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International Journal of Wildland Fire **2008**, *17*, 1–7

Fire Climatology in the western United States: introduction to special issue

Thomas W. Swetnam[A] *and R. Scott Anderson*[B]

[A]Laboratory of Tree-Ring Research, The University of Arizona, Tucson, AZ 85721, USA.
Email: tswetnam@ltrr.arizona.edu
[B]Center for Environmental Sciences and Quaternary Sciences Program,
Northern Arizona University, Flagstaff, AZ 86011, USA.
Email: Scott.Anderson@nau.edu

Abstract. Advances in fire climatology have derived from recent studies of modern and paleoecological records. We convened a series of workshops and a conference session to report and review regional-scale findings, and these meetings led to the 10 papers in this special issue. Two papers focus on fire and climate patterns in the modern era using documentary records, four papers utilise tree rings to evaluate recent centuries of change, and four papers evaluate charcoal and pollen in lake, bog, and alluvial sediments over the Holocene. Here we summarise some of the key findings from these papers in the context of other recent fire climatology literature. These studies illustrate the value of long-term perspectives and spatial networks of fire and climate data in discovering the patterns and modes of past fire regime and climate variations.

Warming temperatures and increasing drought occurrence in many regions of the world are resulting in widespread ecosystem impacts (ACIA 2005; IPCC 2007). One of the most dramatic ecological responses to climate change is wildfire. The importance of climate in driving past, present, and future fire regimes has greatly increased the need for better understanding of fire climatology. As distinct from fire meteorology, which addresses relatively fine-scale spatial processes over short time periods (i.e. days to weeks), fire climatology addresses broad-scale spatial and temporal processes (i.e. seasons to millennia).

Advances in fire climatology in recent years have been facilitated by improved historical datasets and understanding of regional to global climate variability and fire regime responses (Veblen *et al.* 2003). The 'Fire and Forest Meteorology' Conferences and Proceedings (extending back to 1970s, and see the special issue of *International Journal of Wildland Fire* **16**(2), 2007) include a plethora of foundational papers on fire meteorology and climatology, but primarily focusing on 20th century datasets. A rich literature on pre-20th century fire climatology has developed in recent years using paleoecological approaches, specifically fire scars and forest age structures from tree rings, and charcoal in lakes, bogs, soils, and alluvial sediments. The new availability of long time series of fire occurrence and extent in broad spatial networks has been particularly important (Fig. 1) (e.g. Kitzberger *et al.* 2007; Power *et al.* 2008). At the same time that fire history data networks have improved, spatial/temporal networks of instrumental and reconstructed climate variables (e.g. temperature, precipitation, drought and ocean-atmosphere indices) have also become more available for comparisons (e.g. see NOAA's Paleoclimatology Program, http://www.ncdc.noaa.gov/paleo/paleo.html, accessed 7 February 2008). Further impetus to fire climatology advances include a revolution in our understanding of global ocean-atmosphere oscillations and teleconnections to regional climates (e.g. the El Niño–Southern Oscillation [ENSO] and the Pacific Decadal Oscillation [PDO], McCabe and Dettinger 1999; Diaz and Markgraf 2000; McCabe *et al.* 2004), and increasing evidence of secular warming and drought trends in the boreal zones, Western North America, and elsewhere (ACIA 2005; IPCC 2007).

We convened a series of workshops and a conference session for the purpose of promoting communications and collaborations among paleoecologists, fire historians, and climatologists working in western North America. The first workshop was held in Tucson in March 2002, and another was held in May 2005 (see http://www4.nau.edu/firehistory/ for abstracts, accessed 7 February 2008). We conceived of this special issue on fire climatology at the Flagstaff workshop, with a goal of reporting state-of-the-art, regional case studies, including both modern and paleofire data and methods. Subsequently, in November 2006 we organised a session on fire climatology at the 3rd International Fire Ecology & Management Congress in San Diego. Most authors of the papers included in this special issue spoke at that session.

