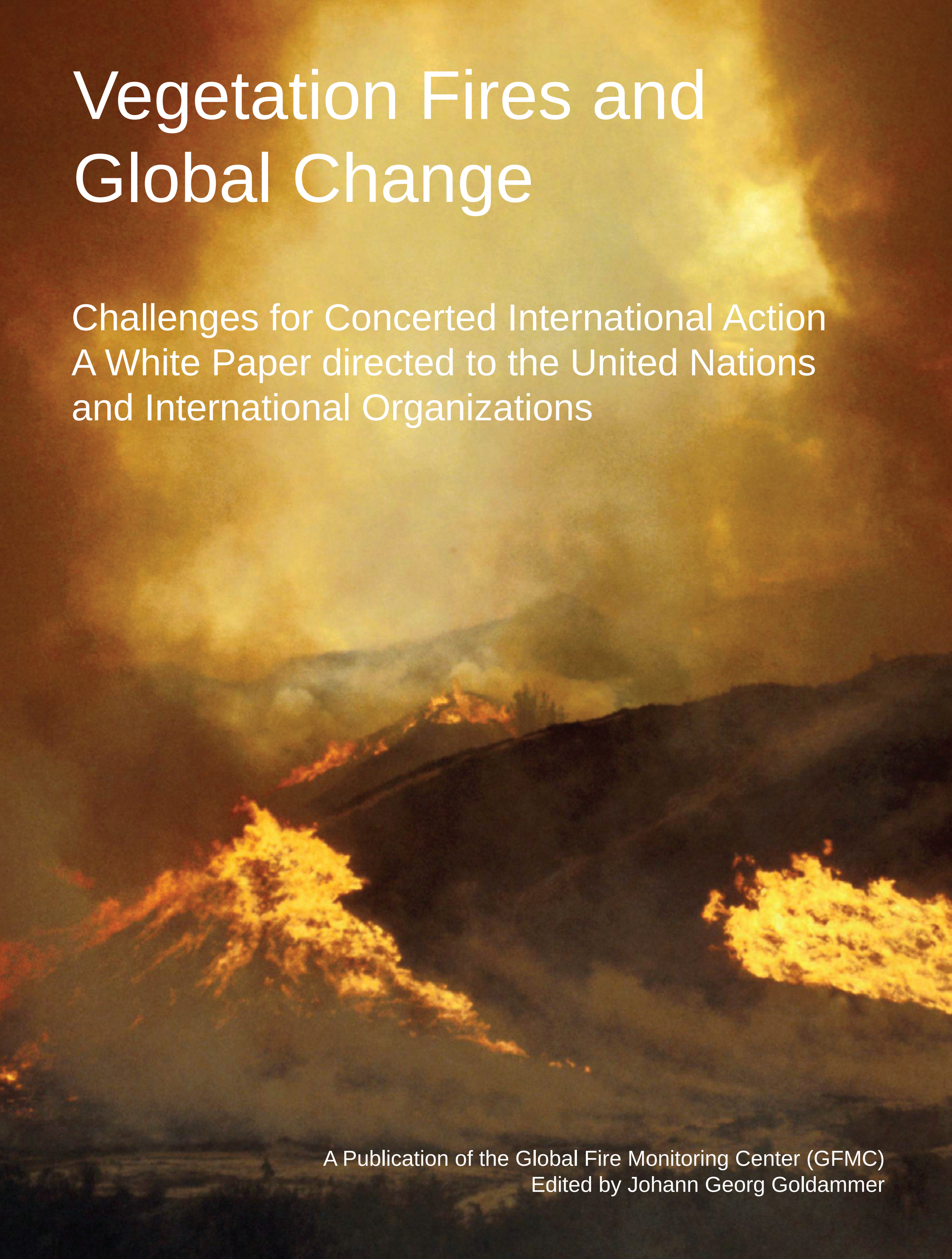

Vegetation Fires and Global Change

Challenges for Concerted International Action
A White Paper directed to the United Nations and International Organizations

A Publication of the Global Fire Monitoring Center (GFMC)

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This White Paper has been commissioned by the UNISDR Wildland Fire Advisory Group through its Secretariat, the Global Fire Monitoring Center (GFMC), Associate Institute of the United Nations University

ISDR
United Nations
International Strategy for Disaster Reduction

Global Fire Monitoring
Center (GFMC)

UNITED NATIONS
UNIVERSITY

Foreword by Ms Margareta Wahlström
Special Representative of the United Nations Secretary-General for Disaster Risk Reduction

During the 1980s and 1990s a rapid increase of the use of fire in conversion of tropical and subtropical forests and other native vegetation was observed globally. Fire-induced loss of biodiversity, the destruction of natural ecosystems properties, the consequences of vegetation fire emissions on the global atmosphere and climate alerted the international science community. The 1990s and the first decade of the 21st Century revealed that precursor signals of climate change, associated with more frequent extreme droughts, would create conditions favorable for increasing occurrence of large wildfires with severe consequences on the environment and human security.

Sadly, these projections have become reality, with an increasing occurrence of more destructive large fire episodes throughout the world. These are the result of human-induced alterations of the Earth system and increasing recurrence and severity of weather extremes.

In 2001, the World Conservation Union (IUCN) and the Global Fire Monitoring Center (GFMC) suggested that the theme of "Wildland Fire" become one of the areas of work of the Inter-Agency Task Force (IATF) of the International Strategy for Disaster Reduction (ISDR). In order to secure the participation and inputs of the international community concerned with wildland fires, the GFMC initiated the formation of the Global Wildland Fire Network and the Wildland Fire Advisory Group.

GFMC and the Wildland Fire Advisory Group have solicited the inputs of a wide group of scientists to review the state of vegetation fire at global scale and to develop this report. The report provides first-hand sources and information for national and international policy makers and actors of civil society, on the most pressing developments in the global world of fire.

In order to take advantage of the rich experience in fire management in many countries, systematic and efficient exchange of scientific-technical expertise and fire management solutions is required. With an increasing demand for sharing technical and human resources, the transition from informal information exchange and networking to a more systematic and formalized cooperation seems to be more necessary than ever.

GFMC has contributed for over 15 years to international efforts in fire management and in wildfire disaster risk reduction, in particular, at the fire science to policy interface. This report is a timely contribution to the consultations for the post-2015 framework for disaster risk reduction. It increases awareness about one of the most significant natural and yet meanwhile primarily human-influenced factor in the global environment and provides useful direction for countries and communities on how to deal with the complexity of benefits and destructivity of fire.

