities established by MODIS, but is still undergoing calibration and evaluation.

4.2. Pitfalls and pauses for thought

The coverage of modern global fire activity provided by the available remotely sensed fire data archive contributes excellent information on patterns of fire but not without its uncertainties and warts. Here, we summarize particular caveats of the satellite-based remotely sensed fire data products.

Short duration of the data is a challenge of most remotely sensed products. The timeframe of less than 20 years coverage is not long enough to capture representative data from locations with moderate or low-frequency fire return intervals or characterize the full variability in events contributing to fire regimes. Accordingly, the absence of fire in the satellite record for some regions of the world does not necessarily mean an area is fire-free over ecological time scales of decades to centuries (see *What is a zero* in the succeeding texts). In contrast, some areas that appear to have a signature of very frequent fires or large areas burned in the data-record may in fact not be very fire-prone; in other words, the last decade of observation could include anomalous or rare events.

Furthermore, the fire-from-space perspective provided by satellite data lacks fine-resolution in behavior and fire effects important to many local and landscape studies where we recognize the importance of a mosaic of fire and effects across scales from centimeters to kilometers (e.g., Agee, 1996).

Layers of uncertainty are associated with the fire data archived in the active and burned area datasets. There is a sequence of filtering that leads to the data provided to the user: first, fire behavior actually happens on the ground, from which some characteristics of burning are detected by the satellite sensor at a set sensitivity and spatial and temporal resolution, from which postacquisition processing determines the quality of data and modifies the end-product, from which one will likely aggregate or manipulate for the modeling exercise. The burned area and hotspot data include estimates of uncertainty (Giglio *et al*., 2009) but still do not guarantee perfect data. Errors of omission (e.g., Figure 4) include understory burns obscured from the sensor by forest canopy, small fires of low intensity and/or short duration, and omission of fires due to cloud cover or smoke (Giglio *et al*., 2009; Loboda *et al*., 2011). Errors of commission include detected hotspots that are not fire, including industrial heat source (Hantston *et al*., 2013). The data analyst must always recognize a suite of potential errors in the data contributing to the statistical signal-to-noise ratio. Uncertainty estimates that accompany the data products are helpful but still require thoughtful interpretation by the scientist using the data. Somewhat related, the active fire and burned area datasets do not easily discriminate the number of individual fires or the area burned by particular events. Accordingly, a large area burned in a 1-month period could represent one event or multiple small events so that the spatial configuration of the fire footprint is not currently available.

Fires detected from satellite sensors are a combination of events from human-ignitions and lightning-ignitions with no way of discern the two. A mixture of biophysical and eco-cultural processes generates the patterns we see in the global fire record. Human-caused and lightning-caused fires are likely to have different constraints on their activity. Fires in many of the wet tropical rainforests are assumed caused by humans, from clearing of forest for pasturage and agriculture (Cochrane, 2003), whereas the majority of fires in North American boreal forests are caused by lightning (Kasischke and Turetsky, 2006). However, even within similar biogeoclimatic regions, the level of human influence may vary, and this heterogeneity can propagate through estimators to spatial predictions of fire activity where there is in fact little or none.

