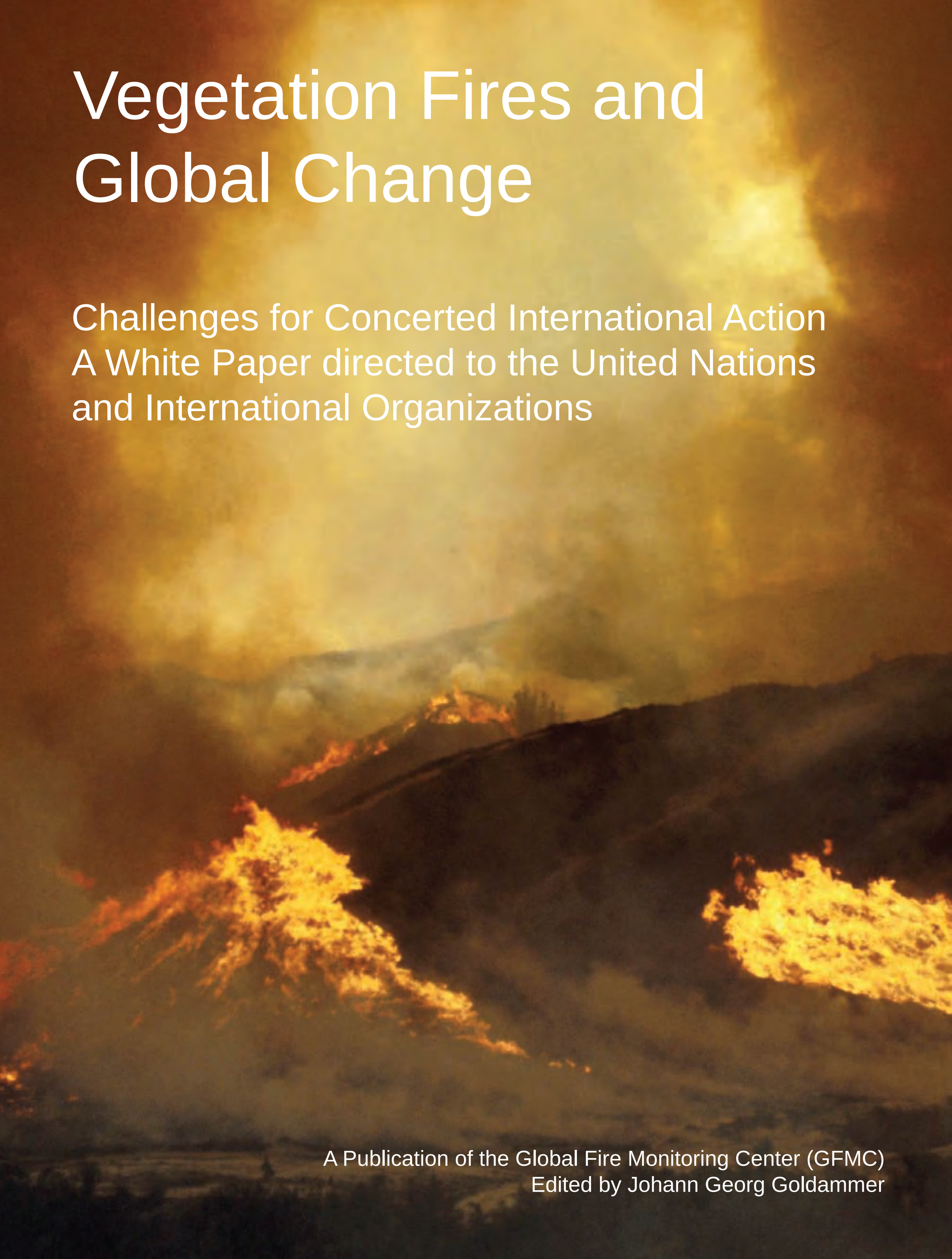
Vegetation Fires and Global Change

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
Challenges for Concerted International Action
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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.

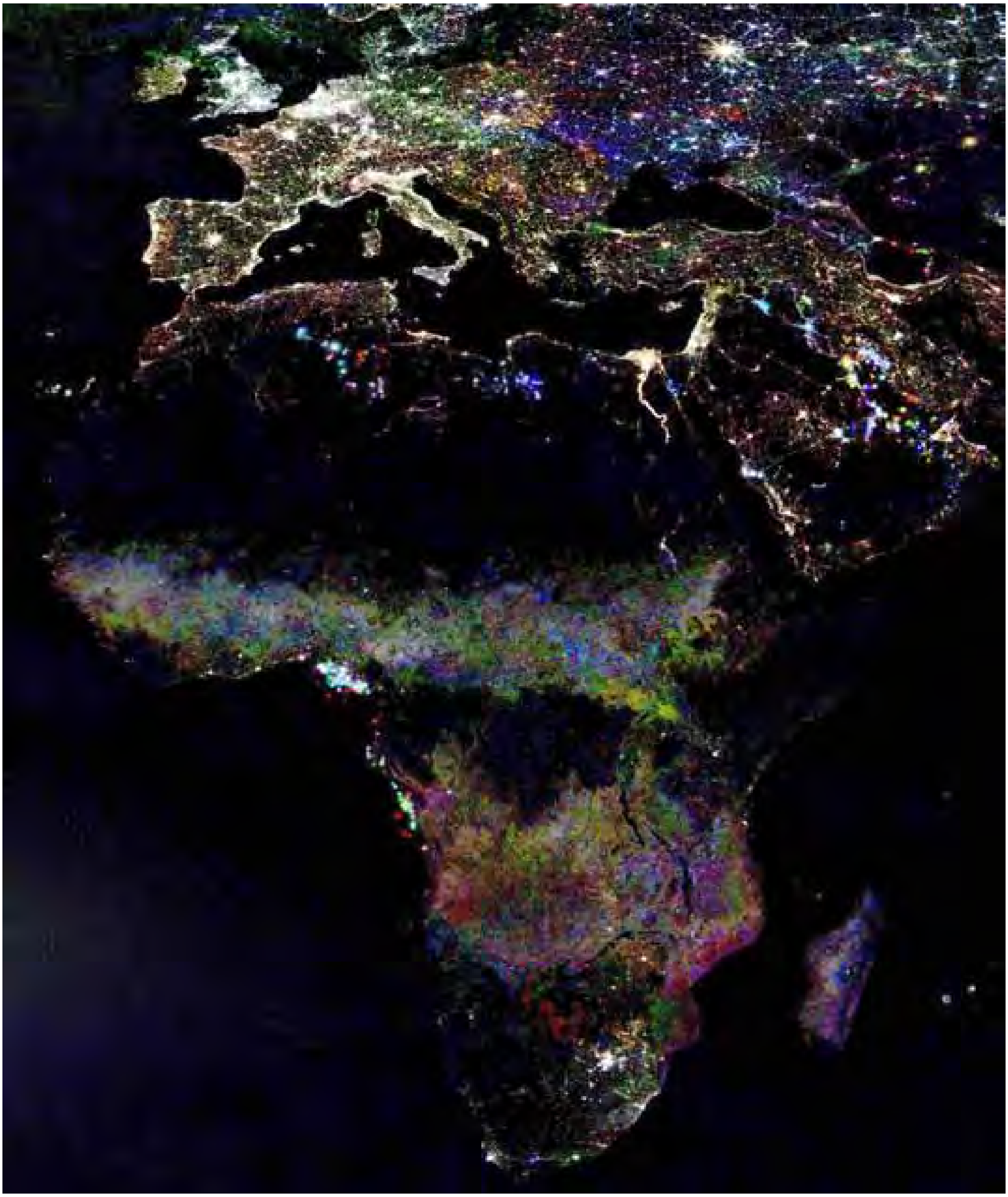

Figure 2.1. The two realms of Earthly combustion: one lit by the industrial burning of fossil biomass, and the other by the burning of surface biomass; a three-year composite (blue: 1992, green: 2000, red: 2008). Source: DMSP nightlights processed by the NOAA National Geophysical Data Center; courtesy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

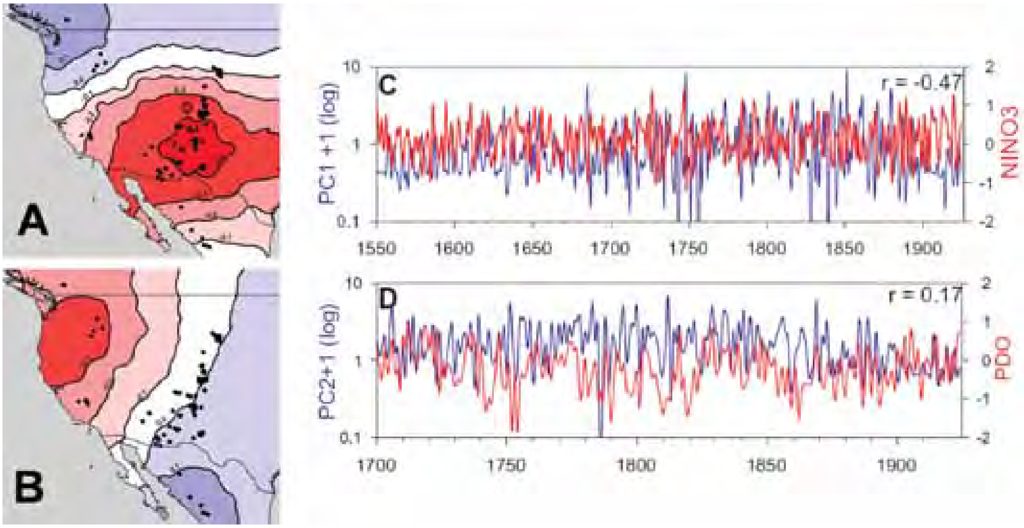

Figure 3.2. A spatial network of fire-scar chronologies in the western US, showing correlation values of 1st and 2nd principal components of the fire chronologies (PC1 & PC2) with tree-ring width reconstructions of summer PDSI (maps, Cook et al. 1999), ENSO (r = -0.48, p<0.001) and PDO (r = 0.17, p<0.05) (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.

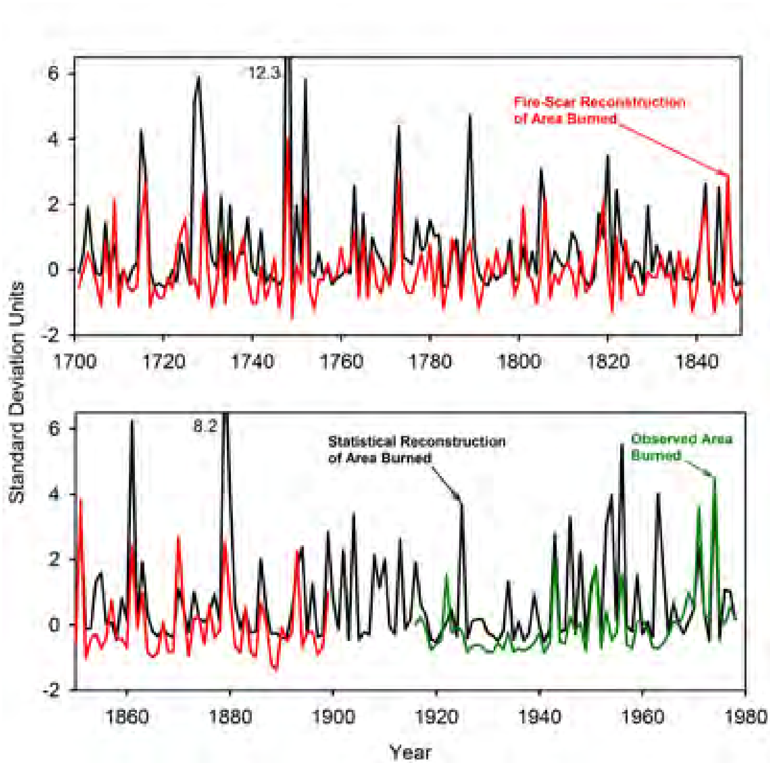

Figure 3.3. A reconstruction of area burned in the southwestern United States (Arizona and New Mexico) from tree-ring width chronologies calibrated with modern area burned data (black line) compared to fire-scar based fire reconstructions (red line) (Spearman's r = 0.61, p<0.05) (Westerling and Swetnam,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

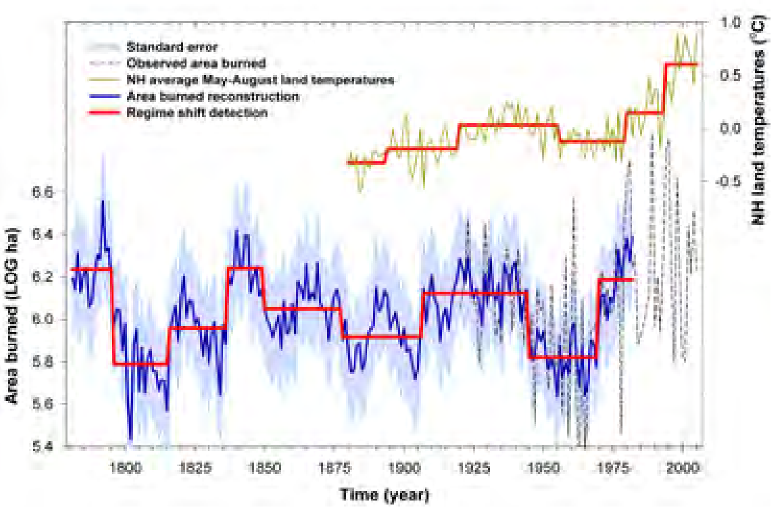

Figure 3.4. A reconstruction of area burned in Canada using a network of tree-ring width chronologies calibrated with the Canadian Large Fire Database (lower time series), and compared with Northern Hemisphere temperature (upper time series) (Girardin, 2007).

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

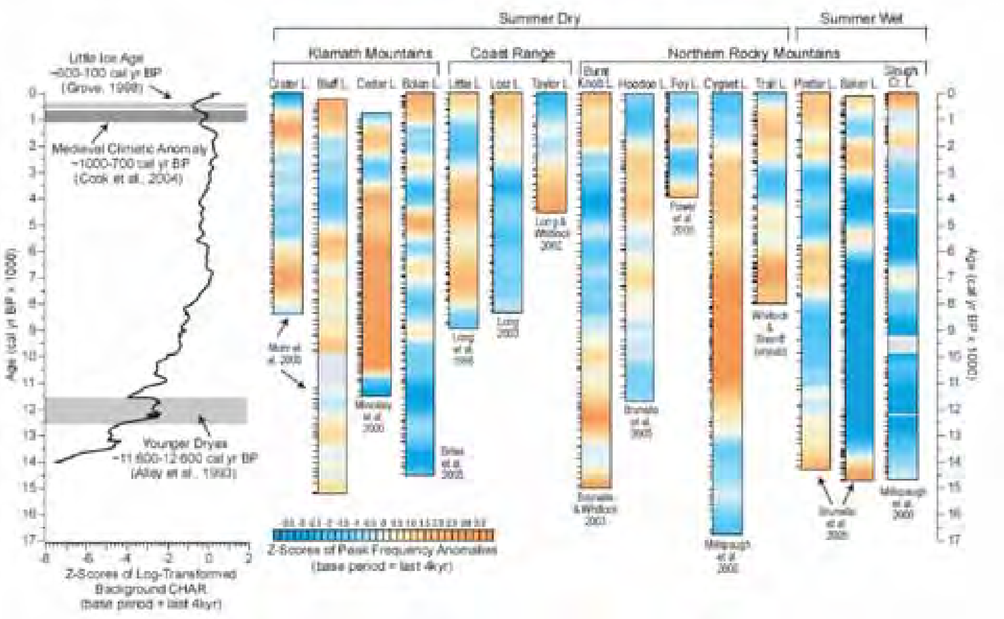

Figure 3.6. Fire-history patterns for the last 17,000 years based on 15 charcoal records from the northwestern U.S.A. (left) and long-term trend in charcoal accumulation rates summarized for all sites, showing relation to global climate events (right). Fire-frequency anomalies show times of lower-than-average 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

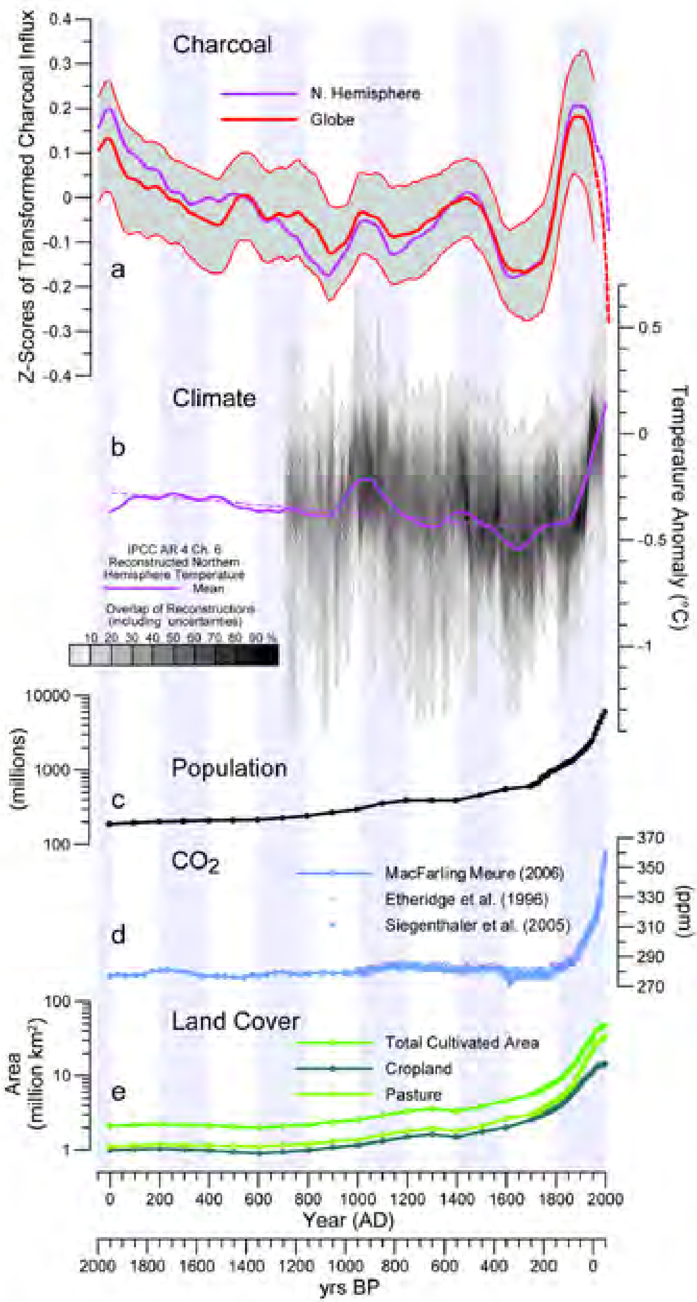

Figure 3.7. Biomass burning based on charcoal data from 442 lake and wetland records, compared with reconstructions of climate, population, atmospheric carbon dioxide and land-cover change for the last 2000 years (Marlon et al., 2008).

(Ogden et al., 1997; Wilmshurst et al., 2008). Evolving in the absence of fire, most New Zealand tree species are not well-adapted to fire. About 40% of the rainforests of New Zealand were lost during an initial period of intense burning, and much of the South Island of New Zealand was converted from forest to grass- and shrublands at that time. This initial burning was followed by a second period of fires in the 19th century as Europeans burned to extend and maintain grasslands (Ogden et al., 1997). Charcoal data suggest that the initial burning period lasted less than a century at most sites and may have consisted of only one or two burning events (McWethy et al., 2009). Erosion, loss of nutrients, and shifts in lake chemistry from acidic to alkaline accompanied these fires and likely deterred ecological recovery.

Conclusions

Fire history studies identify some generalities and potentially predictive patterns, but they also discourage simplistic assumptions about current fire regimes and their persistence in the face of climate change. The following observations are noteworthy:

- The past confirms that fires are a dominant natural disturbance in nearly all terrestrial ecosystems, including wet rainforests, subalpine forests, low-elevations forest, steppe, and tundra. The natural variability in disturbance regimes should be used to inform fire management and policy. For example, stand-replacing fires historically have characterized and continue to be the natural disturbance regime of subalpine forests in the northern and central Rockies, and shrub-dominated landscapes of southern California, North America. Unlike low-elevation forests in the American Southwest, which were historically maintained by frequent low-severity fires, landscape-scale fuel-reduction treatments in stand-replacement fire-regime types do not have a sound ecological basis and may not be effective at reducing high-severity fire risks (Schoennagel et al., 2004; Keeley and Zedlar, 2009).
- 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 links are well understood in a number of regions from paleofire records (e.g., Kitzberger et al., 2007; Marlon et al., 2009). Wet/dry lagging relations and ocean-atmosphere oscillations (e.g., ENSO, PDO, AMO) exert significant control over past and current fire regimes in some regions (e.g., Kitzberger et al., 2001, 2007; Haberle and Ledru, 2001). Better understanding of these relationships is useful for seasonal to decadal forecasting and is also needed to disentangle natural from anthropogenic causes of recent secular changes.
- Humans and nature interact in ways that can amplify or dampen the climatic signal. The exact character of these interactions in the past is clear in some places and uncertain in many. Separating anthropogenic and natural drivers of past fire regimes is thus difficult and controversial (Vale, 2002; Bowman, 1998; Burchard, 1992; Bowman et al., 2012). The research in New Zealand and elsewhere (e.g.,

Pyne, 1995) shows that the consequences of anthropogenic burning in areas with few natural ignitions are profound and long-lived.

- Fire-history studies support the interpretation that increased 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. Modern fire occurrence data for the western U.S., for example, show increasing numbers of large wildfires in recent decades and a strong association with independent records of rising spring temperatures (Westerling et al., 2006). These inter-annual to decadal relationships, however, may not hold true in other regions (Krawchuck et al., 2009). Further, there is need for more study of the effects of changes in policy, fire management tactics and data reporting to determine what role these changes may have played in driving variations and trends in fire occurrence time series in different regions. Future projections for the northwestern U.S. may be similar to the higher-than-present fire frequency that occurred when summer drought was greater in the early Holocene. Similarly, charcoal data from shrub tundra regions of northern Alaska indicate the possibility of a fire regime more typical of modern boreal forests as a result of future warming (Higuera et al., 2008). 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 (Bartlein et al., 2008; Trouet et al., 2006; Flannigan et al.; 2005). It is also possible that novel fire-climate patterns may develop in a greenhouse-warmed world, but in any case, identifying such novel conditions will depend upon historical perspectives for comparison.

Interpreting the fire activity of recent years requires the understanding gained from a longer time perspective. Fire-history data disclose that some regions have experienced little change in fire frequency over several millennia. Other areas have arrived at present fire conditions following a trajectory of human-caused change in ecosystems and steadily increasing fire frequency or severity, and still others have reached modern conditions as part of a long-term decline in fire activity from the early or middle Holocene. Simply knowing the time since the last fire is not enough to understand the range of variability in fire regimes, the role of climate, vegetation, and humans, nor the fire response in the future under projected climate change conditions.

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4 Current Fire Regimes, Impacts and the Likely Changes – I: Past, Current and Future Boreal Fire Activity in Canada

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Abstract

Forest fire has been natural and essential to forest ecosystem health and maintenance across much of Canada since the last Ice Age, and has been a particularly dominant disturbance regime throughout Canada's vast boreal region. Over the past century Canada has developed highly sophisticated forest fire management programs designed to protect the public and forest values from unwanted fire, while also permitting fire to burn naturally in vast regions of the country where values-at-risk do not warrant fire suppression. It is neither economically or physically possible, nor ecologically desirable to suppress fires in these remote regions. Appreciating this philosophical dichotomy is essential to understanding the role of fire and fire management in Canadian forests. The complexity of wildland fire management issues in Canada is growing, and these pressures will continue to escalate. As we move forward in the 21st century it is extremely unlikely that the rapidly increasing complexity of wildland fire management that has been experienced over the past two decades will subside. These pressures will continue to escalate, and innovative policies and practices that address both the root causes and the symptomatic problems of wildland fire must be developed and implemented. In spite of this level of adaptation, it seems certain that a new accommodation with wildland fire is on the horizon in Canada.

Keywords: Boreal forest, Canadian Wildland Fire Strategy, modified suppression zones, wildland-urban interface, lightning fire

Canadian Fire Context

The evolution of forest management in Canada, particularly over the past century, has been accompanied by a parallel growth in the development of forest fire management programmes designed to protect forests from unwanted fire. Consideration of the natural and essential role of fire in many ecosystems in Canada is central to understanding the extent and impacts

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of fires in this country. Such awareness is also key to understanding the philosophy of fire management practices in Canada.

Canada has a land base of 910×10^6 ha, of which 402×10^6 ha are forests or other wooded land, and with an unevenly distributed population of approximately 33 million people, located mostly close to the border with the United States and some distance from Canada's primary forests. Canada is a forest nation, with forests being intimately linked to the country's cultural, economic and social development over the past one to two centuries. More than 93% of the forest land in Canada is publicly owned, the vast majority being owned and managed by provincial and territorial governments, with a small proportion (e.g. national parks and First Nations lands) under federal responsibility. The economic and recreational importance of this resource, along with the need to protect life and property, are the primary reasons Canada has developed one of the world's most sophisticated forest fire management programs. A large percentage of Canadian forests, particularly in the far northern regions of the country, are only marginally productive and do not form a part of the country's commercial forest lands.

Forest fires have been a dominant disturbance regime in Canadian forests since the last Ice Age around 10,000 years ago. Fire is natural and essential across much of Canada's forested landscape, and along with insects, disease, wind, and natural regeneration, helped to shape the character of Canadian forests before the country was settled. Fire is particularly significant in Canada's vast boreal forest region, where primary boreal species such as pine, spruce, birch, and aspen have adapted to fire to the point where it is essential to their existence, and adequate species regeneration requires the high-intensity crown fires natural to this region. Periodic lower-intensity fires are also required to maintain surface fire regimes in other forest regions of Canada. Fire organizes the physical and biological attributes of the boreal biome, shaping landscape diversity and influencing energy flows and biogeochemical cycles, particularly the carbon cycle (Weber and Stocks, 1998; Kurz et al., 1995; Harden et al., 2000). Canadian forests are therefore strongly connected to the fire regime, and are dependent on the frequency, extent, and severity of forest fires. In Canada, and across the circumpolar boreal zone, maintenance of natural forests, and the processes that support their existence, is crucial to maintaining a balanced global terrestrial biosphere.

However, Canada is a forest nation, with the industrial use of forests being intimately linked to the country's cultural, economic and social development. Forest industry expansion across Canada over the past century has resulted in the forest sector becoming the largest contributor to Canada's positive trade balance. Forest recreation is also an expanding Canadian activity. Clearly, such extensive utilization of the forest requires adequate protection from fire. Reconciling the natural role of fire in ecosystem maintenance with the need to protect life, property, and valuable products derived from the forest is a complex challenge.

Use of Canadian forests, for both industrial and recreational purposes, has increased dramatically in the past century. Along with the increased access and utilization has come a concurrent increase in forest fire incidence and the fire suppression capability mobilized to address this problem (Stocks and Simard, 1993). Organized fire suppression became more successful, but significant wildfire years were common. During periods of extreme fire weather, Canadian forests continued to sustain the large, high-intensity wildfires to which they had become adapted over millennia. During the 1970s there was a growing realization in Canada that total fire exclusion was neither economically feasible nor ecologically desirable. The pursuit of this goal had entailed considerable social and economic costs and, despite constantly increasing expenditures, there was no corresponding decrease in the number and impact of forest fires. This was coupled with an increasing awareness of the important and natural role of fire in maintaining forest health, productivity, and biodiversity, particularly in the boreal and temperate forest regions of Canada. These changes led to the evolution of a new fire management strategy in which consideration is given to the ecological role of fire, the economics of fire suppression, and the priority of values-at-risk. At the top end of the priority scale an ever-increasing number of wildland-urban interface (WUI) areas, and high-value forest industry and recreational sites receive vigorous protection. On the other hand, fire is often allowed to operate naturally in lower priority areas such as wilderness parks or remote forested areas of limited economic value where fire is a natural and necessary shaper of forest ecosystems. This policy of "modified suppression" is in effect in the northern regions of the provinces of Quebec, Ontario, Manitoba, and Saskatchewan, as well as most parts of the Northwest and Yukon Territories

Forest Fire Management in Canada

In Canada, responsibility for forest management, and therefore fire management, rests with each of the 13 autonomous provinces and territories, as the bulk of forested land in Canada is public, and owned by the provinces/territories. The federal government is responsible for fire management on federal lands (e.g. National Parks and First Nations reserves). In National Parks an emphasis is placed on maintaining ecological integrity by reintroducing periodic landscape-scale fire through prescribed burning and wildfire monitoring. In addition, 80% of aboriginal communities are located in forested areas and these communities negotiate agreements for protection. While provincial governments in Canada have the primary responsibility for forest fire management, the federal government has a primary responsibility for the health and safety of Canadians, and is also the "insurer" of last resort in providing disaster assistance. A number of federal agencies are involved in some aspect of wildland fire.

Fire suppression costs are consistently rising in Canada, due to a number of factors, including changes in fire weather, the use of more costly equipment, the expansion of fire protection zones northward to match growing forest operations, and increased costs associated with protection of an expanding wildland-urban interface. Annual suppression costs, not including public and industrial losses, are highly variable annually, but are averaging Can$700 million (Fig. 4.1) and can be as much as Can$1 billion in an extreme fire season. The provinces of British Columbia, Ontario, Alberta and Quebec generally account for approx. 80% of total Canadian fire management expenditures.

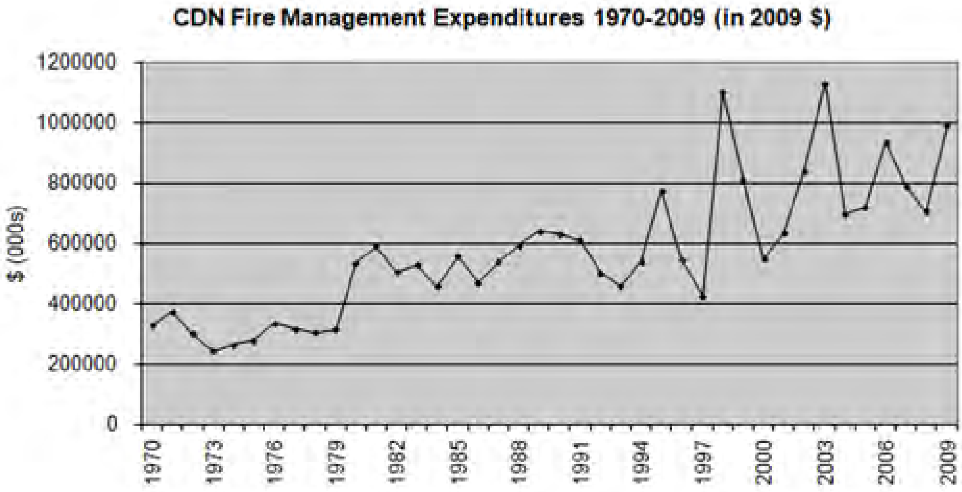


Figure 4.1. Canadian Fire Management Expenditures Post-1970 (in 2009 Can$). Source: B.J. Stocks Wildfire Investigations Ltd. (unpublished data).

The graph in Figure 4.1 clearly shows a steady increase in fire management costs throughout the 1970s, 1980s and much of the 1990s. Since that period, however, costs have risen more dramatically, and the inter-annual variability in costs has also increased substantially.

The nationally decentralized provincial fire management systems work quite efficiently in low and moderate seasons; by when fire activity becomes extreme, provinces rely on one another to supplement suppression resources. After a series of major fire seasons in the early 1980s, the Canadian Committee of Resource and Environment Ministers created the Canadian Interagency Forest Fire Centre (CIFFC) in 1981. Located in Winnipeg, CIFFC is a cooperative venture established to share information and fire management resources among its federal, provincial, and territorial member agencies.[3] Over the past two decades, CIFFC has made a major contribution to fire management in Canada by conducting information and resource exchanges (including personnel, equipment and aircraft), establishing national standards for equipment and personnel, negotiating a pre-arranged cost recovery system, formulating working groups to address common interagency issues, and serving as a contact point for international requests and cooperation. Agencies have increasingly recognized that there are considerable economic efficiencies to be gained (estimated to be millions of dollars annually) in risk management by sharing resources through CIFFC and these practices have become an important part of the fire management business.

Over the past 80 years, Canadian fire management agencies have grown in size and sophistication to address expanding responsibilities in protecting Canadian forests from un-

3 www.ciffc.ca

wanted fires (Stocks and Simard, 1993). Operational fire managers and fire scientists in Canada have worked closely together to develop highly sophisticated systems to predict the occurrence, behaviour, and impact of forest fires in various ecosystems across the country. Two key objectives in successfully controlling fires are early detection and initial attack when fires are small. This involves prediction of the most likely locations where fires will start (both lightning and human-caused fires), and the implementation of enhanced detection (primarily aircraft patrols) in those areas. When fires are detected, initial attack forces are deployed by land or helicopter, and are often supported by aircraft dropping water, foam, or fire retardant chemicals.

Extent and Impact of Forest Fires in Canada

Canadian fire management agencies have been largely successful in controlling a major percentage of the fires that occur in high-value areas of the country. However, extreme fire danger conditions, often coupled with multiple fire starts, occasionally overwhelm fire suppression resources, and large areas burn.

Forest fire statistics have been archived since 1920 in Canada. Prior to the advent of satellite coverage in the early 1970s, it is believed that many fires in remote regions were not detected or monitored, such that the record for this period is somewhat incomplete. Bearing this in mind, the annual number of recorded fires in Canada (Fig. 4.2) has increased rather steadily from around 6,000 fires in the 1930-1960 period, to an average of around 8,000 fires during the 1970-2010 period, most likely the result of a growing population and expanded forest use, along with an increased detection capability. From Figure 4.2, it is also evident that the area burned by Canadian forest fires fluctuates greatly from year to year, from under 0.5×10^6 ha to more than 7×10^6 ha in extreme years. In comparison to the 1950s and 1960s, average annual area burned has been increasing over the past three decades (Fig. 4.3). Major fire years occurred in 1980, 1981, 1989, 1994, 1995, and 1998. Although variable between regions of the country, lightning is responsible for an average of 35% of Canadian fires, yet lightning fires account for 85% of the total area burned. This is due to the fact that lightning fires occur randomly, often in significant numbers, over large areas, presenting access problems not usually associated with human-caused fires. As a result, lightning fires often grow larger, as detection and subsequent initial attack is often more delayed. Lightning fires dominate in the northern remote regions of Canada where population levels are low. Recreational activities, forest industry operations, and homeowners living in or near the forest, are primarily responsible for accidental human-caused fire occurrence, which dominates in the intensively protected forest regions of Canada.

The sophisticated fire suppression systems in place across Canada are largely successful, in that the vast majority of fires (approx. 97%) are contained at an early stage (<200 ha). However, the approx. 3% of fires that exceed 200 hectares in size, account for around 97% of the total area burned. Over the past four decades, an average of approx. 2×10^6 ha burned annually in Canada, with close to 50% of this area burning in remote "modified suppression"

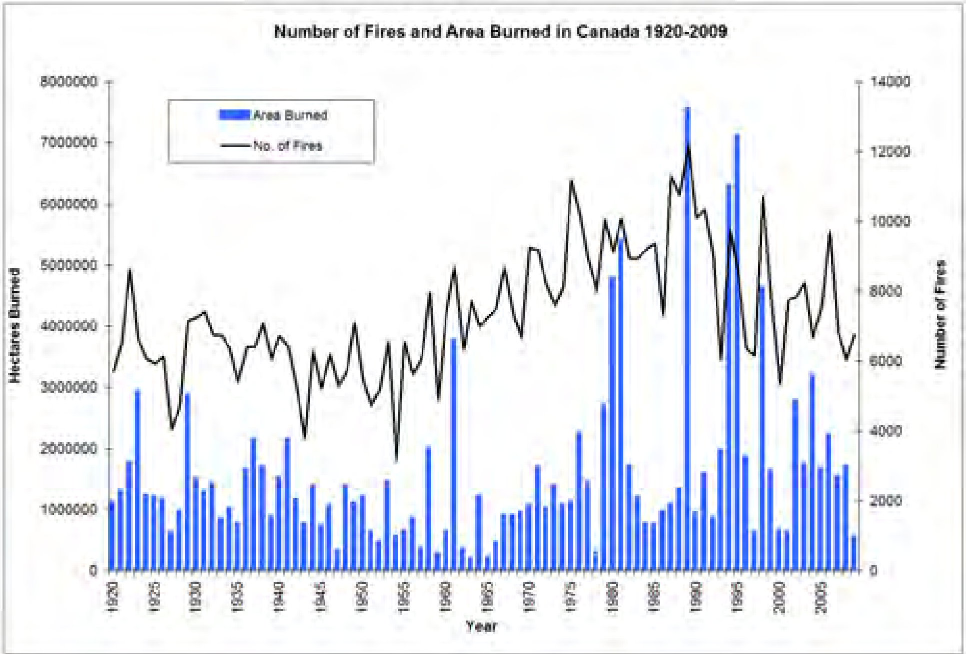


Figure 4.2. Annual number of fires and area burned in Canada 1920-2009.
Source: Canadian Forestry Database Program.

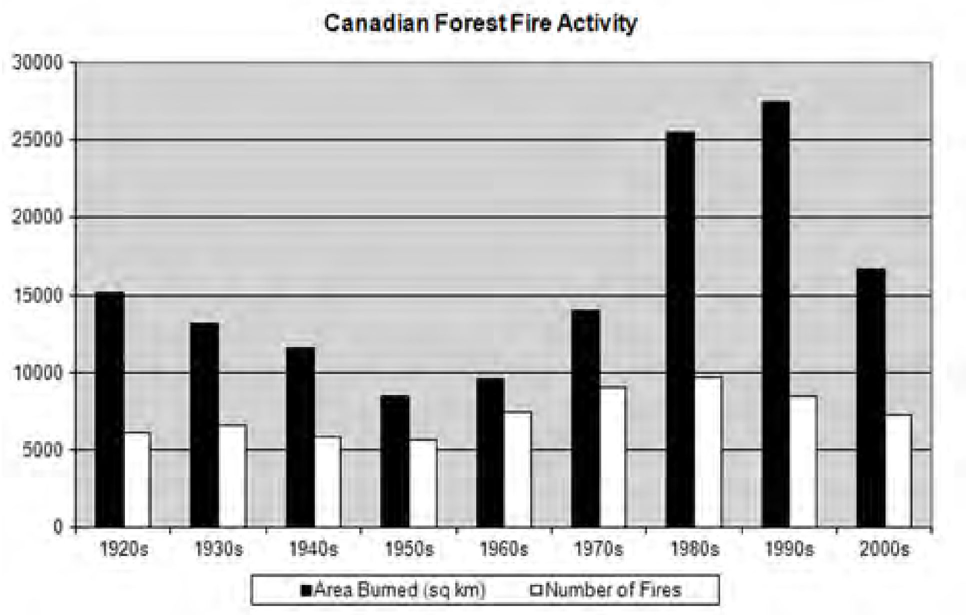


Figure 4.3. Annual number of fires and area burned in Canada, averaged by decades (1920s through 2000s). Source: B.J. Stocks Wildfire Investigations Ltd.

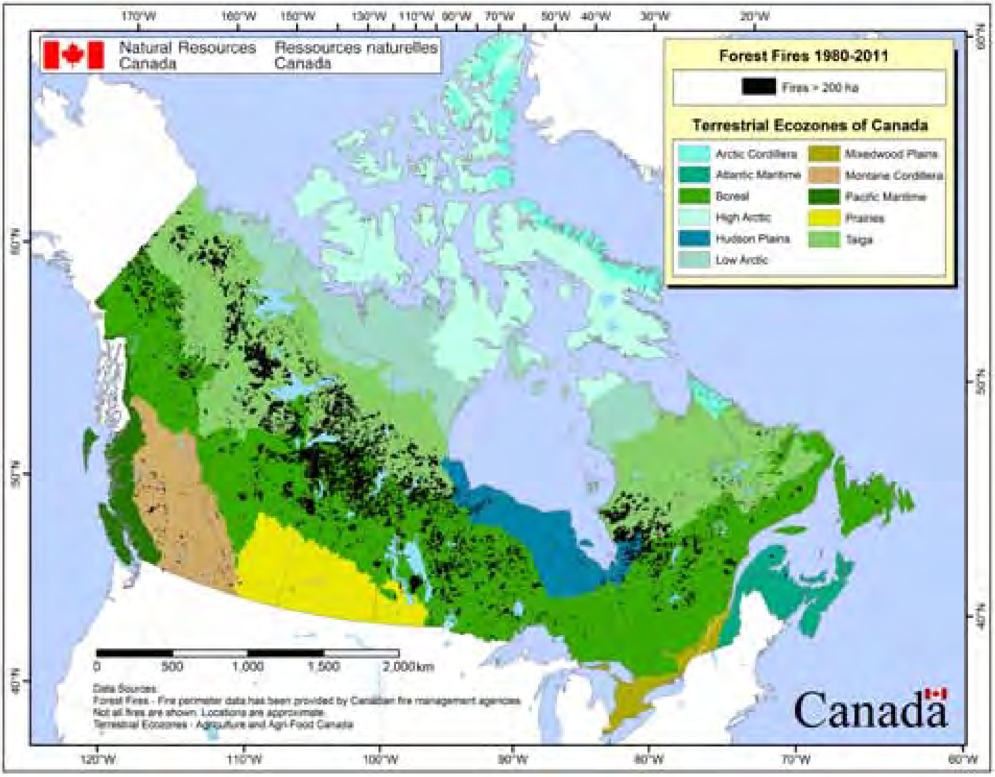


Figure 4.4. Distribution of fires >200 ha (black polygons) during the 1980-2011 period.

zones, primarily in the northern regions of west-central Canada (Stocks et al., 2003). The contribution of these fires to the total area burned in Canada can be seen in Figure 4.4, which shows the distribution of 1980-2011 large fires (>200 ha in size) across Canada.