United Nations, Geneva, 2 May 2013

Foreword by United Nations University (UNU)

This White Paper "Vegetation Fires and Global Change" is a global analysis of the role of vegetation fires in the Earth System. Besides a review of the history and the current global situation of vegetation fires, the White Paper has a strong focus on the assessment of the expected / projected trends of future fire regimes in the main vegetation zones under the influence of climate change and human interventions in the global environment. The contributions of this volume reveal that globally, fire regimes are altering, driven by socio-economic and demographic developments, land-use change and climate change.

The underlying reasons for the application of fire in land management, the causes of anthropogenic wildfires and the natural function of vegetation fires are complex and have a range of environmental, social and humanitarian implications. The benefits of local fire application or the damages caused by destructive fire events are often exceeded by secondary, negative post-fire developments, such as vegetation degradation, erosion, flooding, or landslides. Yet there are further long-lasting environmental consequences of fire emissions at transboundary and planetary-scales, with impacts on human health and security, and repercussions on the composition and functioning of the global atmosphere.

The authors of this volume have worked together with the Global Fire Monitoring Center (GFMC) in the last four years to contribute, review and revise the White Paper. The GFMC has accomplished this ambitious work as a contribution of the Max Planck Institute of Chemistry and the United Nations University (UNU), to which GFMC is serving as Associated Institution.

The UNU acknowledges this White Paper as an important basis and source for the United Nations system and its member states to be consulted when addressing environmental, social and humanitarian problems arising from vegetation fires, and when defining and utilizing opportunities to take advantage of the benign role of fire in some ecosystems and land-use systems. In this regard the initiative of GFMC has proven its role and contribution for UNU as a 'think tank' of the UN system.

Jakob Rhyner
UNU Vice Rector for Europe
Head, UNU Institute for Environment and Human Security

Vegetation Fires and Global Change
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Preface

The White Paper "Vegetation Fires and Global Change" is a global state-of-the-art analysis of the role of vegetation fires in the Earth System and is published as a collective endeavor of the world's most renowned scientists and research groups working in fire science, ecology, atmospheric chemistry, remote sensing and climate change modeling.

Back in 1992 the first global scientific analysis "Fire in the environment: The ecological, atmospheric and climatic importance of vegetation fires" was published as the output of a Dahlem Workshop held in Berlin, Germany. The goal of the Dahlem Workshop was to 'examine the role and impact of natural and anthropogenic fires on ecosystems, the atmosphere and climate' (Crutzen and Goldammer, 1993). The scientists contributing to the Dahlem Workshop aimed to inspire the wider scientific community to further explore the gaps of knowledge in the manifold interactions between fire and the natural and cultural environment, as well as the implications and impacts fire has on Earth System processes (Goldammer and Crutzen, 1993). In the subsequent years wildland fire science and related disciplines experienced rapid acceleration in sectoral and interdisciplinary research projects and programmes. The "Biomass Burning Experiment: Impact of Fire on the Atmosphere and Biosphere" (BIBEX), set up under the umbrella of the International Geosphere-Biosphere Programme (IGBP) and its International Global Atmospheric Chemistry (IGAC) project, was a pioneering vehicle in the cooperative and collective scientific endeavor to address complex fire-related issues of regional, transcontinental and global scales (Andreae et al., 1993; Lindesay et al., 1996).[1]

However, during the 1990s wildfire episodes with severe environmental and humanitarian consequences were increasingly experienced across the world. In response, the Fire Ecology Research Group, which had been founded at Freiburg University (Germany) in 1979 and transited to the Max Planck Institute for Chemistry (Germany) in 1990, began to further promote transfer of scientific insights in the world of fire to policy and decision makers internationally. The Fire Ecology Research Group recognized the need to foster the international dialogue and scientific and user-oriented outreach work in fire management, and has labored toward this ideal since taking over the leadership of the UNECE/FAO Team of Specialists on Forest Fire[2]. In 1998 the Global Fire Monitoring Center (GFMC) was founded and assumed operation at the interface of fire science and the user community.[3] From the outset, the GFMC was positioned under the auspices of the United Nations In-

1 BIBEX website: http://www.fire.uni-freiburg.de/bibex/Welcome.html
2 http://www.fire.uni-freiburg.de/intro/team.html and
http://www.unece.org/forests/fcp/methodsandprocesses/forestfire.html
3 http://www.fire.uni-freiburg.de

ternational Decade for Natural Disaster Reduction (IDNDR) in the 1990s. After the phase-out of the IDNDR, its successor arrangement, the United Nations International Strategy for Disaster Reduction (UNISDR), and the *Hyogo Framework for Action 2005-2015 "Building the Resilience of Nations and Communities to Disasters"* became the international structures under which the GFMC facilitated the creation of the Global Wildland Fire Network[4] and an advisory body to the United Nations – the UNISDR Wildland Fire Advisory Group.[5]

These groups and networks have played key roles in organizing a series of international conferences since the late 1980s which have developed, besides general policy recommendations, a number of concrete but informal and voluntary frameworks for enhancing international cooperation in forest fire management, notably at the International Wildland Fire Summit (Australia, 2003)[6] and the 4th and 5th International Wildland Fire Conferences[7]. These informal and voluntary networks and frameworks are well known and accepted within the community of fire experts collaborating regionally and globally.

The aim of the White Paper is to support the endeavour of the United Nations and its affiliated processes and networks, notably the United Nations International Strategy for Disaster Reduction (UNISDR), the *Hyogo Framework for Action 2005-2015 "Building the Resilience of Nations and Communities to Disasters"* and the Global Wildland Fire Network, to address global vegetation fires for the benefit of the global environment and humanity.

At the time of publication the *UNECE/FAO Forum on Crossboundary Fire Management* is in the process of preparation and will be held in November 2013 at the United Nations in Geneva. This Forum aims at enhancing informal processes of cooperation in fire management toward the development of an international regime of coordinated wildfire preparedness and response. The White Paper, in part, provides rationale and evidence for such coordinated, international action.

This White Paper has been commissioned by the UNISDR Wildland Fire Advisory Group through its Secretariat, the Global Fire Monitoring Center (GFMC), Associate Institute of the United Nations University and Secretariat of the Global Wildland Fire Network.