A defining feature of the Tucson and Flagstaff workshops and the session in San Diego was inclusion of both modern and paleofire perspectives. The philosophy of this interdisciplinary approach is that integration of the unique insights from historical studies working with different data types across a range of spatial and temporal scales and resolutions can provide broader and deeper understanding of fire climatology. For example, paleofire/climate interpretations benefit from the more detailed and spatially extensive records available from modern documentary sources, particularly in the evaluation of mechanisms and relatively short-term and fine-scale processes. Modern fire/climate interpretations are informed by the

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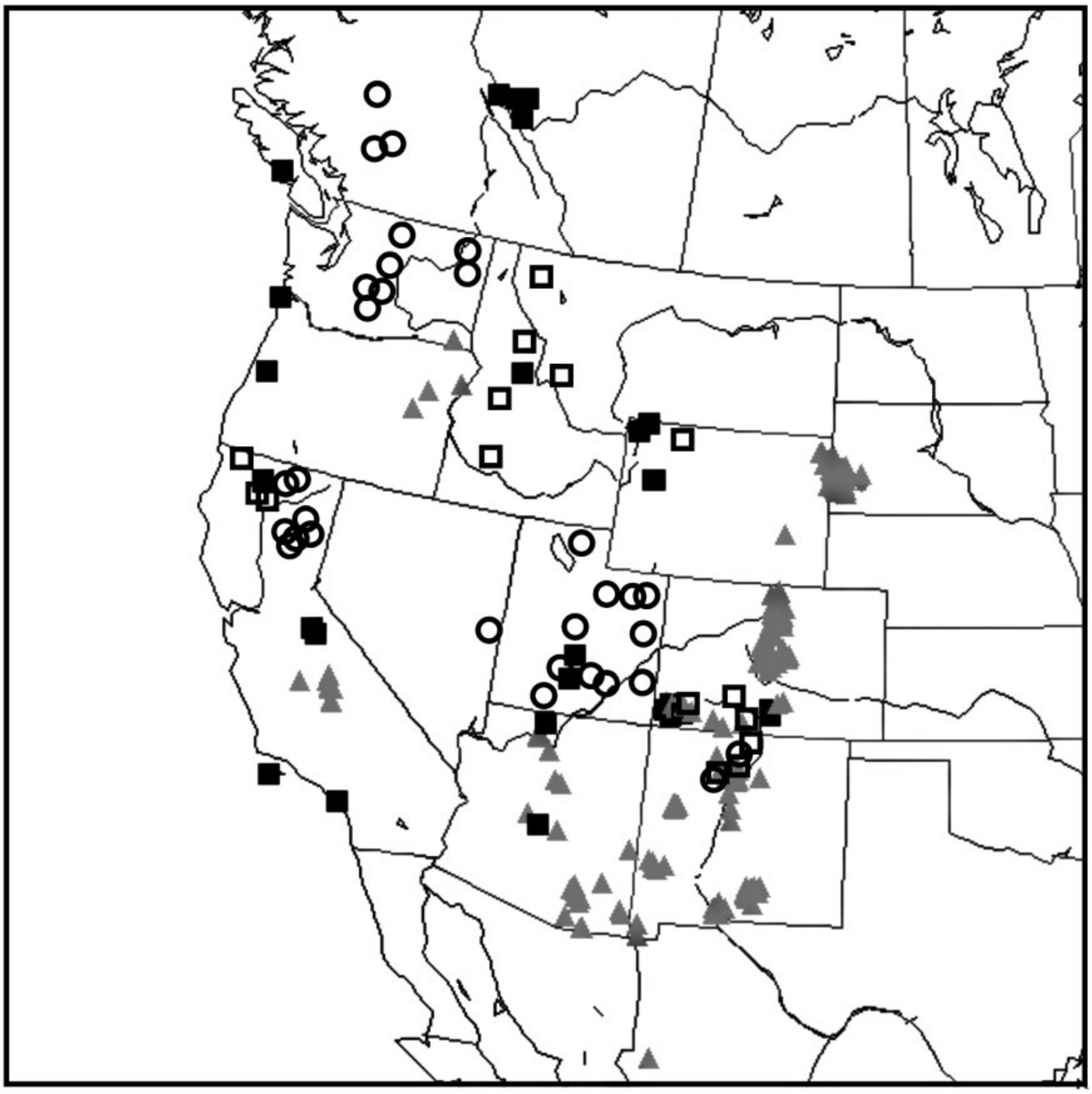