Clearly, the largest areas burned occurred in west-central Canada, in a band running from northwestern Ontario through northern Manitoba and Saskatchewan into the Northwest Territories, regions containing large areas where extreme fire weather and lightning activity are common, values-at-risk to not warrant aggressive fire suppression, and fires most often burn naturally. Most forested regions of southern Canada sustained fewer large fires as a result of intensive protection, although large fires are still a factor in these areas. Fires in excess of 100,000 ha are not uncommon in Canada, and fires exceeding 1×10^6 ha have been recorded. The difference in fire dynamics between the intensively protected regions of Canada and those areas where "modified" suppression is practiced and fires for the most part burn naturally is evident from Figure 4.5. Although the number of fires occurring in "modified" zones is much smaller than in the intensively protected regions, the area burned is larger, primarily due to the policy of letting fires burn naturally where possible. Fires in "modified" suppression zones are generally only attacked when they threaten communities, and even then, usually only in a "defensive" mode.

Emerging Forest Fire Issues in Canada

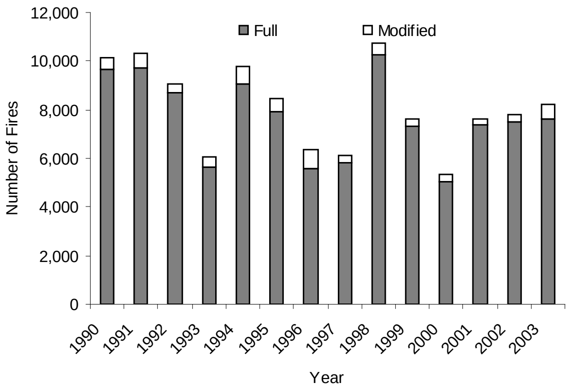
In recent years a number of issues and concerns around the current and future state of fire management in Canada have been identified. Some of the most important emerging issues were a major impetus in the development of the Canadian Wildland Fire Strategy (CWFS), and are discussed below (Wotton and Stocks, 2006).

Public Awareness and Involvement

Public awareness of forest issues in Canada, including fire management practices, has been growing quickly in recent years, partly due to the success of public awareness programmes and expanded media coverage. This is particularly true with First Nations peoples, forest land owners, and ex-urbanites moving to the Wildland Urban Interface (WUI). All expect to be consulted before new policies are initiated, and involved in this process. In addition, they expect that the protection and defense of their immediate values is the responsibility of the government. This growing emphasis on a civil society, with a greater public role/responsibility in resource management decision-making, requires fire management agencies to emphasize the inclusion of all stakeholders in policy development. It also requires an informed public that understands that not all fires are bad and that fire suppression effectiveness has limits. Across Canada the growing emphasis on public safety has made wildland fire an issue for all levels of government (federal, provincial/territorial, and municipal), and they are now working more closely together to maximize effectiveness (Canadian Wildland Fire Strategy [CCFM], 2006).

Forest Health and Productivity

The successful suppression of fire in many regions of Canada has led to a shift to older age classes or forests in later successional stages, particularly in forests normally maintained by periodic surface fires. This could lead to significant changes in wildfire potential and resultant fire regimes, as increasing fuel accumulation levels would result in fires of higher intensity, increasing control difficulties and escaped fires. Fire exclusion in many ecosystems creates an environment favourable to the development of major insect infestations over large areas (e.g. the Mountain Pine Beetle in western Canada, and the Eastern Spruce Budworm in eastern Canada), which in turn is often followed by large fires fuelled by excessive dead woody material (Fleming et al., 2002). This large-scale infestation could have significant carbon feedback to climate change (Kurz et al., 2008).



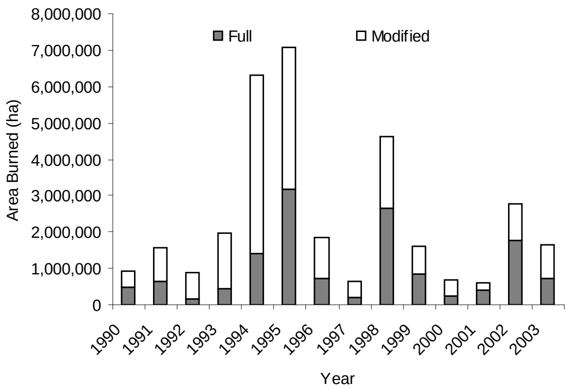


Figure 4.5. Area burned and number of fires in Canada by protection response (full or modified) for the 1990-2008 period. Source: CIFFC.

Competition for Forest Land Base

Canadian forests are now exposed to increasing and competing demands on the land-base. Forest industry is under pressure to continually increase wood supply to meet market demands while accessible Canadian forests are almost fully committed, and international competition is increasing. There is growing pressure from environmental groups and the public in general to set aside and protect more forest areas for recreational activities, biodiversity conservation etc. Aboriginal groups also require expanded access to forest lands for traditional pursuits, including the growing Non-Timber Forest Products (NTFP) industry.

Expanding Wildland-Urban Interface (WUI)

In recent years there has been large increase in the number of homes and communities constructed adjacent to and among forests and other flammable vegetation. Living close to the forest has become desirable to many ex-urbanites and expensive communities are growing in the WUI. These homeowners have little knowledge of wildfires or the need to protect their homes. In addition, very few of these communities have building codes that require residents to build wildland fire-resistant homes and/or manage fuels on their property. The threat of WUI wildfires became common knowledge to all Canadians in the summer of 2003, when continued extreme fire danger conditions and multiple ignitions in the interior of British Columbia overwhelmed suppression capabilities, and fires destroyed homes in a number of communities. A total of 334 homes and 10 businesses were destroyed and over 45,000 people evacuated, and total economic impact on the province of British Columbia will measure in the hundreds of millions of Canadian dollars. A number of provincial/territorial fire management agencies, along with municipal governments are attempting to institute hazard mitigation programs within and around these communities, but this is a formidable task given the rate of WUI expansion and increasing wildfire threats. These programs should consider the biophysical aspects (e.g. fuel reduction/modification) along with the social aspects (e.g. public awareness/involvement) of hazard mitigation. In addition, communities in northern Canada, which are primarily aboriginal or associated with resource-extraction industries, currently require better protection against fire impacts through hazard mitigation. These communities depend on the forest around them for their livelihood, so that even fires that do not impact a town-site directly can significantly affect the future of that community. Evacuations of many northern communities occur almost annually to guard against direct or indirect (health effects) impacts from fire (Canadian Wildland Fire Strategy [CCFM], 2006).

Climate Change

It is a generally accepted conclusion among scientists and a growing percentage of the public that climate change is a reality, and that impacts across Canada will be profound, and largely unavoidable, over the next century (Stocks et al., 1998; Flannigan et al., 2005). Research to date indicates that both the incidence and severity of forest fires will increase dramatically. The result will be larger areas burned, shorter fire-return intervals, a shift to a lower forest age-class distribution, and a net loss of terrestrial carbon to the atmosphere, likely resulting in a positive feedback wherein more fire leads to greater atmospheric carbon which leads to greater warming and more fire (Bond-Lamberty et al., 2007). Any trend towards increased fire activity and impacts will put extreme pressure on Canadian fire management agencies, and they will be unlikely to maintain their current level of control over fire impacts. Recent studies indicate substantial costs would be required to attempt to keep escaped fires at current levels, and escaped fires increasing significantly using current resource strength under a changing climate (Flannigan et al., 2009). It appears that fire suppression as practiced today will not be economically sustainable in the future, as we will not be able to meet current targets in terms of area burned and escaped fires. This will have direct effects on wood supply and the competitiveness of forest industry, along with approximately 300 forest industry-dependent communities in Canada. It may also have an impact on Canada's commitment to carbon sequestration and emissions reduction under the Kyoto Protocol, particularly with increased carbon loss through more severe forest fires and the new exposure of carbon-rich peatlands to future fire (Amiro et al., 2009; Turetsky et al., 2002).

Forest Fire Management Infrastructure

Forest fire suppression is an increasingly costly business relying on a large investment in very expensive equipment (e.g., airtankers, helicopters) and infrastructure. For suppression activities to remain safe and efficient, aging equipment and infrastructure must be replaced as it reaches the end of its expected lifetime. For example, 50% of the Canadian airtanker fleet (45 aircraft) is 30 years of age or older with less than 10 years of remaining economic life expectancy. However, over the past decade or more fire management agencies, like all other government organizations, have been subject to frequent budget reductions and spending constraints. Furthermore, over the past decade, fire management costs have increased and, particularly when WUI fires occur, are becoming more variable and unpredictable on an inter-annual basis. Naturally, as with equipment and infrastructure, the fire management workforce is aging as well. The demographics of fire management in Canada are changing, and government budgetary restraints have reduced hiring and training activities. Nearly 50% of the current permanent fire management staff in Canada is due to retire in the next 10 years. While on the surface this problem would appear to be adequately addressed through increased hiring, the training path to developing highly qualified fire managers is lengthy (taking a good part of a career), and previous budgetary restraints and the ensuing delays in training have greatly reduced the number of personnel on the training track. As a result, in some jurisdictions there is a lack of qualified personnel to replace retiring fire managers (Born and Stocks, 2006).

These emerging issues, combined with the growing realization that fire management in Canada has reached its physical and economic limits and that diminishing marginal returns can be expected from increased expenditures, raises the possibility that fire management in Canada is at a crossroads. This realization has prompted initial efforts on the development of a new Canadian Wildland Fire Strategy designed so that all levels of government (federal, provincial/territorial, and municipal), along with citizens and corporations, will share the risks of wildland fires in the 21st Century. The CWFS has been approved by all provincial and territorial forest ministers in Canada, along with the federal government, but has yet to be funded to any extent. Still, an agreed-upon strategy that charts a path forward for forest fire management in Canada at a time of great uncertainty is a major accomplishment. The political motivation to implement the CWFS will likely only come after the next major fire event in Canada galvanizes public and political support.

As we move forward in the 21st century it is extremely unlikely that the rapidly increasing complexity of wildland fire management that has been experienced over the past two decades will subside. These pressures will continue to escalate, and innovative policies and practices that address both the root causes and the symptomatic problems of wildland fire must be developed and implemented in a timely manner across all regions and jurisdictions of Canada.

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5 Current Fire Regimes, Impacts and the Likely Changes – II: Forest Fires in Russia – Past and Current Trends

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Abstract

While there is a lack of reliable or comprehensive statistics on wildland fires published or available on internal agency databases for the territories of the former Union of the Soviet Socialist Republics (USSR), which would allow accurate quantification, satellite-remote sensing since the 1990s provided an increasingly improved insight in the extent of fires burning in the Russian Federation. Although there are still uncertainties and discrepancies of the area burned in the Russian Federation based on NOAA / AVHRR and TERRA / MODIS data, partly verified by high-resolution products such as SPOT or Landsat imagery, fires depicted on forests, agricultural lands and other open land ecosystems are reaching magnitudes of 10 to 30 million ha vegetated land cover burned in individual years. The fire management capabilities of the Russian Federation and other countries of the Former Soviet Union largely declined as a consequence of the political, economic and administrative transition. In the Russian Federation the decentralization of authority for forest and fire management, based on the Forest Code enacted in 2007, resulted in further temporary reduction of fire management capability since regional authorities were not properly prepared to assume full responsibility. The fire season of 2010 resulted in severe damages and impacts of fires and fire smoke pollution on society in Western Russia and prompted high public and political awareness, and investments in fire management. However, the recently observed magnitude and trend of wildfires, and the predicted consequences of regional climate change on vegetation cover, wetlands, permafrost and fire regimes, coupled with the impacts of socio-economic changes, on increasing wildfire hazard, risk and vulnerability imply that the extent and severity of fires in future will affect ecosystems and the global atmosphere, and most likely will continue to affect society.

Keywords: Vegetation fire smoke pollution, agricultural burning, rural exodus, transboundary smoke transport, aerial fire protection.

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Quantifying Fire Activity and Impacts in Russia

The USSR Era

The boreal and sub-boreal forests, grasslands and agricultural lands of the Russian Federation, notably in Siberia, have long been noted as a region where extensive fire activities are common; earlier Russian fire literature supports this conclusion (Shostakovich, 1925; Lutz, 1956; Kurbatskii, 1975; see also numerous sources cited in Goldammer and Furyaev [1996]). However, no reliable or comprehensive statistics were ever published by the former Union of the Soviet Socialist Republics (USSR) which would allow accurate quantification of the magnitude of the problem in the country. Periodically, some qualitative accounts of the role of fire in the Siberian forests were published, but these contained only partial statistics at best, which did not permit even rudimentary analysis. During the particularly severe fire year of 1987, satellite analysis revealed that, along with the wildfires affecting Northeast China which burned in excess of 1.3×10^6 ha, fires in eastern Siberia affected more than 10×10^6 ha (Stocks and Jin, 1988; Cahoon et al., 1991, 1994). While the absolute accuracy of this estimate may be questionable due to the coarse resolution of the satellite imagery used, it still provided, in the absence of any official statistics from the National Aerial Forest Fire Center (*Avialesookhrana*) for the USSR, a reasonable indication of the enormous forest fire problems that existed in this region in 1987. While fire activity in the USSR could be assumed to fluctuate from year to year, as is the case in other boreal countries, the 1987 scenario was strong evidence that a significant proportion of the earth's large boreal forest fires occur in Siberia. Figure 1 shows official area burned statistics for the 1980-1999 period for Russia, Canada and Alaska, clearly illustrating that, while area burned can vary inter-annually by an order of magnitude in Canada and Alaska, Russian area burned totals are relatively constant, raising serious questions about the validity of these statistics (Stocks et al., 2001).

The Post-USSR Era

With the dissolution of the USSR in the early 1990s, western and Russian fire managers and scientists began to work cooperatively, and a more realistic representation of forest fire impacts in Russia began to emerge. At an international conference in Krasnoyarsk in 1993 (Goldammer and Furyaev, 1996) official Russian fire statistics for the 1956-1990 period were presented (Korovin, 1996), which indicated that, on average, 16,500 fires burned over ~0.65×10^6 ha annually in the former USSR, with very little annual variation. Russian fire managers agree, however, that these numbers are a gross underestimation of the actual extent of boreal fire in Russia, primarily due to an incomplete reporting structure that left large regions of the country unmonitored, and also emphasized under-reporting actual fire statistics, particularly fire sizes and area burned. A NOAA AVHRR satellite receiving station was established in Siberia in 1995, permitting much more accurate estimations of area burned in Siberia. Previously unmonitored regions of Russia are now covered under the new

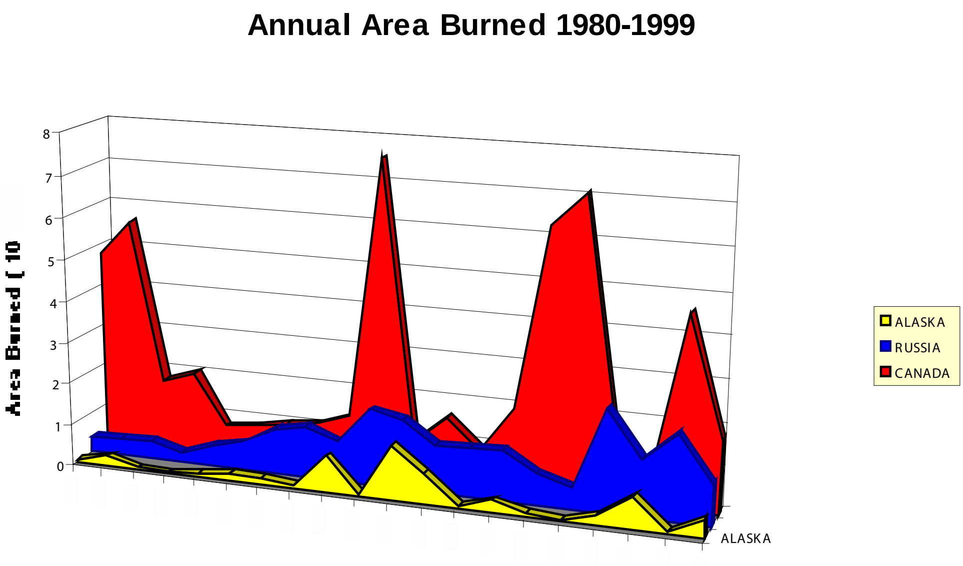


Figure 5.1. Official statistics of annual area burned in Russia, Canada and Alaska 1980-1999.

satellite-based system of fire detection and monitoring. Satellite data reveals much larger areas burning in Siberia than official records indicate (e.g. Sukhinin et al., 2004; Soja et al., 2004, 2007; Huang et al., 2009), and this is illustrated in Tables 5.1 and 5.2 which compares official fire agency statistics with those reported by the independent remote sensing institution of the Russian Academy of Sciences (Sukachev Institute for Forest, Krasnoyarsk) for the 1996-2005 period for Russia and for the 2000-2010 period for the Asian part of Russia. There are a number of reasons for these discrepancies, including:

- A reduced capability of national and regional fire management organizations in Russia to monitor fires by conventional ground and aircraft patrols due to severe financial constraints.
- The area of coverage – official records are based on coverage over 690×10^6 ha, satellite coverage has been extended to monitor over 1×10^7 ha, and includes all vegetation types (forest, tundra, steppe etc.).
- Some overestimation of areas burned by small fire events due to the system-inherent low spatial resolution of the AVHRR sensor as well as the resolution of the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor on NASA's satellite TERRA, which has been used for wildfire detection since 2007.
- Some smaller fire events going undetected by satellite due to cloud cover and/or sensor detection limits.

The data are based on various sources of ground reports and satellite-derived data. Tables 5.1 to 5.3 cover overlapping the years 1996-2012 (with overlapping data for 2000-2005), but refer to different regions, i.e. not to the entire territories of the Russian Federation, and are results of different evaluation methods. Thus, while these tables cannot be compared or interpreted directly, they provide a magnitude of the issue. And the discrepancies between the various dataset merit closer investigations.

Table 5.1. Comparative fire statistics for total vegetated area and forest area burned in the Russian Federation in the period 1996 to 2005, based on agency reports and remote sensing.

Year	Agency Reports based on Ground and Aerial Observations [1]			Satellite-Derived Data (NOAA AVHRR) Based on Fire Counts and Derived Area Burned [2]		
	Number of Fires Reported	**Total Area Burned** (m ha)	**Forest Area Burned** (m ha)	**Number of Fire Events investigated**	**Total Area Burned** (m ha)	**Forest Area Burned** (m ha)
1996	22 623	2.3	1.8	7 103	6.0	3.8
1997	23 090	0.9	0.6	3 598	4.5	3.6
1998	15 931	3.0	2.4	6 255	11.5	6.7
1999	18 138	0.7	0.5	7 940	5.4	3.3
2000	13 447	1.1	0.9	8 399	9.7	5.9
2001	14 561	1.2	0.8	7 095	7.6	4.2
2002	19 066	1.8	1.2	10 355	11.8	6.6
2003	21 699	2.6	2.2	16 112	17.4	14.5
2004	16 729	0.5	0.4	9 477	5.8	3.1
2005	10 923	0.9	0.7	24 272	12.8	7.2

1 Agency data provided by *Avialesookhrana* of Russia for the forest land under the jurisdiction of the Federal Forest Agency (Federal Forest Fund). On average these data represent ca. 90% of fires recorded statistically. The remaining 10% are data collected within the responsibility and jurisdiction of other agencies, e.g. the National Park Service.

2 Satellite data provided by the Sukachev Institute of Forest, Remote Sensing Laboratory, Russian Academy of Sciences, Siberian Branch, Krasnoyarsk, Russian Federation (courtesy A. Sukhinin). The Krasnoyarsk satellite receiving station covers the Russian Federation between the Ural mountains in the West and Sakhalin Island in the East and recording fires and area burned independent of land ownership.

Table 5.2. Comparative fire statistics for total vegetated area burned in the Asian part of Russia in the period 2000 to 2012, based on remote sensing data processed by the Sukachev Institute of Forest, the FIRMS MODIS Burned Area Product and the official statistics provided by *Avialesookhrana* of Russia. Source: Laboratory of Forest Monitoring, V.N. Sukachev Institute of Forest.

Year	Sukachev Institute of Forest[1]		FIRMS MODIS Burned Area Product[2] (r=0,65)	*Avialesookhrana*[3] (r=0,55)
	Total Area Burned (m ha)	Total Area Burned without 1-days fire (m ha)	Total Area Burned (m ha)	Total Area Burned (m ha)
2000	6.9	4.3	2.3	1.00
2001	6.6	3.9	3.9	0.82
2002	11.7	8.8	5.8	1.18
2003	21.6	17.6	16.7	2.08
2004	5.8	2.8	2.9	0.42
2005	11.6	5.8	4.1	0.72
2006	17.8	12.6	7.2	1.16
2007	12.7	8.9	5.2	1.11
2008	22.9	16.4	13.6	2.23
2009	14.7	10.4	7.5	1.95
2010	12.9	9.2	4.4	1.13
2011	26.4	20.7	8.0	1.18
2012	38.3	33.4	9.6	1.53

[1]Based on NOAA/AVHRR and TERRA/MODIS data, partly verified by using of SPOT and Landsat imagery.
[2] http://earthdata.nasa.gov/data/near-real-time-data/firms
[3] Agency data (for Ural, Siberian and Far East Federal Districts) provided by *Avialesookhrana* of Russia
Note: The correlation coefficients are for pair of Sukachev Institute of Forest and FIRMS, and Sukachev Institute of Forest and Avialesookhrana data (r=0,65 and r= 0,55 respectively)

Table 5.3. Number of fires and area burned in the Asian part of the Russian Federation based on NOAA/AVHRR and TERRA/MODIS data (partly verified by using of SPOT and Landsat imagery) for the period 2006-2012. Fires depicted on agricultural lands are one-day events occurring in spring. The data of 2012 (up to October 2012) reveal that out of 38 million hectares burned in the Asian part of Russia and 33.4 million ha burned as events of a duration longer than one day, i.e. fires burning in terrain other than agricultural areas. While half of the number of fires depicted by satellite are considered short-living agricultural fire events, the area burned by these fires is less than half of the area burned. The total area of land area, including forest lands, affected by wildfires in 2012 is unprecedented and amounts close to 34 million ha. Source: Laboratory of Forest Monitoring, V.N. Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, Russian Federation.

Year	Total		Thereof Forest		Thereof Non forest		Thereof 1-Day Spring Fires		Total without 1-Day Spring Fires	
	Number (x1000)	Area (m ha)	Number (x1000)	Area (m ha)	Number (x1000)	Area (m ha)	Number (x1000)	Area (m ha)	Number (x1000)	Area (m ha)
2006	26.0	17.8	9.0	8.3	17.0	9.5	13.5	5.2	12.5	12.6
2007	23.7	12.7	8.5	5.9	15.2	6.8	11.0	3.8	12.7	8.9
2008	28.6	22.9	9.3	10.7	19.3	12.2	18.5	6.5	10.1	16.4
2009	19.7	14.7	5.4	5.2	14.3	9.5	12.4	4.3	7.3	10.4
2010	18.8	12.9	4.7	4.3	14.1	8.6	10.6	3.7	8.2	9.2
2011	24.4	26.4	8.4	12.4	16.0	14.0	15.6	5.7	8.8	20.7
2012	**23.7**	**38.3**	**9.2**	**22.7**	**14.5**	**15.6**	**12.1**	**4.9**	**11.6**	**33.4**

A multi-sensor analysis investigated the fires of 2003 occurring in the region around and Southeast of Baikal lake between 110.27°E to 131.00°E and 49.89°N to 55.27°N by evaluating scenes of MODIS, MERIS and ASTER and comparing these with NOAA AVHRR (Huang et al., 2009; Fig. 5.4). The study revealed that on a total land area of 130 million more than 20.2 million ha of forests and other lands had been affected by fire in 2003 – an area larger than reported by the Sukachev Institute (Tab. 5.2).

Besides the obvious discrepancies between the various fire products derived from satellite sensors there are some additional caveats concerning the interpretation of satellite-derived fire data. Without a clear reference to the ecosystem characteristics and fire regimes – particularly fire characteristics and impacts – satellite data cannot be compared directly with agency reports. According to on-site field research by the GFMC in Central Asian part of Russia, fires are often reported only if protected forests have been damaged directly and visibly, e.g. by crown scorch, timber damage or foliage consumption with subsequent mortality. Thus, fires burning in so-called "grass forests" – open, park-like pine or larch stands with a grass cover which are regularly underburned – may not result in an immediately visible damage.

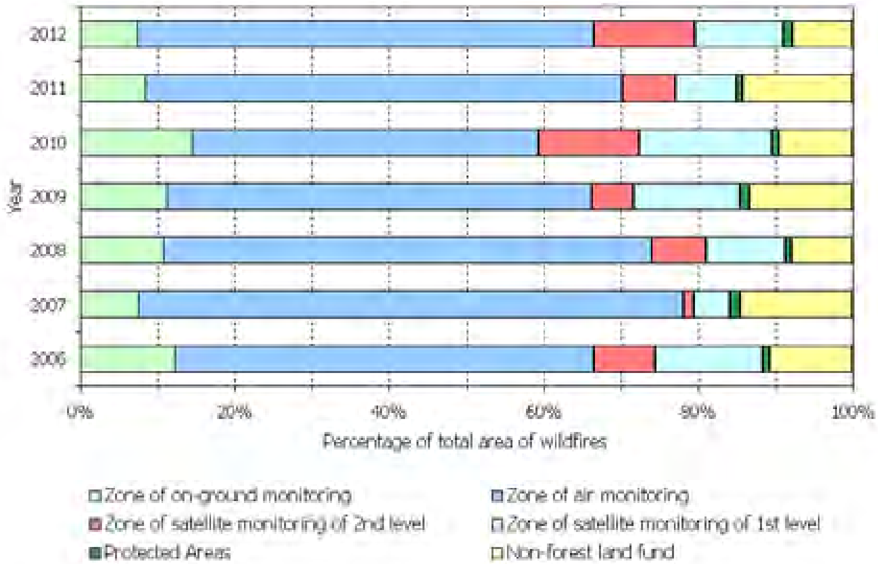


Figure 5.2. Breakdown of area burned in the Asian part of Russia by zonal classification (Fire Monitoring Zones: see Figure 5.3) in the time period 2006 to October 2012 on the territories of the Russian Forest Fund, non-forested lands within the Russian Forest Fund, and special protected areas. The 'Ground Monitoring Zone' involves ground patrolling and detection of wildfires. The 'Air Monitoring Zone' is currently the largest zone and involves patrolling and detection of wildfires by aircraft. The 'Satellite Monitoring Zones', Levels I and II, involve satellite assets for fire detection and monitoring with limited or none response. Source: Laboratory of Forest Monitoring, V.N. Sukachev Institute of Forest, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, Russian Federation.

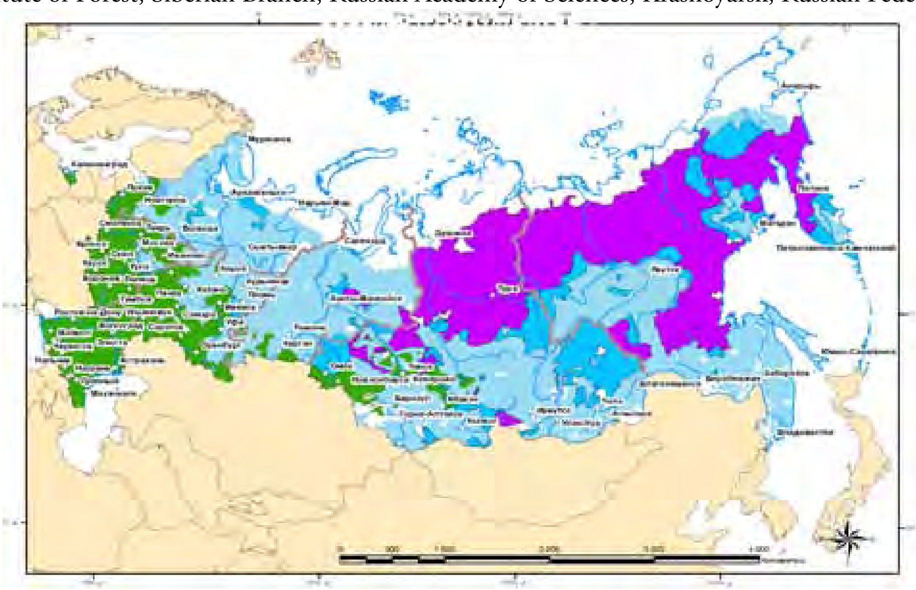


Figure 5.3. Fire Monitoring Zones in the Russian Federation. Source: Avialesookhrana.

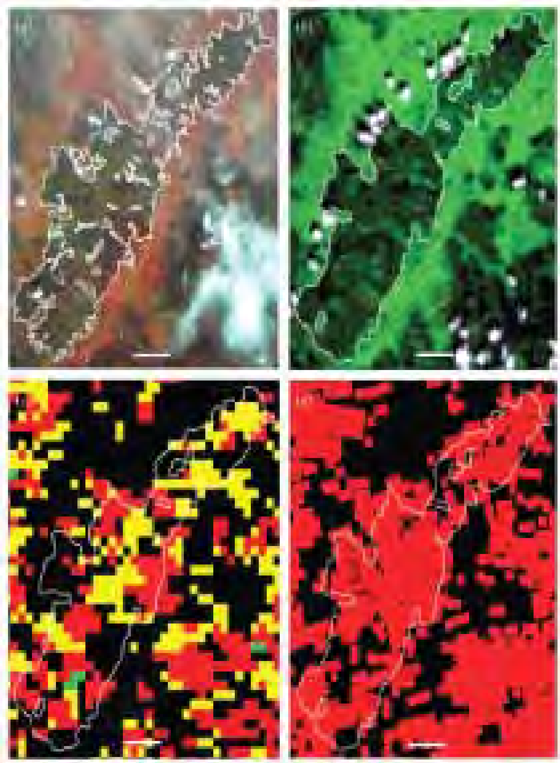


Figure 5.4. Comparison of a fire scar as detected by (a) ASTER acquired on 12 July 2003, R3G2B1, (b) MERIS acquired on 13 July 2003, R6G10B1, (c) MODIS hotspot composite acquired between 14 March 2003 and 11 July 2003 and (d) AVHRR fire product of 2003. Scale bar: 5 km. Source: Huang et al. (2009).

It is clear that many questions remain concerning the actual extent of fire activity in Russia, even with extensive satellite coverage in recent years. To address this problem, a study is underway using all archived fire season AVHRR imagery over Russia post-1979 (when the AVHRR instrument was first deployed) to analyze fire scars to determine monthly and annual area burned. This work involves the use of new fire scar mapping algorithms, combined with internet access to all available imagery, resulting in the development of monthly composite images that show the spatial distribution of large fires. Preliminary analysis of area burned trends during the 1979-1995 period shows that, as anticipated, area burned exhibits great inter-annual variability (Stocks and Cahoon, 2011). Although some evaluation remains to be done in 2013, particularly on low fire years with smaller fires that are more difficult to map, it appears that area burned varies between ~1×10^6 ha in low years (e.g. 1980, 1981, 1982, 1983) to ~$8\text{-}10\times10^6$ ha in severe fire years (e.g. 1984, 1985, 1986, 1987). Further analysis will be undertaken, in close cooperation with Russian remote sensing scientists to validate Russian satellite area burned estimates post-1995. With growing international interest in the future of the global boreal zone, where climate change impacts are forecast to have regional to global implications, it is critically important to have forest fire statistics that are reliable, and can be used by the international modeling community with confidence. The reconstruction of area burned in Russia for the 1979-1995 period, which is currently underway and will, when combined with post-1995 data, provide a reliable 30-year database that can be used for future climate change projections, including carbon budget impacts (Stocks and Cahoon, 2011).

Fire Management in Russia

The period 1930-1991

Although ground-based forest fire protection had been practiced in the Russia for many decades, the early 1920s brought recognition that effective protection of the vast Russian taiga required aircraft, and operational research was focused in this area (Kovalev, 2005). Experimental aerial reconnaissance flights were undertaken sporadically, with the beginnings of a formal aerial protection program initiated in the early 1930s. Operational flights for fire detection and monitoring began in the central Urals, Siberia, and the Far East regions of Russia, under the All-Union Scientific Research Institute of Agriculture and Forestry Aviation, and later the All-Union Trust for Forest Aviation. This formalization of aerial fire protection led quickly to rudimentary attempts at dropping chemicals and water from aircraft and, in 1934 a smokejumping program was initiated. New bases were established across Siberia, and the program expanded dramatically after World War II using surplus military aircraft and demobilized paratroopers. The aerial forest protection service *Avialesookhrana* began using helicopters to transport firefighters and equipment (some mechanized) in the mid-1970s, and began to exert a major influence on the area burned throughout Russia, especially in regards to suppression of human-started fires near settlements. At that time over 8000 smokejumpers and rappellers were employed in the Aerial Forest Protection Service *Avialesookhrana*. On average they were able to suppress about 70% of the fires at initial attack. About 600 aircraft were rented from aviation enterprises. By the late 1980s the Soviet Union had amassed the largest firefighting system in the world (Goldammer, 2006).

The period 1991-2010

After the political and economic transition of the Soviet Union to the Russian Federation in 1991 budgets for fire management (prevention, detection, monitoring, and suppression) were greatly reduced. With these changes in Russia, the past gains in fire suppression have become difficult to sustain as the area receiving fire protection, the frequency of reconnaissance flights, and the numbers of fire fighters that can be hired and deployed decreased dramatically. Consequently the average size of fires at detection and initial attack has increased

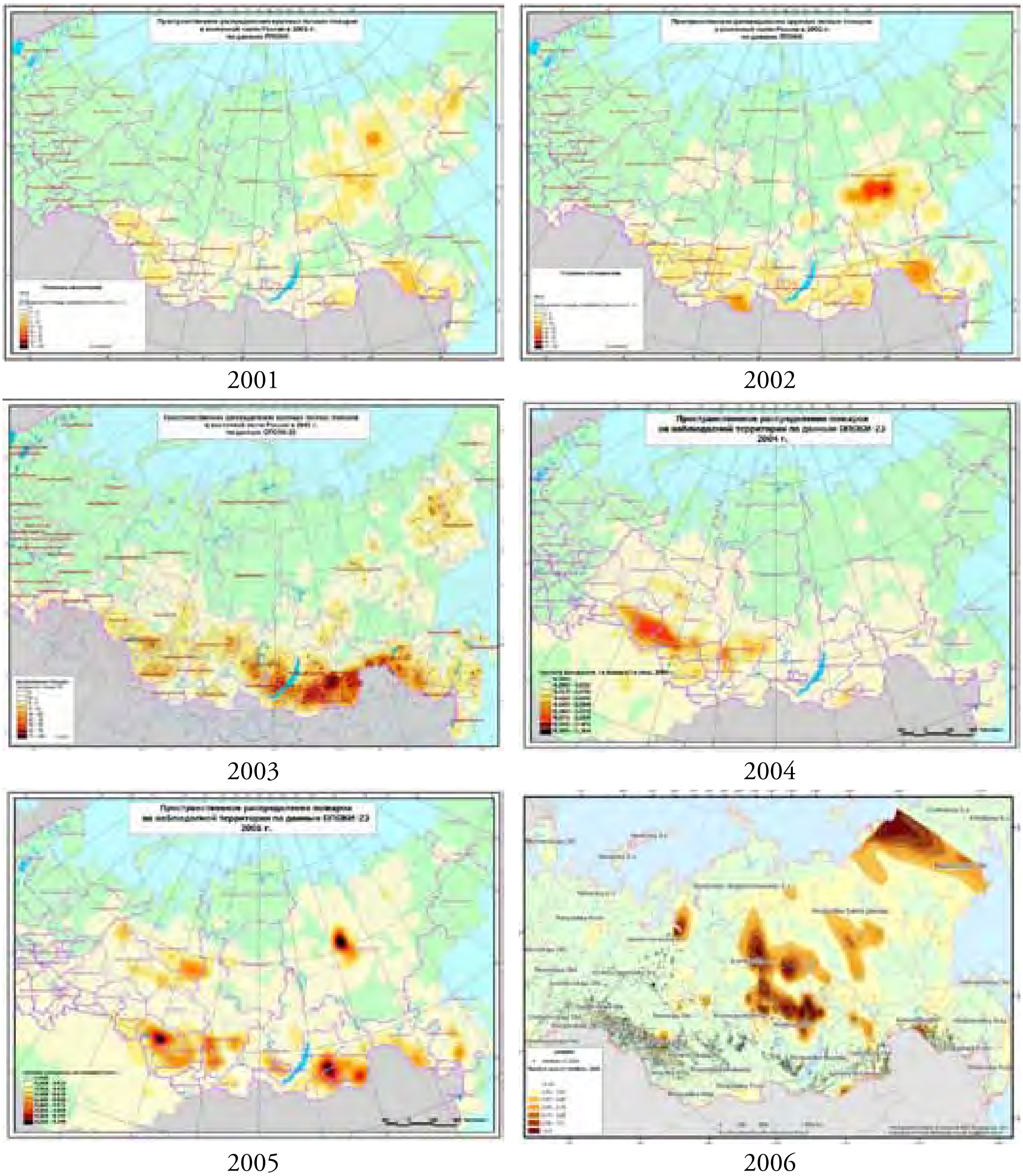


Figure 5.5a. Spatial distribution of areas burned by different degrees in the Central and Eastern Asian part of Russia in the fire seasons of 2001-2006, derived from interpolated NOAA/AVHRR and MODIS (Terra) forest fire data. Zones are delineated by colors that represent the relative area of wildfires to the value of total burned area marked by the color. Source: A. Sukhinin (2001-2005) and E. Ponomarev (2006), Laboratory of Forest Monitoring, Sukachev Institute for Forest, Krasnoyarsk, Russian Federation.

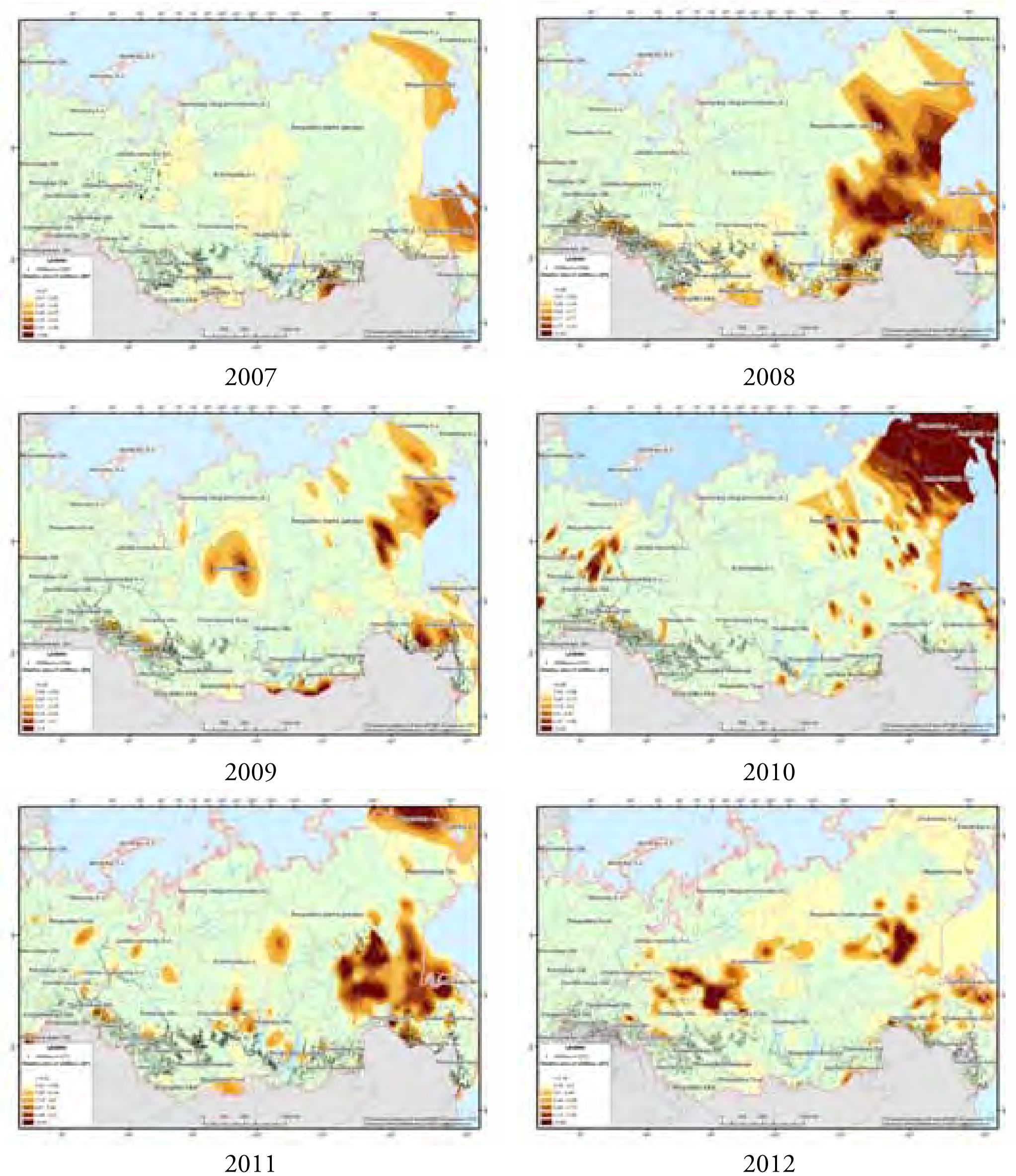


Figure 5.5b. Spatial distribution of areas burned by different degrees in the Central and Eastern Asian part of Russia in the fire seasons of 2007-2012, derived from interpolated NOAA/AVHRR and MODIS (Terra) forest fire data. Zones are delineated by colors that represent the relative area of wildfires to the value of total burned area marked by the color. Source: E. Ponomarev, Laboratory of Forest Monitoring, Sukachev Institute for Forest, Krasnoyarsk, Russian Federation.

in recent years resulting in an increase of the number of large fires (i.e., fires affecting >200 ha) (Goldammer, 2006).