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I am indebted to the contributing authors and express my appreciation for their endurance in the years 2009 to 2013 to contribute, review and revise the White Paper in order to consider the rapidly and dynamically evolving science. By sequence of chapters the lead and contributing authors are:

Stephen J. Pyne, Thomas W. Swetnam, Cathy Whitlock, Brian J. Stocks, Mike D. Flannigan, Anatoly I. Sukhinin, Eugene Ponomarev, Larry Hinzman, F. Stuart Chapin,

4 http://www.fire.uni-freiburg.de/GlobalNetworks/globalNet.html
5 http://www.fire.uni-freiburg.de/GlobalNetworks/Rationale-and-Introduction-1.html
6 http://www.fire.uni-freiburg.de/summit-2003/introduction.htm
7 http://www.fire.uni-freiburg.de/sevilla-2007.html and http://www.fire.uni-freiburg.de/southafrica-2011.html

Masami Fukuda, Susan Page, Jack Rieley, Agata Hoscilo, Allan Spessa, Ulrich Weber, Mark A. Cochrane, José M. Moreno, V. Ramón Vallejo, Emilio Chuvieco, Richard J. Williams, Ross A. Bradstock, Geoffrey J. Cary, Liz Dovey, Neal J. Enright, A. Malcolm Gill, John Handmer, Kevin J. Hennessy, Adam C. Liedloff, Christopher Lucas, Max A. Moritz, Meg A. Krawchuk, Jon E. Keeley, Winston S.W. Trollope, Cornelis de Ronde, Meinrat O. Andreae, Guido van der Werf, Kirsten Thonicke, Jose Gomez Dans, Veiko Lehsten, Rosie Fisher, Matthew Forrest, Lynn Gowman, Mike Wotton, William J. de Groot, Armando González-Cabán, Milt Statheropoulos, Sofia Karma, William J. Bond, Guy F. Midgley, Christopher O. Justice, Ivan Csiszar, Luigi Boschetti, Stefania Korontzi, Wilfrid Schroeder, Louis Giglio, Krishna Prasad Vadrevu, David Roy, Johann Georg Goldammer

Sadly, one of the authors left us too early: Anatoly Ivanovich Sukhinin, Head of the Laboratory of Forest Monitoring, V.N. Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, Russian Federation, passed away in July 2011, during the process of our joint work. On behalf of the collective group of authors this volume dedicated to the memory of this devoted scientist.

Freiburg, 23. August 2013
Johann Georg Goldammer

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Contents

1 Introduction – The White Paper on Vegetation Fires and Global Change

Johann Georg Goldammer[1]

With the arrival of the Pleistocene, humans gained the ability to ignite and manipulate fire, and have maintained a relationship with fire since that time – carrying and spreading it everywhere on planet Earth. Fire foraging, fire hunting, pastoral burning, and slash and burn agriculture are examples of fire practices that emulate natural precedents. Human use of fire has evolved from control over ignition to include control over fuels and, in the last 150 years, the widespread substitution of biomass fuels with fossil fuels. With the arrival of humanity itself as a fire creature, it is now difficult in many ecosystems to separate the 'natural' role of fire from that influenced by humans.

Today, fire interacts with human environmental concerns in terms of catastrophes, carbon and climate. Future fire management will not only require implementing fire where it belongs and restricting it where it does not, but also must address the increasing vulnerability of flora, fauna, ecosystems and our society – all already affected by global environmental changes, notably changes of climate and land. This is an increasingly challenging undertaking given increasing social, economic and environmental pressures at a global scale.

At the present time only a few countries have implemented policies addressing the role, consequences and management of vegetation fires comprehensively and across sectors. It seems that information generated and synthesized to support the development of informed policies is scant.

The Global Wildland Fire Network, which is operating under the United Nations International Strategy for Disaster Reduction (UNISDR) and partnering with a large number of national and international agencies and organizations, through its Wildland Fire Advisory Group, provides advisory support to the United Nations. The Global Fire Monitoring Center (GFMC), acting as Secretariat of the UNISDR Wildland Fire Advisory Group in conjunction with the United Nations University – the *think tank* of the UN system – felt obliged to take the initiative for developing a White Paper on Vegetation Fires and Global Change that would close this gap.

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This White Paper has a strong focus on analyzing the historic, current and expected / projected trends of future fire regimes in the main vegetation zones. In other words: It is not the intent of the White Paper to develop a comprehensive and all-embracing analysis of the multi-facetted aspects of global fire ecology. The chapters rather provide an insight to the state-of-science at the end of the first decade of the 21st century that may be considered useful for medium- and long-term fire management planning at national and international levels.

Several international (global) conventions, such as the three "Rio Conventions" (Convention on Biological Diversity [CBD], United Nations Convention to Combat Desertification [CCD], and the United Nations Framework Convention on Climate Change [FCCC]) and the Ramsar Convention on Wetlands are examples of international legal agreements that provide rationale and a catalogue of environmental protection obligations for signatory countries. However, none of these or any other legally binding conventions or informal or voluntary international instruments, such as the *Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters*, are explicitly addressing wildland fires as a driver of environmental degradation. Nor do they address the need for integrating natural and prescribed management fires in those ecosystems and land-use systems that require fire for maintaining their function, sustainability and productivity. There are also not yet protocols in place that provide internationally accepted standard methods and procedures for countries that provide and receive assistance in wildland fire emergencies that would ensure inter-operability, efficiency and safety of cooperating parties.

The contributions of this White Paper reveal that globally, fire regimes are altering in parallel with and under the influence of socio-economic developments, land-use change and climate change. Increasing vulnerability of society to the direct and secondary effects of wildland fires, as well as the transboundary nature and consequences of wildland fires are prompting countries and international organizations to define their common interests in enhancing sustainable and integrated fire management capacity. The requirement for systematic and efficient sharing of scientific and technical expertise, solutions and resources, including transboundary cooperation, means that the transition from informal information exchange and networking to a more systematic and formalized cooperation is more necessary than ever.

2 Prologue

Stephen J. Pyne[1]

Humanity as a Fire Creature

This geography of fire on Earth changed dramatically when a creature appeared who had the capacity to kindle sparks at will.

Probably *Homo erectus* could maintain fire, and did. But *Homo sapiens* could start it out of a general toolkit by striking, drilling, and abrading. It's a species monopoly that we will never willingly surrender. Over and again, myths about the origin of fire testify to a common scenario: humanity was weak and helpless; then fire came, usually by stealth or theft, occasionally by violence; and humanity shot to the top of the food chain. Fire meant power.