Fig. 1. Published and archived fire history sites in western Canada, USA, and Mexico. Solid black squares are charcoal sediment fire histories archived in the International Multiproxy Paleofire Database (IMPD, see http://www.ngdc.noaa.gov/paleo/impd, accessed 7 February 2008); open squares are charcoal/sediment fire histories reported in this special issue that are not yet archived in IMPD; grey triangles are fire-scar/tree-ring fire histories archived in the IMPD; open circles are fire-scar histories reported in this special issue that are not yet archived in IMPD.

much longer paleofire/climate records, illustrating specific fire-climate relationships that are only discernable at longer time scales (e.g. decadal to centennial). Long-term records also provide sufficient temporal replication of events and trends to provide statistical power in tests of significance. The two chief types of paleorecords – fire scars in tree rings and charcoal in sediments – can also be highly useful in a comparative manner, because they have different spatio-temporal resolutions and breadth/length, and so their joint perspectives can provide contrasting or complementary insights about fire regime changes and responses to climate.

Here we summarise some of the key findings from the set of 10 modern and paleofire papers, with a particular focus on new insights that have a bearing on the state of our understanding of fire climatology.

Modern fire climatology from documentary records

Documentary records of fire occurrence – including mapped locations, timing, causes, and areas burned, etc. are becoming more available in compiled databases. National wildfire databases are generally now available for most regions of Canada and the United States spanning two decades or longer of the late 20th century (e.g. Van Wagner 1988; Schmidt *et al*. 2002; Stocks *et al*. 2002). Longer modern datasets have been laboriously compiled by some researchers for smaller regions (e.g. Rollins *et al*.

2002). Although these records typically suffer from incompleteness and various reporting biases, they offer the most detailed available representation of spatial and temporal patterns of fire occurrence. A growing literature has made use of these records to evaluate broad-scale fire-climate patterns (e.g. Westerling *et al*. 2003, 2006; Gillett *et al*. 2004; Keeley 2004; McKenzie *et al*. 2004; Collins *et al*. 2006; Crimmins 2006; Holden *et al*. 2007; Morgan *et al*. in press).

In this special issue we include two modern fire climatology papers. The first, by Bartlein *et al*. (2008), compiles and illustrates the temporal-spatial structure of fire activity over the Western USA for the eleven-year period from 1986 to 1996. Bartlein *et al*. (2008) demonstrate new geographical approaches to fire climatology, which serve to illuminate the nature of modern fire occurrence and variability. This work introduces innovative graphical approaches for visualising the space-time patterns of both lightning and human-caused wildfires in the region. 'Hovmöller diagrams', for example, are applied to show the latitudinal and time-transgressive nature of lightning and human set fires. In a series of annual maps, the biogeographic importance of mountains and vegetation is clearly discerned in driving the spatial density of lightning-set fires (much higher in mountain areas than in lowlands), and the relatively high concentration of human-set fires near population centers and travel corridors. Interested readers may visit a related website, where Bartlein and collaborators have posted other still and animated graphics providing additional detail and insights (http://climate.uoregon.edu/fire/, accessed 7 February 2008).

A second paper on modern fire climatology is a sub-regional case study set in Southern California by Dennison *et al*. (2008). Given the recent series of very large fire events in the chaparral and forest landscapes of this region, this paper is a timely example of how studies of climate variability and fire can be valuable in assessing potential climate causes and mechanisms. They evaluated live fuel moistures (LFM), precipitation variables and remote sensing data from satellites (NDVI) and fire history data from the Santa Monica Mountains for the period 1984 to 2005. They show that most large fires occurred when a LFM threshold below 77% was achieved. Moreover, most large wildfires occurred in the fall when Santa Ana winds were more frequent. Their findings also point to an important role for spring drought, although no long-term trends in spring precipitation and timing were evident in modern data. The potential role of human-caused climate changes (i.e. greenhouse gas-induced warming and drought) in promoting recent large wildfires in Southern California remains an important but largely unresolved question because of the complex interactions of human population changes, weather, climate and fuels during the modern period (Keeley 2004; Syphard *et al*. 2007). Additional modern fire climatology research and longer term perspectives from paleofire investigations will improve our understanding of these complex interactions in this region and elsewhere.