The general leadership and coordination of all aerial forest fire protective operations were implemented by the Federal State establishment – the National Aerial Forest Fire Center *Avialesookhrana*, located in Pushkino City, Moscow Region, up to the end of 2006. The Forest Code of Russia of 4 December 2006 regulates that starting 1 January 2007 forest fire management is under the responsibility of the regions of the Russian Federation. The Emergency Committee (EMERCOM of Russia) is involved during forest fire emergency situations. Other ministries and departments – the owners and users of the Russian Forest Fund – are also involved. Altogether these structures form the forest fire protection system.

With the reported loss of workplace of about 70 000 forest wardens all over Russia by 2010 as a consequence of decentralization, the authority of the government to ensure sustainable forest management and to reduce illegal forestry activities had been weakened during the first years after the enactment of the new Forest Code (Goldammer, 2010). The traditional system of forest fire protection, coordinated and implemented from central level through the National Aerial Forest Fire Center *Avialesookhrana* and its 24 regional bases and sub-regional units with its specialized forest firefighters, had been abolished. By summer 2010 many regions were not yet prepared and had not prioritized investments for capacity building, equipment purchase and the necessary wide range of measures in fire prevention and preparedness for wildfire situations.

The first three years after the enactment of the new Forest Code (2007-2009) the fires seasons were characterized by rather moderate fire weather. While the regions were struggling with the reorganization and the wildfires, no single inter-regional assistance was implemented between 2007 and 2009 since every region had limitations in finances and availability of firefighter special forces and could not share them with the neighboring regions. To encounter this development it has been proposed to build a Federal Reserve (with up to 1000 smokejumpers) (Goldammer, pers. observation and local communication), which would allow to provide prompt federal aerial fire response during high and extreme fire danger situations which are arising in high spatial variability over the years within the territories of the regions (Fig. 5.5 a, b).

The Fire Season of 2010

The fire season of 2010 triggered significant attention of civil society of Russia concerning the public perception and awareness of the fire problem in the country. In the fourth year after the enactment of the Forest Code the Russian Federal Service for Hydrometeorology and Environmental Monitoring *Roshydromet* classified July 2010 the warmest month ever recorded in Moscow since the beginning of modern meteorological recording 130 years ago. According to *Roshydromet* the temperature of July 2010 exceeded the long-term average by 7.8°C (compared to the previous record in July 1938 with 5.3°C above average). Record high temperatures varying between 35°C and 38.2°C were registered for more than seven consecutive days end of July, with the heat wave continuing into August. The daily temperature of 38.2°C on 29 July was the highest ever in Moscow (compared to a long-term average of approximately 23°C). The minimum night temperature of nearly 25°C also scored a significant increase compared to the historical average of about 14°C. Those temperatures are characteristic for a heat wave of a rare intensity and duration (Goldammer, 2010).

The hot and dry weather conditions resulted in plant drought stress as reflected by the Normalized Difference Vegetation Index (NDVI) in Southwestern Russia (Fig. 5.6) or by the fire danger forecasts for the Russian Federation by national and international providers (Fig. 5.7 a, b).

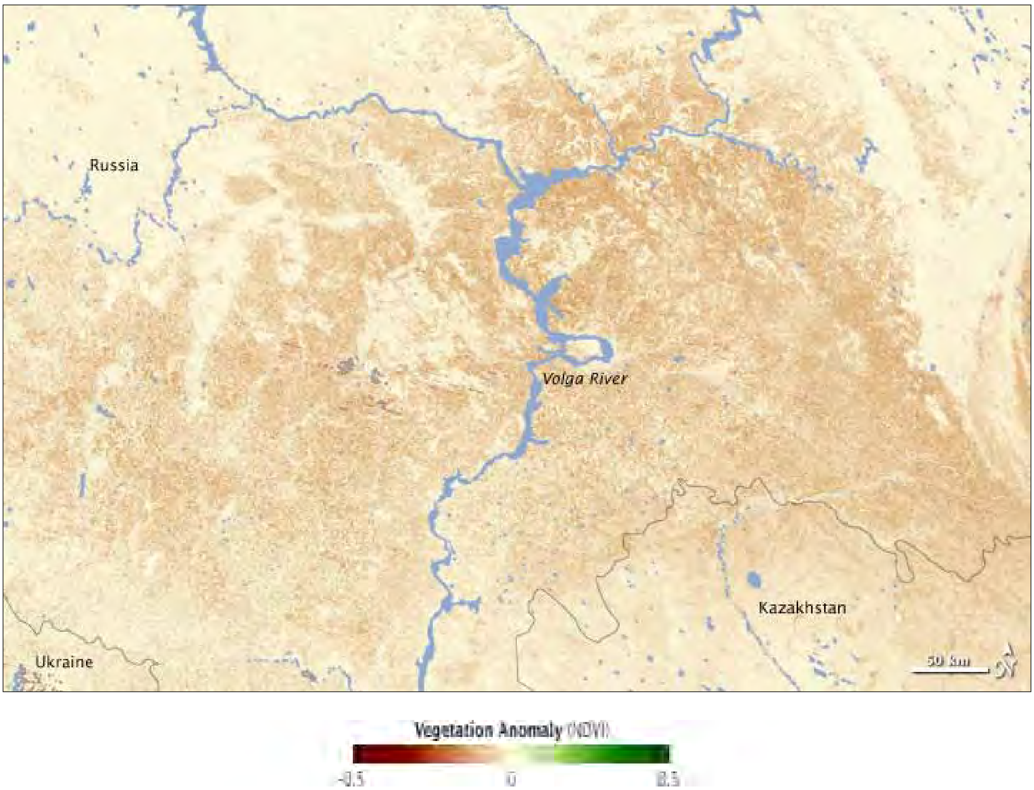
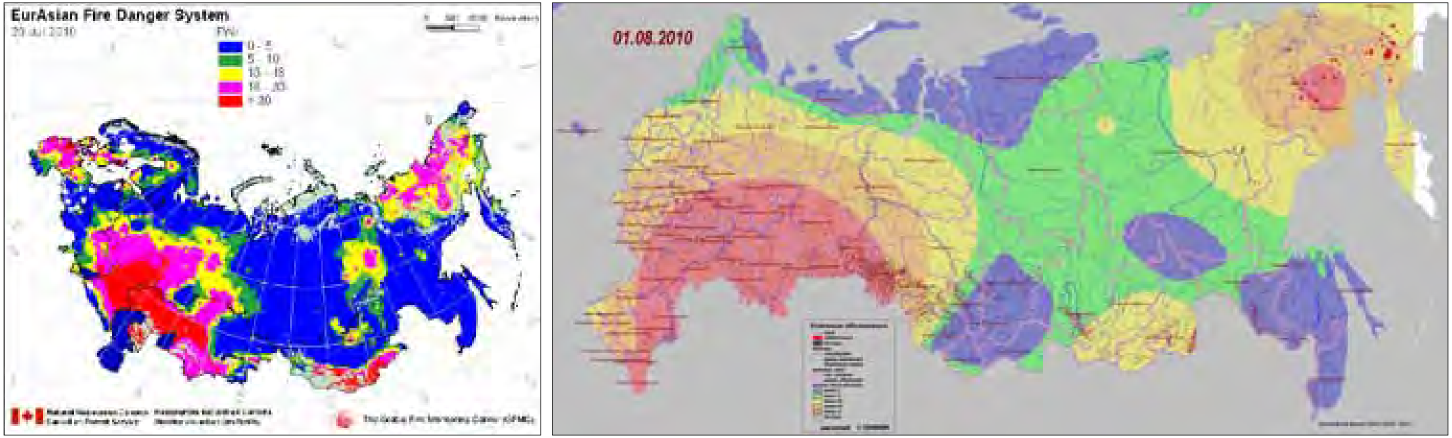


Figure 5.6. This satellite-derived Normalized Difference Vegetation Index (NDVI) map, a reflection of photosynthesis activity, is based on MODIS data (on NASA's Terra satellite) and reveals the drought stress of plants throughout Southwestern Russia in the middle of 2010. This map shows the NDVI anomaly that compares photosynthesis between 26 June and 11 July 2010, to average conditions observed in late June and early July between 2000 and 2009. Below-average plant growth is shown in brown, while average growth is cream-colored (*Note:* Above-average growth in the region would have been represented in green). Source: NASA.



Figures 5.7 a and b. Fire danger forecast maps were provided daily by national and international institutions. Left (a): The forecast of the Eurasian Experimental Fire Weather Index (FWI) for 20 July 2010 (left) reflects the drought in Western Europe, Western Russia and the Northeast of Russia (Source: Canadian Forest Service and GFMC). Right (b): The fire danger map for Eastern Siberia for 1 August 2010 was generated by the Sukachev Institute for Forest, Krasnoyarsk.

Figures 5.8 a and b. Left (a): Wildfire blow-ups in Nizhniy Novgorod region on 26 July 2010, with smoke drifting towards the metropolitan area of Moscow. Source: NASA MODIS image. Right (b): Extended wildfires burning in the Northeast of Russia were depicted by the MODIS satellite sensor on 25 July 2010. Source: NASA.

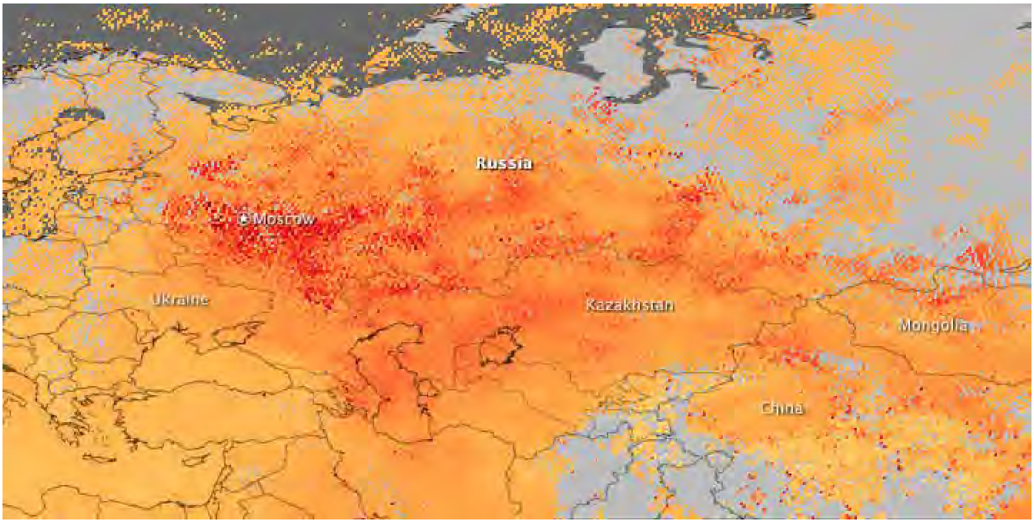


Figure 5.9. Data collected by „Measurements of Pollution in the Troposphere" (MOPITT) sensor on NASA's Terra satellite, shows carbon monoxide concentrations over western Russia between 1 and 8 August 2010, largely a consequence of the wildfires. Source: NASA.[4]

The degree of air pollution in the greater Moscow region during the last days of July and in August 2010 was extreme, resulting in unprecedented humanitarian problems. People with cardiovascular and respiratory diseases, elderly and very young people had been exposed to a high health risk, caused by the combustion products of burned organic matter (cf. Statheropoulos et al., this volume, Chapter 18). By early August the call for ambulances and hospital admissions increased. Premature deaths due the combined effects of heat stress and smoke pollution contributed to the increased daily mortality rate of about 700 persons per day during the days of extreme heat and smoke pollution (average mortality rate in Moscow: 350 to 380 persons) (Goldammer, 2010).

In October 2010 the Economic Development Ministry of Russia published Russia's mortality data of summer 2010 in the Moscow Times. [5] According to this report 55,800 additional (above long-years average) deaths were recorded in July and August 2010 in Russia, which are likely to be attributed to premature deaths as a consequence of both the extreme heat and extended fire smoke pollution. The total number of people directly killed by fire has been estimated 63, and 9 villages and a total of ca. 3000 houses and

4 http://terra.nasa.gov/About/MOPITT/about_mopitt.html

5 Report of the Economic Development Ministry of Russia, published in The Moscow Times, 27 October 2010, on file at the GFMC repository: http://www.fire.uni-freiburg.de/media/2010/10/news_20101027_ru.htm

infrastructures were burned, besides other assets such as military and firefighting equipment (Goldammer, 2010).[6]

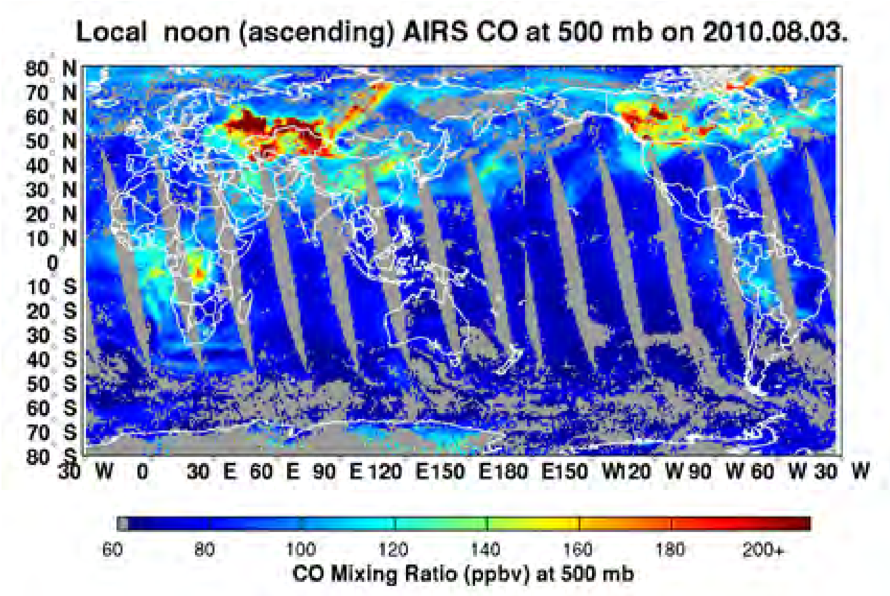


Figure 5.10. Atmospheric Infrared Sounder (AIRS) carbon monoxide measurements of 3 August 2010 reveal the extension of the smoke plume drifting towards the Trans-Baikal region. Similar CO plumes are observed over wildfires in Western Canada. Source: NASA.[7]

Emerging Issues and Problems

Land Use and Land-use Change

The recent socio-economic changes in many rural regions of Russia are a main cause of changing the fire hazard and the ignition sources. Similarly to many regions in Western Europe intensive traditional agriculture and pastoralism in Russia is being successively abandoned (for more details on the rural exodus in Russia see Goldammer, this volume, Chapter 22). Young people are urbanizing, and many former peasant villages are becoming now weekend or summerhouse resorts, with urban people living there temporarily in vacations,

6 See also the Special Issue of UNECE/FAO International Forest Fire News (IFFN) No. 40 (2010), which is covering the fire season of 2010 in boreal Eurasia, and related articles: http://www.fire.uni-freiburg.de/iffn/iffn_40/content40.htm

7 http://airs.jpl.nasa.gov/

without having dependence on and responsibility for careful and sustainable management of lands that are surrounding these resorts. Leisure fires running out of control, as well as abundant uncontrolled garbage pollution in forests and along rivers, are phenomena that had been noted increasingly over the last years – but society and authorities did not respond.

The abandonment of exploitation of peat is posing additional risks. In many regions of Western Russia peat bogs were drained and colonized in the Soviet era, particularly in the 1960s, for agriculture, settlements, and bioenergy production. Many of these formerly cultivated lands have been abandoned (ca. 2.75 million ha) – but not restored to their original wetland character. Thus peat formation and bog recovery is extremely slow if not impossible. With the fires the process of peat bog destruction is accelerated and may become irreversible if regional drying would occur in the coming decades, with further implications of the contribution of peatland fires to the net export of terrestrial carbon to the atmosphere. Re-wetting of peatlands has been put on the agenda of the Russian government, supported by bilateral cooperation with Germany, but is still in its infancy stage.[8]

Forest Degradation

In the 1990s and early 2000s forest exploitation became rampant in many areas of Russia, particularly in Siberia and in the Trans-Baikal region. The lack of a functioning forest management (and fire management) infrastructure, along with severe economic conditions, have combined to accelerate forest degradation. The depletion of China's forest resources and the increasing demand for timber products in the China market have created enormous pressures on the forest resources of Mongolia and the Russian Federation. Timber dealers have encouraged or bribed local people to set fire to forests in order to increase the permissible salvage logging areas. Fire-damaged timber is then harvested for sanitary reasons at low stumpage prices, and this can be a lucrative source of income (MNR, 2005; Goldammer, pers. observation and local communication).

Following the Europe and Northern Asia Ministerial Conference on Forest Law Enforcement and Governance (FLEG) in November 2005, which addressed the problem of criminal actions and corruption that are weakening the rule of law, loss of revenue to governments, the private sector and local livelihoods, and a reduction in the contribution of forests to the fulfillment of internationally agreed development goals, the European Neighbourhood and Partnership Instrument (ENPI)[9] FLEG Program "Improving Forest Law Enforcement and Governance in the European Neighborhood Policy East Countries and Russia" contributed significantly in raising awareness for the need of legal and sustainable forest management and utilization practices in the seven participating countries (Armenia, Azerbaijan, Belarus, Georgia, Moldova, Russia, and Ukraine).

8 „Restoring Peatlands in Russia – for fire prevention and climate change mitigation": http://www.succow-stiftung.de/peatland-restoration-in-russia.html; see also Joosten et al. (2012)

9 Regulation (EC) No 1638/2006 of the European Parliament and of the Council of 24 October 2006

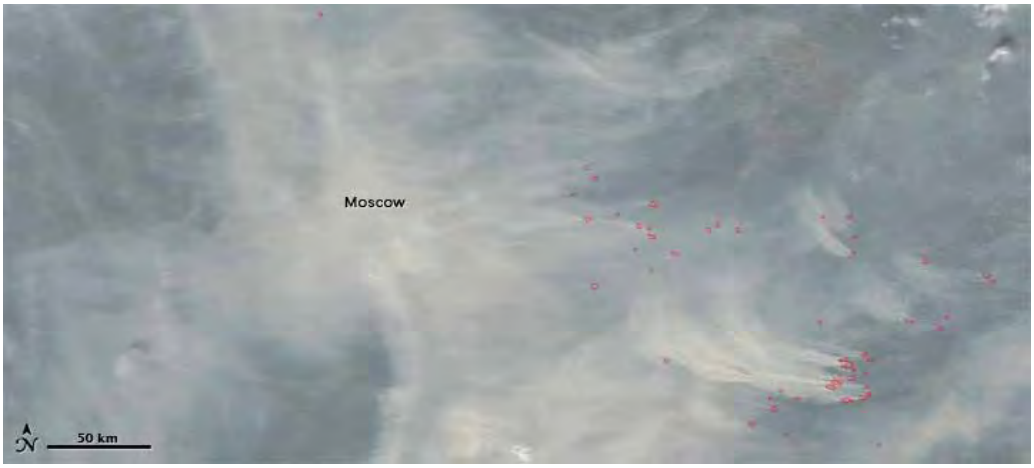


Figure 5.11. Smoke pollution in Moscow Region, 7 August 2010. Source: MODIS image provided by NASA. http://www.fire.uni-freiburg.de/GFMCnew/2010/08/07/20100807_ru.htm

Figure 5.12. This satellite image shows two strong convective activities with *pyrocumulus* formation, representing intensive blow-up fires in forests and high peat-swamp vegetation. Source: NASA MODIS Terra scene, acquired on 1 August 2010, 250m resolution.

Figures 5.13 and 5.14. The majority of wildfires in 2010 arose from careless burning of crop residues within and around rural hamlets and villages, including burning of abandoned lands. Photos: GFMC.

Figure 5.15. Drained peat bogs in Orekhovo Zuevo district (Moscow Region), near the village Chistoe Severnoe, were affected by the wildfires in summer of 2010. The nearby city of Elektrogorsk was founded in 1912 with the establishment of the first large peat-fired power station to supply electricity for Moscow region. It was the beginning of exploiting drained peatlands for electricity production, which has been phased out during the recent years. The fires of August 2010 entered deep, desiccated turf layers, first causing trees to topple and continue to smolder despite of firefighting efforts. Photo: GFMC, August 2010.

Another factor contributing to the overall degradation of forest sites are the consequences of large clearcuts. In the dark coniferous taiga forests in the northern part of Siberia, large-scale clearcuts of the 1990s are showing little natural regeneration. This has also been observed in some southern light taiga forests where the combination of removal of seed trees, large sizes of clearcuts, and recurrent fires are leading to replacement of forests by steppe and shrub vegetation. These "green desert grasslands" are maintained by regular fires – a phenomenon that has also been observed on a large scale in Mongolia (Goldammer, pers. observation and local communication). Repeated fires have been recently associated with increased insect infestations in many regions of Russia.

Transboundary Transport of Vegetation Fire Emissions

Long-distance inter-continental transport of smoke from fires burning in Russia and other countries in Central Asia has also been observed in recent years, including 2008 (Warneke et al., 2009). In 2003 the extended wildfires in the Trans-Baikal region (Huang et al., 2009) resulted in severe smoke pollution in Mongolia and China (Goldammer, 2006). Smoke plumes generated by fires burning in forests, grasslands and swamps in Irkutsk, Chita and Buryatia regions traveled as far as Sakhalin, Japan and North America, making smoke impacts a major transboundary issue (Fig. 5.16 to 5.18). The northern hemispheric smoke pollution generated by fires burning in Russia has attracted international, interdisciplinary scientific interest. Emissions from boreal fires, and the likelihood that fire activity in this region will dramatically increase with climate change, resulted in boreal fires becoming a major component of recent International Polar Year studies. In the spring and summer of 2008, the NASA-led ARCTAS (Arctic Research of the Composition of the Troposphere from Aircraft and Satellite) project used coordinated satellite and aircraft measurements to sample, track and model smoke transport from Siberian and Canadian boreal fires to the Arctic region and beyond. This investigation is aimed at determining the impact of boreal fire emissions on the Arctic environment and climate, an issue of urgent importance given recent climate change scenarios in that region. Transboundary smoke transport issues also emphasize the need to quantify Russian fire activity in a manner that can be used by both the global carbon budget and atmospheric chemistry modeling communities to address scientific gaps. Both the area burned and the behavior of fires burning in the ecosystems of Russia (fuel consumption, energy release rates) need to be quantified to provide the baseline data required by the modeling community (Conard et al., 2002).

A reason of concern are the emissions of soot particles (particulate matter) during spring fires. Agricultural burning in the early months of the year are quite common all over Eastern Europe / Western Russia (Korontzi et al., 2006). At that time of the year the airflows are driving the smoke to the Far North – to the Arctic. A study of the U.S. Clean Air Task Force (CATF) revealed, by evaluating the comprehensive science on this issue, black carbon-containing particulate matter, a product of incomplete combustion of biomass and fossil fuels, is transported to the Arctic via smoke, remains in the atmosphere for about a week (CATF, 2009). During that time, it can disturb the local climate system in a number of ways. First, as black carbon settles in the Arctic's troposphere it absorbs solar radiation that would otherwise reach the surface. As the troposphere warms, it emits long-wave radiation downward. The net effect is a heating of the surface. Black carbon also affects the Arctic climate by reducing surface reflectivity, or albedo. As soot particles "wash out" of the atmosphere, they land on snow and ice, darkening surfaces in ways that are usually imperceptible to the human eye, but even these small concentrations are able to absorb significantly more of the sun's rays. As the surface warms, the snow crystals coalesce into denser, coarse-grained structures that further absorb energy and can speed the pace of melting. Dedicated research on the magnitude and transport of black carbon from the Eurasian region to the Arctic is underway and reveals the significance of the issue and the questions that remain to be answered (McCarty et al., 2012; Sheldon, 2012). Meanwhile the "Arctic Black Carbon Initiative" of the U.S.D.A. Forest Service and Foreign Agricultural Service is implementing technical exchanges and cooperation between U.S. and Russian experts addressing the reduction of black carbon emissions from agricultural burning (Kinder, 2012).

Climate Change

Interdisciplinary research over the past two decades has led to the firm conclusion that human-caused climate change is inevitable, and there are strong arguments that it is already occurring, particularly at high latitudes (Stocks and Flannigan, this volume, Chapter 4). The global boreal zone is expected to be affected early and substantially by climate change, although predicting the rate and extent of climate change impacts is fraught with uncertainty. Central Siberia has the most continental climate on earth, and forest fires can be expected to increase both in frequency and severity with climate change, as extreme events become more common. Indeed, forest fires will likely accelerate vegetation shifting, and provide a positive feedback to climate change (Stocks et al., 1998; Flannigan et al., 2000).

The climate-driven change of permafrost regimes, reinforced by increasing occurrence and severity of wildfires, will lead to a release of paleo-gases, notably methane that is currently trapped in permafrost and wetlands. A recent estimate of the global circumboreal terrestrial carbon pool reveals a magnitude of 1672 Pg of organic carbon stored in the northern permafrost region (Tarnocai et al., 2009), of which about 1466 Pg, or 88%, occurs in perennially frozen soils and deposits, and accounts for approximately 50% of the estimated global belowground organic carbon pool. The combined effects of regional warming and fire will likely contribute to an acceleration of the transfer of radiatively active trace gases and carbon from the terrestrial pools to the atmosphere (see also Hinzman et al., this volume, Chapter 6).

Protection of Fire-sensitive Biodiversity

One of the striking examples of biodiversity-rich, fire-sensitive regions is the Amur-Sikhote-Alin Ecoregion in the South of the Far East of Russia. The region has been classified by the World Wide Fund for Nature (WWF) as one of the "Global 200 Ecoregions". It includes

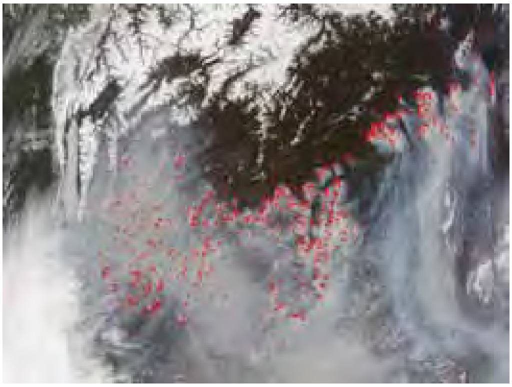
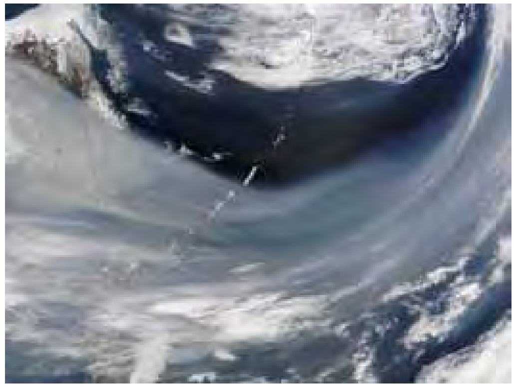


Figure 5.16



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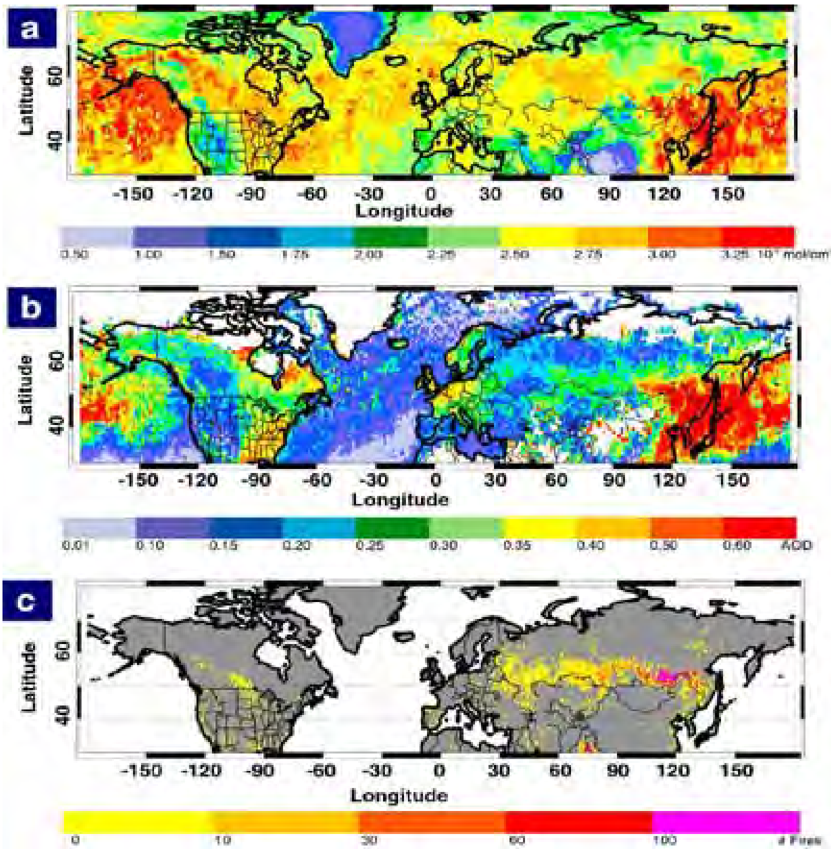

Figure 5.18

Figure 5.16. Fire activities on 8 May 2003 at 0400 UTC (11:00 local time) Southeast of Baikal Lake recorded by MODIS. **Figure 5.17.** Smoke column stretching from fires in the Transbaikal Region to Sakhalin, Japan, and Alaska (8 May 2003). Source of Figures 5.4 and 5.5: NASA-MODIS. **Figure 5.18.** Multi-sensor characterization of fire emissions and fire activities on 10 May 2003. **(a)** Carbon monoxide (CO) concentration captured by the MOPITT instrument on the Terra satellite, with values ranging from zero (dark blue) to 360 parts per billion (red), depicting the long-range transport of the relatively long-living CO; **(b)** Terra / MODIS fine mode aerosol optical depth (AOD) depicting fine shorter-living combustion-generated particles; **(c)** Terra / MODIS fire counts. Source of Figures 5.18 a-c: Edwards et al. (2004) (courtesy: J. Geophysical Research).

Figure 5.19. Neighboring countries had been affected by the Western Russian smoke plumes. While in 2006 the smoke from Russia's peat fires drifted to West and North Europe, this image of 1 August 2010) shows the smoke plume from the greater Moscow region drifting to Ukraine – on a day when high fire-smoke alert had been declared in its capital Kiev. Image and interpretation: NASA MODIS Aqua scene (acquired on 1 August 2010, 250m resolution) and GFMC.

23 different forest formations and sub-formations, 150 forest types, over 200 tree and shrub species, and overall – about 2,000 species of vascular plants and an unusually rich fauna with about 20 species of amphibians and reptiles, over 250 species of birds, about 70 species of mammals, including the 'flagship' endangered species – the Amur tiger (Kushlin and Milenin, 2005). Flora and fauna elements of East Siberian, Okhotsk-Kamchatka, Manchurian and Hindo-Malayan origins share the same habitat in the unique broadleaved-coniferous forests of this ecoregion. The region includes forest ecosystems that have been almost totally destroyed in the neighboring countries of China, Korea and Japan.

Although wildfire has always been a constituent element of the ecosystem cycle in the ecoregion, this natural cycle has been altered by decades of extensive forest logging, mining and other economic activities. The subsequent large tracts of secondary forests with accumulated post-harvest woody debris are much more prone to accidental wild or human-induced fires, and therefore become conduits of more frequent fires to the adjacent natural forests. As a result, forest fires now represent a major threat to the natural status and dynamics to fire-sensitive forest ecosystems and biodiversity (Shishikin et al., 2012).

Management of Fire-Adapted Forest Ecosystems

On the other hand it has been recognized that some forest ecosystems in Russia and adjoining countries of the Euro-Siberian region of the Holarctic have co-evolved with natural fire and show remarkable adaptations to recurrent surface fires of low- to moderate intensities (GFMC, 2010; Goldammer, 2013). The effects of fire disturbances include removal of dead and live accumulated biomass, recycling of nutrients, stand thinning and regeneration of forest stands. Fire disturbances are creating valuable wildlife habitats. Recurrent surface fires of low intensity result in an overall reduction of the risk of severe and large destructive fires, which are considered threat to sustainable forest management and utilization, and may lead to large, uncontrollable outbreaks of pests and diseases (Goldammer and Furyaev, 1996). With the presence of natural fires over millennia some forest types can be classified as fire-tolerant, fire-adapted or even fire dependent. Thus, a complete exclusion of fire from some forest ecosystems is neither ecologically desirable, nor economically feasible (Valendik et al., 2013).

While the need for an integration of natural and human-made fires in forest has been postulated by the science community (Valendik et al., 2013) and recognized by the Federal Forest Agency (Anonymous, 2005), the use of prescribed fire for wildfire hazard reduction in forests is not yet developed in practice. As of 2012 there are no regulations on prescribed natural and prescribed fire management operations under canopy of forests in Russia.

Considering the increasing importance of managing long-term stable forest cover, forest productivity and carbon sequestration, a panel of experts suggested to revise the policy and practice of fire management in the Russian Federation (Anonymous, 2012). The proposed "Krasnoyarsk 10-Point Programme on the Future of Fire Management in Russia" is calling for integration of planned and prescribed natural and accidental wildfires, as well as prescribed management fires, in the fire management policy. A catalogue of measures was suggested to complement legal and other normative instruments which would allow the application of prescribed fire, to develop methodological guidelines for prescribed burning under forest canopy and to develop educational programs and continuous professional education for the training of forest firefighters and fire management specialists at different levels. The recommendations also address the protection of villages and the need for developing concepts for the prescribed use or avoidance of fire on agricultural and other non-forested lands of the Russian Federation (Anonymous, 2012).

Involvement of Civil Society

The fire season of 2010 has revealed that impacts of a few wildfires burning in Western Russia were able to paralyze the capital Moscow, countless cities, towns and villages. The majority of fires had been caused by human activities and occurred in cultural landscapes, which are undergoing rapid transformation from intensive rural land-use to peri-urban land-use systems. The magnitude of individual wildfires and the extent and duration of smoke pollution strained the capacities of the agencies responsible for fire response. Immediate response by civil society – volunteer groups and rural populations directly affected by fire – showed both willingness and need for civil society to share action and responsibility in fire prevention and wildfire defense. Based on the experience of the All-Russian Volunteer Fire Organization[10] and the deployment of volunteer firefighters from the Far East of Russia to Western Russia during the wildfire emergency in 2010[11] the government of the Russian Federation through the Ministry for Emergency Situations (EMERCOM) has supported the strengthening of the volunteers[12], which by the end of 2012 reached a force of about 800,000 persons nationwide.[13] The Federal Forest Agency is currently collaborating with international partners to strengthen community involvement in fire management, e.g. for reducing excessive agricultural burning (Kinder, 2012) or development of capabilities for self-defense of villages against wildfires (Anonymous, 2013). The transition of a formerly centralized state-owned fire protection system to a decentralized system with participation of civil society remains a demanding challenge for the coming years.

Conclusions

The size of Russia's forests and other vegetation types currently affected by fire, the expected consequences of regional climate change on vegetation cover, wetlands, permafrost and fire regimes, coupled with the consequences of socio-economic and land-use changes, are expected to result in increasing wildfire hazard, risk and vulnerability of ecosystems and society. The extent and severity of fires in future will continue to affect and even alter ecosystems, including peatlands, and thus terrestrial carbon stocks. With this scenario in mind Russia is challenged with a mammoth task to develop and implement a policy and enhance capacities of state authorities and civil society to protect vegetation resources from destructive fire and to allow the use of prescribed fire where appropriate and ecologically benign.

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11 „Far East volunteers sign up to extinguish wildfires in European Russia", published on 9 August2010 by http://en.rian.ru/russia/20100809/160122927.html

12 „Russia needs a million volunteer firefighters – emergencies chief", published on 29 August2010 by http://en.rian.ru/russia/20100829/160386265.html

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6 Current Fire Regimes, Impacts and the Likely Changes – III: Boreal Permafrost Biomes

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Abstract

Forest fires in the boreal forest project an immediate effect upon the surface energy and water budget by drastically altering the surface albedo, roughness, infiltration rates, and moisture absorption capacity in organic soils. Although the forest fire creates a sudden and drastic change to the land cover, it is only the beginning of a long process of recovery and perhaps a shift to a different successional pathway. In permafrost regions, these effects become part of a process of long-term (20-50 years) cumulative impacts. Burn severity may largely determine immediate impacts and long-term disturbance trajectories. As transpiration decreases or ceases, soil moisture increases markedly, remaining quite wet throughout the year. Because the insulating quality of the organic layer is removed during fires, permafrost begins to thaw near the surface and warm to greater depths. Within a few years, the once permanently frozen soil may thaw to the point where it can no longer completely refreeze every winter, creating a thawed layer in the soil called a *talik*. After formation of a talik, soils can drain internally throughout the year. At this point, soils may become quite dry as the total precipitation received annually in interior Alaska is quite low. The local ecological community must continuously adapt to the changing soil thermal and moisture regimes. The wet soils found over shallow permafrost favor black spruce forests. After a fire creates a deeper permafrost table (thicker active layer) the invading tree species tend to be birch or aspen. The hydrologic and thermal regime of the soil is the primary factor controlling these vegetation trajectories and the subsequent changes in surface mass and energy fluxes. Permafrost provides the structural integrity to hillsides and stream channel banks. As permafrost thaws, thermal and fluvial erosion can cause drastic changes in surface morphology and may make restoration efforts useless. The rapidly changing climate in the Arctic and Subarctic present greater complexities and imperatives in understanding the role of fire in ecosystem evolution. Although ecosystem response to climate change is often thought to be a relatively slow process, it is now apparent that increases in fire frequencies and intensities, coupled with permafrost degradation, will lead to large-scale ecosystem changes. Understanding these shifts in vegetative communities and quantifying the consequences of thawing permafrost are essential to developing reliable predictions of future climate and ecosystem trajectories.

Keywords: Permafrost biome, talik formation, permafrost thaw, discontinuous permafrost zone, thermokarst

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Environment, Vegetation, and Fire

Permafrost consists of soil or rock that remains frozen for at least two consecutive years and generally characterizes regions with a mean annual temperature below 0°C. Permafrost underlies about a third of the terrestrial surface and includes extensive areas of tundra, wetlands, and boreal forest (Brown et al., 1998). Permafrost exerts a strong influence on ecosystem dynamics through controls over drainage and vegetation. The active layer is the soil layer above permafrost that freezes and thaws each year. In lowlands where lateral drainage is slow, soil moisture usually remains quite high in the active layer. Soils with a thin active layer (30-50 cm) are common in the boreal permafrost biome. Permafrost restricts drainage and reduces summer soil temperature, producing an environment that restricts decomposition and favors the accumulation of a surface organic mat, frequently covered by mosses and lichens. When this surface organic layer dries out, it constitutes a well-aerated fine fuel that burns readily and carries a surface fire. For this reason the fire regime of boreal permafrost biomes is quite different than that of non-permafrost forests and warrants special attention in efforts to predict changes in the global fire regime.