Humanity's species monopoly became the signature of our ecological agency. Other creatures dig holes, knock over trees, hunt, and dig up plants – we do fire. To cast this argument in biocentric phrasing, humanity's acquisition of fire further advanced the biological construction of fire. We complete the cycle of fire for the circle of life.

From this point on, wherever humans went, and they went everywhere, they carried fire. Since virtually every technology they possessed – from cooking to devising other tools – depended on fire somewhere in the chain of causality, fire further leveraged the human presence.

Ignition became more or less constant across the Earth. That did not mean every place burned: the power of fire resided in its power to propagate, and outside of hearths, that meant the landscape had to be in a condition to carry it. Humanity then magnified its firepower by modifying landscapes to accept it, primarily by increasing the available fuels through slashing, drying, draining, or introducing livestock. More places could burn and they could burn in longer seasons. Still, this extension had its limitations: a biota could only produce so much surface hydrocarbon as fuel before extractions exceeded its ability to recover.

The solution has been to exhume fossil biomass in the form of lignite, coal, petroleum, natural gas, and so on. These require special chambers to combust in. Increasingly, humanity's firepower is thus being routed through machines and applied to the land indirectly

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through petrochemicals, tractors, chain saws, and transportation systems that have redefined what constitutes a natural resource. Through technological substitution – electric stoves for wood-burning ones, for example – and through outright suppression open flame is receding. The Earth is dividing into two grand combustion realms, one that burns surface biomass, and the other, fossil biomass. They tend not to coexist, or they overlap only through a period of transition.

Pyrotechnologies

Since free-burning fire dates back to the early Devonian, some 425 million years ago, much of the living terrestrial world has evolved with flame, and has reached various accommodations with it. In recent decades the realization has grown how intimate this association can be. The removal of fire from ecosystems long accustomed to it has proved as ecologically disruptive as the sudden introduction of fire into ecosystems for which it is not naturally present.

Unsurprisingly, most human fire practices on the land emulate natural precedents. Fire foraging relies on the observation that certain useful flora grow best after being burned. Fire hunting mimics the fire drives evident in natural burns. Pastoral burning seeks the same flush of nutritious grasses and forbs that draw wild game to burnt sites. Slash-and-burn agriculture is simply applied fire ecology, with an identical cycle of exuberant growth by exotics, followed by a rapid recovery of native species.

So, too, pyrotechnologies abstract from free-burning fire their critical chemistry and remake them into tools. Pliny the Elder observed with a mix of awe and dismay that "we cannot but marvel that fire is necessary for almost every operation." Fire is the ultimate interactive technology, an almost universal technological solvent. Fire does work, fire catalyzes, fire transmutes: it does this in hearth and field equally. Wherever people go, they carry fire, and whatever they do, fire appears somewhere in the chain of causality. We have distributed fire to every continent. We have brought fire to Antarctica. We go into space on a pillar of flame.

Fire Industrializes

From the perspective of fire history the vernacular identification of industrialization with the combustion of fossil fuels is altogether apt. Its essence is that the Earth's keystone fire species began to route its firepower through machines. The process isolated fire's traditional output – its heat, light, and transmutative powers – from the sites of their use. By technological substitution and active suppression industrialized societies have banished open fire from houses, cities, fields, and, where possible, even from wildlands.

Satellite images of the Earth show clearly a division between regions dominated by industrial combustion and regions still characterized by open burning. Only in a few nations do the two appear to coexist; but that simultaneity disappears upon closer inspection as a fine-grained mosaic of segregation emerges. Moreover, such scenes appear to be transitional.