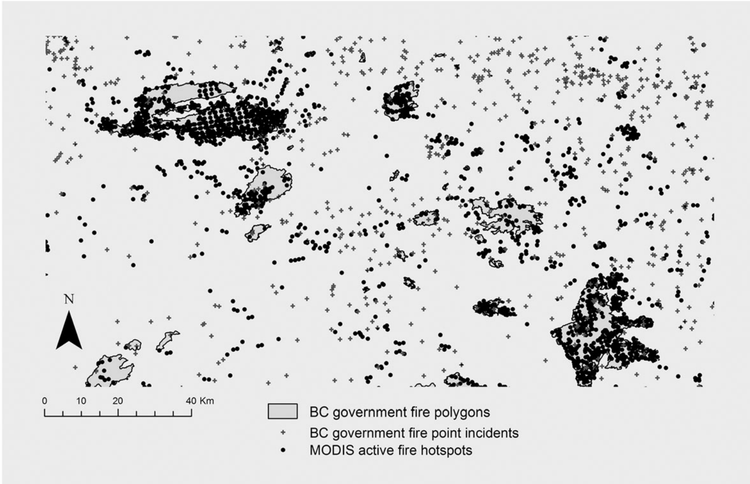

Figure 4. A comparison of MODIS active hotspots against fire polygons and point incidents mapped by the provincial government of British Columbia, Canada (http://www.data.gov.bc.ca/). Data are presented for a matched period from January 2000 to 2012 in a 160 km2 region of central interior British Columbia (BC). MODIS hotpots were screened to include those attributed with 100% certainty in the records. Management polygons and point incidents are not perfect representations of fire. Point incidents include any smoke-related or fire-related incident reported to government suppression and management agencies and are known to include location errors. Fire polygons are mapped by the fire agency supplemented with satellite imagery of fire perimeters and are considered the best available data for the region. Numerous hotspots occur outside areas mapped by fire managers as incidents or polygons, illustrating potential errors of commission; large areas of management polygons do not include hotspots and suggest potential errors of omission

What is a zero? The question of interpreting nil values in the global fire datasets has been an ongoing discussion in our research group and includes aspects of scale, technical limitations, and near-nil values. As mentioned earlier, the temporal duration of the satellite data is relatively short in comparison to ecological time or that of fire regime. For example, while many grassland, woodland, and open-forest ecosystems are resilient under a regime of low severity and low intensity fire every decade or two (e.g., Swetnam *et al*., 1999), forest systems of many temperate or boreal regions burn at higher intensities with a greater time since last fire that varies on the range of decades to centuries (e.g., Johnson *et al*., 1998). Clearly, the latter timescales are not fully supported in the satellite record. While at first blush this short period might suggest the data are inappropriate for fruitful global fire assessment, the coarse-resolution archive provides a service in this regard. Coarse-resolution data, where a broad spatial and/or temporal resolution is used as the study unit, is more likely to capture at least one instance of low-frequency events that may characterize the region. For example, a space-time "voxel" with dimensions of 100 km and 10 years is more likely to capture at least one instance of a low-return interval event that characterizes the region than is a 10-km and 1-year voxel or a 1-km and 1-month voxel. Furthermore, though the point-level frequency of fire events may be rare, these low-frequency events can be characterized in a statistical–correlative model using a space-for-time representation where areas of similar climate and/or vegetation capture instances of events then used to characterize a low probability across the broader system. The spatial and temporal resolution used to analyze data has implications on the structure of the data, the data model including "missingness" of fire events, the explanatory variables sensible at any given scale, computing power required for estimation, and our understanding of fire interpreted from the results.

The question of interpreting nil values is important with respect to detection of fire events. As introduced earlier, some fires might not be detected by satellite if they burn in the understory of a thicker forest canopy, for short duration or at low intensity, under cloudy or smoky conditions (e.g., Loboda *et al*., 2011). Regional or national fire atlases based on management records of fire activity are available for some parts of the world and clearly show differences in fire recorded regionally from fire detected by satellite (Figure 4; Giglio *et al*., 2006). Though post-processing of satellite data aims to obtain the best estimates of active fire or burned area as possible, it is difficult to avoid misclassification of events such as differentiation of pile burning or agricultural fire from forest, bushfire, or savannah fire. Depending on the question being asked, the clear definition of what fire events are being captured and included, or potentially not captured, requires thought and should contribute to interpretation of model output.

A look into the global fire data from either a spatial or non-spatial perspective will quickly bring to eye the question of nil versus near-nil values. Some regions of the globe have experienced relatively small, but still visible-from-satellite amounts of fire. For example, in the GFED burned area records, roughly 13% of 0.5° units experience a burned area of greater than zero but less than 1% (Figure 1, proportion of burning >0 to 0.01) over a 13-year period. Our earlier work on global fire occurrence (Krawchuk *et al*., 2009; Moritz *et al*., 2012) involved simplification of active fire observations into a categorical grid where presence of fire over a decadal-climatological period was represented by "1," regardless the extent of burning or the number of times burned. This simplification was a first step to understanding the potential for global alteration in fire distribution with climate change (Krawchuk *et al*., 2009) and among an ensemble of GCMs (Moritz *et al*., 2012). The discretization likely affected estimates of increases or decreases in fire with future climate change, such that an intuitive next step in global pyrogeographic analysis is to work through analyses of burned area and/or modified estimates of fire occurrence/frequency.