Arctic tundra generally interacts with the arctic air mass during both summer and winter and has growing conditions that are too cold to support forest development or high rates of evapotranspiration. High-arctic ecosystems are too unproductive to produce a well-developed organic mat, and those low-arctic ecosystems with well-developed organic mats are generally too wet to carry a fire. As climate warms and the arctic front moves northward, temperate high-pressure air masses penetrate more frequently into the low arctic. The resulting warm dry conditions allow the surface organic mat to dry and produce enough surface heating to drive convection and the formation of air-mass thunderstorms with lightning that can ignite occasional fires. For example, the Anaktuvik River fire, which burned 100,000 ha during the warm summer of 2007, is the largest Alaskan tundra fire on record.

Permafrost-dominated boreal forest characterizes areas with a continental climate south of arctic tundra. These are dominated by the arctic air mass in winter and the temperate air mass in summer. The low radiation input and cold temperatures in winter lead to inversions with cold surface air temperatures that promote soil cooling and the preservation of permafrost and the formation of a thick surface organic mat. In summer, however, high-pressure systems with warm dry weather dry the surface organic mat, and intense surface heating drives convection to produce air-mass thunderstorms with lightning that ignites fires. Boreal permafrost biomes therefore have both large fuel loads and weather conditions that favor the occurrence of extensive fires, which have characterized this biome in Alaska for the last 6000 years (Lynch et al., 2002; Lloyd et al., 2006).

Permafrost-dominated boreal forest occurs most extensively in eastern Eurasia and western North America, where the boreal climate is most pronounced and continental, and marine moisture sources penetrate least frequently. The lichen-dominated woodlands of eastern Canada have a climate that is intermediate between that of tundra and boreal forest. These forests infrequently experience conditions dry enough to support soil drying and wildfire, but have sufficient fuel for extensive fires when fire weather is severe.

The fire-prone regions of Alaska and western Canada are underlain by discontinuous permafrost, with permafrost being present primarily on north-facing slopes and in valley bottoms where winter inversions are most intense. The discontinuous nature of the permafrost distribution promotes a mosaic of vegetation types with dense forests of very fire-prone black spruce (*Picea mariana*) and thick organic layers developing in permafrost areas. In bottomlands, these are interspersed with wetlands and lakes that act as fuel breaks. In uplands, permafrost-free south-facing slopes are occupied by deciduous forests and either white spruce (*Picea glauca*) (Alaska) or lodgepole pine (*Pinus contorta*) (Canada) forests, which burn less readily than black spruce. Deciduous forests lack a moss layer on the forest floor to carry fire, and their leaves have too high a water content to burn readily, so they act as a fuel break except under the most extreme conditions (Johnson, 1992). White spruce has a thinner organic mat than black spruce and does not retain lower branches that allow fire to move into the canopy and therefore is less fire-prone than black spruce. Lodgepole pine, which displaces white spruce in drier conditions in western Canada, is just as fire-prone as black spruce, making that landscape mosaic particularly susceptible to extensive fires. This is the region of North American boreal forest that has the shortest fire return interval (30-80 years) and most extensive fires. Alaska has a fire return interval of about 80-150 years (Yarie, 1981; Viereck, 1973).

The soils in the fire-prone regions of interior Alaska are dominated by organic layers that vary from a few centimeters to several meters. On permafrost-free south-facing slopes, the surface is typically covered with a duff layer that is often quite dry but usually quite thin. Where ice-rich permafrost exists near the surface, infiltration is greatly limited, yielding soils that are usually cold, very wet, and anaerobic and, as a result, develop thick organic layers. Although these soil types may exist in close proximity and experience nearly the same climatic conditions, soil moistures can range from very dry to saturated within a few meters lateral distance. Permafrost-free forests, with a thin duff layer and a grass understory are most fire-prone in early spring, when the previous year's grass forms a flammable fine fuel; dry weather following snowmelt can produce a high fire potential in these forests. However, when areas underlain by ice-rich permafrost (typically black spruce with thick organic layers) become very dry, particularly in late summer with deeply thawed soils, the fire potential can be extreme.

The boreal forest of Eastern Siberia has extensive forests of fire-prone *Larix gmelinii*, which occupies both lowlands and all topographic aspects of uplands (Osawa et al., 2003). Only riparian areas, which support deciduous forests, and lakes and wetlands have low flammability. This landscape has greater continuity of flammable fuels than boreal North America, and fires are therefore more frequent and extensive.

It has been noted that in Mongolia and Siberia, taiga and permafrost display an interdependent co-existence. Annual precipitation is quite low (200-300 mm per year), too low to permit taiga in general to develop. However, underlying permafrost impedes the downward water percolation and maintains adequate moisture in upper soil layers sustaining the boreal forest, which in turn insulates and protects the underlying permafrost. However, when the taiga is disturbed by forest fires, the surface energy balance is altered and the permafrost tends to thaw. Thawing of permafrost leads the drying of surface layers and is associated with salt concentration process. Low water content in surface soil and salinization of soil may result in the interference of forest regeneration (Tsuchiya et al., 2001).

The fuels in the permafrost-dominated boreal forests of western North America and eastern Siberia produce a unique fire regime that differs from that of other fire-prone forests. The surface organic mat consists primarily of fine fuels that dry quickly (often within 24 hours) and propagate fire at the low wind speeds that generally characterize these regions. However, fires readily move into the canopy and spread rapidly under windy conditions, including those convective winds generated by the fire itself. The resulting mixed-fire system allows fires to remain active by smoldering combustion in the organic mat, often for weeks and even over winter, but to move rapidly through the canopy under conditions of severe fire weather. This differs from the canopy fires of lodgepole pines and subalpine fir, where most of the fuel load is in the canopy, or the ground fires of ponderosa pine forests of western North America, where trees are fire resistant, and grass and other ground fuels carry the fire. Pine forests of central Siberia are also characterized by ground fires, and trees have fire-resistant bark (Wirth, 2005). The unique fuel structure of the boreal permafrost biome has required a different fuel classification system and different fire prediction and behavior models than in either the canopy- or ground-fire conifer forests further south. We still lack a basic understanding of the physical processes that determine when fires in Alaska will become large and burn deeply; these are the fires more likely to require suppression action or remediation or have long-term effects – like thawing or permanent loss of permafrost, leading to shifts in roadbeds, drainage or creation of wetlands, or aberrations in water table that could affect villages.

Wildfires in the boreal permafrost biome of Alaska have an immediate effect on surface energy and water budgets by drastically altering the surface albedo, roughness, infiltration rates, and moisture absorption capacity in organic soils (Hinzman et al., 2001). However, this is only the beginning of a long (20-50 years) process of recovery and succession that can follow multiple pathways. Burn severity (the proportion of the surface organic mat combusted) strongly influences both the immediate impacts and long-term disturbance trajectories. Black spruce forests are frequently patchy with approximately 20% of the area unburned within a fire perimeter and a highly heterogeneous burn severity. These trees have thin bark and are usually killed by even low-intensity fires. As transpiration decreases or ceases, soil moisture increases markedly, remaining quite wet throughout the year (Fig. 6.1). Because the insulating organic layer is reduced in thickness or eliminated during fires, its insulative quality declines, and permafrost begins to thaw near the surface and warm to greater depths. Within a few years, it may thaw to the point where it can no longer completely refreeze during winter, creating a permanently thawed layer in the soil called a *talik* (Hinzman et al., 2003). After formation of a talik, soils can drain internally throughout the year. At this point, soils may become quite dry, because the total precipitation received annually in interior Alaska is quite low (and most of the precipitation is typically offset by evapotranspiration). The local ecological community that develops after wildfire depends on the soil thermal and moisture regimes. The wet soils found over shallow permafrost favor black spruce regeneration. After a severe fire, permafrost thaws more deeply (thicker active layer), resulting in a deeply thawed mineral seedbed that favors establishment of deciduous shrubs and trees such as willow, birch, and aspen. The hydrologic and thermal regime of the soil is the primary factor controlling these vegetation trajectories and the subsequent changes in surface mass and energy fluxes. Permafrost provides the structural integrity to hillsides and stream channel banks, but unfortunately permafrost disturbed by fire does not necessarily recover as it has in years past due to warmer environmental conditions.

Changing Boreal Fire Regime

The boreal permafrost biome and the arctic tundra to the north are warming as rapidly as any region on the planet, a trend that is projected to accelerate in the coming decades (ACIA, 2005; IPCC, 2007). Annual area burned in the North American boreal forest tripled from the 1960s to the 1990s, largely due to the increased frequency of large fires (Kasischke et al., 2002; Kasischke and Turetsky, 2006), with projections of continued increases in annual area burned as warming continues in the future (Chapin and Starfield, 1997; Stocks et al., 1998; Rupp et al., 2002). The increase in area burned has been particularly pronounced in late summer, when soils are thawed most deeply and the organic horizon has the greatest potential to dry out. These late-season fires are particularly severe, leaving a high proportion of exposed mineral soils or very thin organic mats (Kasischke and Turetsky, 2006).

Although Alaska has a relatively short record of fire statistics, it is apparent that the total number of fires and the area burned has increased in recent decades. The total area burned in the last decades (2000-2009) was about equal to the total area burned in the preceeding 30 years (1970-1999). The most recent decade also had the greatest number of extreme fire events in the period of record (Fig. 6.2).

Table 1 shows numbers of fires and burned area in the recent decades. Note that records collected prior to 1950 are incomplete (data was collected from remnant fire documentation, maps, etc.). Official fire record keeping did not start until 1950. Although the human population has increased over this period, the contribution of man to total area burned has decreased from about 25% in the 1950s and 1960s to about 5% or less in recent decades (Kasischke et al., 2010).

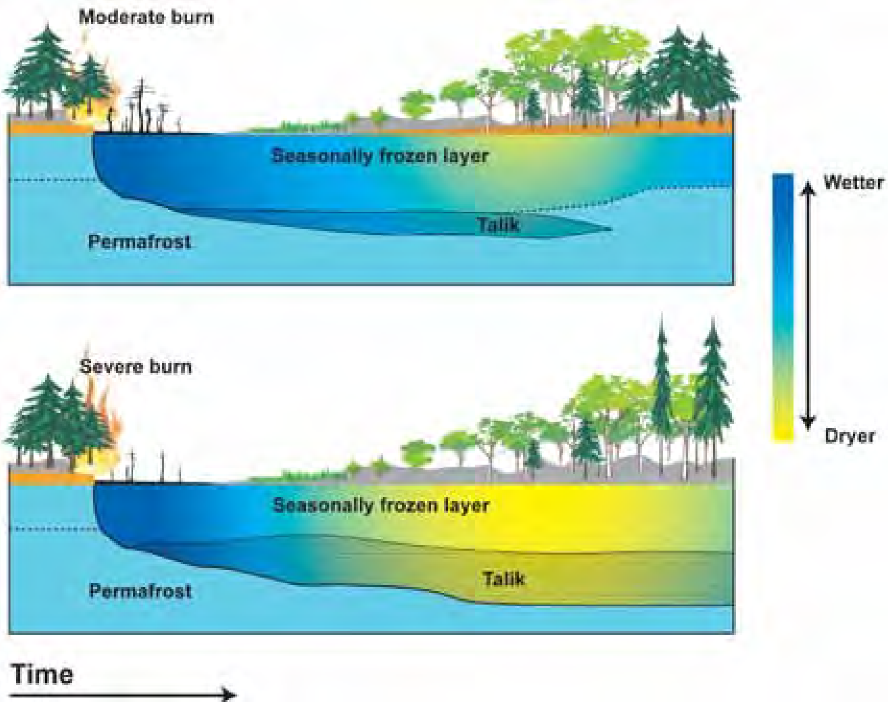

Figure 6.1. Impacts of fire following a moderate (top) and severe (bottom) fires in the boreal forest. Fires in boreal regions project an immediate and long-lasting impact to underlying permafrost. The active layer tends to increase in thickness each summer until it becomes too thick to completely refreeze during the winter (a talik forms). At that point, water may drain throughout the year and the soils become drier than neighboring unburned areas. Depending upon the climate, the talik may eventually refreeze, or the permafrost may continue to degrade. Source: Hinzman et al. (2003).

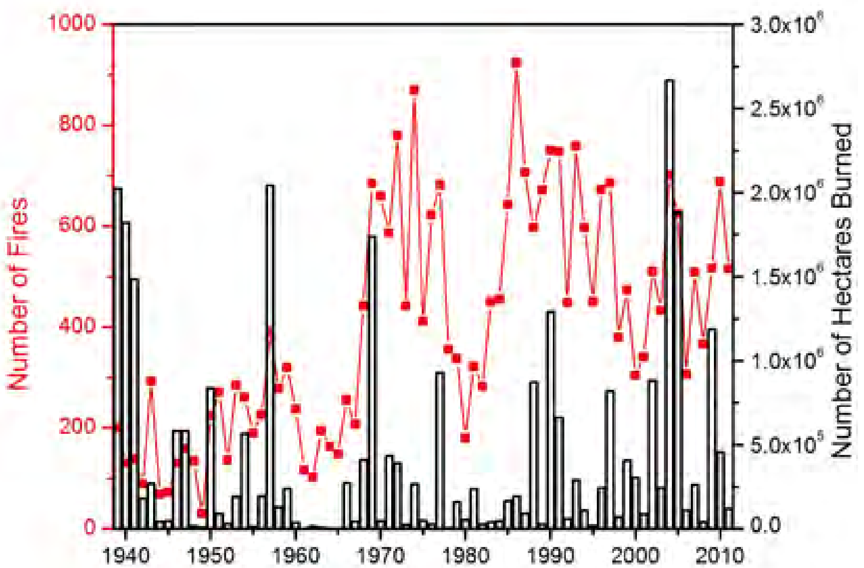

Figure 6.2. Alaska fire statistics 1970-2010. Source: Alaska Interagency Coordination Center, Predictive Services Branch (http://fire.ak.blm.gov/aicc.php).

Table 6.1. Alaska fire statistics by decades 1940-2009. Source: Alaska Interagency Coordination Center, Predictive Services Branch (http://fire.ak.blm.gov/aicc.php).

Decade	Average Hectares Burned per year	Average Number of Fires per year
1940-1949	503,265	125
1950-1959	432,537	258
1960-1969	252,725	255
1970-1979	233,183	574
1980-1989	175,350	523
1990-1999	396,765	597
2000-2009	766,960	461

The resulting effects on permafrost, surficial erosion, and vegetation can be surmised based on field studies and regional-scale hydrologic, thermal, and ecological modeling. In general, permafrost responds very slowly to climatic variations. However, the recent trend of increased frequency and severity of boreal forest fires (Kasischke and Teretsky, 2006) can have a rapid and dramatic effect on permafrost (Yoshikawa et al., 2003). Depending on its severity, fire destroys or reduces the thickness of the surface organic mat, removing insulation that would otherwise buffer ice-rich permafrost from climate warming. This loss of insulation initiates a progression of permafrost thaw, melting ice, and surface subsidence. Soils that might thaw to a depth of 30-50 cm in an unburned forest frequently thaw to depths of 2-5 meters after a severe wildfire, resulting in talik formation or even complete loss of permafrost. Given that surface permafrost temperatures are within 1°C of thawing in the discontinuous permafrost zone of Alaska (Osterkamp and Romanovsky, 1999), and the permafrost layer is generally less than 20m thick, wildfire is the ecological factor most likely to speed permafrost loss in a warming climate.

Increased fire severity creates a seedbed that is more favorable for small-seeded deciduous trees, which seldom establish on organic mats greater than 2-3 cm deep (Johnstone and Chapin, 2006). After severe fires, forests that were previously monospecific stands of black spruce are regenerating as deciduous forests or as mixtures of black spruce and deciduous trees (Johnstone and Kasischke, 2005; Johnstone and Chapin, 2006). The resulting increase in the proportion of deciduous stands on the landscape could act as a negative feedback to the trend of increasing fire frequency.

Changes in fire regime will likely alter the feedbacks to climate through several processes (Fig. 6.3). Fire combusts organic matter, releasing the carbon as CO_2 and acting as a positive feedback to climate warming. However, the replacement of a dark complex forest canopy by a more reflective smooth snow-covered or herbaceous canopy increases surface albedo and reduces surface roughness, both of which reduce energy absorption – thus acting as a negative feedback to warming. The net effect of fire on these and other climate feedbacks appears to be a small negative feedback to climate warming. In ice-rich permafrost zones, thawing of massive ice can produce thermokarst that release methane, a potent greenhouse gas. Although the effects of fire on individual climate feedbacks are well understood, their net effect is uncertain and warrants further research.

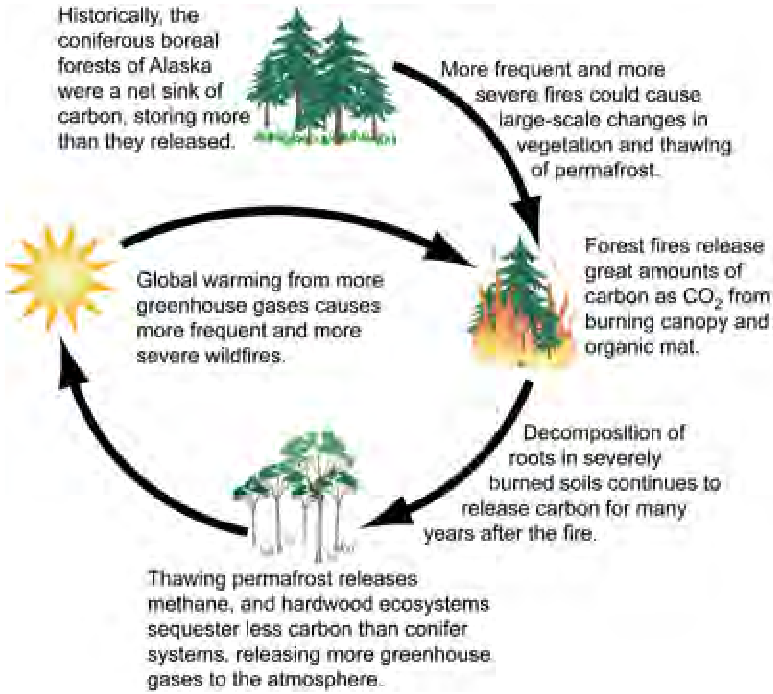

Figure 6.3. The occurrence of wildfires in the boreal forest has important climatic and biogeochemical consequences with large-scale global impacts, including positive feedbacks resulting from increased CO_2 and methane emissions from permafrost. Source: Hinzman et al. (2003).

Soils in boreal and Arctic ecosystems store almost twice as much carbon in permafrost as is currently present in the total global atmosphere (Schuur et al., 2008; Zimov et al., 2006). Permafrost thaw and the microbial decomposition of previously frozen organic carbon are considered one of the most likely positive climate feedbacks from terrestrial ecosystems in a warmer world. The annual flux of methane from degradation of permafrost in the post-fire taiga region is greater than 1.8×10^{11} g yr^{-1} (short term). The annual flux of CO_2 from direct emissions during fires in east Siberia over the total area burned (10×10^6 ha in 2003) is estimated at 0.2 Pg of carbon (Fukuda, 2005). Kim and Tanaka (2003) found that the microbial respiration estimated after a boreal forest fire was almost three times as high as the respiration before the fire. This indicates the post-fire conditions may stimulate microbial respiration because of higher nutrients and enhanced soil temperature. The microbial respiration was estimated to be 14.7 t C ha^{-1} in burned black spruce stands over a decade after the fire, suggesting burned black spruce forests are a crucial source of atmospheric CO_2.

Schuur et al. (2009) documented increased losses of soil carbon with permafrost thaw that, over decadal timescales, exceeds increased plant carbon uptake at rates that could make permafrost a large biospheric carbon source in a warmer world.

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7 Current Fire Regimes, Impacts and the Likely Changes – IV: Tropical Southeast Asia

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Abstract

The Southeast Asian region is experiencing some of the world's highest rates of deforestation and forest degradation, the principle drivers of which are agricultural expansion and wood extraction in combination with an increased incidence of fire. Recent changes in fire regimes in Southeast Asia are indicative of increased human-causd forest disturbance, but El Niño–Southern Oscillation (ENSO) events also play a role in exacerbating fire occurrence and severity. Fires are now occurring on a much more extensive scale - in part because forest margins are at greater risk of fire as a result of disturbance through logging activities, but also as a result of rapid, large-scale forest clearance for the establishment of plantations. Millions of hectares have been deforested and drained to make way for oil palm and pulpwood trees, and many plantation companies, particularly in Indonesia, have employed fire as a cheap land clearance tool; uncontrolled fires have entered adjacent forests or plantation estates, and burnt both the forest biomass and, in peatland areas, underlying peat. Forest fires cause changes to forest structure, biodiversity, soil and hydrology. Repeated fires over successive or every few years lead to a progressive decline in the number of primary forest species. Fire leads to reduction in both aboveground and below ground organic carbon stocks and also changes carbon cycling patterns. In non-peatland areas, losses of carbon from fire affected forest vegetation exceed greatly soil carbon losses, but on carbon-rich substrates, e.g. peat, combustion losses can be considerable. Peatland fires make a major contribution to atmospheric emissions of greenhouse gases, fine particular matter and aerosols and thus contribute to climate change as well as presenting a problem for human health. The scale of emissions is unlikely to reduce in coming decades, since climate modelling studies have predicted that parts of this region will experience lower rainfall in future and greater seasonality. Protecting the rainforests of this region from further fire disasters should be at the top of the global environmental agenda, with highest priority given to peatland areas.

Keywords: Peatland fire, lowland tropical forest, land clearing, carbon cycling, Mega Rice Project

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Introduction

The Southeast Asian region is currently experiencing some of the world's highest rates of deforestation and forest degradation (Achard et al., 2002; Langner et al., 2007). Forty percent of the forests existing in Indonesia in 1950 had been cleared by the end of the millennium (Global Forest Watch, 2002) and an average annual clearance rate of 1×10^6 ha during the 1980s, has increased to an average of 2×10^6 ha per year since 1996 (Global Forest Watch, 2002). The principle proximate drivers of this rapid deforestation are agricultural expansion and wood extraction (Geist and Lambin, 2002), but forest disturbance has also increased the risk of fire, leading to further loss and fragmentation of the region's remaining forests (Siegert et al., 2001). During 1997-1998, for example, large-scale wildfires occurred throughout Southeast Asia; these were linked to rapid land use changes, further exacerbated by an extended ENSO-related drought (Page et al., 2002). This fire episode (Tacconi et al., 2007), led to an increased awareness of the wide-ranging impacts that uncontrolled fires in this region have on biodiversity, economy, human well-being and climate (Schweithelm, 1999).

Fires are not a new phenomenon in the tropical forests of Southeast Asia. Occasional wildfires have occurred over several millennia (Goldammer and Seibert, 1989, 1990; Goldammer, 1992, Hope et al., 2005) but, prior to human-induced modification of the forest, rainforest fires were relatively rare events. Even when they did occur, the long interval between fires would have provided adequate time for recovery of pre-fire forest structure and biodiversity. In recent years, however, rainforest fires have become both more frequent and extensive, with human activities implicated in fire ignition as well as the changes in land cover which enable fires to establish and spread. Langner and Siegert (2009), for example, demonstrated that ~21% of land in Borneo was subjected to fires during 1997-2006, with 6.1% (4.5×10^6 ha) of the forest affected more than once. They noted that some of the most extensive fires occurred in areas of peat swamp forest, particularly in Kalimantan and Sumatra.

Fire and Land Use Change

Recent changes in fire regimes in Southeast Asia are indicative of increased forest disturbance, but ENSO events also increase fire occurrence and severity. The ENSO-fire relationship is not a new one. There are, for example, accounts of extensive fires in the 15th and 16th centuries (Dennis, 1999; Taylor et al., 1999), when land use conversion activities would have been far less intensive than today, which appear to have been linked to ENSO droughts. Berlage (1957) demonstrated that ~93% of all droughts during 1830-1953 occurred during ENSO events. This pattern was repeated during the second half of the 20th century, with some of the worst fires associated with strong ENSO episodes, including the fires of 1972-73, 1982-83 (the 'Great Fire of Borneo'), 1994, 1997-98, 2002 and 2006 (Aiken, 2004; Baker et al., 2008; Fuller and Murphy, 2006; Malingreau et al., 1985; Tacconi et al., 2007; Wyrtki, 1975). The 1982-83 fires were estimated to have burnt 3.2×10^6 ha, of which 2.7×10^6 ha were forest (Schindele et al., 1989), including 0.55×10^6 ha of peat swamp

(Lennertz and Panzer, 1984). The 1997-1998 fires affected a much larger area estimated to be 11.7×10^6 ha of forest in Indonesia alone, of which approximately 2.4×10^6 ha was peat swamp forest (Page et al., 2002).

Analysis of recent land cover change has underscored the close link between land management and fire activity (Langner and Siegert, 2009). There has been an expansion in the use of fire over larger areas and for longer periods of time than would have previously occurred using traditional slash and burn techniques. The latter are sustainable if the time period between the burning events is long enough and burning is practiced on a small scale, enabling forest regeneration, but fire is now occurring on a much more extensive scale. In part this is because forest margins are at greater risk of fire as a result of disturbance and forest fragmentation through intensive logging activities, but there has also been rapid, large-scale forest clearance for the establishment of large plantations, particularly replacing peat swamp forests, which are now the last remaining extensive areas of lowland rainforest in equatorial Southeast Asia.

Peat swamp forests, which formerly covered 25×10^6 ha of Southeast Asia (Page et al., 2008a), are characterized by the presence of thick peat deposits that are acidic, nutrient-poor and waterlogged and thus present a problematic agricultural environment. Nevertheless, millions of hectares of peatland in Southeast Asia, especially Indonesia and Malaysia, have been deforested, drained and burned to make way for agriculture and settlement, especially oil palm and pulpwood (*Acacia*) estates which produce raw materials for the vegetable oil, biofuel, pulp and paper industries. Many plantation companies, particularly in Indonesia, have employed fire as a cheap and rapid land clearance tool to clear thousands of hectares of logged-over forest; many of these fires have run out of control, entering adjacent forests or drained plantation estates, where they have burned both forest biomass and surface peat.

The risk of fire on peatland is increased greatly by drainage, which lowers the water table, exposing a greater volume of dry peat to combustion. This effect is demonstrated by a study of the fire regime in the former Mega Rice Project (MRP) area on peatland in southern Central Kalimantan (Hoscilo, 2008a) (Fig. 7.1). During 1973-1996, fires affected 24% of a 450,000 ha study area. Most burn scars were located along forest edges (i.e. disturbed forest), usually in close proximity to human settlements which provided a source of ignition. More remote, intact forests were unaffected by fire, even during extended ENSO droughts. This situation changed markedly in the next decade. Following construction of an extensive canal network in 1995-96, the fires of 1997 affected about 34% of the area, i.e. 10% more than had burned during the previous 23 year period (1973-1996) whilst, in 2002, fires affected 22% of the area. In total, more than half of the study area burnt during 1997-2005, with many locations experiencing multiple fires. This was a consequence of deforestation, peatland drainage and increased human access; drainage increased fire risk, whilst people provided the fire ignition source.

Ecological and environmental (atmospheric) impacts

Forest fires cause changes to forest structure, biodiversity, soils and hydrology, as well as increasing greenhouse gas, particulate and aerosol emissions to the atmosphere. Natural fires in undisturbed, old-growth rainforest in this region have, until recently, been rare (Goldammer and Seibert, 1989), but there is evidence that, given a sufficiently long fire return period, these forests have a natural recovery response. Goldammer and Seibert (1989), for example, provided evidence by ^{14}C ages of charcoal that the now diverse rainforests of East Kalimantan were subject to fires between 13,500 and 350 years ago. Given the recent increased incidence of fire in this region there is a pressing requirement to understand the vegetation response to intensive and repeated fires. To date there have been only a few ecological studies examining post-fire vegetation response in lowland forests on mineral soils and even fewer investigations in peat swamp forest. This knowledge is crucial in order to: a) understand fire regimes, b) diminish future fire risk, and c) manage degraded forest land towards a mature stage of regeneration.

Studies of lowland forests have shown that fire causes increased tree mortality, with highest losses in the understorey (trees with dbh <10 cm) (Slik et al., 2002) even at low fire intensity and flame length (Baker et al., 2008), and converts forest stands with a high diversity of primary species into ones dominated by a few fire-adapted or pioneer species (Toma et al. 2005). Since climax trees need a considerable length of time for their growth and reproduction, it is likely that repeated fires within a short time interval will lead to a decrease in their numbers. Slik et al. (2008) found that dipterocarp forest structure was strongly affected by fire but recovered quickly. In contrast, species composition showed no or limited recovery and above-ground biomass (AGB) was reduced greatly and remained at a low level even after seven years.

Secondary forest regrowth can be a carbon sink over the medium term and thus studies of post-fire vegetation recovery are important to understand changes in ecosystem carbon flux. In a long-term monitoring study of post-fire forest regrowth in East Kalimantan, Toma et al. (2005) demonstrated that if fire kills large specimens of primary forest species, the lost biomass is unlikely to be completely restored since the AGB attained by pioneer trees (such as *Macaranga* spp.) was far less than the biomass of climax species lost by burning. More rapid AGB accumulation can only occur when pioneer species are replaced by primary forest species, ie. over a long time scale. In studies carried out on post-fire vegetation response in peat swamp forest in Central Kalimantan, Page et al. (2008b, 2009) and Hoscilo et al. (2008b) have shown that peatland subject to a single, low intensity fire undergoes succession to secondary forest, achieving a biomass equivalent to about 10% of that of undisturbed forest within nine years. Compared to mineral soils, the recovery of peat swamp forest is much slower. Nykvist (1996), for example, showed that the biomass of eight-year old lowland dipterocarp forest in Sabah had recovered 24% of pre-fire biomass. Following multiple fires in peat swamp forest, the numbers of tree species and individual trees, saplings and seedlings within the secondary vegetation are greatly reduced and, at the highest levels of degradation, succession back to forest is diverted to a retrogressive succession to communities dominated

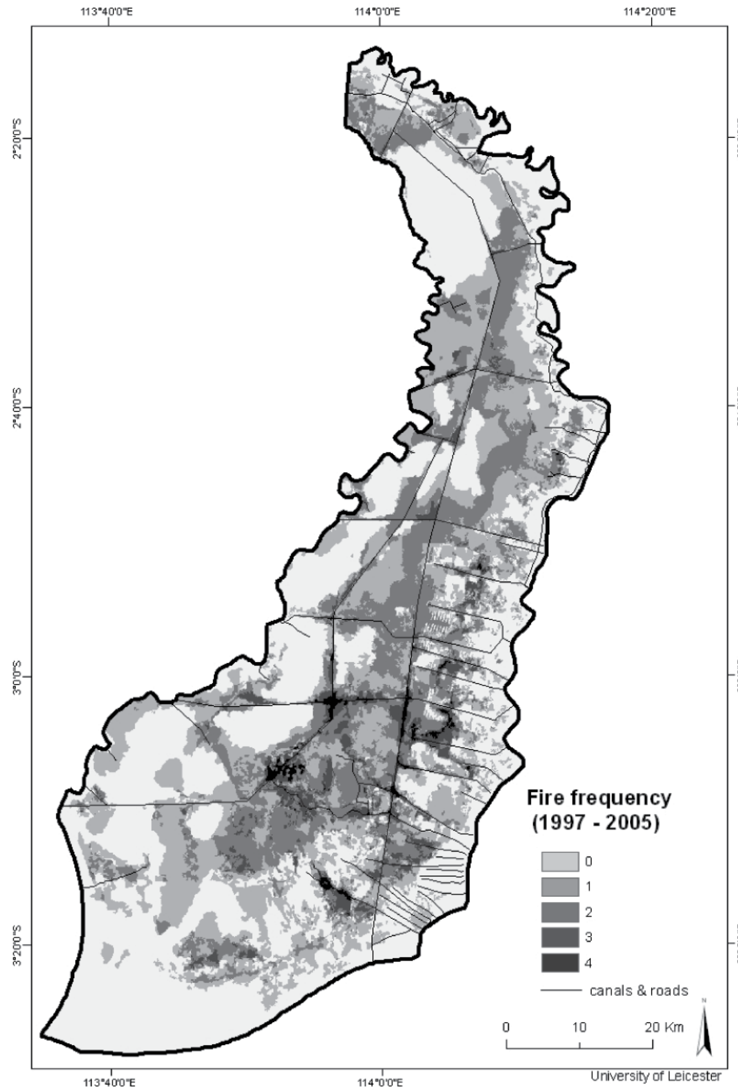

Figure 7.1. Spatial distribution of single and multiple fires over the period 1997-2005 in Block C (4,500 km^2) of the former Mega Rice Project (MRP) area in southern Central Kalimantan province, Indonesian Borneo (Hoscilo, unpublished results; see also Page et al. [2008, 2009]). This area of peat swamp forest was extensively drained during 1995-1996 as a result of MRP infrastructure development (the network of canals and roads is overlaid on the map). Peatland drainage has greatly enhanced both the risk and extent of fires, illustrated by the large number of sites that have burnt two, three or four times, particularly in proximity to canals. During ENSO-related droughts (1997, 2002 and 2006), forest and peatland fires in the MRP led to high greenhouse gas and particulate emissions to the atmosphere (Fig. 7.3).

by ferns with very few or no trees (Fig. 7.2). At this point, both biomass and hence the potential for carbon sequestration are greatly reduced.

Several studies have highlighted invasion of ferns and grasses as a particular feature of repeatedly burned forest in Southeast Asia (Cleary and Priadjati, 2005; Slik et al., 2008; Van Nieuwstadt, 2002; Woods, 1989). A high density of non-woody vegetation suppresses tree regrowth since it can overgrow and out-compete many seedlings and saplings in the early stages of their development. In addition, fire reduces seed availability and dispersal, leading to a decline in seedlings and saplings, and removes the vegetative regeneration potential of tree bases and roots, which are burned away. Van Nieuwstadt et al. (2001) reported a loss of 85% of the dormant seeds in the surface litter layer and 60% in the upper soil layer in lowland forest following fire. A further consequence of repeated fires on tropical peatland is land subsidence, a result of peat dewatering, biological oxidation and combustion losses, which lead to an increased risk of flooding in wet seasons. Van Eijk and Leenman (2004) and Wösten et al. (2006) describe post-fire vegetation trends in Berbak, Sumatra, where areas burnt only once and subject to shallow, short duration flooding during the wet season were able to undergo succession to a relatively species-diverse, well structured forest vegetation. Sites subject to multiple burns, peat subsidence and deep or prolonged flooding, however, have a much more poorly developed and less diverse vegetation dominated by flood-tolerant, non-woody vegetation.

In a study of peatland fires in Borneo, Spessa et al. (2009) demonstrated that the occurrence of uncontrolled fires was favored by the increased fire susceptibility of both over-drained peatland areas and previously disturbed forests. The greater the losses in tree cover between 1997 and 2005, for example, the more fire activity was observed. The results of this study, and those described above, are consistent with studies conducted in other tropical ecosystems disturbed by fire, e.g. in Amazonia, where recurrent fires transformed tree-dominated ecosystems to mostly grassy ecosystems which, in turn, promote even more fires as part of a so-called 'vicious positive feedback loop' (Cochrane et al., 1999; Cochrane, 2003). The same process is occurring in Southeast Asia, where increased fire frequency has converted forest vegetation, at low risk of fire, to fern- and grass-dominated savannah-type communities, which dry out quickly during periods of low rainfall and thus burn more easily, creating a positive feedback through increased flammability.

In addition to changes in vegetation structure and diversity, fire also leads to reductions in both aboveground and below ground organic carbon stocks and changes in carbon cycling patterns. Losses of carbon from AGB usually greatly exceed those from soil but, in regions with carbon-rich substrates, e.g. peat swamp forests, combustion losses from belowground stocks can be much greater than AGB losses. For this reason, fires in peatland areas require particular attention, since they make a substantial contribution to global greenhouse gases (Bowman et al., 2009) and, through the production of fine particular matter and aerosols, result in a wide range of human health problems (Heil and Goldammer, 2001). The devastating 1997-1998 Indonesian fires were one of the largest peak emissions events in the recorded history of fires in equatorial Southeast Asia, if not globally (Schultz et al., 2008;

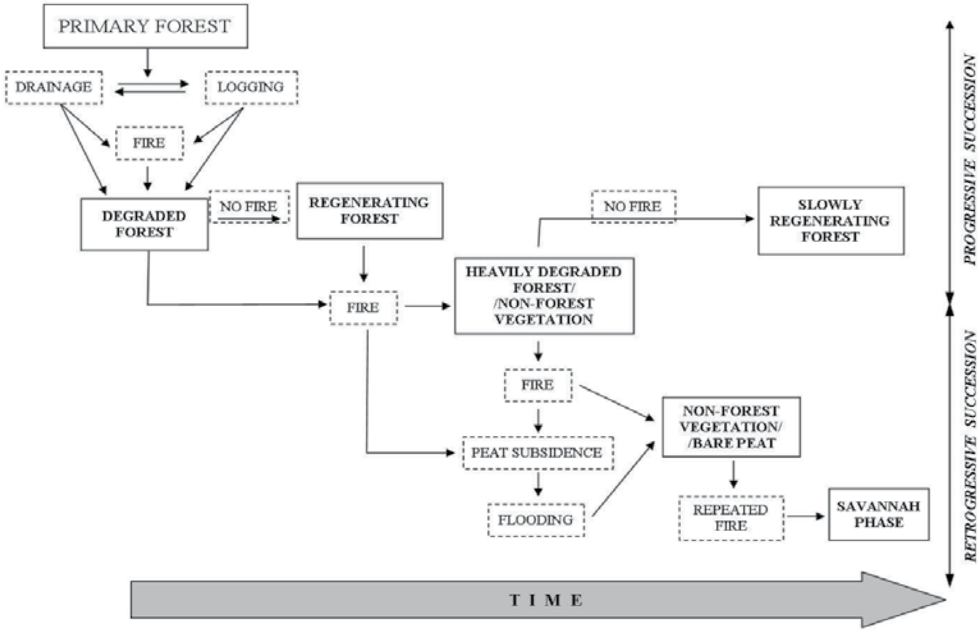

Figure 7.2. Relationship between single and multiple fires and phases of vegetation succession against time in peat swamp forest. With repeated fires, progressive succession towards forest is replaced by a retrogressive succession to 'savannah' type vegetation dominated by ferns, sedges and grasses and with few or no trees (adapted from Page et al. [2008b]).

van der Werf et al., 2006). Page et al. (2002) conservatively estimated that the Indonesian fires in 1997 released more than 870 Tg of carbon to the atmosphere, which was equivalent to 14% of the average global annual fossil fuel emissions released during the 1990s. This value was confirmed by Schultz et al. (2008), who estimated 1997 emissions from Indonesia at 1.136 Pg carbon, and van der Werf et al. (2006, 2008), who estimated 1997 emissions from equatorial Southeast Asia at 1.089 Pg carbon, over 90% of which was released from Indonesia. These emissions represent a serious perturbation in terms of climatic forcing from trace gases and aerosols. The magnitude of emissions, particularly from tropical peatland fires (Fig. 7.3), is unlikely to be reduced in coming decades, since climate modeling studies have shown that parts of equatorial Southeast Asia will experience reduced rainfall and greater seasonality in future decades (Li et al., 2007).

Conclusions

Forest fires in Southeast Asia, and the environmental changes that they bring about, have had significant impacts on the atmosphere, the carbon cycle and ecosystem services, notably

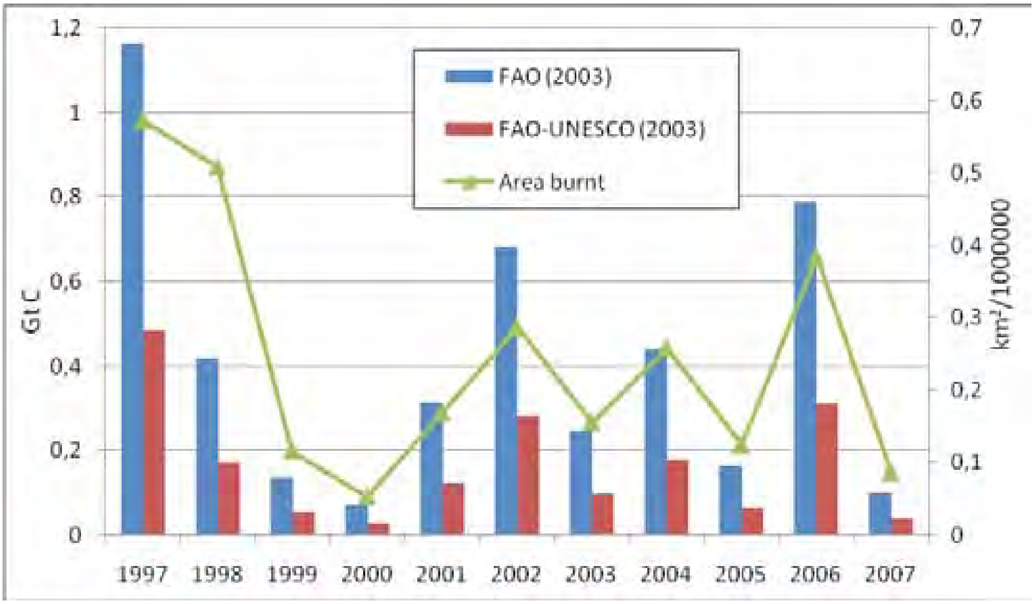

Figure 7.3: Estimated annual total carbon emissions from peat burning versus annual total area burnt for Borneo over the period 1997-2007. Peat surfaces were derived from two soil maps (FAO, 2003; FAO-UNESCO, 2003). Peat bulk density was assigned a value of 128 kg m^{-3} and the carbon fraction was assumed to equal 0.54. The depth of peat burnt in areas classed as histosols was assumed to be 50 cm (after Page et al., 2002) and in areas classed as humic gleysols to be 40 cm (Spessa et al. unpublished results). There are considerable uncertainties associated with estimating carbon emissions from peat fires; data are needed on peatland extent, which is poorly known, area and depth of peat burnt. Despite these uncertainties, the data illustrate the scale of recent fires in this part of Southeast Asia.

carbon and water storage and biodiversity. Protecting the rainforests of this region from further fire disasters should be at the top of the global environmental agenda, with greatest attention given to peatland. Not only do forest fires make a significant contribution to atmospheric carbon emissions and, consequently, to global climate change, they also cause considerable human misery and hardship. Protecting the remaining forests from logging, drainage and land conversion should be seen as a high priority, as undisturbed forests are at very low risk of combustion. Where there is an over-riding economic imperative for land development then land clearance should not involve the use of fire whilst, in peatland already converted to agriculture or plantations, improved water and land management practices, especially those that maintain a high water table, could contribute to a greatly reduced risk of fire.