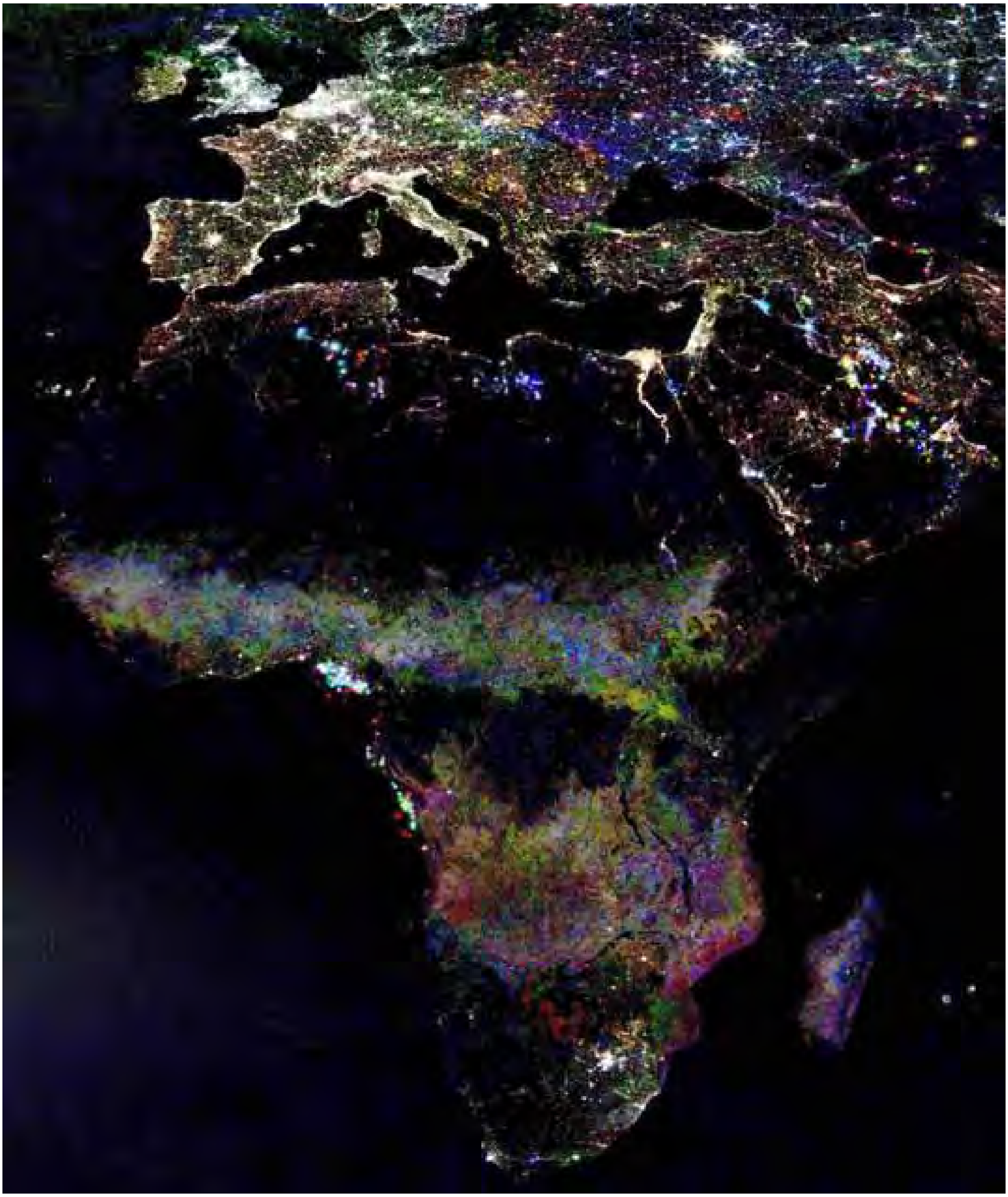

Figure 2.1. The two realms of Earthly combustion: one lit by the industrial burning of fossil biomass, and the other by the burning of surface biomass; a three-year composite (blue: 1992, green: 2000, red: 2008). Source: DMSP nightlights processed by the NOAA National Geophysical Data Center; courtesy Christopher Eldridge.

Where the transition lags it does so in countries like India, Indonesia, or Mexico, where traditional village life persists, often with official sanction amid a vigorous petro industry. With time they, too, will convert.

The period of conversion – what might be termed the pyric transition – is typically a time of promiscuous and abusive burning. Like the better known demographic transition that accompanies modernization, the population, in this case of fires, explodes as old ignitions persist and new ones arise, all amid landscapes unraveled and delaminated by an influx of capital, the appearance of transportation systems, and combustion-powered machinery. Eventually, the conversion works through its cycle, and as confined combustion replaces open burning, the population of fires plummets below replacement values. Many landscapes (notably, reserved sites) begin to suffer from fire deprivation, a kind of fire famine. Agencies set up to protect against the reckless burns of the transition find themselves retooled to promote fires in the protected estates. In principle, such fire demographics will stabilize.

Yet our shift in fire habits from open flame to internal combustion has profoundly unhinged the Earth system. We have removed fire from ecosystems that have long adapted to it, altered its regimes with unintended consequences, and saturated the atmosphere and oceans with its effluents. We are the link between free-burning fire in a nature preserve and the gasoline-powered engines of automobiles.

Humanity, in brief, is the planet's keystone species for fire: it's what we do that no other creature does. When we decided to reroute our firepower through the machinery of industrial combustion, we have fundamentally, if inadvertently, begun to remake the entire Earth. The bottom line: fire is almost everywhere in nature and suffuses almost every act of humanity's material culture. It will be found wherever people are. The issue is what form combustion takes and with what consequences.

Fire as Problem

Today, those problematic concerns center on catastrophe, carbon, and climate. Fire as a disaster – burning cities and exurbs, burning in hurtful ways natural areas and parks. Fire and carbon – fire as inextricably intertwined with the grand geochemical cycle of carbon, helping convert forests to fields and immense carbon-sequestering peatlands to plantation, releasing the carbon from fossil biomass through machinery. Fire and climate – combustion's complicity in accelerating the production of greenhouse gases and upsetting the global atmosphere to the extent that it unhinges the climate, and that altered climate then (often) stimulating wildfires.

There are places where fire belongs, where no other process can do the necessary biological work and where ecological integrity requires the right regimen of burning. There are also places where fire, or the wrong pattern of fire, is intrinsically damaging and needs to be removed or realigned with its environment. And there are places where technology can substitute for fire, where humanity can acquire the heat, light, and power it desires without fire's presence.

The future of fire will require that humanity will make the choices that will keep fire where it belongs and remove it where it doesn't. That is what it means to be a keystone species for fire.

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3 Paleofire and Climate History: Western America and Global Perspectives

Thomas W. Swetnam[1] *and Cathy Whitlock*[2]

Abstract

Documentary-based fire histories and paleo-ecological reconstructions from tree rings and charcoal in sediments confirms that fires have been a dominant natural disturbance in nearly all terrestrial ecosystems for many millennia, including wet rainforests, subalpine forests, low-elevation forests, steppe, as well as in tundra. Disturbance regimes varied substantially among different ecosystem types and regions and through time as a consequence of both humans and climate variation. Combined analyses and comparisons of independent fire and climate histories indicate that climate is and has been a dominant control of variability in fire regimes. Long-term fire-climate linkages are well understood in a number of regions from modern and paleofire records. Wet/dry lagging relations and ocean-atmosphere oscillations exert significant control over past and current fire regimes in some regions. Fire-history studies indicate that spring and summer temperatures and earlier spring snowmelt, observed at present and projected in the future, are likely to be accompanied by increasing fire activity in some areas of the western U.S.A. Modeling studies in Canada and in other regions indicate that future fire regime responses to climate change will not be uniform, with projected increases in fire occurrence in some regions and decreases in others. Strong fire-climate linkages in the future will likely arise from similar circulation features and climate teleconnections that have promoted fire in the past and at present. It is also possible that novel fire-climate patterns may develop in a greenhouse-warmed world. In any case, identifying and understanding such novel conditions will depend upon historical perspectives for comparison.

Keywords: Paleofire history, fire history, disturbance regimes, tree-ring analysis, fire-climate linkages

The Role of Paleofire History in Understanding Global Change

Fire is widely recognized as a critical component of the Earth system, but its role in carbon and energy balances, climate change, and ecosystem dynamics is still poorly understood

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(Bowman et al., 2009). Historical information on fires spans many time scales from satellite observations of the last two decades, to documentary records that extend back centuries, to tree-ring data that span centuries to millennia, and long-term sediment and geologic records that cover the last several millennia and have also been described through Earth history. Although suitable fuel, fire-conducive weather, and ignition are required for fire at any given time and location, the importance of climate, vegetation, and humans in shaping fire regimes has varied through time. Fire-history information is necessary to understand the suite of natural and human drivers that have shaped biomass burning in the past, as well as the degree to which current fire regimes are being altered by climate and land-use change (Lavorel et al., 2007).

Recent advances in "paleofire" research have greatly increased our ability to reconstruct past fire occurrence at regional, continental and global scales (Veblen et al., 2003; Gavin et al., 2007; Swetnam and Anderson, 2008; Power et al., 2008). The two primary proxy records are fire scars in tree rings and charcoal in lake, wetland, and other sediments. A common strategy used with both data types has been the development of numerous local-scale chronologies of past fire events, and then assembly and compilation of these local-scale chronologies into regional- to global-scale networks and time series.