5. EXPLANATORY DATA: CONDITIONS, RESOURCES, AND IGNITION AGENTS

Beyond the exploration of fire data themselves, there are many sources of data that contribute geographic information on the biophysical resources and conditions expected to regulate where and when we see fire. For fire models to contribute toward ongoing global climate impacts assessment, it is necessary that explanatory variables used in statistical–correlative models include data in a manner that allows for projection of future fire with climate change. Climate data are available for historical, current, and future periods as output from GCMs contributed through the CMIP archive (Taylor *et al*., 2012) and other servers of climate change data associated with the physical science arm providing information to the Intergovernmental Panel on Climate Change (IPCC, 2013). Given the variability demonstrated among future projections from GCMs, current best practice is to consult these data as ensembles covering a clearly identified range of future emissions scenarios or representative concentration pathways (e.g., Moritz *et al*., 2012). Technical aspects of the climate data can be acquired with the datasets themselves, and we will not go into depth here. The native spatial resolution of a GCM is generally around 250-km and most frequently aggregated at a 30-year climatological resolution due to concerns that finer temporal scales of the data are not as robust. Spatial downscaling and manipulation of data can provide finer spatial and temporal resolution at the expense of increases in computing storage space and brings further model-based caveats and assumptions in exchange for more detail.

Scale is important in considering relevant explanatory variables to be included in pyrogeographic statistical models. Within the last few years, the growth in publicly available earth-atmosphere data served online has increased so that acquisition and examination of potential candidate variables for stochastic–mechanistic understanding of fire regime is moderately straightforward. Similar to the climate data from GCMs, these data are often served at a "climatological" scale and at relatively coarse spatial resolution due to constraints of data acquisition, validation, and storage. For example, Krawchuk *et al*. (2009) use a 100-km spatial resolution and decadal temporal resolution to examine global patterns in fire occurrence based on active fire data and characterize the distribution of fire using climatological normals downscaled by collaborators. Moritz *et al*. (2012) clarify the focus on climatological versus seasonal or inter-annual scales and extremes in a conceptual figure of global pyrogeography (Figure 3), proposing that climate norms may not be adequate for characterizing fire activity in certain parts of the world. It is an open question as to where normals might be strongest predictors and where extremes and inter-annual variation might contribute more information. Then again, it is possible that inter-annual variation or extremes in key climate parameters may be captured quite well by longer term norms as suggested by Parisien *et al*. (*in press*) in Canada's boreal forest. The global burned area data are available at monthly resolution but to use these products effectively for change assessments, explanatory variables for modern and future projections must, ideally, match this scaling; alternatively, the fire data can be aggregated. The key for using these data effectively is to propose an appropriate scale of data, both in resolution and extent, to match the fire data question at hand, and ask, "What does a particular modeling input and output actually represent, relative to the resolution of the grid being used?"

One aspect of the fire environment that is particularly tricky to capture in any model is initiation potential (ignition), whether by lightning or humans. At a landscape or regional scale, fire initiation potential is often characterized by lightning activity and/or human footprint; however, both these causal agents include nuances such that the fire-relevant process is difficult to capture in a model of global scale. For example, regional studies indicate the polarity and return strength (Rakov and Huffines, 2003) of lightning affects the likelihood of a lightning strike resulting in a fire event, and the efficiency of the strike likely varies with vegetation type, antecedent dryness, and amount of precipitation co-occurring during a thunderstorm (Latham and Schlieter, 1989). Representing these contingencies at a global scale is difficult given global data on lightning are available as annual or monthly climatological flash rates from the LIS/OTD dataset (Goodman, 2014). While we know that lightning causes fires, lightning flash rates are weak predictors of empirical global fire patterns (Krawchuk *et al*., 2009; Bistinas *et al*., 2014), and likely confounded by the mixture of fire causes represented in global burned area and active fire data. Further, for global change assessment, there is little certainty in the potential for shifts in lightning activity such that spatial patterns in flash rate would likely need to be considered constant.