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8 Current Fire Regimes, Impacts and the Likely Changes – V: Tropical South America

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Abstract

The biodiversity-rich Amazon forest is a region of growing concern because several global climate model scenarios of climate change forecast reduced precipitation and much higher temperatures in some regions. To date, fires have generally been spatially co-located with road networks and associated human land use because almost all fires in this region are anthropogenic in origin. Climate change, if severe enough, could alter this situation, potentially changing the fire regime to one of increased fire frequency and severity for vast portions of the Amazon forest. High moisture contents and dense canopies have historically made Amazonian forests extremely resistant to fire spread. Climate change will affect the fire situation in the Amazon directly, through changes in temperature and precipitation, and indirectly, through climate-forced changes in vegetation composition and structure. The frequency of drought will be a prime determinant of both how often forest fires occur and how extensive they become. Fire risk management needs to take into account landscape configuration, land cover types, and forest disturbance history as well as climate and weather. Maintaining large blocks of unsettled forest is critical for managing landscape level fire in the Amazon. The Amazon has resisted previous climate changes and should adapt to future climates as well, if landscapes can be managed to maintain natural fire regimes in the majority of forest remnants.

Keywords: Amazon rain forest, shifting cultivation fire, El Niño events, drought stress, fire-vulnerable species

Introduction

The land cover of tropical South America is dominated by the Amazon, the world's largest formation of tropical forests. These forests play a vital role in the maintenance of biodiversity, water and carbon cycles, as well as regional and global climate (Schneider et al., 2000; Salati and Vose, 1984; Houghton et al. 2000). Although the Amazon forms portions of most of the countries of South America, roughly 80% of it is located in Brazil as is the Atlantic

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rainforest (*Mata Atlantica*) which now exists only as fragments near the coast. This vast expanse of forest has been settled by various indigenous populations for several thousand years and may have experienced extensive areas of clearing, high population densities, and widespread forest fires during extreme drought conditions (Meggers, 1994; Mann, 2006). Around the margins of the Amazon and at higher elevations are various grass and shrublands. The major savanna and grassland ecosystems of tropical South America include the Colombian and Venezuelan *Llanos*, the *Llanos Moxos* of Bolivia, the *Gran Sabana* of Venezuela and Brazil, the *Pantanal* of Brazil/Bolivia, the *Cerrados* of Brazil and various *Paramo* and *Puna* grasslands at higher elevation in the Andean countries Peru, Ecuador and Bolivia. Additional anthropogenically derived grasslands exist in some regions of Colombia, Venezuela and northern Brazil (UNEP, 2002).

Fire is an endemic component of many of the savannas but recently has become increasingly prevalent across widespread portions of the forested landscape. It is the primary tool used to clear forests and maintain wide expanses of pastures and farmlands with approximately 20 million ha of forested and previously cleared lands being intentionally burned each year (UNEP, 2002). The fires in these landscapes fall into three main categories; deforestation, maintenance, and forest fires (Cochrane, 2003). Deforestation fires, where slashed vegetation is burned, burn intensely for several hours and then may smolder for days. Maintenance fires, that consume charred vegetation remnants from the initial deforestation fires, move rapidly as narrow fire lines through grass and early second growth. Accidental forest fires, which have escaped into standing forests, vary from extremely low-intensity fires in previously undisturbed forests to very intense fires in previously degraded forests and can burn for weeks (Cochrane and Laurance, 2008). Human land use is synonymous with fire use but climate change and the accumulation of degraded forests threaten to release fire from control and make it a dominant source of ecological disturbance.

Fire and Land Use

Fire is a useful tool because it quickly and effectively reduces the biomass of newly cleared forests to nutrient rich ash that can fertilize crops. Fire is also needed to create charcoal, cook food and reduce trash and debris piles. In summary, fire is a very versatile and necessary tool for rural settlers. Fire use has costs as well as benefits, however. Fire becomes a problem when it escapes from its intended purpose and causes unanticipated economic and environmental damages (Cochrane, 2003). Escaped fires damage forests and destroy crops, pasturage, infrastructure (e.g., fence posts, buildings etc), and livestock, occasionally leading to severe economic hardship for local populations (UNEP, 2002).

Shifting Cultivation – Slash-and-burn agriculture has been practiced for thousands of years in the tropics (Pyne, 1997). Within a desired plot, most or all of the trees are felled and then left to dry for several weeks or months. Burning seasons vary across the region but, in all areas, the timing when the practice of slash-and-burn can take place is constrained by the dry season, when little or no rain falls. The objective for the farmer is to reduce the pile of debris, while simultaneously releasing the contained nutrients so that they may act as fertilizer for the soon to be planted crops. When productivity wanes, the plot may be cycled to pasture for cattle or fallowed for a time.

Ranching – Ranching is a widespread land use in the Amazon and many of the tropical South America's natural grasslands. Cattle ranching predominates but gives way to llamas and alpacas in the higher Andean pastures. The process for clearing land for pasture is largely the same as for slash-and-burn agriculture, but the clearing often occurs at larger spatial scales as extensive tracts of land are converted to pasture. Newly created pastures may be seeded with grass or simply allowed to regrow. In either case, they will become increasingly overgrown, as second growth vegetation from the forest starts to take over. Pastures can either be recleared by hand, with machetes, or, as is more commonly practiced, burned again to kill off the forest regrowth. Many pastures are reburned every two to three years (Kauffman et al., 1998; Fearnside, 1990). However, in some regions (e.g., Rondonia) the practice may involve burning for several consecutive years to kill the resprouting vegetation. Subsequent burning is rarely needed afterward (Cochrane, 2009). In natural grasslands managed as pasture, many areas are burned one or more times during the dry season to force new green shoots to form and improve palatability for cattle.

Industrial agriculture – Industrial agriculture can pertain to any of a number of crops that are used in intensive agriculture, including coffee, coca, cotton, corn and other grains. In the lowlands, industrial agriculture is largely synonymous with soybean farming in much of tropical South America. Previously confined to the drier *Cerrado* region, new less daylength-sensitive cultivars have allowed the expansion of soybean agriculture north into the Amazon. Heavily concentrated in the southern Amazon, primarily Mato Grosso, this land use is spreading to other Amazonian states (*e.g.* Pará, Rondonia, Roraima) and within Bolivia. Soybean-related deforestation involves the clearing of very large areas using heavy equipment. Biomass is quickly removed by use of multiple fires during a single year, with residual materials continually piled until the whole site is burned clear to bare soil. Increasing prices of both soybeans and beef are positively correlated with the number of fires in the Amazon (Arima et al., 2007). Once a soybean field is established, however, fire is generally not used to maintain it.

Logging – Selective logging is another major landscape modifier in the Amazon. Although not directly related to fire use, this land use is quickly changing how fire spreads and behaves in many regions. At least 350 Amazonian tree species are commercially harvested (Martini et al. 1994) and annual roundwood production arriving at Brazilian sawmills is upwards of 28×10^6 m^3. The great majority (95%) of timber extraction is done without management (Veríssimo et al., 2002b) and 50% has been harvested illegally (Lentini et al., 2003). Predatory timber extraction has characterized the Amazonian timber boom and exhausted forest resources in the old logging centers of eastern Pará, north-central Mato Grosso, and southern Rondônia. Lumber mills are now relocating to new timber frontiers in north-central Pará (Pacajás and Anapu river regions), western Pará (along highway BR163), and southwestern Amazonas (Veríssimo and Cochrane, 2003). The annual forest area being logged is comparable in size to that being deforested each year. Between 1999 and 2002, 1.2-2.0×10^6 ha of forest was logged each year, roughly 60-120% of the forest area cleared in the corresponding years (Asner et al., 2005).

An intact forest may resist fire encroachment for more than a month without rain, but selectively logged forests may become flammable in as few as 6-8 rain-free days (Uhl and Kauffman, 1990). The vast majority of the Amazon's 3 million plus ha of existing logged forests (Matricardi et al., 2001) are within the fire-dominated 'Arc of Deforestation' (Cochrane et al., 1999). This means that fire-dependent land uses and fire-exacerbating logging operations are occurring in close proximity. The combination of human access, provided by logging roads, and the forest damage caused by logging activities, make logged forests extremely vulnerable to fire. This vulnerability may last for decades after the logging activities have ceased. Therefore, instead of fires being contained by the moist and dense foliage of an intact forest, easily-flammable logged forests, with their heavy fuel loads and porous canopies, act to further link the region's agricultural lands and expose more forests to potential fire events. Logged forests frequently burn and, once damaged, are extremely prone to recurrent fires (Cochrane and Schulze, 1999), dramatically changing the fire regimes of these forests.

Zoning – The Brazilian government has been implementing major infrastructure projects to increase access to the natural resources of the Amazon. Investments, totaling $40 billion from 2000-2007, have been used to vastly expand the region's transportation system and power grid (Laurance et al., 2001a). Balancing these activities is the government's stated commitment to developing a new forest policy based on well-managed production within its expanded system of national forests (*Flonas*). By 2010, the Brazilian government plans to have established 50×10^6 ha of *Flonas* in the Amazon, 10% of the territory (Veríssimo et al., 2002a). This process is well underway, with approximately 30×10^6 ha of established national and state forests. Establishment is just the first step in what is envisioned to be a paradigm shift in how the timber industry operates and, to a larger extent, how development proceeds in the Amazon (Veríssimo and Cochrane, 2003). The intent is to stabilize the timber industry and promulgate wide-spread adoption of forest management practices to avoid a progression of boom-and-bust logging towns causing chaotic and unplanned regional development. If a system of working forests is to be established within the purview of existing infrastructure (sawmills, roads, energy, human resources), then it will need to take fire into account (Veríssimo et al., 2002a,b). Zoning of land use to separate fire-dependent land use and fire-vulnerable forests is key to preventing rampant landscape fires.

Fire and Landscapes

Land cover is changing rapidly in the Brazilian Amazon. In recent decades, road construction has provided access for millions of settlers to previously remote and inaccessible forests (Laurance et al., 2001b). The resultant deforestation from human land use has fragmented many of the remaining forests. Nearly 20,000 km of new forest edge is being created by

Figure 8.1. South American fires in 2007. Image illustrates the distribution and density of fires in 5 x 5 km squares for the entirety of 2007. The background land cover image is the Blue Marble from NASA's Earth Observatory while the fire data are from FIRMS (Fire Information for Resource Management System, University of Maryland [http://maps.geog.umd.edu/firms/]). Color provides the density range of between 1 (yellow) and 12 (red) fire events on each grid square (adapted from Cochrane and Barber [2009]).

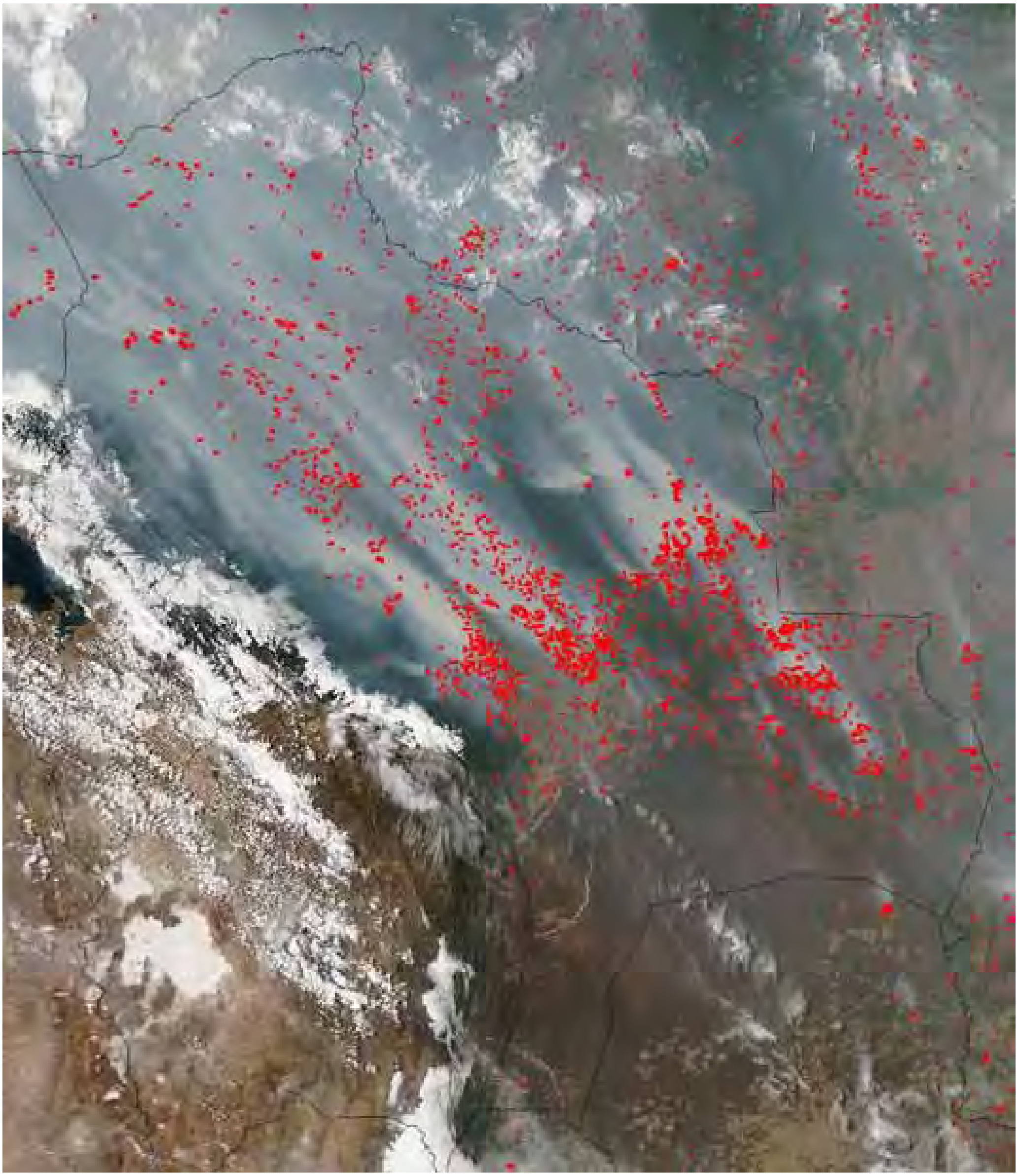

Figure 8.2. South American fires in 2007. The MODIS scene depicted on 27 September 2007 is a rather typical phenomenon occurring annually in the Brazilian-Bolivian border region, with extended smoke transport towards North-Northwest. Source: NASA.

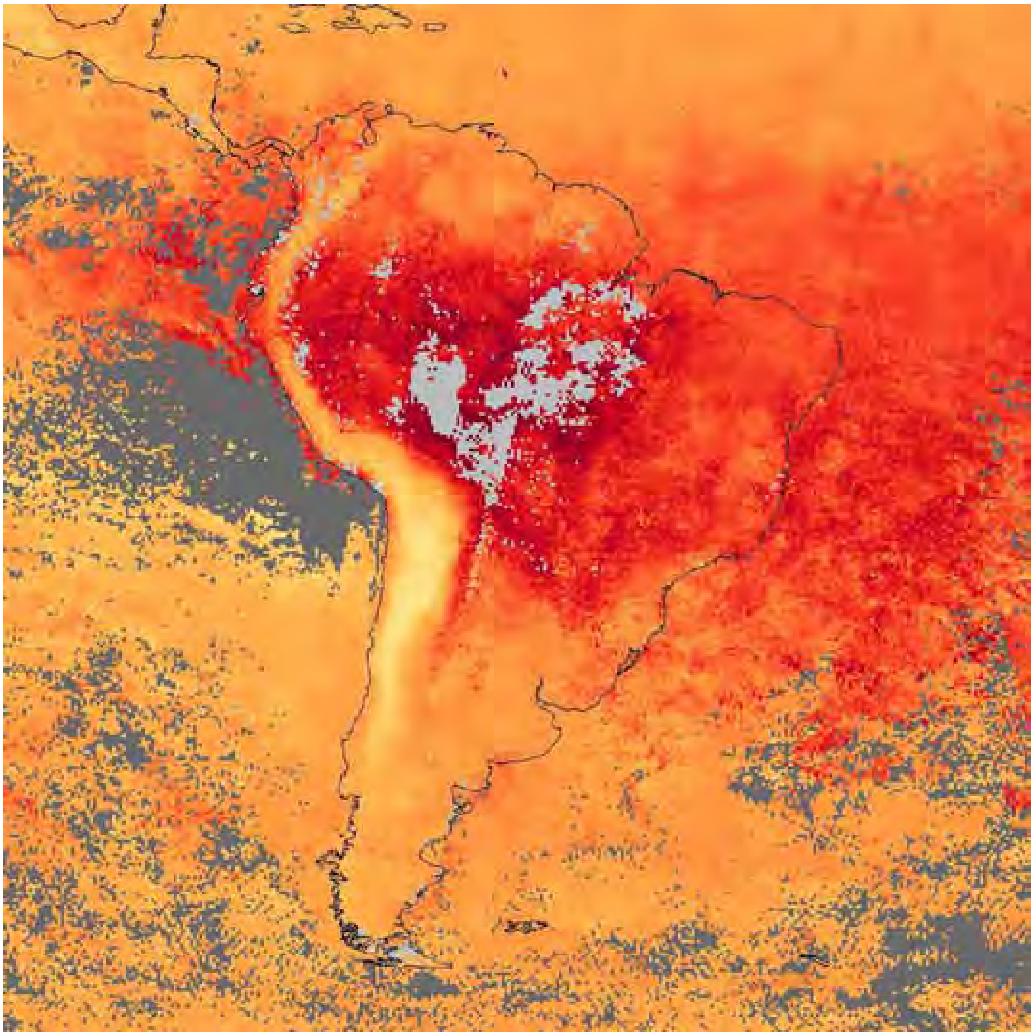

Figure 8.3. This image of the continent shows satellite observations of carbon monoxide for September 2007, measured by the measurements of Pollution in the Troposphere (MOPITT) sensor on NASA's Terra satellite. The image shows the column density of carbon monoxide (number of molecules of carbon monoxide in a 1-square-centimeter column of the atmosphere). Source: NASA.

deforestation processes each year (Cochrane and Laurance, 2008). If forest edges created by logging operations are included, edge formation may be as high as 32,000 to 38,000 km per year (Broadbent et al., 2008).

Fragmented forest remnants exist within a matrix of fire-maintained cattle pastures and slash-and-burn farming plots. Unsurprisingly, fires often escape control and penetrate into surrounding forests (Cochrane and Schulze, 1999), especially during periodic El Niño events when drought-stressed trees lose many leaves and fuels become particularly dry (Cochrane et al., 1999; Laurance and Williamson, 2001). The relationship between forest burning and distance from forest edges is nonlinear but quite strong, explaining up to 92% of observed forest burning (Cochrane et al., 2004).

There is obvious synergism between fragmentation and fire. As forests become increasingly fragmented, more of the remnant forests are associated with nearby edges where the vast majority of fire ignitions occur. As edges proliferate, so does the chance for remaining forests to burn. Most fires occur within several hundred meters of the forest edge, although some fires can penetrate several kilometers into forests (Cochrane, 2001a). These burns can be considered a large-scale edge effect (Cochrane and Laurance, 2002), as they are much more common within 10 km of edges than further into the forest.

There is clear evidence that disturbance regimes in the Amazon are being dramatically altered. The natural fire-return interval is at least 500-1000 years. At present, however, fire rotations in regions where fragmentation and logging occur together imply that over half of the remaining forests are experiencing fire every 5-10 years (Cochrane, 2001a). This rapid fire-return interval prevents regeneration of rainforest canopy trees and results in natural forests being replaced by degraded, fire-resistant vegetation (e.g. invasive grasses, shrubs, and a few pioneer tree species).

Climate Change in Tropical South America

There is increasing consensus among global-climate models (GCMs) that the climate in tropical South America will continue to warm over the next century. GCMs indicate a probable mean temperature increase of 1.8 - 5.1°C for tropical South America by 2099 (IPCC 2007; A1B scenario). Temperatures in the western Amazon are expected to rise more than in the east, potentially as high as 10°C (Cox et al., 2004).

Several GCMs predict moderate (IPCC, 2007) to severe (Cox et al., 2000) reductions in regional precipitation but the consensus GCM prediction is for little or no average precipitation change in tropical South America. Spatially, the east is expected to dry somewhat while the west gets even wetter (IPCC, 2007). Annual rainfall measurements from 1960-1998 have not shown significant precipitation changes but the eastern Amazon, thought to be most at risk of large precipitation reductions, has in fact gotten steadily wetter (Malhi and Wright, 2004). In a study of 9 GCM climate change forecasts under different future emissions scenarios, the mountainous portions of the western Amazon were found to be the region most likely to experience 'novel' climate conditions by the end of the 21st century

(Williams et al., 2007). Expected changes in extreme weather events include more days with intense precipitation in central Amazonia and weaker precipitation intensity in the north-east (Hegerl et al., 2004).

Average regional annual precipitation levels may be stable but changes in the spatial and temporal rainfall distribution may have serious implications for fire susceptibility and future vegetation. The north coast of South America, along the Caribbean, is projected to dry by 5-15% while the Pacific coast or western South America becomes 10-15% wetter annually. Eastern South America shows little change in annual rainfall but much of the area is projected to have substantially reduced precipitation (5-50%) during the dry season while receiving somewhat (5-10%) more rainfall in the wet season (IPCC, 2007). Model-derived expectations are that, other than the north-west region, the Amazon will experience longer periods between rainfall events (Tebaldi et al., 2006). This is critical because fire susceptibility is more closely related to the time since last rain than total rainfall amounts (Uhl and Kauffman, 1990; Cochrane and Schulze, 1999).

Land Cover Change and Climate

Land cover changes can affect climate through several processes. Standard land cover change scenarios in the Amazon (IPCC, 2007) may have little or no global effect on climate but may have substantial regional impact, potentially raising Amazonian temperatures 2°C by 2100 (Feddema et al., 2005). Recycling of evapotranspiration is responsible for 25-50% of regional precipitation (Eltahir and Bras, 1996; Li and Fu, 2004), therefore, even partial deforestation reduces evapotranspiration and is expected to reduce regional precipitation (Salati and Nobre, 1991; Costa and Foley, 2000). However, recent indications are that regional rainfall might actually increase over deforested areas due to local convection processes (Da Silva and Avissar, 2006). These effects may be scale dependent, however, requiring large amounts of heterogeneous regional deforestation (D'Almeida et al., 2006). The net effect on precipitation will be a combination of greenhouse gas-related climate change and land cover effects (Johnson and Cochrane, 2003).

Fire and Climate

Climate will affect the fire situation in tropical South America directly, through changes in temperature and precipitation, and indirectly, through climate-forced changes in both vegetation and fuel composition and structure (Pausas and Bradstock, 2007). These effects will occur at a range of temporal and spatial scales. If temperatures increase and precipitation is reduced, then potential fuels that are normally too wet to burn will dry more quickly and more often, thereby increasing the susceptibility of vegetation to burning. Smoke from tropical fires also suppresses regional rainfall by creating an excess of cloud condensation nuclei, creating water droplets that are too small to precipitate (Rosenfeld, 1999; Ackerman et al., 2000). The frequency of drought will be a prime determinant of both how often forest fires occur and how extensive they become. El Niño years have generally been associated with the largest fire events in the Amazon (Cochrane et al., 1999; UNEP, 2002) but intense drought and fire conditions need not be associated with El Niño (IPCC, 2007).

The Amazon has evolved under the auspices of a relatively benign but not unchanging climate. The forest has proven remarkably stable during previous global climate changes (Bush and Silman, 2004, Cowling and Shin, 2006). The potential for climate-change-related dieback of the Amazon (Cox et al., 2000) appears to have been overstated (Cochrane and Barber, 2009). Current GCMs and RCMs systematically overestimate future precipitation reductions (IPCC, 2007; Hasler and Avissar, 2007). In 2005, an extensive drought, one of the most extreme on record, did not cause trees in the southwestern Amazon to reduce leaf area; in fact the trees increased their effective leaf area while rivers literally ran dry. The vegetation was never water limited and instead responded as if it were normally light limited by clouds. However, the region did experience historically unprecedented and widespread forest fires.

Over longer time scales, vegetation responses to climate change may drive changes in regional fire regimes. If the eastern Amazon is now at risk of significant warming and drying, these forests could potentially transition from being highly resistant to fire (Uhl and Kauffman, 1990) to becoming extensively flammable in the near future (Cochrane and Barber, 2009). However, since wildfire in the Amazon is almost exclusively driven by human activity (UNEP, 2002), future fire regimes will be a product of both climate changes and human land management practices. Savanna (Cerrado) vegetation would succeed forests when nearby but, throughout much of the basin, grass or scrub vegetation would dominate. These ecosystems would be characterized by frequent low intensity fires that would reinforce climate exclusion of mature forest species.

Conclusions

Fire affects rainforests throughout tropical South America to differing degrees. Effects are more pronounced in regions with extended dry seasons, selective logging and large populations. Massive forest fires have been reported from forests throughout southern, northern, central, eastern and southwestern Amazonia in Brazil (UNEP, 2002). In the Amazonian state of Roraima alone, between 1.1×10^6 and 1.4×10^6 ha of undisturbed forest burned in 1998 (Barbosa and Fearnside, 2000; Shimabukuru et al., 2000) and have suffered recurrent burns in recent years. Other fires in the region include more than 7,000 forest fires in Colombia in 1997 (Brown, 1998), intense fires in forest concessions and agricultural lands in Bolivia in 1993 and 1994 (Mostacedo et al., 1999), and 1999 (Musse, 1999), and numerous fires across the Guyana Shield including Brazil, Colombia, Venezuela, Suriname and Guyana in 1998 (Grégoire et al., 1998). Additional rain forests of the Mata Atlantica region of Brazil are also threatened by fire. These forests have been 90% deforested and exist only as fire susceptible fragments.

The crux of the fire problem in Amazonian forests is not so much the introduction of fire into these ecosystems but the frequency with which they are being burned. Infrequent fire disturbance has left tropical rainforests evolutionarily ill-adapted to current patterns of burning. Resilience to climatic stress through moisture recycling (Eltahir and Bras, 1996; Li and Fu, 2004), enhanced by the deep-rooting capacity of many forests (Nepstad et al., 1994), allowed many tropical forests to persist through severe droughts of previous glacial periods (Kleidon and Lorenz, 2001). Despite adaptations to drought conditions, rainforests can and do burn.

In anthropogenic landscapes, fire is a continual presence making it a matter of time until a sufficiently intense drought opens up the forest to fire (UNEP, 2002). If nothing is done to protect or restore fire-damaged forests, then the result will be rapid forest degradation and a deteriorating ability to control fire across the landscape. As more degraded forests accumulate, forest fires will become more common and more widespread. Increased fire contagion will impact residents of the affected region by damaging crops and properties. The increased risk of fire will tend to make investment in perennial crops or tree plantations unattractive and promote more fire-tolerant activities such as ranching. In addition to the direct effects on the population, the fires will indirectly harm residents via smoke-caused or antagonized illnesses.

The amount of forest that is impacted by fire will vary from year to year. In the absence of changes in the way fire is being used and managed throughout the Amazon, forest remnants will continue to erode even if deforestation and logging cease. Once fire becomes an established disturbance in a region's remaining forests it becomes increasingly difficult to prevent future fires (Cochrane et al., 1999; Cochrane, 2003). Within the Brazilian Amazon, 26×10^6 ha of forest could currently be undergoing this process, leading to the eventual release of 3.9 Pg C (Cochrane, 2001b). The size and intensity of wildfires will be a function of both climate and fire suppression activities. If burning forests have been previously undisturbed, then fire damages will likely be light and affect mostly smaller sub-canopy trees. Conversely, areas, which have been previously logged or burned, may burn intensely, killing even large trees, and severely damaging the forest canopy (Cochrane and Schulze, 1999). In regions where the fire situation cannot be arrested, large amounts of fire-induced deforestation will occur and more fire tolerant scrub or savanna vegetation will replace forests.

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9 Current Fire Regimes, Impacts and the Likely Changes – VI: Euro Mediterranean

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Abstract

Every year, more than 0.5 million ha of vegetated lands are burned in the countries of Southern Europe, around the Mediterranean, threatening human and natural values: The Mediterranean region is second to the tropics in biodiversity in the world. Mediterranean plant species and ecosystems were selected in a world with fire. But fire regimes were characterized by a long fire cycle (>100 yr). This cycle was accelerated as humans occupied the land and fire became part of the management tools. However, during the second half of the 20th century, as rural people rapidly urbanized, unproductive land was abandoned and fuels accumulated, wildfires became more frequent and widespread throughout the territory, and catastrophic. This process might have been favored in some countries by afforestation with flammable species. Currently observed changes of fire regimes, such as increased frequency and severity of fires, threatens ecosystem stability and their provision of services through degradation loops that impedes the recovery of the vegetation towards more mature stages. In addition, long-term over-exploitation of Mediterranean ecosystems during millennia makes them more sensitive to fire impacts. Future land-use and land-cover is very likely to continue as a result of climate change and additional socioeconomic changes, thus adding more land to that already existing in a state of abandonment, with the corresponding consequences of worsening fire hazard. Future climate scenarios project increases in temperature that are higher than the global mean, plus decreases in rainfall. Additionally, and increase in the frequency and intensity of droughts and heat waves is anticipated. This is very likely to increase fire risk in most areas, as well as the frequency of extreme situations, thus affecting the probability of fire, in particular of large fires. Regeneration under such conditions can be slower or impeded, hence contributing to the degradation of these lands.

Keywords: Mediterranean fire regimes, fire-persistence traits, post-fire regeneration, fire-prone shrublands, fuel accumulation

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Introduction

Every year, ca. 50,000 fires are recorded in Europe, mainly in the South, in the Mediterranean region, where they burn 0.5×10^6 ha (San Miguel and Camia, 2009). Despite similar or even more dangerous climatic conditions in the countries of the southern rim of the Mediterranean Sea, or in part of the Anatolian Peninsula, fires in these areas are fewer (Dimitrakopoulos and Mitsopoulos, 2006), although Turkey suffered the largest fire in their historical records in 2008, amounting to some 20,000 ha. The mild and wet winters, warm and dry summers, moderately fertile soils and moderate to high primary productivity in much of the region provides an almost perfect combination for fires to occur during the summer. The importance of fire predates the advent of man. Plant fire-persistence traits such as the very thick bark of *Quercus suber* L. (Zedler, 1995), the serotiny of many *Pinus* species (Tapias et al., 2001), or the presence of soil-seed banks that are activated by fire related cues (Trabaud and Oustric, 1989), among other, indicate that fire must have played an important role since long. Phylogenetic analysis of plant species confirms this (Pausas and Verdú, 2005). The variety of climates, substrates, soils and land forms has been molded by man since millennia by using, among other management tools, fire to produce highly diverse landscapes (Naveh, 1995). Biodiversity is among the highest in the world (Myers et al., 2000). Anticipating changes in fire trends and the factors that control them is critical for the conservation of these areas and the maintenance of the ecosystem services they provide.

What do we Know about Past Fire Regimes?

Fires are thought to have naturally occurred in the Mediterranean since at least the Miocene (Dubar et al., 1995). Human use of fire dates as far back as 400,000 years. Evidences obtained from sedimentary deposits covering the Late Quaternary through the Holocene indicate that extant species were exposed to fire. The fire regime emerging from some of the best characterized sequences is one of long fire-return interval (300-400 yrs) that increased during the course of the Holocene, as the climate became warmer and drier, to still long fire cycles (150 yr) (Carrión et al., 2003). A pattern of low/high fire frequencies associated to cold/warm moist/dry conditions is also apparent in other areas around the Mediterranean during the earlier part of the Holocene (Vanniere et al., 2008). Fire frequency became much higher with the advent of man (Carcaillet et al., 2002). Abrupt changes have been documented when fire frequencies reached 30-50 yr. The increased fire frequency and the associated changes in vegetation in favor of shrublands, together with ruderal species, indicate that fires were mainly linked to the management of the territory. Man use of the territory through historical times has involved the use of fire, grazing, ploughing and coppicing, among other. By the turn of the first millennium forest retrogression started to peak. Since then and until the middle of the 20th century the occupancy of the territory remained at its highest. Therefore, extant landscapes and vegetation composition are the legacy of centuries of intensive use of the land.

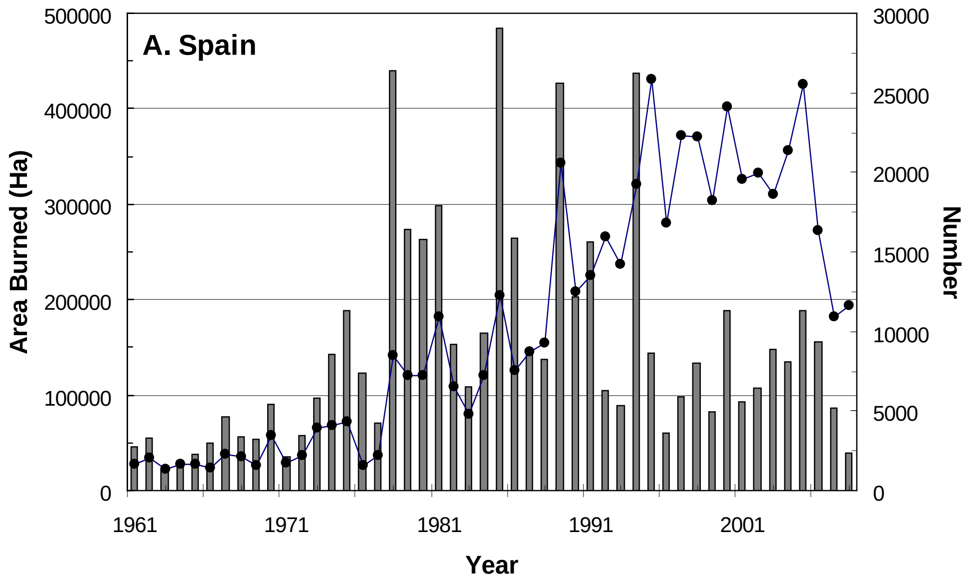
Industrial Development and Forest Fires

Trends land-use land cover

By the second half of the 20th century the process of extensive land use is halted and reversed. Rural exodus, mechanization of agriculture, reduced extensive grazing, forestation in many marginal areas and changes in life styles became the norm. All of this introduced important changes in land-use and land-cover (Le Houérou, 1992). Landscapes poor in tree cover or in vegetative cover in general gave rise to others that little by little accumulated vegetation, trees or shrubs, and in which management was less active. Fires started to become more frequent, and a significant relationship between fuel accumulation rate and fire has been found in some countries (Rego, 1992). Landscapes became more homogeneous and highly interconnected (Peroni et al., 2000; Moreira et al., 2001; Lloret et al., 2002; Mouillot et al., 2005). This possibly contributed to enhancing fire risk, provided that discontinuities are important to deter fires (Vega-Garcia and Chuvieco, 2006; Viedma et al., 2009). Fires themselves may have further added to this process of homogenization (Viedma et al., 2006). Further, it has been shown that forest areas, once burned, tended to reburn at an accelerated rate (Vázquez and Moreno, 2001; Salvador et al., 2005). This tendency to increase forest and wildland areas has been taking place in all South European countries. In addition, afforestation, often with highly flammable conifers was frequent.

Trends in forest fires and their spatial and temporal patterns

Although the forest fire statistics are incomplete for the first part of the 20th century, the available data indicates that wild-fires were not important, at least in the forested areas, which were the ones for which statistics were compiled, until the middle of the century (see Pausas et al. [2008] for the Levant of Spain). By the late 1960s wildfires started to occur at an increasing rate in all countries of the EC (Alexandrian and Esnaut, 1998). The number of fires has continued rising, although that is in part due to a change in the compilation of statistics. Area burned, which is less sensitive to compilation procedures, increased during the 1970s and into the 1980s, by which time Spain and Italy had reached maximum values (see Fig. 9.1A for Spain). Greece and Portugal followed suit with some delay (Fig. 9.1B). It is important to note that the increase in fire during the 1980s did not correspond with the changes in the mean climate, which were different in the East and West sides of the Mediterranean. Therefore, while a climate effect cannot be ruled out, certainly other factors came into play. During this decade of transition none of the northern African countries or Turkey experienced a similar increase. In fact, using this decade as a reference, Portugal and Italy had a fire rotation period of about half a century (42 and 53 yrs), France, Spain and Greece of about one century (83, 110 and 110 yrs, respectively), but Morocco, Algeria, Tunisia and Turkey were far from these figures (2000, 500, 250 and 1670 years, respectively) (Moreno et al., 1998). These contrasting burning rates have continued into the 1990s (Goldammer, 2002). Although these numbers must be taken with caution provided that statistics are not



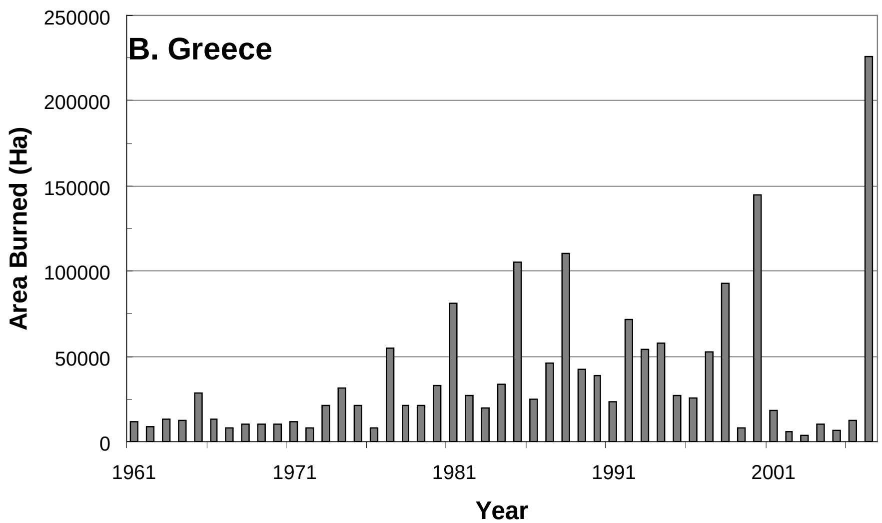


Figure 9.1. (A) Total yearly number of fires (filled circles) and area burned (bars, ha) for Spain, and (B) area burned for Greece during the last half century. Source: Ministerio de Medio Ambiente, Medio Rural y Marino; Anonymous (2007).

consistent across countries, the magnitude of the difference suggests that different processes were going on depending on the degree of development of these countries (Vélez, 2009). Fires became more frequent during the second half of the 20th century, but also more widespread. The analysis of change in the geographic distribution of fires in Spain illustrates this process: early in the 1970s fires were more restricted to areas were forest dominated. With time, fires became widespread throughout the whole country (Fig. 9.2; Moreno et al. [1998]).

Around the Mediterranean most (≈95%) fires are caused by humans, either by accidents or intentional (San Miguel and Camia, 2009). A small percentage of fires can be considered to have been ignited by lightning (in Spain just 4%), although they tend to cause larger impacts (in Spain around 10% of burned area), because they usually occur in remote forest areas, where the detection and first attack take longer, and they are frequently associated to extreme meteorological conditions with dry thunderstorms, and strong winds which make difficult the use of aerial extinction resources. In general, the length of the fire season and the temporal pattern of fire occurrence vary across regions and with type of ignition (negligence, arson, agriculture-related activities, and lightning). Lightning-ignited fires tend to concentrate almost exclusively in the summer while fires related to pasture burning are more widespread during the year, well into spring and fall, accidental fires being somewhere in between. These patterns can vary from one region to another. Fires vary also in their location within an area, and geographic distribution depending on the source of ignition.