An emergent property of these network compilations is the spatial synchrony of fire events and fire-regime changes in many regions. This is evident as years, decades and centuries of high or low fire activity across enormous areas. Such repeated synchrony across long temporal and broad spatial scales is attributed to climate drivers (e.g., variations in temperature, precipitation, and drought). Comparison with independently derived proxies of climate demonstrates these fire-climate linkages and also reveals both unique and general fire climatology patterns in the past. The effects of human land uses on fire activity are also apparent in local-, regional-, and global-scale fire chronologies and show the enduring effects of livestock grazing, forest clearance, and fire suppression.

Extensive networks of regional- to global-scale fire histories are useful for understanding past fire climatology and assessing modern changes within a long-term context. These perspectives are increasingly important as the planet is warming and broad-scale patterns of biomass burning are changing (e.g., Gillett et al., 2004; Westerling et al., 2006). Paleofire data are also essential for developing and testing Earth system models that consider the synergisms between climate change, biomass burning, vegetation feedbacks, and carbon and energy dynamics in the future (Spessa et al., 2003). Additional work is needed to expand paleofire networks into new regions, to compare paleofire proxies and modern fire records, and to improve our understanding of the interactions between fire, vegetation, humans and climate.

The following examples and summaries illustrate regional and global-scale paleofire networks and some of the insights they have provided so far:

Western North American Fire-Scar and Tree-Ring Networks of Fire History

The record of past forest fires is often well-preserved within tree-ring sequences as "fire scars" on the lower boles of trees (Fig. 3.1). Individual fire scars can be dated to the year, and often to the season of occurrence. Spatial networks of fire-scarred trees have been sampled and analyzed at the scales of forest stands to watersheds and mountain ranges to study detailed spatial ecological patterns (e.g., Heyerdahl et al., 2001; Taylor et al., 2003; Hessl et al., 2007, Falk et al., 2011). As might be expected, regional networks of fire chronologies (multiple stand-level composites) have proven to be the most insightful for understanding broad-scale fire climatology.

The most extensive fire-scar/tree-ring network analyzed so far is a set of 238 chronologies from western North America (Kitzberger et al., 2007) (Fig. 3.2). As observed in a number of other fire-scar network studies within this sub-continental area (e.g., Swetnam, 1993; Veblen et al. 2000, Heyerdahl et al., 2008), there are strong patterns of fire synchrony among sites and sub-regions, and among independently derived proxy records of climate (Fig. 3.2). In particular, wet/dry oscillations associated with large-scale ocean atmosphere patterns (e.g., El Niño Southern Oscillation [ENSO], Pacific Decadal Oscillation, and Atlantic Multi-Decadal Oscillation) are evident in fire-climate comparisons (Kitzberger et al., 2001, 2007). The ENSO-fire associations are already used in "predictive services" efforts in the US to provide "seasonal outlooks" for fire-management planning.[3]

A recent application of tree-ring proxies in fire climatology is the use of regression techniques developed and extensively applied in dendroclimatology for the purpose of reconstructing regional area burned time series from combinations of fire scars, ring-width chronology networks, and modern documentary data (Westerling and Swetnam, 2003; Girardin, 2007; Roos and Swetnam, 2011) (Fig. 3.3 and 3.4). An important value of this approach is the ability to extend calibrated estimates of area burned (i.e., hectares burned per year, decade, etc.) back in time before satellite or documentary records are available. This allows for direct quantitative comparisons with modern changes in fire regimes and climate at regional and broader scales (Fig. 3.3 and 3.4).

To further advance fire climatology investigations with tree-ring data, it will be necessary to expand and extend existing networks. The 238 site network in western North America has very sparse coverage in many areas, and filling in these gaps will improve our understanding of synoptic fire-climate patterns through time. Tree-ring based networks are beginning to be developed in the eastern United States, Scandinavia, Siberia, and parts of South America. Once such data are contributed to international network databases, such as the International Multiproxy Paleofire Database (IMPD: http://www.ncdc.noaa.gov/paleo/impd/paleofire.html), they are available to the scientists, educators, land-use managers, and the public.

3 http://www.nifc.gov/nicc/predictive/predictive.htm

Figure 3.1. Fire scars are created on the lower boles of trees by surface fires that injure the growing tissue beneath the bark (cambium), but do not kill the tree (upper left), creating open fire scar cavities (upper right). Giant sequoias in the Sierra Nevada, California were repeatedly scarred by surface fires over the past three millennia (Swetnam, 1993; Swetnam et al., 2009). By examining cross sections from dead trees (lower left) tree rings and fire scars are clearly visible and can be dated to the year and season. (lower right). This particular tree (lower left) had an innermost ring date of 256 BC and contained more than 80 different fire-scar dates. Composites of fire-scar chronologies from individual trees and from forest stands provide time series reflecting fire occurrence and extent across a range of spatial scales (Photo credits: Tony Caprio).

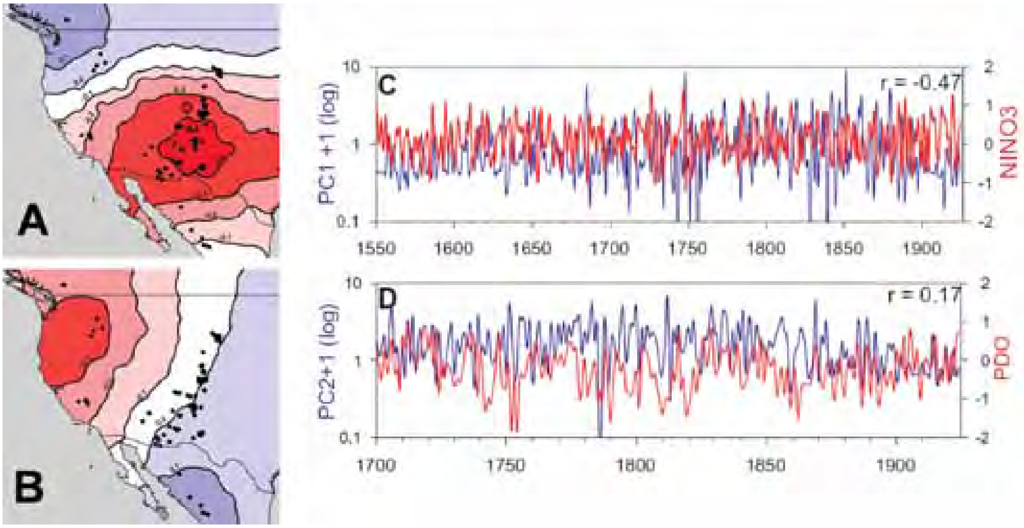

Figure 3.2. A spatial network of fire-scar chronologies in the western US, showing correlation values of 1st and 2nd principal components of the fire chronologies (PC1 & PC2) with tree-ring width reconstructions of summer PDSI (maps, Cook et al. 1999), ENSO (r = -0.48, p<0.001) and PDO (r = 0.17, p<0.05) (Kitzberger et al., 2007). The pronounced ENSO/PDO-related, Pacific Northwest/ Southwest "dipole", well known from modern climatology analyses, is strongly evident in this paleo-fire/climate analysis.