Paleofire climatology from tree rings and fire scars

Tree-ring based fire climatology investigations have flourished in recent years, with numerous publications deriving from investigations at mountain range to regional, and even continental scales (e.g. Veblen *et al*. 2000; Kitzberger *et al*. 2001, 2007; Heyerdahl *et al*. 2002, in press; Swetnam and Baisan 2003; Grissino-Mayer *et al*. 2004; Hessl *et al*. 2004; Brown and Wu 2005; Schoennagel *et al*. 2005; Taylor and Beaty 2005; Sibold and Veblen 2006). These studies have been enabled, in part, by the availability of independent climate reconstructions from tree-ring width and density measurements. They also have been stimulated by recognition among fire historians of the power of network strategies in climatological investigation, involving fire-scar chronology compositing and comparison techniques from numerous sites. A general principle of this strategy is that significant statistical patterns of fire event synchrony among a spatial network of sites is the hallmark of climatic influence. When sampled at a sufficiently broad scale and number of independent locations, synchronous inter-annual to centennial patterns of fire occurrence are most probably due to climatic drivers because there are no other known environmental factors that could create such repeated co-occurrence among numerous widely dispersed locations (Swetnam and Betancourt 1990, 1998; Swetnam 1993).

A set of four papers in this special issue draw upon annually resolved fire-scar chronologies to demonstrate regional network approaches in high-resolution paleofire climatology. Fire-scar chronology networks spanning the past 200 to 500 years are compiled and analysed from Utah and Nevada (19 sites, Brown *et al*. 2008), eastside forests in Oregon, Washington and British Columbia (15 sites, Heyerdahl *et al*. 2008), the Colorado Front Range (58 sites, Sherriff and Veblen 2008), and the Southern Cascades of northern California (7 sites, Taylor *et al*. 2008). Although other published papers have drawn upon some of the data included in these networks, all papers here report entirely new fire-scar chronology networks, or new network compilations, as well as new fire climatology investigations. All four studies focus on exploration of inter-annual to decadal time scale associations of regional fire patterns with drought indices (Palmer Drought Severity Indices), various other climate parameters (seasonal precipitation and/or temperatures), and the two major ocean-atmosphere oscillations known to importantly affect climates of the western USA – the ENSO and PDO. Brown *et al*. (2008) and Sherriff and Veblen (2008) also evaluate the potential influence of the Atlantic Multidecadal Oscillation (AMO).

All four papers confirm that drought has been an important factor driving regionally synchronised fire activity for at least several centuries. Specifically, regional fire events co-occurring in the same sets of years in numerous sites within regions were well correlated with dry or dry/warm conditions. This is not a surprising result, but the subtle and not-so subtle differences observed in strength of drought-fire associations during and preceding the large fire years within and among regions is illuminating and novel to our understanding. For example, previous year wet patterns followed by dry conditions were often associated with large fire years in the Great Basin (Brown *et al*. 2008) and Colorado Front Range (Sherriff and Veblen 2008), but less so or not at all in most sites in the Southern Cascades (Taylor *et al*. 2008), and the relatively dry but productive forests of the eastside Pacific North-west (Heyerdahl *et al*. 2008). Where wet/dry lagging patterns were important, they tended to be particularly so in the lower elevation forests where grass and other fine fuel accumulations were probably critical for fire ignition and spread. It is useful to note in regard to the value of interdisciplinary approaches, that the importance of wet/dry lagging patterns in fire-climate relations in the South-western USA was first identified with paleofire research (Baisan and Swetnam 1990; Swetnam and Betancourt 1998). Wet/dry lagging patterns were subsequently confirmed as important in the modern period in various sub-regions and elevations using documentary records (e.g. Knapp 1995; Westerling *et al.* 2003; Crimmins and Comrie 2004; Collins *et al.* 2006).