Fires are extreme phenomena, the result being that few fires account for a very large percentage of area burned (2.6% of fires larger than 50 ha account for 76% of the area burned in Southern Europe) (San Miguel and Camia, 2009). This varies across regions, with more moist/cool regions being less extreme than dry/warmer ones (Ricotta et al., 2003). The degree of extreme-fire varies also at a given area between years. In this case, more cool/moist areas and warm/dry areas vary less than areas with a more contrasted climate (Vázquez and Moreno, 1995).

Fire policies and fire fighting capacity

All fires are suppressed, and this policy has been maintained until now. As fires started to occur, fire fighting capacity of EU Mediterranean countries became a priority, and little by little fire fighting capacity was built up. Each summer more than 400 aircraft provide support for fire suppression in the EU Mediterranean countries. Expenditure in prevention and suppression amount to more than 2.5 billion € per year. Of this, 60% goes to suppression equipment, personnel and operations, the rest being for fire prevention work (Vélez, 2008). A reflection of this is increment in fire fighting capacity is that, on average, there has been a tendency to decrease the mean size of fires. Although, in general, the number of large fires seems stable (San Miguel and Camia, 2009), in some areas it is increasing (González and Pukkala, 2007).

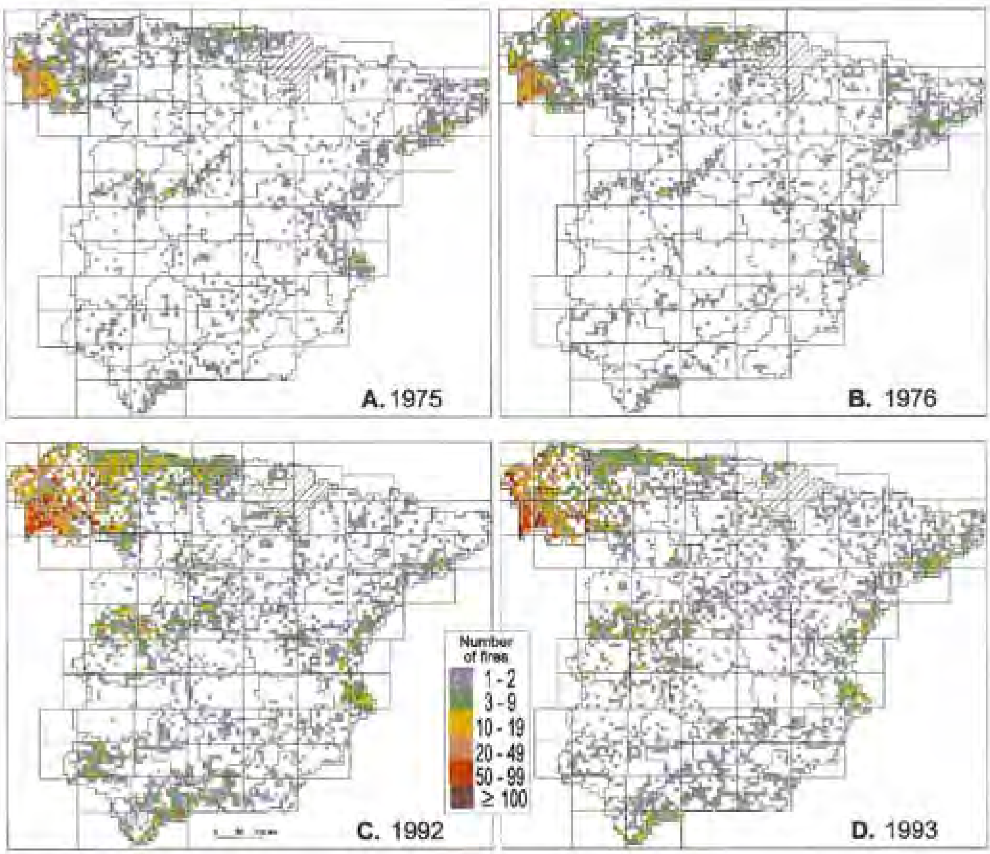


Figure 9.2. Number of fires per grid-cell (10x10 km) in Spain during: (A) 1975; (B) 1976; (C) 1992; (D) 1993. Although a similar area was burned during these years, the geographic distribution changed notably. Source: Moreno et al. (1998).

Ignitions and the wild-land urban interface (WUI)

A major concern for fire managers in Southern European countries is that a significant proportion of the wildfires affect peri-urban areas as well as areas densely inhabited by tourists in summer, when wildfires mostly occur. This adds additional risk provided: 1) the dramatic increase of secondary housing along the coasts and in the vicinity of large conurbations that often invade the wildlands; and 2) the generalized land abandonment in the surrounding of small villages and farms, where natural vegetation is invading the old fields and getting close to the houses. In these areas, the risk of causalities and of direct damage to homes and infrastructures is very high, as the Greece fires of 2007 sadly demonstrated.

Fire, weather and climate

The close relationship between weather, climate and fire has been attested in many places whereby high temperatures and low precipitation play a most significant role, albeit in the case of rainfall this can be non linear and with lag effects; few particularly severe weather days can account for a large percentage of the area burned (Vázquez and Moreno, 1993; Piñol et al., 1998; Viegas, 1998; Pausas, 2004; Trigo et al., 2006). Interestingly, it has been found that the fire-size frequency structure matches that of the weather-severity frequency structure in several regions (Boer et al., 2008), which hints at a close local relationship between weather, climate and fires. Multiple, very large fires episodes, concomitant with most severe climate and weather extremes (drought and heat waves) are additional recent features of fires in the region. Episodes such as in the Spanish Levant in 1994, Portugal in 2003 and 2005, and Greece in 2007, mark unprecedented records of how extreme fires can become in the region. Under these conditions, fires can expand towards areas in which until now they were absent or rare.

What fires burn?

The fact that current fires are overwhelmingly driven by man has some important consequences for what areas and vegetation types are being burned. Contrary to what might be expected, fire incidence is not highest at the places were climate-driven fire danger is highest. On the contrary, in some of the more mesic areas of the Iberian Peninsula, where the potential vegetation would not even be of Mediterranean type, fire-occurrence is at its highest (Vázquez et al., 2002). Since people cause most fire, they influence where and when these occur and temporal patterns can be highly predictable (Díez et al., 1994). Thus, in favorable (warmer, drier) years the fire season can be shorter, not longer (Vázquez and Moreno, 1995), which contradicts normal expectations.

During the course of the century, at least in Spain, the types of vegetation burned have been changing, from more wooded-dominated areas to shrubland-dominated areas. This may reflect in part the changes in land use and land cover experienced during this time. Fires, however, do not burn at random the vegetation that is available (Nunes et al., 2005). Syphard et al. (2009) showed that needle-leaf forests are burned preferentially across the

Mediterranean. Fire occurrence may be linked to particular abiotic or human factors. In areas where lightning is the main source of ignition, fires preferentially occur at higher elevations and in places where tree vegetation is dominant. Fires also have preference for certain topographic locations, or distances to towns or roads (Mouillot et al., 2003; Badia-Perpinyà and Pallares-Barbera, 2006; Syphard et al., 2009). In general, remote, less densely populated, more distant and less accessible areas tend to burn less. This is important for future conservation planning, and calls for a need of planning that is compatible with the conservation of these areas, if only by modifying urbanization patterns to reduce ignition sources. Furthermore, since it is likely that in the past the first areas to be abandoned were those more distant to towns and less fertile, that means that new abandonments will tend to occur closer to towns, were ignition sources are more abundant, and in more fertile areas, hence with higher productivity, which would increase the risk of fire. The combination of afforestation with conifers close to towns in former cultivated relatively fertile areas seems the worst option.

Ecosystem responses and threats of current fires

Although Mediterranean ecosystems are considered to have evolved under the influence of fire (Pausas and Verdú, 2005; Pausas et al., 2006), during the last decades fire regimes have been deeply altered. This fact, in combination with other long-term anthropogenic disturbances, may cause further fire-induced degradation beyond the resilience domain of Mediterranean ecosystems. As a consequence of this long-term human impact, most of the Mediterranean basin is now regarded as 'degraded' (TNC, 2004). Therefore, fire impacts on ecosystems should be analyzed in terms of the interactions between direct fire-induced processes and previous human-induced degradation processes. Post-fire regeneration in fire-dependent ecosystems usually follows the autosuccession process (Trabaud, 1994). However, this model does not always occur. There are several woody species that do not regenerate either after a single fire (Riera and Castell, 1997; Retana et al., 2002) or after short fire intervals (e.g., *Pinus halepensis* and *P. pinaster*; cf. Vallejo and Alloza [1998]). In addition, post-fire weather conditions and/or seed bank exhaustion can drastically affect regeneration of obligate seeder species (Baeza, 2004). In hot spots of recurrent fires, reduced vegetation growth is observed (Díaz-Delgado et al., 2002; Delitti et al., 2005). Post-fire vegetation recovery is important in itself but also because it is a major factor controlling post-fire erosion and flash flood risk (Vallejo and Alloza, 1998). High soil erosion rates are irreversible at the ecological time scale; therefore, it is a major potential impact of wildfires.

Several sensitive fire situations can be recognized in the Mediterranean at present: a) wildfires affecting fire-sensitive ecosystems in regions where natural fires were uncommon; b) unprecedented fire frequency or severity – altered fire regime – over fire-dependent ecosystems; c) unprecedented combination of fire regime and other disturbances, e.g. oldfields. Abandoned lands constitute a major priority on fire prevention and post-fire restoration. Old fields are colonized by opportunistic species, which in the early stages are mostly obligate seeders (Gallego et al., 2004). These species have short life cycles and many of them generate an abundant and persistent seed bank. Woody seeders often lead to high fuel load accumulation and thus to fire-prone shrublands (Baeza et al., 2006). Wildfires affecting fire-prone shrublands that have colonized old fields often enter into short-interval fire cycles that stop any further secondary succession towards more mature ecosystems. Many opportunistic shrubs have the ability to colonize both old fields and burned ecosystems (Baeza and Vallejo, 2006). In the short-term, ecosystems dominated by obligate seeders regenerate slowly after fire, thus leaving bare soil exposed to wind and water erosion for relatively long periods of time (Vallejo, 1999). Therefore, land abandonment facilitates fire cycles that result in ecosystem degradation loops. Recovering ecosystem resilience in those abandoned lands would thus require breaking degradation loops and promoting secondary succession towards more mature, more resilient plant communities (Vallejo and Alloza, 1998).

Future Trends

Land-use / land-cover

Projections for the last part of the century indicate that the process of abandonment or change of use of marginal areas will continue, with further concentration of agriculture in more fertile areas. Additionally, the European Agricultural Policy is recently promoting reforestation with native species in marginal areas, to favor carbon sequestration. The surface devoted to agriculture decreases depending on the emission scenario considered. Less emission-intensive scenarios (such as the B1) produce reductions in agricultural areas for Spain of 33% by the year 2080. On the other hand, more emission-intensive scenarios (A1) project reductions of up to 70% for the same date (Metzger, 2004; Rounsevell et al., 2006). Consequently, it is foreseeable that the process of land-use change will continue during this century. A reduction of the surface devoted to agriculture could imply an increase in the surplus land dedicate to other uses, mainly forestry in all its facets, including wildlands, with the corresponding increment in fuels and hazard for these landscapes.

Climate and fire risk

Annual temperatures are projected to increase in southern Europe and the Mediterranean (SEM) more than the global average (for the A1B scenario and the period 2080-2099, the projected global warming is 2.8ºC, whereas for the SEM is 3.5ºC). Warming will be largest towards the south and the interior, and will be highest in summer (4.1ºC, for the same scenario and period). Maximum temperatures are likely to increase more than average or minimum temperatures. Warming will be greater with increased GHG emissions (Christensen et al., 2007). Annual precipitation is very likely to decrease in most of SEM, and the number of wet days is very likely to decrease. Precipitation changes will not be homogeneously distributed between seasons, with summer precipitation tending to experience greater reduction (24% reduction in summer vs. 12% reduction in the annual total for the same period and scenarios as above). Precipitation changes will vary throughout the region,

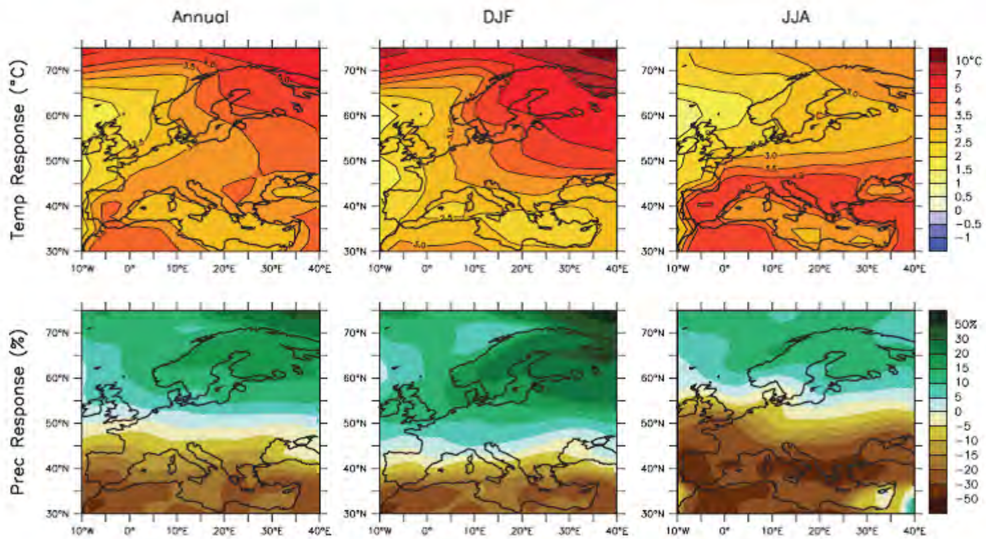


Figure 9.3. Simulated temperature and precipitation changes over Europe for the A1B scenario. Top row: annual mean, winter (DJF), summer (JJA) temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Bottom row: same as top, but for fractional change in precipitation. Source: Christensen et al. (2007).

and the greatest reductions are likely to occur more towards the south (Fig. 9.3). Other changes for SEM include decreases in relative air humidity and cloud cover, particularly in summer; no significant changes in 10-m mean annual wind speed are expected, except for a light increase in summer (Christensen et al., 2007).

Inter-annual temperature variability is likely to increase in summer for most of Europe. This means that, if during a given period the maximum temperature of a set of the warmest years exceeds the mean of the period by a certain value, in the future this value will be even greater, and will be added to the larger mean that is expected due to warming. This variability also extends to daily temperature variability, with the highest maximum temperature increasing more than the median maximum temperatures. Changes in synoptic patterns are projected to produce heat waves of increasing severity, duration and frequency through much of SEM and Central Europe (Meehl and Tebaldi, 2004). There is uncertainty with regard to extreme, summer, short-term precipitation in the Mediterranean. Much larger changes are expected in the frequency of precipitation extremes; for SEM, large increases in the frequency of low summer precipitation are projected. The number of dry spells and the risk of drought is likely to increase in SEM (100-yr droughts are expected to occur under certain scenarios by the end of the century every 10-yr or less), notably in southern Europe (Lehner et al., 2006).

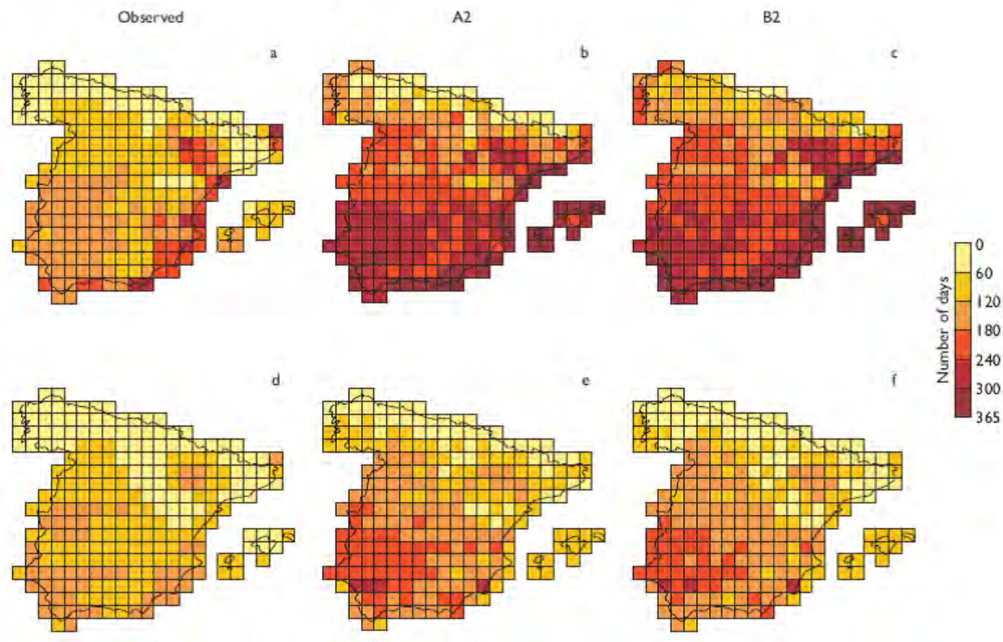


Figure 9.4. Observed (a, d) and modelled (b, c, e, f) values for the Period of Alert (a, b, c) (number of days between the first and last day during the year that FWI≥15 continuously for a week) and Period of Risk (d, e, f)(number of effective days during the PA in which FWI≥15) during a 30 year period in Spain. Observed values are based on daily data of the MARSSTAT database from the Joint Research Centre of the EC at Ispra (IT), and the period 1975-2004. Modelled data are the median of the A2 and B2 SRES scenarios of 5 Regional Climate Models with daily data for the period 2071-2100, made available by the Spanish Institute of Meteorology (Madrid, Spain). Cell size is 50x50 km. From Moreno et al. (2010).

Climate change is likely to reduce nutrient turnover and nutrient availability, reduce soil moisture and, ultimately, reduce growth and primary productivity (see Alcamo et al. [2007] for a review of climate change impacts). However, this will not be evenly distributed and will change through time. For instance, if general productivity would decline by the end of the century, in many uplands, where productivity is more controlled by temperature than humidity, increase in temperature could increase productivity (Gracia et al., 2005), thus adding enhanced capacity of the system to recover, consequently resulting in increased fire hazard and sustain additional fires. Plant water stress is very likely to increase as well as plant (including trees) mortality (Gracia et al., 2005), thus potentially increasing fuel hazardousness in many areas. Recurrent droughts, particularly in places where until now they were not frequent, may add to this (Peñuelas et al., 2010). Large (more than 40%) plant species losses are projected to occur based on several scenarios (Thuiller et al., 2005), which mean a reduced potential for regeneration in the event of fire, although the exact threat is poorly known.

Increased temperatures and reduced precipitation will very likely cause increases in fire danger conditions in current areas and extend these to areas in which fires were previously not frequent or absent. The fire season will very likely be longer and more severe (Moriondo et al., 2006; Moreno et al., 2010) (Fig. 9.4). Increased dry spells and droughts, and higher temperatures, particularly maximum temperatures will very likely increase the frequency of extreme fire danger conditions and with it the probability of fire, particularly of large fires. The post-fire regeneration potential of many areas will very likely suffer from reduced precipitation and increased probability of drought. If, as it happened in the past, drought is concomitant with large and widespread fires, this means that the potential for recovering after fire of large extensions might be in peril, thus increasing the probability of vegetation change. This would be especially critical in the highly vulnerable semiarid ecosystems that are expected to increase their surface area in Southern Europe. Increased frequency of fires threatens the persistence of trees, and causes changes in abundance and composition of species (Espelta et al., 2008; Vilá et al., 2008). Increased drought may shift fire-prone areas to the North in Europe. However, along the transition between different vegetation types, huge amounts of decaying fuels may be exposed to increased meteorological fire danger conditions giving way to future periods of very high fire risk (Peñuelas et al., 2009).

The Challenge of Managing and Conserving Mediterranean Areas

In regions of the world that have not been so severely altered by man, the fire-vegetation paradigm can be characterized as follows: vegetation at a given place is the result of past fire regime; different places differ in their successional stage after fire, and these follow their course until a new fire starts the process again. In this case, the environment imposes constraints and variability should be attributable to this. Natural climate change and variability would be the factors that would modify the system response at the time scales at which they operate. However, in areas with such a long history of human occupation such as the Mediterranean, the vegetation at any given place is the result of the multiple interacting factors associated with different human activities. The differences among patches in a landscape are related to the environment but through the role of man. The origin and regime that characterizes any piece of vegetation is probably unknown and was unstable through the years, as much as its land-use history. Extant vegetation may be in transition after cessation of traditional use of the land. Difficult as it is to project future impacts of climate and other global changes on the vegetation of any system in the first type, much more difficult it is to do so in Mediterranean areas. Restoration has no easy models to use as a reference, and many ideas need to be revisited at the light of new paleo-ecological evidence. Given the threat of changes in fire regimes and other climate and global changes over the values at hand, not the least its distinct and rich biodiversity, the challenge of conserving these territories under the ongoing climate and land-use/land cover changes and other global changes is paramount

(Fischlin et al., 2007). In the short term, people must increase their preparedness for a most challenging increased fire risk in the area.

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10 Current Fire Regimes, Impacts and the Likely Changes – VII: Australian Fire Regimes under Climate Change: Impacts, Risks and Mitigation

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Abstract

Australia is the most fire prone of all continents. Climate change will affect fire regimes in Australia through the effects of changes to temperature, rainfall, humidity, wind – the fire weather components – and through the effects of increases in atmospheric CO_2, and changes in moisture, on vegetation, and therefore fuels. Examination of weather data from south-eastern Australia over the period 1973-2007 has indicated that fire danger (as measured by the annual sum of the Forest Fire Danger Index, ΣFFDI) rose by 10-40% at many sites from 2001-2007 relative to 1980-2000. Increases in ΣFFDI have also been detected in some other parts of Australia. Climate change projections are for warming and drying over much of Australia, and hence an increased risk of severe fire weather, especially in south-eastern Australia. Modelling suggests an increase of 5 to 65 per cent in the incidence of extreme fire danger days by 2020 in this region. Climate change will have complex effects on fuels. On one hand, elevated CO_2 may enhance vegetation production and thereby increase fuel loads. On the other hand, drought may decrease long-term vegetation production (thereby decreasing fuel loads) and may decrease fuel moisture (thereby increasing potential rates of spread). The outcomes of these process on fuels, and hence fire regimes, are highly uncertain, and require further research.

Keywords: Fire-prone landscapes, tropical savannas, temperate sclerophyllous forests, Forest Fire Danger Index, climate-change scenarios

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Introduction

Australia is the most fire prone of all continents (Bradstock et al., 2002; Russell-Smith et al., 2007). All of Australia's dominant landscapes – the temperate sclerophyllous forests, woodlands and shrublands of the south-west and eastern seaboards, the tropical savanna grassy forests and woodlands of the north, and the semi-arid and arid woodlands, shrublands and grasslands of the vast interior (Groves et al., 1994) – are subject to recurrent fire. Fires in the tropical savannas of the north account for the majority of annual area burnt. However, over the past decade, there have been major fires (>1×10^6 ha) in arid, central Australia and in the temperate forests of south-eastern Australia (Russell-Smith et al., 2007; Bradstock, 2008). On 7 February 2009, catastrophic fires, driven by unprecedented high temperatures and winds, burnt 430,000 ha in Victoria, destroyed over 2000 homes, and claimed 173 lives; this was Australia's worst natural disaster.[9]

Regional weather systems, and the dynamics of biomass growth (to produce combustible fuel) and fuel moisture (to produce fuel that is sufficiently dry to burn) are important drivers of biogeographic trends in Australian fire patterns (Russell-Smith et al., 2007; Williams et al., 2009). Thus, fire regimes vary considerably across the country. In the tropical savannas of the north, fire regimes are generally high frequency and relatively low intensity (e.g. 1 to 5 year recurrence intervals; <10,000 kW m^{-1}) as a consequence of the annual production and curing of grassy fuels (Williams et al., 2002). In contrast, in the eucalypt-dominated forests of the temperate south, fire regimes are relatively low frequency/high intensity (e.g. multi-decadal recurrence intervals; >10,000 kW m^{-1}) as a consequence of infrequent co-occurrence of severe fire weather and prolonged drought (Gill and Catling, 2002; Bradstock, 2008). Fires also occur in the arid zone at decadal frequencies, following years with higher-than-average rainfall and increased grassy biomass production (Allan and Southgate, 2002; Russell-Smith et al., 2007).

Climate change will affect individual fires through the effects of changes to temperature, rainfall, humidity, wind – the fire weather components – and through increases in fuel production in response to the impacts of elevated atmospheric CO_2 and changes in moisture on vegetation. Because individual fires may change in their characteristics, so too may fire regimes. There is general debate about the relative importance of these drivers (climate, weather, fuel, ignitions), and related influences of land management, in shaping fire regimes (Westerling et al., 2006; Marlon et al., 2008). Ecosystems are impacted by fire weather, as affected by climate change, to produce the bio-physical hazard that intersects with humans and their values. Thus, understanding the biogeography of Australian fire regimes, and how they respond to variation in the factors governing fire weather, fuel amount and connectivity, is important for understanding how climate change may affect fire patterns at landscape scales, and the impacts of such changes in regime on ecosystems, people and property.

9 http://www.royalcommission.vic.gov.au/;
http://www.wewillrebuild.vic.gov.au/media-centre/170-bushfire-authority-reports-on-progress-100-days-on-.html

This chapter reviews some of the complex interactions between climate change, fire regimes, and risk to ecosystems and to people and property in Australia, summarizing key findings of a recent Australian Commonwealth Department of Climate Change publication, 'Interactions between climate change, fire regimes and biodiversity in Australia: a preliminary assessment' (Williams et al., 2009). The study examined the potential impacts of climate change on fire weather and fuels, the potential to model climate change impacts on regional fire regimes using fire models, the implications of changed regimes for biodiversity conservation, potential fire management implications, and the extent to which management actions may mitigate the risk posed by altered fire regimes under global climate change scenarios.

Climate Change and Fire Weather

Examination of weather data from south-eastern Australia over the period 1973-2007 has indicated that fire-weather risk has increased, with more days of very high and extreme fire-weather (Lucas et al., 2007). Fire danger, as measured by the Forest Fire Danger Index (FFDI; Luke and McArthur, 1978), summed over the year (ΣFFDI; Lucas et al., 2007), rose by 10-40% at many sites from 2001-2007 relative to 1980-2000. Most stations showed a significant positive trend, with a few exceptions near the coast and at Canberra. Upward trends in ΣFFDI have also been detected in some other areas of Australia, for example Cairns (tropical north-east), Perth (temperate south-west), Kalgoorlie (arid south-west) and Alice Springs (arid centre). An example for Melbourne (temperate south-east) is given in Fig 10.1.

Climate change impacts on fire weather in south-eastern Australia were also assessed by Lucas et al. (2007). Modeling based on historical daily weather patterns from various sta-

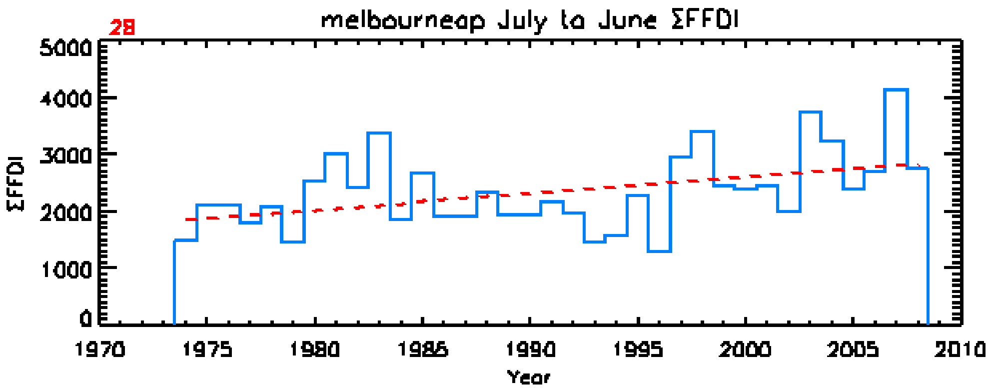

Figure 10.1. Trend in annual, cumulative forest fire danger index (ΣFFDI) at Melbourne airport, south-eastern Australia. Linear regression line is shown in red. The linear trend is 28 points per year, as indicated by the red number at the top left of the figure. Source: Lucas et al. (2007)

tions in south-eastern Australia, and the outputs from a range of IPCC climate change scenarios, suggests an increase in both the cumulative annual fire danger, and in the incidence of days of severe fire weather. By 2020, the increase in ΣFFDI is generally 0-4% for the low emissions scenarios and 0-10% for the high scenarios. By 2050, the increase is generally from 0-8% (low) and 10-30% (high). As a rule, changes expected under the high scenario are roughly twice as large as those in the low scenario. With respect to the incidence of days of severe fire weather (individual days when FFDI is >25), the modelling shows an increase of 5 to 65% in the incidence of extreme fire danger days by 2020. Thus, further increases in the frequency of extreme fire-weather events in this region are likely. Projections for capital cities in south-eastern Australia are presented in Tables 10.1 and 10.2.

Climate Change and Fuels

Climate change will have complex effects on fuels. On one hand, elevated CO_2 may enhance vegetation production (Wang, 2007), and thereby increase fuel loads. On the other hand, declines in annual moisture availability (already occurring in southern Australia, and projected to decline further; CSIRO and Bureau of Meteorology, 2007) may decrease long-term vegetation production, and hence fuel loads, because the productivity of terrestrial ecosystems is strongly positively correlated with gross measures of climate including annual rainfall (Begon et al., 2006). On the other hand, drought may decrease the moisture of fuel that is present, thereby increasing potential rates of spread of fire.

Potential impacts of climate change on fuels can be assessed by using space-for-time analyses along environmental gradients. Assuming that fuel accumulation rates (as determined by the balance between rates of litter fall and decomposition) will relate to future rainfall in the same way that they do today, then under a scenario of declining rainfall, fuel loads are likely to decline in the long-term. Table 10.3 illustrates this for a 20% decline in rainfall for jarrah (*Eucalyptus marginata*) forests in south-west Western Australia, where the relationship between forest production and annual rainfall is well-known (e.g. Sneeuwjagt and Peet, 1985). Further cases are explored in Williams et al. (2009). In each case, the rate of fuel production declined and the time needed for fuel to accumulate to critical levels in relation to fire suppression increased. Similar analyses can be undertaken for other biomes where rainfall-productivity relationships are known. However, caution is required in such interpretations given the possible offsetting effects of higher water use efficiency of vegetation under higher CO_2, and interactions with other limiting factors, such as nutrient availability.

Modeling Climate Change Impacts on Fire Regimes

With increased incidence of severe fire weather days as a consequence of climate change, we may generally expect a higher frequency of fire if the other conditions for fire (i.e. sufficient fuel loads and ignition) are met. Analyses were undertaken of the impact of a moderate (2°C) increase in mean annual temperature on the fire regimes of the Australian Capital Ter-

Table 10.1. Projected changes to forest fire danger index (FFDI) for capital cities in south-eastern Australia. Annual (July to June) average cumulative FFDI (ΣFFDI) for 'present' conditions (based on 1973–2006 data), and for projected changes (% change) under the 2020 and 2050 climate change scenarios, relative to 1990. The outputs are for two climate change models: CCAM (Mark 2) – results are denoted 'mk2' – and CCAM (Mark 3) – results are denoted 'mk3'. Source: Lucas et al. (2007).

Site	Present ΣFFDI	% change							
		2020 low mk2	2020 high mk2	2020 low mk3	2020 high mk3	2050 low mk2	2050 high mk2	2050 low mk3	2050 high mk3
Adelaide	2708	2	5	3	8	3	16	5	25
Brisbane airport	1990	1	5	0	4	3	19	2	16
Canberra	2493	3	9	3	11	6	30	7	37
Hobart	1314	-1	-1	0	0	-1	-1	0	3
Melbourne airport	2306	2	7	3	9	4	22	6	30
Sydney airport	1897	1	4	3	10	2	11	6	31

Table 10.2. Projected changes to number of days with FFDI of at least 25. Average number of days per year with a fire danger rating of 'very high' or 'extreme' (FFDI ≥ 25) and the percentage change (%) from the current value under low and high CO_2 emissions scenarios. Values for present ('now') are for 1973–2007. Climate change models CCAM (Mark 2): 'mk2' and CCAM (Mark 3) 'mk3'. Source: Lucas et al. (2007).

Site	Now	2020				2050			
		Low mk2	Low mk3	High mk2	High mk3	Low mk2	Low mk3	High mk2	High mk3
Adelaide	18.3	19.2	19.8	20.8	22.3	19.9	20.8	26.1	30.2
%	–	5	8	13	22	9	14	43	65
Brisbane airport	5.2	5.4	5.3	5.9	5.8	5.7	5.6	8.5	7.5
%	–	4	2	14	12	9	7	63	45
Canberra	16.8	18.3	18.9	21.5	22.8	20.0	20.6	29.9	33.4
%	–	9	13	28	36	19	23	78	98
Hobart	2.0	2.0	2.0	2.0	2.1	2.0	2.1	2.0	2.2
%	–	-3	-3	-2	5	-2	2	0	8
Melbourne airport	14.8	15.7	15.9	17.0	17.6	16.2	16.5	21.2	23.6
%	–	6	7	15	19	9	12	43	59
Sydney airport	7.6	7.8	8.1	8.3	9.4	8.0	8.7	9.8	14.2
%	–	2	6	9	23	4	14	28	87

ritory (ACT), using the FIRESCAPE landscape fire model (Cary, 2002; Cary et al., 2009). These analyses (Cary, 2002) showed that under this warming scenario, average fire intensity increased by 25%, potential area burnt increased, and the simulated interval between fires decreased significantly (from ca. 40 years to 20 years).

Table 10.3. Current and potential fuel load (t ha^{-1}) in relation to time since last fire in jarrah (*Eucalyptus marginata*) forest of south-western Australia, along a gradient of declining tree cover. The gradient is from wet to dry jarrah forests and woodlands (canopy cover from 80%, through 50% to 20%). Columns with values in *italics* are estimated fuel loads, assuming a 20% reduction in annual rainfall in the vegetation type in the adjacent column and a linear relationship between rainfall and forest canopy-type productivity. Cell values in **bold** show accumulation of critical fuel loads in relation to fire suppression for jarrah forests (9-10 t ha^{-1}) under present and projected -20% rainfall conditions. The time taken to reach critical fuel levels (column 1) varies amongst canopy and rainfall levels. Note that once dry, open jarrah forest (20% canopy cover) is reached, fuel loads under the climate change assumptions used here are not projected to exceed 10 t ha^{-1} within 25 years of previous fire. (Data interpreted from Sneeuwjagt and Peet [1985]).

Age yr	80% canopy t ha^{-1}	-20% rainfall t ha^{-1}	50% canopy t ha^{-1}	-20% rainfall t ha^{-1}	20% canopy t ha^{-1}	-20% rainfall t ha^{-1}
1	3.5	*2*	2.4	*1*	1	1
2	5	*3.5*	4	*1.6*	1.6	1.6
3	7.2	*5*	5.2	*2.5*	2.5	2.3
4	8.5	*6*	6.3	*3.4*	3.4	2.8
5	**9.8**	*7*	7.5	*4.2*	4.2	3.3
6	10.8	*8*	8.5	*5*	5	3.7
7	11.8	*8*	**9.5**	*5.8*	5.8	4
8	12.8	***9***	10.3	*6.5*	6.5	4.3
10	14.4	*10*	11.5	7.7	7.7	4.8
12	15.5	*11*	12.7	**8.8**	8.8	5.4
15	17.5	*12*	14.2	*10.5*	**10.5**	6
20	20.2	*13*	16.5	*12.7*	12.7	7
25	22.5	*15*	18.5	*15*	14.8	7.7

Climate Change Impacts on Fire Regimes in Different Biomes

Fire regimes across Australia currently differ because of variation between regions and biomes in the rate of vegetation (and hence fuel) production, the rate at which fuels dry out, the occurrence of suitable fire weather for the spread of fire across the landscape, and the frequency of ignition. In tropical savannas, climate change is unlikely to have major effects on area burned and fire frequency. This is because the primary climatic and fuel drivers of fire (biomass, low moisture, spread capacity), as determined by the annual wet-dry climate, are non-limiting on an annual basis. Similarly, in arid regions, drought and fire weather are essentially non-limiting on an annual basis, and landscape scale fires will continue to be limited to periods following above-average rainfall, even under climate change scenarios. However in southern sclerophyll (mostly eucalypt) dominated vegetation, where both overstorey and understorey are dominated by woody plants, the primary effect of climate change on fire regimes will stem from the projected increase in the frequency of occurrence of days of extreme fire weather, which has the potential to increase both fire intensity and area burnt, and to shorten the intervals between fires.

Future fire regimes will also be affected by other agents of change, such as invasions of exotic species. Across the savannas, for example, land use change (intensification of grazing; spread of exotic grasses) may exert a stronger influence on future fire regimes than climate change.

Climate Change, Fire Regimes and Biodiversity

The potential effects on biodiversity of changes to fire regimes induced by climate change were examined in four regional case studies, from different biomes in southern and northern Australia (Williams et al., 2009). Shorter intervals between fires pose an elevated risk to some biodiversity values in all case studies, especially in temperate biomes dominated by sclerophyllous vegetation. Some elements of biodiversity will be sensitive to potential changes to fire intensity as a result of climate change. Stronger or more frequent drought may reduce plant growth rates and levels of seed production, and increase time to reproductive maturity and also increase rates of inter- (and post-) fire plant death. In combination with (on average) less favorable post-fire weather conditions, rates of post-fire regeneration are also likely to be adversely affected. Thus, there may be increased risks to regeneration of both interval- and intensity-sensitive plant populations as a consequence of changed climate and changed fire regimes.

Managing Fire Regimes and Risk in Fire-Prone Landscapes Under Climate Change Scenarios

Management of fire at landscape scales is likely to become more complex as a consequence of climate change because of the uncertainty associated with the interactions between biophysical and socio-economic factors that drive fire regimes. However, there are no prescriptive, generic 'solutions' to the problem of managing risk to multiple values and assets posed by changes to climate and fire regimes.

Prescribed burning is an important component of landscape fire management across land tenures and biomes in Australia. It can have major effects (positive and negative) on all landscape values. There have been recent calls in southern Australia for substantial increases in the use of prescribed burning (e.g. by 2 to 3 times) to reduce the risk posed by more frequent and/or intense unplanned fires. Modeling for the temperate, sclerophyll-dominated ecosystems of the Sydney region, however, suggests that, to counteract the effects of a high-emissions climate change scenario on area burnt by unplanned fire, very large (>5-fold) increases in prescribed burning would be needed (Bradstock et al., 2008). Such an increase may not necessarily be a general threat to biodiversity values in such landscapes, despite the relatively high abundance of interval-sensitive species. However, it may not be feasible based on cost and resources, and its potential effects on other landscape values. The relative benefits and costs of prescribed burning, and its effectiveness in achieving multiple land management and wider societal goals in different land tenures requires much more research. Potential changes to fire regimes as a consequence of climate change provide an excellent opportunity to further this research internationally.

The human side of the risk equation in Australia is changing as fire-prone rural settlements and activities are being joined by rapidly expanding urban-rural interfaces around the nation's major cities. People are moving into rural environments for a variety of reasons, including lifestyle change and affordable housing. This expansion of the rural interface is occurring as the risk of very severe wildfires increases. At the same time drought, and a rural sector exposed to global market forces, have reduced the resilience of many rural people, with the potential result that wildfire preparedness is reduced and the risk of severe fire impact is increased (Whittaker, 2009).

Managing this risk is complex. In Australia emphasis has been on fire detection and suppression, fuel management, and a strong focus on community safety. While each state and territory in Australia is responsible for implementation, there has been a national approach to community safety since 2005 as a result of work by the Australian peak fire agency association (Australasian Fire and Emergency Services Authorities Council (AFAC). This is based on historical evidence that properly prepared and defended houses can survive wildfires (Handmer and Tibbits, 2005). It is based on three streams of evidence concerning house performance during fires, the interactions between landscape, houses and people during fires, and the dangers of late evacuations (Handmer and Haynes, 2008). Under biophysical and socio-economic change scenarios, the challenge in the coming years and decades will be to determine which approaches provide the best results in terms of safety on the urban interface.

Fuel management, house design and location, and urban planning are all necessary, and some limited planning measures are in place. However, planning has rarely been used for hazard management in Australia as its priority is economic development. It may be appropriate to reassess this and to make planning part of fire risk management. Communicating the nature of fire danger to communities, especially as it changes under scenarios of increased fire risk, and the relative benefits and costs of risk mitigation strategies, is a pressing, national need.