Western North American and Global Charcoal Networks of Fire History

An important source of long-term fire-history information comes from stratigraphic records of particulate charcoal (partially combusted wood, leaves, seeds, and other plant remains) preserved in the sediments of lakes, natural wetlands, and other geologic deposits. Charcoal particles produced by fire are carried aloft; deposited on lake, bog, or ground surfaces; and eventually buried in the sediments. Recovering sediment cores from these natural repositories and extracting, quantifying, and identifying the charcoal particles provide a tool for reconstructing past fire activity (Fig 3.5). Refinements in understanding the mechanisms of charcoal production, transport, and deposition (Patterson et al., 1987; Clark, 1988; Higuera et al., 2007; Duffin et al., 2008); improvements and standardization in charcoal data analysis and interpretation (Whitlock and Larsen, 2001, Gavin et al., 2003; Conedera et al., 2009), and creation of databases from a growing number of sites around the world (e.g., the IMPD) (Power et al., 2008) have greatly refined reconstructions of long-term fire history. In particular, sediment-based studies that examine multiple paleoenvironmental proxy have provided new insights on the interactions and feedbacks between fire, climate, vegetation, and humans over the last 21,000 years, as well as the role of fire in major ecosystem reorganizations.

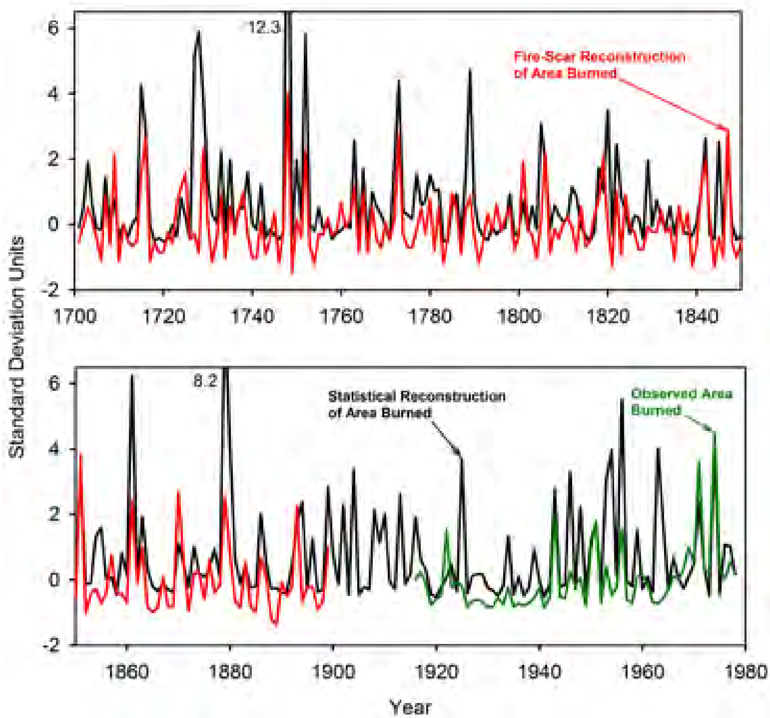

Figure 3.3. A reconstruction of area burned in the southwestern United States (Arizona and New Mexico) from tree-ring width chronologies calibrated with modern area burned data (black line) compared to fire-scar based fire reconstructions (red line) (Spearman's r = 0.61, p<0.05) (Westerling and Swetnam, 2003).

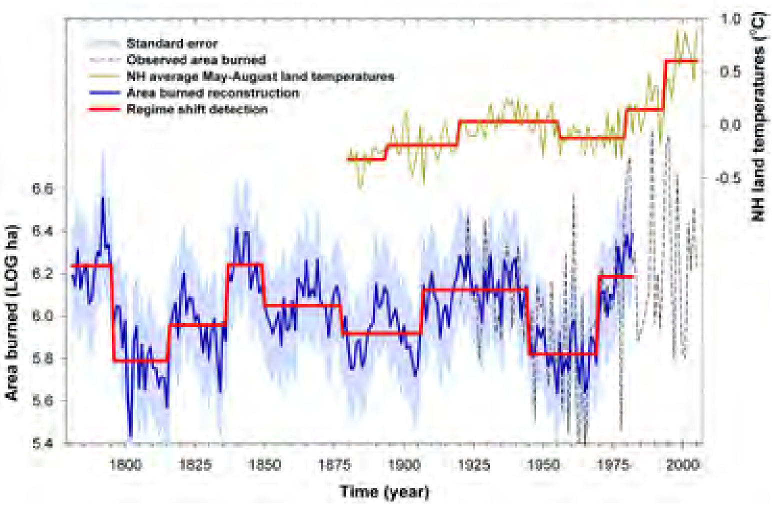

Figure 3.4. A reconstruction of area burned in Canada using a network of tree-ring width chronologies calibrated with the Canadian Large Fire Database (lower time series), and compared with Northern Hemisphere temperature (upper time series) (Girardin, 2007).

Figure 3.5. In high-resolution charcoal analysis sediment cores of lakes are recovered using various coring devices. Cores are split, described, and subsampled in the lab and the large particles of charcoal are quantified from continuous core samples (photo credits top left, clockwise: C. Whitlock, C. Adams, T. Minckley, and K. Gorham).