Broad-scale synoptic patterns of fire climatology are also revealed in all four fire scar network papers. Heyerdahl *et al.* confirm the very interesting, 'dipole' pattern of fire climates in the western US: i.e. the Pacific North-west is often wet (dry) with low (high) fire activity when the South-west is dry (wet) with high (low) fire activity (Morgan *et al.* 2001). This 'see-saw' of climatic pattern has been previously studied using rainfall and various circulation indices (Dettinger *et al.* 1998; Brown and Comrie 2004), and now fire-scar and tree-ring networks of the western USA clearly demonstrate the importance of this phenomenon to fire regimes over multi-century periods in replicated studies (e.g. Westerling and Swetnam 2003; Schoennagel *et al.* 2005; Kitzberger *et al.* 2007; Heyerdahl *et al.* 2008). The dipole has been related to the differential effect of the ENSO on the position and strength of jet streams (Dettinger *et al.* 1998; Brown and Comrie 2004). Brown *et al.* (2008) and Taylor *et al.* (2008) provide further evidence and discussion of the dipole. In particular, they point to the usefulness of fire-scar networks in time-space tracking of the dipole's 'pivot point' (at ~40°N), which has probably moved along a north-west–south-west axis through time as a function of circulation features.

The interacting and specific roles of ENSO, PDO (and AMO in the cases of Brown *et al.* 2008 and Sherriff and Veblen 2008) in the different sub-regions are explicitly explored by all four papers. In general, the inter-annual to decadal fire regime responses track the expected patterns from previously documented ENSO/PDO/AMO teleconnections to climate. For example, synchronous, regional fire years in the fire-scar networks typically corresponded with various states of the ocean-atmosphere oscillations that promoted drier conditions in those regions. Again, the contrast between the Pacific North-west and the Southern Rockies and South-west during some years is striking, and in concert with known differential, regional ENSO/PDO effects. The findings and discussion of Taylor *et al.* (2008) are especially interesting because of the complexity and changing nature of the fire-climate responses in this sub-region of the Pacific North-west, where the dipole 'pivot point' may have shifted through time.

One of the important implications of the wet/dry lags, western USA dipole (and other spatial patterns), and ENSO/PDO/AMO findings in the tree-ring papers is the potential usefulness of these spatio-temporal patterns in long-term fire forecasting. The use of such knowledge is in its infancy, but this application holds some promise for assisting national-scale fire fighting resource allocation and fire use planning in different regions of western North America (see Joint Fire Science Program Fire Science Digest, October 2007, http://www.firescience.gov/Digest/Fire_Science_Digest_1.pdf, accessed 7 February 2008).

Paleofire climatology from sedimentary charcoal and pollen

The longest time scale perspectives of fire and climate come from studies of charcoal and pollen in lake, bog, and alluvial sediments. Four papers in this special issue summarise results of network-based charcoal studies in the Northern Rockies and Cascades, Klamath-Siskiyou region (15 sites, Whitlock *et al.* 2008; and two study areas in the Northern Rockies, Pierce and Meyer 2008), and in the Southern Rockies of southern Colorado and northern New Mexico (6 sites, Anderson *et al.* 2008*a*; 2 sites, Allen *et al.* 2008). Whitlock *et al.* (2008) and Anderson *et al.* (2008*a*) provide insights on millennial-scale influences of climate on fire regimes. A distinct advantage of charcoal/pollen studies are well illustrated here: not only can fire occurrence patterns be tracked through charcoal abundance indices during the past 11 000 years (the Holocene) and longer, but also the corresponding vegetation changes can be evaluated through analyses of pollen abundance indices (e.g. Whitlock *et al.* 2003; Whitlock and Bartlein 2004; Anderson *et al.* 2006, 2008*b*).

Particular century to millennial scale changes are found to be most consistent among the various sites compiled and compared in the different spatial networks. For example, Whitlock *et al.* (2008) show a multi-millennial secular increase in burning throughout the Holocene, and especially during the past 2000 years. The alluvial sediment-based studies of Pierce and Meyer (2008) show variable surges in fire activity during the centuries between ~950 and 1150 AD (~1050 and 850 years before present). These charcoal maxima approximately coincide with exceptional 'Medieval' drought periods that are evident in extensive and independent tree-ring width based climate reconstructions (Cook *et al.* 2004).