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11 Current Fire Regimes, Impacts and the Likely Changes – VIII: Temperate-Mediterranean North America

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Abstract

Although climate change is likely to alter future fire regimes in many temperate-Mediterranean ecosystems of North America, it is not clear how much change to expect. Fire regimes are driven by different variables in different locations and in ecosystems with different fuel structures. More area may burn in western forests with warmer springs and earlier snowmelt, while larger shrubland fires are associated with drier springs and longer droughts. Modeling future wildfire scenarios is instructive, however models are not yet as ecologically meaningful as we need them to be. One of the limitations of these models is that they often do not adequately consider the impacts of changes in fire frequency on fuel structure and subsequent fire intensity. For example, southwestern California historically has experienced a greatly increased fire frequency due to human ignitions and this has had the net effect of type converting shrublands to grasslands with the resulting decrease in potential fire intensity. Fire is often viewed in a negative light, despite being an integral ecosystem process in many temperate-Mediterranean ecosystems of North America. However, wildfire and carbon fluxes in naturally fire-prone regions may be roughly in net steady state over longer timescales, as amounts of carbon fixed approximately equal the amounts released in fires, with the exception of a small percentage sequestered in each fire as black carbon. Well-intentioned, emissions reductions efforts involving wildfire are thus somewhat incomplete and disconnected with ecosystem management goals that affect many public goods and ecosystem services. While there have been some novel ideas about how to manage western forests in the face of climate change, a different approach may be needed for shrubland-dominated wildland-urban interface areas. Adaptation to future climates will require changes in how and where we live, as well as ways to accommodate fire-related effects on key resources and amenities.

Keywords: Natural fire regimes, fire-climate-vegetation interactions, future wildfire scenarios, urban sprawl, human perturbations

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Natural Fire Regimes

Major challenges to addressing fire-related issues stem from an over-simplified understanding of fire's natural role in most terrestrial ecosystems (Bowman et al., 2009). This misconception is important for temperate-Mediterranean (T-M) North America, despite being one of the most intensively studied fire-prone regions of the world. Our focus in this chapter is on recent and projected trends in T-M forest and shrubland ecosystems in the western portion of North America (Fig. 11.1). A particular emphasis is placed on areas where humans may be most vulnerable to climate change effects on fire regimes, especially in the more densely populated western U.S. coastal regions (Fig. 11.2).

Management of fire-prone ecosystems requires that the somewhat complex idea of a fire regime – the range of frequencies, sizes, intensities, and timing of wildfires – be considered with respect to the species or vegetation type in question. Unfortunately, instead of a science-based recognition of different fire regimes operating in different ecosystems (Gutsell et al., 2001; Moritz and Stephens, 2008, Keeley et al., 2009), a one-size-fits-all conception of wildfire and how humans have altered this natural disturbance is quite common. Even so, there has been significant progress at mapping and classifying natural fire regimes for ecosystem management in the U.S. (e.g., Fig. 11.3). Although one can argue about the number of classes and which fire regime parameters are most important in defining classes, such maps can provide broad guidance on how to restore natural fire regimes (e.g., reducing or increasing fire frequencies) and which vegetation types might be sensitive to fire (e.g., deserts).

Anthropogenic Alterations to Fire Regimes

Despite the amount of attention that modern fire suppression effects have received, the full spectrum of human influences on natural fire regimes must be evaluated. A framework for understanding how dominant variables interact is shown in Figure 11.4 (Krawchuk et al., 2009; Parisien and Moritz, 2009), highlighting the constraints of 1) vegetation biomass and related fuel characteristics, 2) warm, dry periods, and 3) ignition timing and location. Suppression of fires has altered the vegetation composition in many T-M forests, leading to fuel accumulation and higher fire severities in recent decades (e.g., Parsons and DeBenedetti, 1979; Agee, 1993; Allen et al., 2002); however, this is most relevant and ecologically damaging in those ecosystems where predictable, frequent, low-severity fires were prehistorically common (Keeley et al., 2009). In contrast, many higher elevation conifer ecosystems of the Rocky Mountains naturally experience long-interval high-severity fires (e.g., Veblen et al., 2000; Ehle and Baker, 2003; Turner et al., 2003), regardless of modern fire suppression effects. Similarly, there is evidence that pre-suppression fires in relatively moist forests in the western Klamath Mountains of northern California (Odion et al., 2004) and the eastern Cascade Mountains in Washington (Hessburg et al., 2007) were of variable severities and often stand-replacing.

Shrubland-dominated ecosystems of T-M North America, especially the vast expanses found in southwestern California, are another example where modern fire suppression has

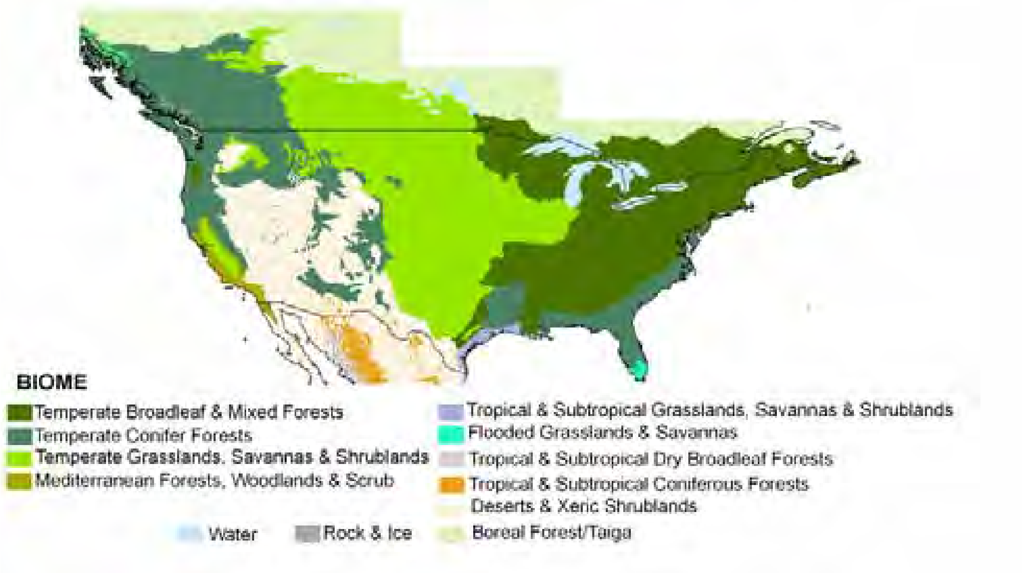

Figure 11.1. Map of terrestrial biomes (Olson et al., 2001), highlighting temperate-Mediterranean (T-M) ecosystems of North America in solid colors. Fire-prone T-M ecosystems dominate much of the region.

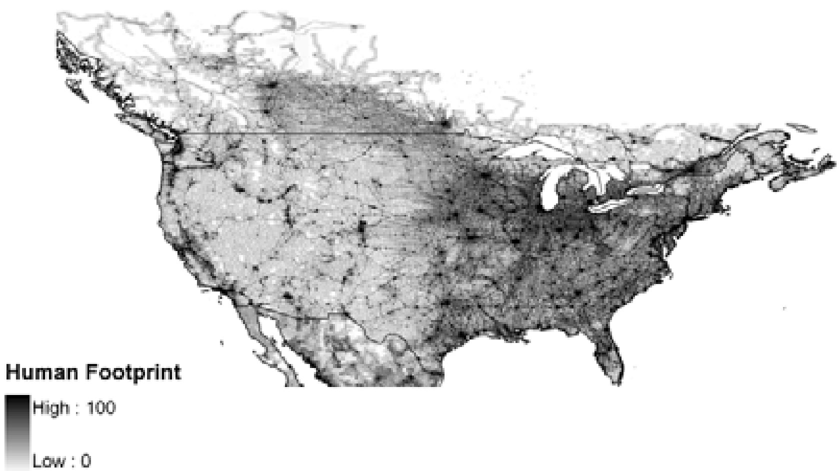

Figure 11.2. A measure of "human footprint" that includes road density, land cover conversion, and urbanization demonstrates that in the west, high levels of human development in T-M ecosystems occur along the coastal regions (Sanderson et al., 2002).

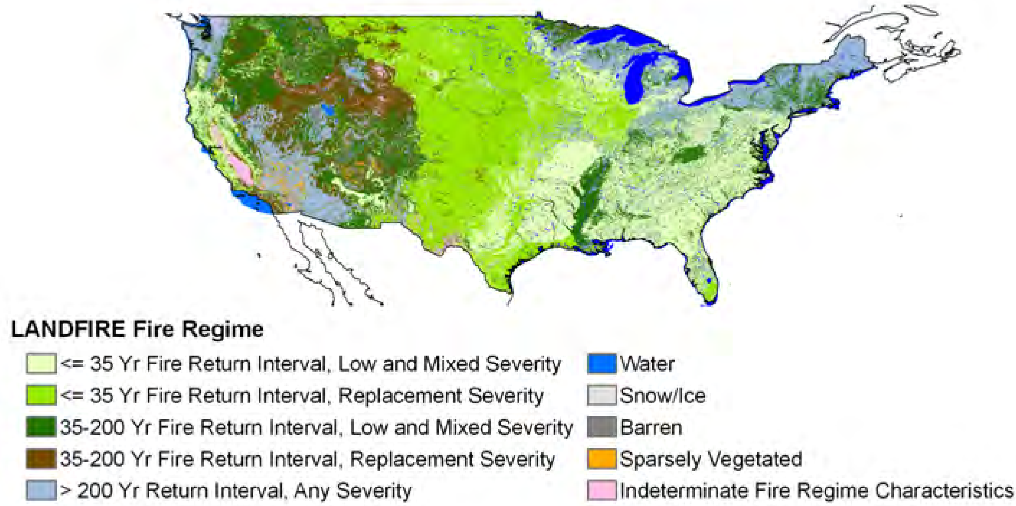

Figure 11.3. Fire regime type classes. Based on assumptions related to potential natural vegetation and associated fire regimes, the U.S. LANDFIRE program has created maps of what natural fire regimes should be in different regions (Schmidt et al., 2002). These data illustrate the LANDFIRE 2009 National Product. Areas included in the >200 Yr return interval include temperate conifer forests, and temperate broadleaf mixed forests as well as deserts & xeric shrublands, each of which have very different fire behavior.

Figure 11.4. For fire to be a recurring natural process, there must be consumable resources periodically available to burn (i.e., fuel amount and spatial configuration), a window in time during which atmospheric conditions support combustion (i.e., fire season of some length and severity), and a coincident ignition. The variation and relative importance among these three factors produce different fire regimes.

not caused marked changes in the natural fire regime. In particular, large and high-intensity shrubland fires have not shown an increasing trend since fire suppression became effective (Moritz, 1997; Keeley et al., 1999). Because extreme fire weather episodes (i.e., hot, dry winds) can drive fire through all age classes in these shrubland ecosystems, human alterations to the ages and spatial patterns of fuels are not the cause of recent large fires (Moritz et al., 2004). Unlike many forested ecosystems, relatively frequent fires can be ecologically devastating to native species of shrubs, leading to type conversion and invasions of non-native grassland species (Zedler et al., 1983; Keeley, 2006). One of the most ecologically harmful human influences in many shrubland ecosystems is therefore an abundance of anthropogenic ignitions (Syphard et al., 2007). This is because increasing numbers of ignitions in both space and time greatly heightens the probability of a fire during an episode of extreme fire weather, allowing repeat burning through juvenile stands of shrubs and local extirpation of native species (Moritz et al., 2010). Future urban sprawl extending into wildland landscapes is thus likely to generate more type conversion, along with increased fire activity but at lower fire intensities.

In summary, past fire suppression effects are certainly important in many T-M ecosystems of North America, but humans have also changed ignition patterns, altered amounts and patterns of fuels through grazing and land use decisions (e.g., timber harvest and habitat fragmentation), and introduced invasive species. Without considering anthropogenic climate change, humans have therefore directly altered in some way two of the three dominant constraints (Fig. 11.4) in most fire-prone ecosystems. Understanding the relative importance of various factors and how climate change is further altering fire regime controls is crucial for maintenance and/or restoration of natural fire regimes.

Climate-related Trends and Likely Future Changes

Increasing fire activity and higher fire severities have been reported for some western forests in recent decades (Westerling et al., 2006; Miller et al., 2009), and this is at least partially attributed to climate change effects on the fire season (Fig. 11.4). In contrast, wildfire in some shrubland ecosystems does not appear to show a climate change signal (Dennison et al., 2008). Although climate change is likely to alter future fire regimes in many T-M ecosystems of North America, it is not clear how much change to expect. This is because fire regimes are driven by different variables in different locations. More area may burn in western forests with warmer springs and earlier snowmelt (Westerling et al., 2006), while larger shrubland fires are associated with drier springs (Dennison et al., 2009). This highlights the importance of understanding interactions of temperature (T) and precipitation (P), as well as their timing, in analyzing wildfire trends due to the length or severity of fire-conducive atmospheric conditions (Fig. 11.4). An exception to this complexity may be prolonged droughts, which are likely to promote fire-conducive environmental conditions in any ecosystem with enough fuels to carry fire.

The problem of anticipating future fire regimes is compounded by the widely held view that a warmer planet will necessarily mean increased fire activity and more intense wildfires. This will not happen uniformly and everywhere, however, since fire is controlled by multiple interacting variables at different scales. One approach to simulating future scenarios is through dynamic vegetation models, which attempt to mechanistically simulate interactions between climate, vegetation, and fire (e.g., Thonicke et al., 2001; Bond et al., 2005). For example, Lenihan et al. (2008) used a dynamic vegetation model and found increases in area burned across California for all future scenarios examined, but variable projections of biomass consumed by fire. Alternatively, the framework of interacting controls in Figure 11.4 lends itself to statistical characterization and modeling of relationships. Consistent with this framework, future climate change projections for California have found that fire may increase in some wetter ecosystems not currently experiencing warm and dry conditions conducive to combustion, while some currently fuel-limited ecosystems may experience even less fire in a warmer and drier future (Westerling and Bryant, 2008). Although future increases and decreases in fire activity will depend on what currently constrains fire activity (i.e., resources to burn, atmospheric conditions, or ignitions), recent models using several global climate projections show relatively consistent increases in fire across most of the northern hemisphere outside of the tropics (Moritz et al., 2012).

Although modeling future wildfire scenarios is instructive, models are not yet as ecologically meaningful as we need them to be, nor do many adequately consider impacts of changes in fire frequency on fuel structure and subsequent fire intensity. It has yet to be seen whether dynamic vegetation models or statistical approaches are best suited to realistic simulations of fire-climate-vegetation interactions. Statistical models are typically limited to estimates of fire activity (e.g., a presence-absence gradient) or area burned in large events. Dynamic vegetation models have many parameters that allow for detailed calibration and fitting to current spatial patterns; however, the fire modules vary in their sophistication. More advanced approaches should eventually capture relationships between climate changes and shifts in fire regimes, so that future ranges of frequencies, sizes, intensities, and timing of wildfires can be estimated. Because fire plays a major role in the persistence and establishment of so many terrestrial plant species, the rates of future change in fire regimes may turn out to be especially important. Where prehistoric rates of climate change have been relatively slow, it appears that vegetation shifts can entrain fire regimes, leading to less alteration in fire activity than one would expect based on climate changes alone (e.g., Higuera et al., 2009). In contrast, many have highlighted the potential for the current rapid rates of climate change to result in much faster changes in future fire regimes (e.g., Overpeck et al., 1990; Turner and Romme, 1994; Flannigan et al., 2000; Krawchuk et al., 2009), meaning that fire may be driving future vegetation shifts instead of vice versa. Our understanding and predictions will be greatly improved when we are able to quantify and model the complex feedbacks and possible threshold transitions inherent in fire regimes and their controls (Fig. 11.4), including how humans influence these controls.

Policy, Management, and Human Vulnerabilities

Wildfires quickly liberate carbon that is temporarily sequestered in plant tissues, instead of more slowly releasing it through decomposition of dead biomass as in fire-free ecosystems. Fire is therefore often viewed in a negative light, despite being an integral ecosystem process in many T-M ecosystems of North America. This is even true for fire-prone California, which prides itself on progressive climate change policy (Moritz and Stephens, 2008). Wildfire and carbon fluxes in naturally fire-prone regions may be roughly in net steady state over longer timescales, as amounts of carbon fixed approximately equal the amounts released in fires, with the exception of a small percentage sequestered in each fire as black carbon (e.g., Schulze et al., 2000). What is missing from most greenhouse gas mitigation discussions is an awareness of how far fire regimes are from natural ranges of variation (e.g., Allen et al., 2002; Keeley et al., 2009), how likely ecological threshold transitions are (e.g., Keeley, 2006; Krawchuk et al., 2009), and what has yet to be quantified in accounting protocols (e.g., soil carbon). The benefits of prescribed burning to restore fire in many forests and avoid uncharacteristic crown fires are even routinely ignored. While well-intentioned, emissions reductions efforts involving wildfire are thus somewhat incomplete and disconnected with ecosystem management goals that affect many public goods and ecosystem services.

It is not yet clear how increasing ecosystem vulnerabilities, due to both global climate change and ongoing local human perturbations, will affect human occupation of the many fire-prone landscapes of T-M North America. While there are some novel ideas about how to manage western forests in the face of climate change (Millar et al., 2007), a different approach may be needed for shrubland-dominated wildland-urban interface (WUI) areas. Many of these shrubland ecosystems are exposed to extreme fire weather events, during which most fire management activities are relatively ineffective (Moritz et al., 2004). If climate change results in more frequent or widespread extreme fire weather events, regardless of the vegetation type in question, humans will face an increasing need to adapt to such conditions in order to coexist with wildfire. The safest strategy is to avoid building in vulnerable environments in the first place, but there are many existing communities where adapting will be complex and involve a variety of tradeoffs (Moritz and Stephens, 2008). Adaptation to future climates will require changes in how and where we live, as well as ways to accommodate fire-related effects on key resources and amenities. Wildfire affects human lives and structures, air and water quality, biodiversity and habitat values, and many more ecosystem services. An integrated and scientific social-ecological framework (e.g., Folke, 2006; Lavorel et al., 2007) is therefore needed to deal with climate change and its likely impacts on fire-prone landscapes of T-M North America.

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12 Current Fire Regimes, Impacts and the Likely Changes – IX: Subsahara Africa

Winston S.W. Trollope[1] and Cornelius de Ronde[2]

Abstract

Fire is recognized as a natural ecological factor of the environment in Africa that has been occurring since evolutionary time scales in the savanna and grassland areas of the continent. The continent of Africa is highly prone to lightning storms and has a fire climate comprising dry and wet periods causing the regular occurrence of fire on the continent. It also has the most extensive area of tropical savanna in the world which is characterised by abundant grass fuel that becomes extremely inflammable during the dry season. The use of fire in the management of vegetation for both domestic livestock systems and in wildlife management is widely recognized. In the 1970s a research program was initiated in South Africa and later extended to East Africa to characterize the behavior of fires burning in savanna and grassland vegetation and determine the effect of type and intensity of fire on the vegetation. This research program successfully developed a greater understanding into the effects of type and intensity of fire in African grasslands and savannas. This in turn has led to the development of more effective and practical guidelines for the fire regimes to be used in controlled burning for domestic livestock and wildlife management systems in the grassland and savanna areas of Africa.

The fynbos vegetation only covers a small portion of the Cape regions of South Africa and have a unique requirement of fire to maintain biodiversity. While prescribed burning has been applied during earlier decades, the vegetation is now generally allowed to grow too old, and is subsequently exposed to a growing number of extremely damaging high-intensity wildfires, which now not only threatens its biodiversity, but also surrounding agricultural lands and industrial timber plantations. Re-introduction of prescribed burning in fynbos is now seriously reconsidered, and in places re-applied.

Industrial plantations have been established in Southern Africa within (mainly) montane and savanna grassland biomes since the late 1800s. Exclusion of fire from these plantations has resulted in an exponential increase in plantations lost by wildfires, and to counteract this, prescribed burning has now been introduced inside even-aged pine stands in these regions at a significant scale.

Keywords: Grassland fire, savanna fire, fynbos fire, decreaser species, increaser species

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Part I:
Functional Role of Fire in Subsaharan Savanna and Grassland Ecosystems

Winston S.W. Trollope

Introduction

Fire is regarded as a natural ecological factor of the environment in Africa that has been occurring since time immemorial. The capacity of Africa to support fire stems from the fact that it is highly prone to lightning storms and has an ideal fire climate comprising dry and wet periods It also has the most extensive area of tropical savanna in the world which is characterized by a grassy understorey that becomes extremely inflammable during the dry season (Komarek, 1971). The use of fire in the management of vegetation, for both domestic livestock systems and in wildlife management, is widely recognized.

Research on the effects of fire has been conducted throughout the grassland and savanna areas of Africa since the early period of the twentieth century (West, 1965) and focused on the effects of season and frequency of burning on the forage production potential of the grass sward and the ratio of bush-to-grass in African savannas. However, in 1971 a conference was convened in the United States of America by the Tall Timbers Research Station at Tallahassee, Florida on the theme "Fire in Africa". This conference was attended by fire ecologists from throughout Africa and the major benefit that accrued from attending this meeting was the realization that in Africa the study of fire behavior and its effects on the ecosystem, as described by type and intensity of fire, had been largely ignored in all the fire research that had been conducted up until that time. This was a turning point in research on the fire ecology of African grasslands and savannas and led to the further recognition that the effects of fire must include the effects of all the components of the fire regime on the ecosystem viz., the *type* and *intensity* of fire and the *season* and *frequency* of burning. As a result a research program was initiated in South Africa in 1972 (Trollope, 1978; Trollope and Potgieter, 1985), which was later extended to East Africa in 1992 (Trollope and Trollope, 1999). The focus of this program was to characterize the behavior of fires burning in savanna and grassland vegetation and to determine the effect of type and intensity of fire on the vegetation. This research program has successfully developed a greater understanding into the effects of type and intensity of fire in African grasslands and savannas (Trollope, 1984; Trollope and Tainton, 1986; Trollope and Trollope, 1999; de Ronde et al., 2004). This in turn has led to the development of more effective and practical guidelines for the fire regimes to be used in controlled burning for domestic livestock and wildlife management systems in the grassland and savanna areas.

Ignition Sources of Fires

Africa is where fire and humanity first interacted and the factor that makes fire on this continent distinctive from other regions is the antiquity of anthropogenic fire (Pyne, 1995) The earliest evidence of the use of fire by man is 1.5 million years B.P. and since then natural

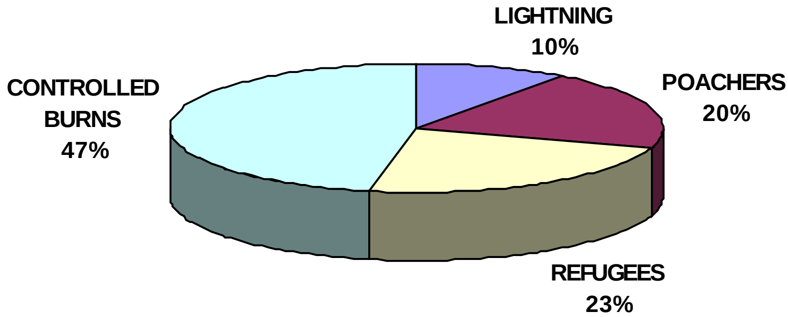

Figure 12.1: The percentage area burnt in the Kruger National Park in South Africa by fires ignited as controlled burns and by refugees, poachers and lightning during the period 1985 to 1992 (Trollope, 1993).

fire regimes have been successively altered by humans in response to increases in the human population. For example the majority of the tropical savannas of the world have been shaped and maintained by anthropogenic fires. Archibald et al. (2012) suggest that African savannas have been shaped increasingly since ~4000 years B.P. as a consequence of land cultivation, notably cattle grazing and fire use, which impacted fuel loads, landscape fragmentation and thus fire regimes. The stage has now been reached that in most regions of the world humans have become more important than lightning as sources of ignition (Goldammer and Crutzen, 1993) and modern fire regimes that are not affected by anthropogenic fires are extremely rare (Bond and van Wilgen, 1996). The dominant role of anthropogenic fires in contemporary in Africa is illustrated by the area of savanna that was burnt by different ignition sources in the Kruger National Park in South Africa during the period 1985 to 1992 (see Fig. 12.1).

Fire Effects in African Grasslands and Savannas

Besides human activities related to urban living and agricultural production, fire is the most widespread ecological disturbance in the world. Research has led to the conclusion that human beings have used fire for over a million years and in Africa fire has extended the grasslands and savannas at the expense of evergreen forests. This reinforces the fundamental conclusion that fire is a general and influential ecological phenomenon throughout the world (Bond and van Wilgen, 1996) and cannot be ignored when considering the management of rangeland ecosystems. It is therefore of primary importance to obtain a clear understanding of the effects of fire in African grasslands and savannas, in order to provide a sound ecological basis to the management of these types of vegetation for both domestic livestock and wildlife purposes. *Fire ecology* refers to the response of the biotic and abiotic components of the ecosystem to the fire regime i.e. type and intensity of fire and the season and frequency of burning (Trollope et al., 1990). Following the 11th Tall Timbers Fire Ecology Congress held in Tallahassee, Florida, in 1971 a research program was initiated in South Africa in 1972 to determine the effect of all the components of the fire regime on the vegetation i.e. effects of type and intensity of fire and season and frequency of burn. This program has gone a long way in describing the effects of the entire fire regime on the vegetation in the grassland and savanna areas of the African continent and the resultant information has provided a strong scientific basis for the use of fire as a management practice in range management programs. These effects of the different components of the fire regime, have been incorporated into the guidelines for the prescribed burning of rangelands and will be dealt with in the forthcoming section.

Interactions between fire and herbivory

The impact of herbivores on vegetation post-fire can significantly alter the botanical composition and structure of rangeland. However, the unfortunate reality is that very limited information is available on the effects of fire and domestic livestock and/ or wildlife in African grasslands and savannas. Nevertheless it is essential information that is necessary for the formulation of viable management practices pertinent to the ecological and economic sustainability of these ecosystems, that are used for both domestic livestock production and wildlife management. In general the sooner, more intensely and more frequently, the regrowth of the recovering burnt plants is grazed or browsed after a fire, the greater is the decrease in their rate of growth and vigor. This can lead to their eventual mortality if this form of defoliation is maintained for extended periods of time resulting in a significant decrease in plant density and cover which in turn can cause increased runoff and accelerated soil erosion. In contrast, the interaction of fire and browsing with goats has been very successfully used in southern African for controlling bush encroachment, resulting in a significant improvement in the condition of the rangelands. However, It must be borne in mind though, that when assessing the effects of the interaction of fire and herbivory in African grasslands, particularly humid grasslands, these plant communities are themselves products of a major interaction of fire and herbivory that occurred in the past, involving the conversion of wooded vegetation into grassland through the effects of fire alone or in the presence of animals. This is well illustrated by examples of the effects of excluding fire and herbivory in the extensive humid fire climax grasslands located in the higher lying moist eastern regions of South Africa (Tainton, 1999). Classical examples are of plots protected from fire and grazing established by Professor J.D. Scott in the 1930s in the Highland Sourveld (Acocks, 1988) at Estcourt in KwaZulu-Natal, South Africa and in 1950 on the Ukulinga Research Station of the University of KwaZulu-Natal, South Africa (Fynn et al., 2004) – see Figures 12.2 and 12.3.

Suffice it to say that the effects of fire and herbivory on the condition of African grasslands and savannas used for domestic livestock and wildlife, can be very significant, and it is essential to take this information into account when formulating range management programs for these types of vegetation.

Figures 12.2 and 12.3. Two examples of the effects of excluding fire and grazing from grassland for extended periods of time leading to the development and dominance of tree and shrub vegetation. The upper photo shows an exclosure plot established in the Highland Sourveld (Acocks, 1988) near Estcourt, KwaZulu-Natal, South Africa, in the 1930s and photographed in 1971. The lower photo shows an exclosure plot established in 1950 on the Ukulinga Research Station of the University of KwaZulu-Natal, South Africa and photographed in 2004.

Prescribed Burning in African Grasslands and Savannas

Experience gained through research on the effects and use of fire in southern and east African grasslands and savannas (van Wilgen et al., 1990), has led to the conclusion that grasses in general and trees and shrubs in general react similarly to the different components of the fire regime. Therefore common guidelines can be formulated for prescribed burning of these two types of vegetation. It is believed that this will best serve the use of fire as a range management practice in the grassland and savanna areas of sub-Saharan Africa. For the sake of clarity, guidelines for prescribed burning will be dealt with separately for the use of fire as a range management practice, in areas used for livestock husbandry and wildlife management, because the broad objectives of management tend to vary for these different forms of land use.

1) Use of Fire as a Range Management Practice for Domestic Livestock Production

Prescribed burning is an important and often essential range management practice in areas used for keeping livestock; whether for commercial or subsistence purposes. The most important factors to consider are the reasons for burning and the appropriate fire regime to be applied. The current view amongst range scientists and progressive livestock farmers on the permissible reasons for burning rangeland are that fire can be used to:

- remove moribund and/or unacceptable grass material;
- control and/or prevent the encroachment of undesirable plants (Trollope, 1989).

These are the basic reasons for burning grassland and savanna vegetation in Africa and are both applicable to areas used for commercial or subsistence livestock farming. Fire is used to alter the spatial use of rangelands, e.g. by setting small fires that result in concentration of grazing, or large fires resulting in dispersing grazing away from grazing hotspots of cattle (Fuhlendorf et al., 2008) and wildlife (Archibald et al., 2005; Waldram et al., 2008). It has been suggested that fire can also be used to control ticks which cause tick-borne diseases in livestock, but this reason is generally discounted, because ticks persist in areas which are frequently burnt. However, Stampa (1959), in a study of the Karroo Paralysis Tick in the Karroid *Merxmuellera* Mountain Veld in South Africa, has shown that this parasite can be successfully controlled by altering the micro-climate at soil level and thereby creating an unfavorable habitat for this organism resulting in its disappearance. Similar evidence has been obtained by Trollope and Trollope (2001) in the Ngorongoro Crater and Serengeti grasslands in Tanzania, where controlled burning by nomadic Masai pastoralists has resulted in a significantly lower incidence of ticks where this practice is applied.

Ecological Criteria for Prescribed Burning

The necessity for burning rangeland depends upon its ecological status and physical condition. Quantitative techniques have been developed to assess the condition of the grass sward in relation to prescribed burning. The first technique involves determining the condition of the grass sward in terms of its botanical composition, ecological status and basal cover and involves classifying the different grass species into different ecological categories according to their reaction to a grazing gradient i.e. from high to low grazing intensities as follows:

DECREASER SPECIES	Grass and herbaceous species which decrease when rangeland is under or over grazed;
INCREASER I SPECIES	Grass and herbaceous species which increase when rangeland is under grazed;
INCREASER II SPECIES	Grass and herbaceous species which increase when rangeland is over grazed.

The second technique involves estimating the grass fuel load using the Disc Pasture Meter developed by Bransby and Tainton (1977) and illustrated in Figure 12.4.

This instrument has been successfully calibrated for much of the grasslands and savannas in southern and east Africa and research has indicated that the calibration developed in the Kruger National Park in South Africa by Trollope and Potgieter (1986) can be used as a general calibration for estimating grass fuel loads for management purposes in these regions of Africa.

Figure 12.4. Disc Pasture Meter developed by Bransby & Tainton (1977) and used to estimate the grass fuel load for prescribed burning in African grasslands and savannas.

The criteria that can be used to objectively decide whether rangeland needs to be burnt or not are that prescribed burning should not be applied if the grass sward is in a pioneer condition dominated by Increaser II grass species caused by overgrazing. Burning is generally not recommended when rangeland is in this condition in order to enable it to develop to a more productive stage dominated by Decreaser grass species. Conversely, when the grass sward is in an under grazed condition, dominated by Increaser I species, it needs to be burnt to increase the better fire adapted and more productive Decreaser grass species and increase the overall palatability of the grass sward. Finally, controlled burning is necessary when the grass sward has become overgrown and moribund as a result of excessive self-shading. These conditions develop when the standing crop of grass is generally >4000 kg ha^{-1} and can be estimated with a Disc Pasture Meter. The criteria used for deciding whether to burn to control or prevent the encroachment of undesirable woody plants, involves the same ecological criteria describing the condition of the grass sward. However, the grass fuel loads required for prescribed burning will differ depending on the encroaching plant species frequently necessitating grass fuel loads >4000 kg ha^{-1} in order to generate high intensity fires.

Fire Regime

The fire regime to be used in prescribed burning refers to the type and intensity of fire and the season and frequency of burning.

a) Type of Fire: It is recommended that fires burning with the wind either as surface head fires in grassland or a combination of surface head fires and crown fires in tree and shrub vegetation be used in prescribed burning, because they cause least damage to the grass sward, but can cause maximum damage to woody vegetation if necessary (Trollope, 1999).

b) Fire intensity: When burning to remove moribund and/or unacceptable grass material, a cool fire of <1000 kJ $s^{-1}m^{-1}$ is recommended. This can be achieved by burning when the air temperature is <20°C and the relative humidity >50%. When burning to control undesirable plants like encroaching bush, an intense fire of >2000 kJ $s^{-1}m^{-1}$ is necessary. This can be achieved when the grass fuel load is >4000 kg ha^{-1}, the air temperature is >25°C and the relative humidity <30%. This will cause a significant topkill of stems and branches of bush species up to a height of 3 m. In all cases the wind speed should not exceed 20 km h^{-1} (Trollope, 1999).

c) Season of Burning: Research in southern Africa has clearly indicated that least damage is caused to the grass sward if prescribed burning is applied when the grass is dormant. Therefore it is recommended that when burning to remove moribund and/or unacceptable grass material burning should preferably be applied when the grass is dormant but under mild weather conditions in terms of temperature, relative humidity and wind during the dry season. Burning to control encroaching plants should be applied before the first rains, initiating the commencement of the growing season (i.e. when the grass is very dry and dormant) to ensure a high intensity fire (Trollope, 1999). "Early burning" at the beginning of the dry season, is practiced in places where low-intensity fires are desired to minimize damage to individual trees or forest patches and to ensure that the fire is controllable.

d) Frequency of Burning: When burning to remove moribund and/or unacceptable grass material the frequency of burning will depend upon the accumulation rate of excess grass litter (Trollope, 1999). Field experience indicates that this should not exceed 4000 kg ha^{-1} and therefore the frequency of burning should be based on the rate at which this phytomass of grass material accumulates. Generally in high rainfall areas (>700 mm p.a.) this will result in the frequency of burning being every 2-4 years. In lower rainfall areas the frequency will be much lower and in fact the threshold of a grass fuel load >4000 kg ha^{-1} will generally exclude fire in these regions particularly where the condition of the rangeland is degraded and excessive grass fuel loads never accumulate (Trollope, 1999).

When burning to control undesirable encroaching plants the frequency of burning will depend upon the growth characteristics of the individual encroaching plan species.

e) Post -Fire Range Management: It is recommended that when burning to remove moribund and/or unacceptable grass material, grazing should be applied as soon as possible after the burn, to take advantage of the highly nutritious regrowth of the grass plants (Zacharias, 1994; Kirkman, 2001). However this practice must be combined with a rotational resting system involving withdrawing a portion of the rangeland from grazing for an extended period of at least a growing season or longer (6-12 months) to maintain the vigour of the grass sward and enable seed production to occur, for plant recruitment. The "resting period" application should be allowed during the season prior to the intended prescribed burn.

2) Use of Fire as a Range Management Practice for Wildlife Management

Prescribed burning is recognized as an important management practice in wildlife management in African grassland and savanna ecosystems. There is general consensus that it is a natural factor of the environment that has been occurring since time immemorial and that it is often essential to apply it for the ecological well-being of both the biotic and abiotic components of these ecosystems (Bothma, 1996; Thomson, 1992; Trollope, 1990). However there is a wide diversity of views held on the most appropriate burning system to use in wildlife areas and these range from the so-called "natural " burning systems based entirely on lightning as the ignition source to actively applied burning systems based on the condition of the rangelands. Experience suggests that the latter approach is more ecologically acceptable and practical to apply in practice.

Range Condition Burning System

The range condition burning system was developed from a fire research program that was initiated in South Africa in the Eastern Cape Province in 1968 and later extended to the Kruger National Park in 1982 and to East Africa in 1992 (Trollope, 1971; Trollope and Potgieter, 1985; Trollope and Trollope, 1999). The system has (and is) being used for prescribed burning in both domestic livestock systems and for wildlife management. It is based on empirical results and its appropriateness for use in wildlife areas is that it provides a practical means of improving and maintaining the species and habitat diversity of natural grassland and savanna ecosystems (Trollope, 1971; Trollope et al., 1995). This is achieved by burning to remove moribund and/or unacceptable grass material, to create or maintain an optimum relationship between herbaceous and woody vegetation if necessary and to encourage wildlife to move to less preferred areas in order to minimize the over-utilization of preferred areas. The basic philosophy of the range condition burning system is that the use of fire to achieve specific management objectives must be based on the condition of the vegetation and its known reaction to the different components of the fire regime i.e. type and intensity of fire and season and frequency of burning. The same ecological criteria recommended for burning for livestock husbandry systems are used to apply a burning program that will achieve the overall management objectives of improving and maintaining species and habitat diversity in grassland and savanna ecosystems.

Fire Regime

The following fire regime is recommended when applying prescribed burns using the range condition burning system:

a) Type of Fire: It is recommended that fires burning with the wind either as surface head fires in grassland or a combination of surface head fires and crown fires in tree and shrub vegetation be used in prescribed burning because they cause least damage to the grass sward but can cause maximum damage to woody vegetation if necessary (Trollope, 1999).

b) Fire Intensity: Fire intensity is an important component of the fire regime that needs to be varied according to the reason for burning, using the same guidelines as recommended for managing rangelands for domestic livestock. In savannas where browsers are an important component of wildlife populations, high intensity fires are often necessary to cause a significant topkill of stems and branches of trees and shrubs up to a height of 3 m to make the vegetation more available for shorter browsing animal species. In all cases the wind speed should not exceed 20 km/h for safety reasons (Trollope, 1999).

As can be expected these detailed prescriptions, prescribed burning is better suited for the use of fire in smaller and more intensively managed conservation areas and game ranches. In these situations prescribed burns are applied and completed in a matter of hours and it is therefore possible to burn under specific atmospheric conditions. Conversely, in large conservation areas, it is more difficult to vary the intensity of fires relative to the reason for burning as well as the duration of the fires, as the latter can extend over significant periods of time. At best this can be achieved by varying the time of burning to different periods during the dormant season, relative to the moisture content of the grass fuel and selected suitable periods predicted by weather forecasts.

c) Season of Burning: In wildlife areas it is also recommended that prescribed burns be applied when the grass sward is dormant, in order to avoid any detrimental effects on the regrowth and basal cover of the sward. The burning window can extend over the entire dry season and the actual timing of fires can be varied according to the reasons for burning.

When burning to remove moribund grass material, prescribed burns can be applied at any time during the dormant season. When burning to reduce the density and size of trees and shrubs it is recommended that fires be applied when the grass fuel is at its lowest moisture content in order to ensure a high intensity fire.

d) Frequency of Burning: As is the case with managing grassland and savanna vegetation for domestic livestock, the frequency of burning required to remove moribund and/or unacceptable grass material will depend upon the accumulation rate of excess grass litter (Trollope, 1989), i.e. grass fuel load >4000 kg ha^{-1}. Therefore the frequency of burning will be variable and a function of the stocking rate of grazing animals and the amount of rainfall an area receives.

When burning to reduce the density and size of trees and shrubs in savanna areas, the frequency of burning cannot be prescribed precisely, because this will depend on the stocking rate of browsing animals and/or the rate of regrowth of the trees and shrubs. In moist savannas (rainfall >700 mm p.a.) generally the rainfall is adequate for the accumulation of adequate grass fuel loads to enable frequent and intense fires to occur every three to four years that will maintain encroaching woody species in the "fire trap" and prevent them from growing taller than approximately three meters. Conversely in arid savannas (rainfall <500 mm p.a.) the rainfall is generally too low and variable for the production and accumulation of adequate grass fuel loads to support regular fires to maintain encroaching woody species in the "fire trap".

In these arid savannas the role of fire in controlling woody species is to reduce and/or maintain the encroaching trees and shrubs at an available height and in a palatable condition for browsing ungulate species. Be cause the intense fires necessary to maintain the woody vegetation at an availalable height and condition for browsing animals only occur after above average rainfall seasons the frequency of burning is very low. Research results from the experimental burn plot trial in the Kruger National Park suggest a burning frequency in excess of burning every 10 years (Trollope et al., 2009)

e) Post-Fire Grazing Management: Grazing after burning in wildlife areas is difficult to control. In order to prevent overgrazing it is important to ensure that the burnt area exceeds the short term forage requirements of the grazing animals, that are attracted to the highly palatable and nutritious regrowth that develops after a burn i.e. burn relatively large areas at any one time (Trollope, 1992). Another strategy that has been successfully used in southern Africa, is to apply a series of patch burns at regular intervals throughout the duration of the burning window during the dormant season. This has the effect of attracting the grazing animals to the newly burnt areas after the different fires thereby spreading the impact of grazing over the entire burnt area and avoiding the detrimental effects of heavy continuous grazing after the burns (Brockett et al., 2001).