Quantification of fire's relationship to the global human footprint is equally complicated to that of fire's relationship to patterns of lightning. We know from local and regional data that humans cause fires through railway sparks, downed power lines, tossed cigarettes, arson, accidental fire escape, land clearing, or woodpile burning. But humans also suppress fires and are responsible for land cover change that can lead to reduced or fragmented resources for fire to burn. Regional analyses show fire occurrence has a hump-shaped relationship with population size, where fire occurrence is minimal at low and high values and burned area decreases with population size (e.g., Syphard *et al*., 2007). At a global scale, studies of current patterns in fire show population explains variability in area burned only in some parts of the world, and with spatially varying polarity in this relationship (Bistinas *et al*., 2013). Knorr *et al*. (2013) show a generalized negative relationship between population and burned area, indicating that only areas with less than one person per square kilometer demonstrate positive correlation with fire activity. The messaging of a reduction in burned area with increased population has been interpreted as a negative effect of humans on fire; however, it is critical to recognize that this does not explicitly assess the question of how many fires are actually ignited by humans. In many parts of the world, we expect humans cause the majority of fires; for example, our current understanding of fire in wet tropical forest is that fire is human-caused from clearing of forest for pasturage and agriculture and would not occur in the absence of human actions (Cochrane, 2003). Important open questions remain about where, when, and at what scale humans affect fire activity and how one might distinguish between the effects of humans on fire initiation versus that on land cover change or fragmentation.

If projection of future fire scenarios is the goal, ideally, explanatory variables of interest would need to be projected to future, or alternatively, some held constant with caveats clearly outlined. Similar to lightning, future projections of fire that include human footprint would either need to incorporate spatial predictions of future population and "footprint" or assume these to be constant. One of the benefits of quantifying fire occurrence at a coarse spatial and temporal scale, *sensu* Krawchuk *et al*. (2009) and Moritz *et al*. (2012), was that supplementary analyses suggested ignition/initiation was likely not limiting for the majority of the globe at the resolution of fires per decade per 50-to-100-km^2 voxel. It is important to consider in what locations and at what resolution ignitions are limiting for fire activity. Solid research and thinking about the driving processes contributing to the fire phenomenon of interest, then exploration of available variables that can represent that process—or perhaps more importantly, the derivation of new nuances to them—are an exciting and key step for further development of our understanding of global fire.

6. CONCLUSIONS

The next steps in global fire analysis to support global change impact assessment requires leveraging of what has already been completed, and moving forward with more advanced statistical methods or creative ways to characterize fire regime data. In this era of mass computing, file size and management are unlikely to constrain the artful statistician or keen pyrogeographic researcher. Statistical packages and software are generally able to wrangle large datasets and take advantage of computing clusters, and for many global pyrogeographic questions, only a trustworthy desktop is required. Climate, land cover, and other ancillary data are readily available online to support thoughtful examination of the drivers underpinning patterns of fire occurrence, intensity, area burned, and seasonality at the resolution supported by GCMs. Development of methods to quantify and visualize uncertainty, including statistical uncertainty, fire uncertainty, and that associated with ensembles of GCMs, are all critical to next steps of climate change assessment. Future learning about fire–climate relationships will come from development of statistical–correlative models based on best practices of data exploration, learning the statistical "mechanics" of the fire regime, collaboration with the process-model community, and creativity.

Global pyrogeography is a hot topic in the global climate change domain; pardon the pun. Fire–climate feedbacks are a growing concern, particularly in tropical forest or peatland systems and arctic near-arctic peatland permafrost (Mack *et al*., 2011), as are fire–vegetation feedbacks. Questions remain as to whether climate change is contributing to large "mega-fires" and high severity events across temperate and boreal forest systems (Stephens *et al*., 2014). The potential for catastrophic shifts in ecosystems via fire activity beyond the sensitive slopes of resilience for current stable states is a concern for grassland/savanna, woodland, and forest ecosystems (e.g., Buma *et al*., 2013). In the recent release of the fifth IPCC assessment report, fire was discussed in the document presented by Working Group II on Impacts, Adaptation and Vulnerability (Scholes and Settele, 2014) to climate change but still with relatively lean information at a synthetic, global scale, highlighting how much more we need to know about the future of fire across the globe. There is clearly a broad need for further analyses of the global fire datasets to contribute a better understanding of fire regime in biosphere–atmosphere processes and to inform future climate change assessments and studies of vulnerability.

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