Charcoal records are intrinsically less spatially resolved and temporally less precise than fire histories based on tree-ring data. Paired studies that consider both types of information have proven to be particularly powerful in reconstructing regional fire history (e.g., Swetnam et al., 2009; Allen et al., 2008; Jiang et al., 2008; Mooney and Maltby, 2006; Brunelle et al., 2005; Whitlock et al., 2004; Pitkänen et al., 1999; Tinner et al., 1998; Millspaugh and Whitlock, 1995; McDonald et al., 1991; Clark, 1990). By utilizing recent area burn data, the annual resolution of tree-ring records over the last centuries, and the decadal resolution of lake-sediment records over the last millennia, it has been possible to examine the dynamics of fire regimes over multiple time scales.

The timing and duration of long-term fire activity in the northwestern U.S.A., inferred from a network of charcoal records, illustrate the information that can be gained from regional comparisons (Whitlock et al., 2003, 2008; Marlon et al., 2006; Whitlock and Bartlein, 2004) (Fig 3.6). Over the last 17,000 years, similar fire frequency patterns were observed at several sites located in different geographic settings across the region. The data suggest that, at a broad spatial scale and on millennial time scales, fire and vegetation responded to slow variations in the seasonal cycle of insolation and its influences on summer temperature and effective moisture, directly, and the strength of atmospheric circulation patterns, indirectly (Bartlein et al., 1998). For example, during the summer insolation maximum of the early Holocene, higher temperatures and more severe drought led to higher-than-present fire activity and fire-adapted vegetation in the Pacific Northwest and Yellowstone region. In addition, fires were more frequent, ca. 1000 years ago, during a dry period known as the Medieval Climate Anomaly (Cook et al., 2004). At finer spatial and temporal scales, charcoal records show site and regional differences that relate to vegetation, local climate, and physical setting. Moreover, the relative importance of regional versus local controls at the local scale may have shifted through time, resulting in greater synchrony of fires during some periods than others (Gavin et al., 2006).

An international effort has led to the creation a paleofire database consisting of over 400 charcoal records from around the world[4]. The first effort of the Global Palaeofire Working Group was to describe the regional changes in fire activity since the last glaciation (Power et al., 2008). Striking patterns in biomass burning emerged, when regional patterns were compared against a base period of the last 4,000 years. For example, fire activity was low nearly everywhere 21,000 years ago, as a result of lower temperatures, reduced levels of CO_2, and reduced fuel biomass during the last glacial maximum (Thonicke et al., 2005). Higher fire activity occurred in southern Patagonia, the northwestern U.S.A., and northeastern Canada ca. 9,000 years ago, and 3,000 years ago in southeastern Australia and New Guinea (see Anderson et al., 2008; Whitlock et al., 2006, 2008; Huber et al., 2003; Carcaillet et al., 2003; Bergeron et al., 2004; Haberle and Ledru, 2001 for regional descriptions).

The paleofire database has also been examined for possible fire-climate-human linkages over last 2,000 years by comparing a composite fire record with trends in global population

4 http://www.bridge.bris.ac.uk/projects/QUEST_IGBP_Global_Palaeofire_WG/database.html

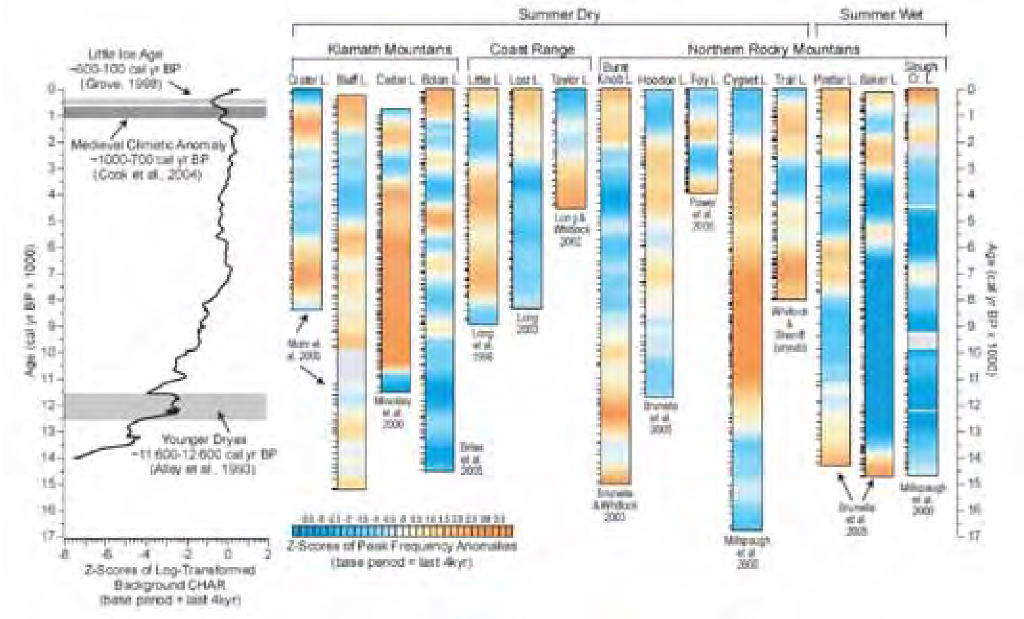

Figure 3.6. Fire-history patterns for the last 17,000 years based on 15 charcoal records from the northwestern U.S.A. (left) and long-term trend in charcoal accumulation rates summarized for all sites, showing relation to global climate events (right). Fire-frequency anomalies show times of lower-than-average fire-episode frequency (blue) and higher than-average fire-episode frequency (yellow). Z-scores are based on the mean and standard deviation of the peak frequency values for the last 400 years of charcoal. Horizontal black lines along each record are individual fire episodes (Whitlock et al., 2008).

growth, atmospheric CO_2 records preserved in ice cores, and estimates of land-cover change for the same period (Marlon et al., 2008) (Fig. 3.7). A notable feature of the last two millennia is the widespread decline in charcoal levels between 0 AD and 1750 AD, ascribed to the effects of cooling in the late Holocene. This period was followed by increased charcoal levels between 1750 and 1870 AD, attributed to forest clearance in the Americas, Europe and Australia. Between 1870 AD and 1950 AD, decreasing charcoal levels are explained by land-use changes and practices that have reduced fire, including, forest clearance, grazing, and fire suppression policies. The recent decline is well expressed at sites from low and middle latitudes and less so at high latitudes, which underscores the human influence. The study concluded that the impact of contemporary human activity has been to reduce biomass burning on a global scale (Marlon et al., 2008).

Where human arrival has been relatively recent, the consequences of anthropogenic burning are clear and striking. New Zealand, for example, has an oceanic climate with little lightning, and few natural fires prior to the arrival of Māori peoples about 700 years ago