Whitlock *et al.* (2008) and Pierce and Meyer (2008) both emphasise the non-equilibrial nature of fire regimes, with fire episode frequencies changing more-or-less continuously in concert with climatic variations. Although the spatial extent of past high severity fires is not explicitly reconstructed with sedimentary charcoal records, they argue that modern high severity fires are not outside historical ranges of variability. Their northern Rockies findings are contrasted with the perspectives of changed fire regimes in South-western ponderosa pine, which have been attributed in part to the effects of fire suppression, and consequent forest and fuel changes leading to extraordinary fire behaviour (e.g. Allen *et al.* 2002). Whitlock *et al.* (2008) and Pierce and Meyer (2008) also highlight the temporal limitations of most tree-ring based studies to the past 500 years, which they assert are unrepresentative of either the Holocene or projected futures changes due to greenhouse gas-induced warming.

A slightly different perspective is presented by Anderson *et al.* (2008*a*) for the subalpine forests of the Southern Rockies. They document the importance of climate in determining fire episode frequencies over long time periods as well, particularly during the early and late Holocene, but also suggest the importance of vegetation inertia in maintaining relative fire episode frequencies for this vegetation type. For large portions of the Holocene, fire episode frequencies are not much different from those documented in tree-ring and stand-age studies for the vegetation type. A key value of the longer, albeit lower temporal and spatial resolution charcoal/pollen data (as compared with tree-ring based networks), is the longer-term context for addressing the questions: How changed are 20–21st century fire regimes relative to longer time scales? Is climate a primary driver of these changes, or are human-caused changes such as grazing, logging, or fire suppression also involved in recent surges in large, high severity fires?

In a rare example of interdisciplinary paleofire research, Allen *et al*. (2008) carry out an explicitly integrated study of tree ring-based data with sedimentary-based data. They use case studies of fire-scar and charcoal chronologies from two wet bogs surrounded by mixed conifer forests in northern New Mexico. In these cases, relatively high frequency surface fires were clearly demonstrated in the fire-scar record from the surrounding forests before the 20th century, despite the relatively high elevations, and cool/wet nature of these sites. Charcoal is highly abundant in both bogs over the Holocene, but the number of identified peaks in the charcoal record underestimates the frequency of widespread surface fires over the past several hundred years of overlap between the tree-ring and sedimentary records. The most striking change in the charcoal record, and the most consistent temporal match with the fire-scar record, is the hiatus of charcoal deposition in the uppermost part of the bog cores. This hiatus, which is unprecedented in more than 7000 years of the charcoal records, coincides with the 20th century absence of widespread fire-scar dates in the tree rings, and the advent of livestock grazing and fire suppression. This South-west finding provides an interesting contrast to the conclusions of Whitlock *et al*. (2008) and Pierce and Meyer (2008) that some Northern Rockies fire regimes have not changed appreciably relative to the modern era.

Overall, we feel that this special issue serves very well to illustrate the power of historical and network approaches in fire climatology. We are confident there will be many more advances in our understanding as additional modern and paleofire datasets are compiled and analysed. Our hope is that this issue will serve to encourage additional studies and prompt sharing of published data in open forums, such as the International Multiproxy Paleofire Database. Data sharing and interdisciplinary collaboration are essential for progress in fire climatology. Promising and necessary approaches for improved interpretation and confidence of historical records are cross-comparison (e.g. Clark 1990; Brunelle *et al*. 2005), calibration (e.g. Westerling and Swetnam 2003; Girardin *et al*. 2006), and testing (e.g. Whitlock and Millspaugh 1996) of multiple types of modern and paleofire records.

Acknowledgements

For support of workshops, publication page charges, and other aspects of the research reported in this special issue we thank the USGS BRD Global Change and associated Western Mountain Initiative research programs. Support for the workshops was also provided by the National Science Foundation (International Programs), NOAA (Office of Global Programs), US Forest Service (Pacific NW Research Station), PAGES (Inter-American Institute), the USDI/USDA Joint Fire Sciences Program, US Global Change Research Program and the Global Change Program of the IGBP. A special thanks to Craig Allen and Cathy Whitlock for help in securing funding and helping organise workshops. We also thank our respective institutions: Laboratory of Tree-Ring Research, University of Arizona and the Center for Environmental Sciences & Education, Northern Arizona University.

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Manuscript received 29 January 2008, accepted 31 January 2008