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Part II:
Functional Role of Fire in Fynbos and Industrial Timber Plantations

Cornelis de Ronde

1. Fynbos

Introduction

The *fynbos* vegetation kingdom of South Africa not only constitutes one of the most species-rich communities of the world, but is also the most prominent natural biome in the Western and Eastern Cape Provinces in South Africa, along the southern fringes of the Indian Ocean. Although only comprising approximately 5.4% of the land cover in South Africa, the biome covers the topography of the rugged mountains in the far south and southwest of the country to the flat coastal plains, where it dominates on nutrient-poor soils (Bond et al., 2004). The aims of conservation in mountain catchments are, among others, to maintain species diversity, and this should be achieved by ensuring that the natural processes necessary for the maintenance of the full complement of species are allowed to operate. Fire is the major natural process which affects species in *fynbos* catchments (van Wilgen et al., 1990).

Role of fire

Fire ecology has in general been well-studied during the past decades from 1950 onwards, and there is now wide recognition that most *fynbos* plant species require fire to complete their life cycle and to maintain biodiversity (Keeley et al., 2012).

Burning stimulates seed release from species with serotinous cone-like structures, which store seeds on the plants for years between fires. Many species in the Proteaceae are serotinous and often dominate *fynbos* stands. Some Restionaceae also retain seeds for long periods and may be weakly serotinous. Many species of *fynbos* plants accumulate seeds in dormant seed banks in the soil. Most have specialized germination cues linked to fire (Bond et al., 2004).

The optimum *fynbos* burning rotation has been set at approximately 12 to 20 years, but in the drier parts of its domain (where the rainfall is less than 500 mm yr^{-1}) this could range from 20 to 30 years. Where these vegetation communities occur within (or bordering) densely populated areas, such as in the southwestern Cape region, human interventions have caused this rotation to be decreased to 6 to 8 years mainly as a result of arson and negligence, which is presenting a serious threat to the maintenance of biodiversity of these *fynbos* communities (Bond et al., 2004; de Ronde et al., 2004). Even at three years of age *fynbos* may burn under severe fire danger conditions (Kruger, 1977; van Wilgen et al., 1990). However, *fynbos* communities accumulate enough fuel to readily sustain a running fire under average summer conditions only when they have reached a post-fire age of four years, thus a fire within *fynbos* before that stage is undesirable (van Wilgen et al., 1990).

While during the years 1950 to 1980 regular block-burning (by means of controlled fire application) was conducted by the organizations in charge of managing the *fynbos*-covered land, particularly on the higher topography, this practice has by today almost disappeared for various reasons such as the disappearance of trained and experienced burners as well as financial constrains. The implications of this are that bordering agricultural and forestry land is threatened more and more by wildfire (Calvin et al., 2004; Geldenhuys et al., 2004), and that wildfire has over the past decade spiraled to extreme proportions, with billions of dollars worth of damage[3], while the maintenance of biodiversity is being threatened and even affected by these serious fires, which either occur too early during the life cycle, or too late and with too high intensity, further increased by alien invaders found on some of the *fynbos*-covered land (i.e. *Hakea* and some *Acacia* spp.).

The situation in the regions where *fynbos* is found, has now reached alarming proportions, and serious concerns about the situation have been raised at all levels of *fynbos* management as well as at high government levels, that prescribed burning application will have to be re-implemented as a matter of urgency. However, serious wildfires have during the past decade taken over this "decision-making process", not only burning-down whole mountain ranges, but also adjoining industrial plantations and agricultural land. Unfortunately there are still *fynbos* communities in some regions more than 50 years old, which are almost completely overgrown with an indigenous fern *Gleichenia polypodioides* and/or exotic weeds on some sites (de Ronde, 1988). Only wildfires under extreme weather conditions can now burn in such complex fuel / vegetation, when the extremely high fire intensity produced can seriously harm biodiversity, and which will then seriously threaten bordering (dense) human populations – the wildland-urban interface (Bond et al, 2004; de Ronde et al., 2004).

2. Industrial timber plantations

Introduction

Although covering <1% of South Africa (1.35 million ha), industrial pine (*Pinus* spp.) and eucalypt (*Eucalyptus* spp.) plantations – established for roundwood production, for either sawn timber or pulp – form a significant proportion of the above-ground biomass and vegetation in some Southern African regions, mainly because of their fast fuel biomass accumulation and subsequent exponential increase in fire hazard and wildfire occurrence. Fuel reduction in the form of slash burning is normally only applied after clear felling these plantation stands, while prescribed burning inside standing pine stands is seldom applied as a fuel management measure (de Ronde et al., 2004a; 2004b), with a few exceptions, where timber companies have during 2008-2009 started applying prescribed burning at a significant scale, in some cases inside more than 15,000 ha (or approximately 10% of the total area under trees) yearly, on a 2-3 year rotation.

3 In the Helderberg mountains near Stellenbosch, South Africa, an estimated $US 150million was lost during February 2009, in the form of damage to timber plantations and vineyards by wildfire.

Fire effects on industrial plantations

The total fire exclusion policy – still being applied in most industrial plantations in Africa – has been shown to result in the proliferation of disastrous wildfires. As some of these even-aged stands are clear felled, and the next rotation is entered, this serious fire hazard situation becomes abundantly clear, particularly where no fuel reduction measures have been applied (de Ronde, 1988; 1990; 1992; de Ronde et al., 2004a). Forest floor fuel accumulations have been reported, with sometimes a total absence of decomposition, e.g. in *Pinus patula* stands at high altitudes (de Ronde, 1992; Schutz et al., 1988), resulting in unacceptable levels of litter loadings and subsequent increase in wildfire hazard (de Ronde, 1992; de Ronde et al., 2004b)

To avoid future wildfire disasters, most forestry companies will have to embark on a significant increase in prescribed burning application inside standing tree stands. The research phase in which the feasibility of prescribed burning for fuel reduction in pine stands has been investigated has been completed, but this proposed prescribed burning program has not been implemented widely, mainly because of management resistance in the paper and pulp industry. Early results of prescribed burning experiments inside eucalypt stands are very promising, but forest management is still very reluctant to accept this type of fuel reduction measures at a large scale, because of unwanted tree stem scorch resulting in carbon deposits inside the bark grooves of timber logs affecting the quality of some end products such as pulp (pers. com. with Sappi Forests staff). During 2007-2008 wildfire damage ran for the first time into billions of $US in South African forest regions, when more than 25,000 ha of industrial pine plantations were damaged by wildfires in the Sabie district, South Africa, during one single day of extreme weather conditions. These companies are in most cases now re-considering the "total fuel protection policy", in favor of selected prescribed burning application as a fire management tool (pers. comm. with some senior managers from a number of these SA companies).

In other countries of Africa, e.g. Mozambique, Tanzania, Uganda, Zambia and Sudan, industrial plantations are now being established at a significant scale, which could eventually exceed the area planted in Southern Africa within a few decades. These investments have been encouraged as a means to reduce CO_2 levels and it is abundantly clear that funding for such projects are more readily available in the context of international efforts to increase terrestrial carbon sequestration. As most of these plantations are established in savanna grasslands with a yearly biomass addition exceeding 4 t ha^{-1}, some of these companies have already experienced serious wildfires as a consequence of the "total fire protection policy" and are now re-considering such silvicultural regimes seriously (personal assessment of the author).

Figure 12.5. Two fire ecosystems meeting near Jonkershoek, Western Cape region, South Africa: The fire-dependent endemic fynbos ecosystem (foreground) with embedded industrial plantations of exotic pine species (background), which in their natural home ranges evolved remarkable adaptations to and dependence on natural fire, but are highly vulnerable to wildfires if fuels are not properly reduced by mechanical extraction or by prescribed fire. Photograph: J.G. Goldammer (GFMC).

Figures 12.6. and 12.7. Prescribed fire application in the early experimental stage in the late 1980s in South Africa. This technique aimed at reducing surface fuel loads moving into application in some areas only approximately 25 years later. Photograph: J.G. Goldammer (GFMC).

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13 Magnitude and Impacts of Vegetation Fire Emissions on the Atmosphere

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Abstract

Biomass smoke affects air quality and climate. The emission of volatile organic compounds (VOC), carbon monoxide (CO), and nitrogen oxides (NO_X) constitutes the precursor mixture for the formation of photochemical smog, leading to production of ozone (O_3) and other oxidants and irritants, which together with the smoke particles adversely affect human health and plant productivity. Vegetation fires including natural and human-caused wildfires, traditional land-use fires including slash-and-burn agriculture, agricultural maintenance and pasture burning, advanced, science-based prescribed fires, fire used as tool in land-use change, biofuel use, charcoal production, and charcoal combustion release about two-thirds as much CO_2 as fossil fuel combustion, some of which is taken up into the biosphere when plants re-grow. For two other greenhouse gases, methane and nitrous oxide, pyrogenic emissions are very significant as well. In the case of methane, vegetation fires emit much more than fossil fuel burning. The pyrogenic sources of N_2O far exceed those from fossil fuel combustion, and rival the sum of all industrial emissions. This makes biomass burning a globally important source of greenhouse gases. Smoke particles influence the Earth's climate and hydrological cycles in ways that are still inadequately understood. Smoke particles absorb sunlight, warm the atmosphere, and reduce the evaporation of water from oceans and land. They also scatter sunlight back into space, which results in surface cooling. Biomass smoke can also change the properties of clouds, including their ability to produce rain. The enhanced aerosol concentration leads to increased numbers, but smaller size, of cloud droplets. This suppresses the early formation of rainfall from convective clouds, but can lead to an invigoration of convection and precipitation by enhanced formation of ice particles in later stages of cloud development. Given the uneven distribution of smoke aerosols in space and time, we must expect substantial regional and global impacts on climate and water availability. In particular, they are likely to change monsoon circulations in critical regions, such as the Amazon and South Asia.

Keywords: Pyrogenic emissions, biomass fires, volatile organic compounds, global radiation budgets, soot particles

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Introduction

Human evolution and the use of fire have gone hand in hand, ever since the origin of our species in the savannas and woodlands of Africa. As a result, air pollution from the smoke of biomass fires has been humanity's constant companion for some two million years, and its ancient impact on human health is reflected in soot deposits in the lungs of mummies. Already the first estimates of pyrogenic emissions suggested that, for some atmospheric pollutants, biomass burning rivals fossil fuel use as a source of atmospheric pollution (Seiler and Crutzen, 1980; Crutzen and Andreae, 1990).

Satellite and airborne observations have shown elevated levels of pyrogenic aerosols, O_3, CO, and other trace gases over vast areas, especially over the tropical continents and the adjacent ocean regions, but also over the boreal forests. As a result, smoke aerosols perturb regional and global radiation budgets by their light-scattering effects and by their influence on cloud microphysical processes (Crutzen and Andreae, 1990; Haywood and Boucher, 2000; Penner et al., 2001; Andreae et al., 2004).

To assess the atmospheric impact of biomass burning, and especially to represent it quantitatively in models of atmospheric transport and chemistry, accurate data on the emission of trace gases and aerosols from biomass fires are required. Emissions must typically be represented in the form of spatiotemporally resolved fields, where the emission per unit area and time is provided at a specified spatial and temporal resolution. In this chapter, we synthesize currently available data on fire emission characteristics for key chemical species. We then combine the emission factor data with exposure estimates for the various fire categories to provide global estimates of emissions of biomass burning. Finally, we examine the impact of these emissions on atmospheric chemistry and climate.

Emission Factors for Chemical Species from Fires in Various Vegetation Types or Burning Practices

Emissions from biomass burning have been investigated both by experimental burning of vegetation fuels in the laboratory and by measuring the emissions from actual vegetation fires in the field, using aircraft and ground sampling. After subtracting the ambient concentrations of the emitted species, the amounts emitted by combustion are obtained. The results are typically stated either as emission ratios to reference species, such as CO_2 or CO, or as emission factors, i.e., the amounts emitted per mass unit of burned biomass. The methodology used in these investigations and some of the problems arising from the different sampling approaches have been summarized in Andreae and Merlet (2001), Guyon et al. (2005), and Yokelson et al. (2008). Table 13.1 shows emission factors for key species that have been compiled using the same approach as described by Andreae and Merlet (2001), but including the results of studies conducted after that paper had been published.

It should be noted that there is a need to replace the static emission factors, such as those in Table 13.1, by a dynamic emission model that represents the influence of combustion conditions on the amounts and proportions of emitted species. In principle, this is possible based on the fact that the different phases of combustion – pyrolysis, flaming, and smoldering – each emit a characteristic mix of compounds that is not highly dependent on the fuel type. Therefore, indicator species, as CO_2 for flaming and CO for smoldering combustion, can be used to estimate emissions of a large number of correlated compounds in the fire emissions. The proportion of these indicator species is often represented as the modified combustion efficiency, MCE (MCE = $CO/(CO+CO_2)$). Such an approach has been used by Janhäll et al. (2009) for aerosol emissions from a wide variety of fires. The practical application of this approach in emission models is presently hampered by the scarcity of measurements that would allow the prediction of MCE or the proportion of smoldering and flaming combustion from parameters describing combustion conditions, such as fuel characteristics (especially fuel structure and fuel moisture), fire weather, and topography.

Emissions from Global Biomass Burning

While the average emission factors for many important species, such as CO and CH_4, are now known with an uncertainty of about 20-30%, large uncertainties persist for regional and global fire emissions because of the difficulties inherent in estimating the amount of biomass burned. While the use of a large variety of remote sensing tools has allowed a much better assessment of the spatial and temporal distribution of open burning in recent years (Langmann et al., 2009), the quantitative estimation of the amounts of biomass combusted per unit area and time is still based on rather crude assessments. A very promising recent development is the use of fire radiative power measured by remote sensing, which has been shown to be directly related to the rate of fuel consumption (Wooster et al., 2005; Ichoku et al., 2008).

Table 13.2 provides a set of global emission estimates for the late 1990s, based on the emissions factors in Table 13.1 and the biomass burning estimates used in Andreae and Merlet (2001). Uncertainties are not explicitly stated in Table 13.2, in part because there is not enough information to estimate them quantitatively. For each entry in Table 13.2, the appropriate error would result from error propagation from the emission factor data in Table 13.1 and the estimates of biomass burned. The inventory-based estimates for biomass burned have changed little over the last decade, but this is more due to the use of a relatively constant underlying information base and methodology than to actual accuracy of the data. A literature survey of papers published between 1980 and 2007 showed a range of estimates of 1430 to 2780 Tg C a^{-1} for total carbon emissions from open biomass burning (savannas, grasslands, and forests), with no clear sign of convergence (Langmann et al., 2009). Until tools become available to perform independent validation of these estimates, we must assume that they are uncertain to at least ±50%.

More recent approaches to estimation of global fire emissions based around modeling and state-of-the-art, multi-stream satellite data are discussed by Spessa et al. (this volume, Chapter 14).

Environmental Impact of Biomass Burning

While in this brief assessment there is not adequate space to discuss the environmental impacts *in extenso*, an indication can be gleaned from a comparison of the emissions of key pollutants from biomass burning and from fossil fuel burning (Tab. 13.2). Biomass burning releases about two-thirds as much CO_2 as fossil fuel burning. It can be argued that a substantial fraction of the CO_2 released from vegetation burning is taken up into the biosphere again after a short time. This only applies, however, as long as burning is done in a sustainable manner, which is not the case for deforestation fires and much of domestic biofuel use. For two other greenhouse gases, methane and nitrous oxide, pyrogenic emissions are very significant as well. In the case of methane, vegetation fires emit much more than fossil fuel burning, and about one-third as much as all fossil-fuel related activities together (including pipeline losses, etc.). For N_2O, pyrogenic sources far exceed those from fossil fuel combustion, and rival the sum of all industrial emissions. This makes biomass burning a globally important source of greenhouse gases.

The large releases of CO, CH_4, photochemically active hydrocarbons, and NO_X lead to the formation of ozone and photochemical smog. This is aggravated by the fact that much biomass burning takes place in tropical regions, where sunlight is intense and photochemical processes are therefore rapid. High pressure and atmospheric subsidence is common in many fire-prone regions, and acts to contain the pyrogenic pollutants and their photochemical products in a relatively shallow boundary layer. The resulting ozone concentrations in regions affected by biomass smoke are comparable to those in industrial regions. While fire emissions clearly dominate atmospheric composition in regions of active burning, their impact due to long-range transport can reach across oceans and continents (Thompson et al., 1996; Forster et al., 2001; Damoah et al., 2006). Fire-enhanced deep convection can loft the emissions from biomass burning into the lower stratosphere (Jost et al., 2004; Trentmann et al., 2006; Rosenfeld et al., 2007; Fromm et al., 2008).

Together with the vast amounts of smoke aerosol particles emitted from fires, the smog gases that prevail in regions affected by biomass burning constitute a serious health hazard. This topic is discussed in more detail in a subsequent chapter.

Beyond their health effects, smoke particles influence the Earth's climate and hydrological cycles in ways that are still inadequately understood. Light-absorbing ("soot") particles absorb solar radiation, and thereby warm the atmosphere, cool the Earth's surface, and reduce the evaporation of water from oceans and land. Furthermore, smoke particles scatter sunlight back into space, which also results in a surface cooling and suppression of evaporation. As a result, biomass smoke has a cooling effect on the planet, which is only partially offset by the warming effect associated by the light-absorbing components of the smoke. (Penner et al., 2003; Ramanathan et al., 2007; Marlon et al., 2008; Ramanathan and Carmichael, 2008).

Biomass smoke can also change the properties of clouds, including their ability to produce rain. Under some conditions, smoke can lead to the complete suppression of cloud formation (Koren et al., 2004). More generally, the presence of enhanced aerosol concentration due to biomass burning leads to increased numbers, but smaller size, of cloud droplets (Feingold et al., 2001; Andreae et al., 2004; Feingold et al., 2005). This suppresses the early formation of rainfall from convective clouds, but can lead to an invigoration of convection and precipitation by enhanced formation of ice particles in later stages of cloud development (Jiang and Feingold, 2006; Koren et al., 2008; Rosenfeld et al., 2008; Zhang et al., 2008). Given the uneven distribution of smoke aerosols in space and time, we must expect substantial regional and global impacts on climate and water availability. In particular, they are likely to change monsoon circulations in critical regions, such as the Amazon and South Asia (Lau et al., 2009; Zhang et al., 2009).

Conclusions

Considerable progress has been made over the last decade with regard to the determination of emission factors from biomass burning. A critical evaluation of the available data shows that a vast number of chemical species have been identified in biomass burning smoke, and that reliable emission information exists for most of the key species. There remain, however, serious gaps for important species, including ones that could be valuable atmospheric tracers, such as acetonitrile. Some combustion types also need further study, e.g., tropical deforestation fires and the various types of biofuel use, including charcoal making. The global emission estimates from biomass burning have been refined, but require further validation. This applies particularly to the estimates of biomass burned as a function of space, time, and type of combustion. An essential task will be the development of dynamic emission models that are able to forecast emissions based on fuel type and properties, meteorology, topography, etc.

The agreement between the results from inverse models and the inventory-based emission estimates is encouraging, but more rigorous constraints of emission estimates could come from regional experiments designed to test the agreement between emission inventories and transport and chemistry models. The emissions from biomass burning have significant impacts on air quality, human health, climate and the water cycle.

Table 13.1. Emission factors (in g species per kg dry matter burned) for pyrogenic species emitted from various types of biomass burning.

	Savanna, grassland	Tropical Forest	Extra-tropical Forest	Biofuel use	Charcoal Making	Charcoal Burning	Agri-cultural Burning
CO_2	1664	1626	1572	1514	478	2573	1458
CO	62	101	106	86	82	220	94
CH_4	2.2	6.6	4.8	7.6	18.9	6.7	8.8
Total NMHC	3.4	7.0	5.7	7.7	17.5	4.6	11.2
C_2H_2	0.27	0.36	0.25	0.71	0.29	0.25	0.20
C_2H_4	0.84	1.48	1.18	1.24	1.49	0.59	0.99
C_2H_6	0.32	1.12	0.72	0.73	2.14	0.66	1.24
PAH	0.0024	0.10	0.100	0.15	-	0.025	0.100
Methanol	1.47	2.95	1.89	4.48	9.28	1.24	4.03
Phenol	0.003	0.23	0.41	0.81	4.25	0.86	0.59
Formaldehyde	0.71	2.22	2.15	0.92	1.06	0.73	1.75
Acetaldehyde	0.50	2.26	0.98	0.37	-	3.81	2.77
Acetonitrile	0.20	0.48	0.29	0.40	-	1.02	0.74
Formic acid	0.63	0.57	2.45	0.46	0.45	0.12	1.14
Acetic acid	2.61	3.57	3.58	18.2	47.9	1.85	5.17
H_2	0.99	3.50	1.78	1.93	-	4.94	2.70
NO_X (as NO)	2.35	2.26	3.41	1.59	0.05	2.32	2.34
N_2O	0.21	0.20	0.26	0.08	0.02	0.35	0.10
NH_3	0.74	0.94	1.63	0.79	4.65	0.80	1.34
HCN	0.23	0.45	0.92	0.10	0.08	0.30	0.41
SO_2	0.37	0.71	1.00	0.27	-	0.05	0.40
CH_3Br	0.0017	0.0078	0.0032	0.003	0.003	0.003	0.003
Hg	0.00009	0.00005	0.00005	0.00005	0.00005	0.00005	0.00005
$PM_{2.5}$	4.9	9.1	12.8	5.2	2.1	1.6	8.3
OC	3.2	4.3	9.1	2.9	-	4.8	3.7
BC	0.46	0.57	0.56	0.51	-	1.50	0.48
CN	3.0E+16	2.5E+15	3.4E+15	4.2E+14	-	3.4E+15	3.4E+15
CCN (1% SS)	2.0E+15	2.0E+15	2.6E+15	2.0E+15	-	2.0E+15	2.0E+15

Abbreviations: NMHC: Non-methane hydrocarbons, $PM_{2.5}$: particulate matter <2.5 μm diameter, BC: black carbon, CN: condensation nuclei, CCN: cloud condensation nuclei at 1% supersaturation.

Table 13.2. Global annual emission of selected pyrogenic species in the late 1990s (in mass of species per year; Tg a^{-1}). *Note:* 1 Tg = 1 million metric tons; dm = dry matter. Fossil fuel burning emissions are from IPCC (Houghton et al., 2001), EDGAR3.2 (van Aardenne et al., 2001), and Andreae and Rosenfeld (2008).

	Savanna and grassland	Tropical forest	Extra-tropical forests	Biofuel burning	Char-coal making	Charcoal burning	Agri-cultural residues	Total	Fossil fuel burning
Tg dm burned	3160	1330	640	2824	152	38	496	8600	---
CO_2	5257	2162	1006	4274	73	98	723	13600	23100
CO	197	134	68	242	12	8.4	46	710	278
CH_4	7.1	8.8	3.1	21.5	2.9	0.26	4.4	48	10
Total NMHC	10.8	9.3	3.6	21.8	2.7	0.18	5.5	54	79
C_2H_2	0.85	0.48	0.16	2.00	0.04	0.009	0.10	3.6	---
C_2H_4	2.67	1.96	0.76	3.50	0.23	0.022	0.49	9.6	---
C_2H_6	1.03	1.49	0.46	2.07	0.32	0.025	0.61	6.0	---
PAH	0.01	0.13	0.06	0.43	---	0.001	0.05	0.7	---
Methanol	4.6	3.9	1.2	12.7	1.41	0.05	2.0	25.9	---
Phenol	1.2	0.3	0.4	2.3	0.65	0.05	0.3	5.1	---
Formaldehyde	2.2	2.9	1.4	2.6	---	0.03	0.9	10.2	---
Acetaldehyde	1.6	3.01	0.63	1.05	---	0.14	1.37	7.8	---
Acetonitrile	0.63	0.64	0.18	1.13	---	0.039	0.37	3.0	---
Formic acid	2.0	0.8	1.6	1.29	0.07	0.00	0.6	6.2	---
Acetic acid	8.2	4.7	2.3	51.5	7.29	0.07	2.6	76.6	---
H_2	3.1	4.7	1.1	5.4	---	0.19	1.3	15.9	---
NO_X (as NO)	7.4	3.0	2.2	4.5	0.01	0.09	1.2	18.4	54
N_2O	0.68	0.27	0.17	0.24	0.00	0.013	0.05	1.4	0.6
NH_3	2.3	1.2	1.05	2.2	0.71	0.03	0.7	8.2	0.4
HCN	0.72	0.59	0.59	0.27	0.01	0.011	0.20	2.4	---
SO_2	1.2	0.95	0.64	0.75	---	0.002	0.20	3.7	111
CH_3Br	0.005	0.010	0.002	0.008	---	0.00011	0.001	0.028	---
Hg	0.0003	0.0001	0.00003	0.0001	---	---	0.0000	0.0006	---
$PM_{2.5}$	15.6	12.0	8.2	14.6	0.32	0.06	4.1	55	252
OC	10.2	5.7	5.8	8.3	---	0.18	1.8	32	7.5
BC	1.5	0.75	0.36	1.4	---	0.06	0.24	4.3	4.5
CN	9.5E+28	3.3E+27	2.2E+27	1.2E+27	---	1.3E+26	1.7E+27	1.0E+29	---
CCN (1% SS)	6.3E+27	2.7E+27	1.7E+27	5.6E+27	---	7.6E+25	9.9E+26	1.7E+28	2.0E+28

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14 Modeling Vegetation Fires and Fire Emissions

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Abstract

Fire is the most important ecological and forest disturbance agent worldwide, is a major way by which carbon is transferred from the land to the atmosphere, and is globally a significant source of greenhouse gases and aerosols. Wildfires across all major biome types globally consume about 5% of net annual terrestrial primary production per annum, and release about 2-4 Pg C per annum, of which approximately 0.6 Pg C comes from tropical deforestation and below-ground peat fires. The global figure is equivalent to about 20-30% of global emissions from fossil fuels. Tropical savannas comprise the largest areas burned and greatest emissions sources from vegetation wildfires. Fires in Mediterranean forests and shrublands, tropical forests and boreal forests are also significant sources of emissions because they are generally characterised by much higher fuel loads per unit area compared with grasslands. Improved satellite data and sophisticated biogeochemical modeling enables emissions assessments on a global scale with fine spatial and temporal resolution. Emissions estimates are still comparable to those based on older inventory-based techniques, but uncertainties remain large. Fires increase during El Niño periods because parts of the tropics where humans use fire as a tool for deforestation experience drought conditions. These spikes contribute to the inter-annual variability of CO_2 and CH_4 observed in the atmosphere. Recently developed dynamic fire-vegetation models are capable of simulating the extent of wildfires as well as their emissions of CO_2 and other greenhouse gases for ambient as well as for projected climatic conditions. The performance of fire-vegetation models however needs to be strongly improved and validated.

Keywords: Modeling vegetation fires, dynamic fire-vegetation models, prognostic fire models, carbon equivalent, emission factors

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Why is Fire an Important Process in the Earth System?

Fire is the most important disturbance agent worldwide in terms of area and variety of biomes affected, a major mechanism by which carbon is transferred from the land to the atmosphere, and a globally significant source of aerosols and many trace gas species (Bowman et al., 2009). Wildfires operate on all continents apart from Antarctica, globally consuming on average perhaps 5% of net annual terrestrial primary production (Randerson et al., 2005), and taking into account below ground peat fires, are estimated, on average, to emit an amount of carbon equivalent to 2 Pg C per annum (van der Werf et al., 2010). This is equivalent to about 20% of global emissions from fossil fuels (Denman et al., 2007). Wildfires are estimated to burn 200-500 million hectares worldwide each year (Lavorel et al., 2007), with burning characterized by a diurnal cycle, generally strong seasonality, and potentially very large inter-annual variability at the regional scale (Giglio et al., 2010). Savannas are, on average, the single largest area burned and greatest emissions source (van der Werf et al., 2010). However, Mediterranean forests and shrublands (Moreno, 1998), tropical forests (Page et al., 2002; Cochrane, 2003) and boreal forests (Balzter et al., 2005), where fuel loads per unit area and thus emissions are typically much greater than in grasslands, are also significant in the global context (Figure 14.1).

Fire disturbance has a major impact on vegetation dynamics by initiating succession, selecting fire-adapted plants in fire-dominated ecosystems and influencing vegetation productivity, and thus litter and fuel load (Whelan, 1995; Goldammer and Furyaev, 1996; Cochrane, 2003; Bergeron et al., 2004). Burning conditions are driven by climate and vegetation state. Fire effects include post-fire mortality of plants and depend on the regeneration mode of the vegetation and fuel composition; these in turn define the burning conditions for the next fire event. Fuel load in ecosystems of highly variable productivity can demonstrably limit or promote fire spread (Mermoz et al., 2005; Spessa et al., 2005; Stephens and Moghaddas, 2005), whereas temperature is the main limiting factor in fire season duration in boreal and temperate ecosystems (where fuel availability is generally high) (Schimmel and Granström, 1997; Flannigan et al., 2005). The inter-annual variability in area burned, fuel consumed and emissions released in parts of the boreal and tropical regions can be as large as a factor of two orders of magnitude, driven principally by climate-related variations in fuel loads, fire susceptibility (e.g. fuel moisture), fire severity and fire duration (French et al., 2002; Sukhinin et al., 2004; Flannigan et al., 2005; Randerson et al., 2005; Kasischke et al., 2005; van der Werf et al., 2006, 2010). Fire is not only an important process shaping ecosystem structure and function on contemporary time-scales, but also on longer time-scales in the past (Feurdean et al., 2012; Pfeiffer et al., 2013).

Fire is a key component of the carbon cycle. Globally, annual pyrogenic C emissions in the last decade are calculated to have peaked in the ENSO year of 1998 (2.8 Pg C yr^{-1}), with a minimum in 2009 (1.5 Pg C yr^{-1}) (van der Werf et al., 2010). Furthermore, above ground wildfires emit on average about 1.5 Pg C yr^{-1} to the atmosphere, with the majority stemming from savanna fires in Africa (50%) and smaller but significant contributions from fires in the tropics, Mediterranean regions, and the boreal zone (van der Werf et al., 2010). From

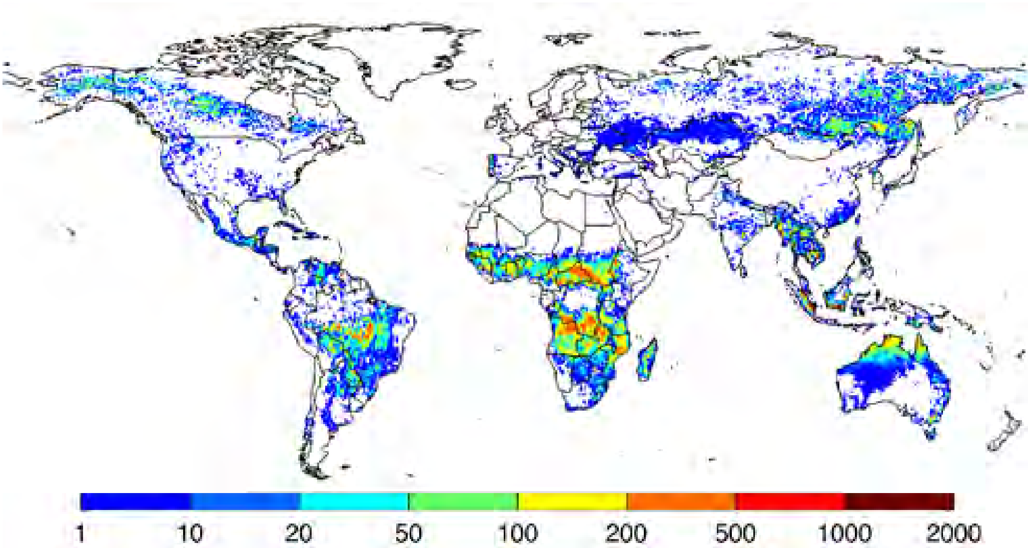

Figure 14.1. Average carbon losses from above and below ground wildfires, 1997-2009 (gC per square metre per annum). Source: van der Werf et al. (2010) Global Fire and Emissions Database (GFEDv3) (http://www.falw.vu/~gwerf/GFED/index.html)

a CO_2 perspective, emissions of these fires are believed to be balanced over decadal scales by carbon uptake from regenerating vegetation. However, this is certainly not the case for the large range of other trace gases as well as aerosols released by fires (Andreae and Merlet, 2001). Nor does it apply to CO_2 released from deforestation and peatland fires, which occur mostly in South America and Southeast Asia. Although uncertain in terms of methods used to estimate burnt area and carbon combusted, these fires emit, on average, about 0.6 Pg C yr^{-1} (van der Werf et al., 2010) and therefore, contribute significantly to the build-up of atmospheric CO_2.

As the review by Andreae (this volume, Chapter 13) highlights, over the past ten years, several studies have provided global estimate emissions from biomass burning, and while differences between studies exist, these differences can generally be accounted for by the data and methods used. For example, annual average global emissions from biomass burning presented in GFEDv3 (van der Werf et al., 2010) are lower than those presented by Andreae (this volume, Chapter 13) at about 4.3 Pg C yr^{-1} because the latter includes biofuel use, at about 1.7 Pg C yr^{-1}, and is based on different data sources, principally older and coarser-scale satellite data. Furthermore, GFEDv3 total estimates are slightly lower than those of the more recent work by Kaiser et al. (2012) who used a different technique for estimating global emissions from wildfires. Kaiser et al. (2012) used daily estimates of Fire Radiative Power (FRP) (Roberts et al., 2005; Wooster et al., 2005) to derive biomass burnt and emissions from wildfires, and calculated a slightly higher estimate from wildfires globally compared with van der Werf et al. (2010) (Kaiser et al.: 2.1 Pg C yr^{-1}; van der Werf et al.: 2.0 PgC yr^{-1}). Regardless of which satellite product is used, it is widely acknowledged that uncertainties associated with cloud cover and overpass timing remain, and as such, further work is underway to reconcile global estimates from biomass burning using satellite and model-based inversion techniques, for example, between the CO measuring space-borne MOPITT (Measurements Of Pollution In The Troposphere) instrument and GFEDv3 (van der Werf, pers. comm.).

Some suggest fire to be the largest source of inter-annual variability in land-atmosphere C fluxes, with an estimated inter-annual variability of approximately 1 Pg C (1997 to 2004) (Patra et al., 2005). Biomass burning contributes up to 50% of global CO and NOx emissions in the troposphere (Galanter et al., 2000) and may be responsible for significant increases in atmospheric growth rates of CO, CO_2 and CH_4 during ENSO events (van der Werf et al., 2004). Simpson et al. (2006) confirmed the influence of biomass burning on large global CH_4 pulses in 1998 and 2002-2003, and that growth rate fluctuations in methane reflect the influence of ENSO activity on large-scale biomass burning in the tropics. However, some contend that there are additional uncertainties on these amounts that are of similar magnitude to the interpreted variability due primarily to uncertainties in the estimates of global area burnt, fuel load and burning conditions under specific fire regimes (French et al., 2004; van der Werf et al., 2006, 2010).

In addition to its impact on global greenhouse gas levels, fire also modifies a variety of land-atmosphere interactions at different spatio-temporal scales (e.g. vegetation transpiration, surface roughness soil erosion, albedo). Forest fires, deforestation and other forest disturbances effectively thin forests, reducing the amount of vegetation transpiring water. In the Amazon, for example, reduced overall transpiration through forest loss results in lowered local atmospheric humidity levels, and increases the probability of future forest fire occurrence (Cochrane, 2003). At the regional scale, transpiration from Amazonian forests is important for downwind precipitation, contributing over 25% to annual rainfall (Cochrane, 2003). Forest fires reduce the ability of affected forests to retain water, exacerbating flooding, erosion and seasonal water shortages. Smoke-borne aerosols from fires disrupt normal hydrological processes and reduce rainfall, potentially contributing to regional drought (Andreae, 2007). Wildfires thus have the ability to significantly perturb Earths radiation budget and climate, with the possibility for positive feedback (Denman et al., 2007).

Regional- and Global-Scale Fire and Emissions Quantification

The effect of fire on climate and atmospheric chemistry is known to be crucial. However, until recently, estimates of wildfire emissions of trace gas and aerosols to the atmosphere have been based almost solely on so-called ‘bottom-up’ inventories or emission models (Hoelzemann et al., 2004; Kasischke et al., 2005) which use the equation of Seiler and Crutzen (1980)

$$C_t = A \times B \times FC \times CE \quad (1)$$

where total carbon emission C_t is the product of the area burnt *A* (ha), the average density of biomass *B* (tons per ha), the carbon fraction of the biomass *FC* and a scaling factor (*CE* for combustion efficiency (fraction of available fuel that actually burns). Emission factors for trace gas and aerosol species (e.g., Andreae and Merlet, 2001) can be used to estimate the release of any other species from the estimates of C_t produced from (1). Early attempts to estimate emissions were based on biome-scale assessments of the input variables (Seiler and Crutzen, 1980).

More recently, satellite data has been used to assess area burned (e.g. Roy et al., 2003, 2008, 2009; Giglio et al., 2010; Tansey et al., 2008) and drive biogeochemical models (e.g. CASA, Randerson et al., 1996) and vegetation dynamics models (e.g. LPJ-GUESS, Smith et al., 2001) to better estimate the spatio-temporal variability in biomass burning and emissions (e.g. van der Werf et al., 2010; Ito and Penner, 2004; Lehsten et al., 2008; Schultz et al., 2008). However, all previous studies have used static emission factors to calculate emissions from wildfires. This neglects the reality that emissions of trace gases and aerosols critically depend on the moisture conditions of the combusted fuel. With wet fuel generating resulting in incomplete combustion and higher ratio of non-CO_2 n-greenhouse gases compared to dry fuel. One attempt to take this into account is to quantify the amount of burned wood versus the amount of burned litter and use this ratio to generate dynamic emission factors (Scholes et al., 1996). In addition, variability in CE and emission factors (e.g. Shea et al., 1996; Kasischke et al., 2005; Korontzi, 2005) can to some extent be simulated based on meteorological conditions and fuel composition.

Satellite-based estimates of fire activity have been highly useful to better understand the role of fire in the carbon cycle, better understand atmospheric processes and trace gas budgets, and quantify changes in air quality impacting people's health. Nonetheless, estimation approaches based solely on remotely sensed burned area measures can only be used for estimating emissions during recent decades at regional-scales; and generally much less continentally or globally since reliable Earth Observation (EO) data at these scales has only now become available for the past decade or so. Moreover, they cannot be used to predict climate-related changes in fire activity and pyrogenic emissions either in the longer-term past, or the future, for example, the next dry season or over decadal timescales.

It is therefore important to have access to validated models that allow one to make predictions outside of the contemporary satellite record. Prognostic fire models, embedded in dynamic global vegetation models (DGVMs), can in principle simulate the effects of changes in climate and vegetation dynamics as a bi-directional feedback with the embedded fire model. This capability is needed in order to investigate how fire and fire-related emissions might change with changing climate conditions and vegetation dynamics and to allow quantification of fire 'risk' based on emerging capabilities for seasonal meteorological forecasting.

Future Climate Change

Fire frequency and intensity are strongly sensitive to climate change and variability, and to land use practices (Denman et al., 2007). Over the last century, trends in burned area have been largely driven by land-use practices, through fire suppression policies in mid-latitude temperate regions and increased use of fire to clear forest in tropical regions (Mouillot and Field, 2005; Schultz et al., 2008). However, there is also evidence that climate change has contributed to an increase in fire frequency in Canada (Gillett et al., 2004) and fire severity in Central Asia (Goldammer, 2006). Several studies using outputs from GCMs to drive calculations of empirical fire danger indexes indicate that fire frequency will increase under the likely scenario of a warmer and/or drier future climate in many carbon-rich forests, including circumpolar boreal forests (Flannigan et al., 2009) and Amazonia (Cardosa et al., 2003; Golding and Betts, 2005).

Future prediction of both burnt area and emissions from wildfires under climate change requires more than just the calculation of fire danger, but rather a process-based understanding of the three main pre-cursors to fire viz. an ignition source, ample fuel, and suitably dry fuel (Pyne et al., 1996). Prognostic fire models, embedded in process-based vegetation models, can in principle simulate the effects of changes in climate and vegetation dynamics on fire activity and emissions. This capability is fundamental in order to investigate how fire and fire-related emissions might change with changing climate conditions, vegetation and land use patterns in future. Similar work cannot be achieved by relying on empirical fire danger indexes because they tell us only about the risk of fire.

Existing Models of Fire-Vegetation Interactions

There have been a number of previous attempts to simulate fire within dynamic global vegetation models (DGVMs) in order to simulate and study climate-fire-vegetation interactions (Lenihan and Neilson, 1998; Thonicke et al., 2001; Venevsky et al., 2002; Arora and Boer, 2006; Scheiter and Higgins, 2009; Kloster et al., 2010, Thonicke et al., 2010). Such models are designed primarily to incorporate the role of fire as a disturbance factor for vegetation dynamics, and to account for corresponding fluxes in the global C cycle (e.g. last glacial maximum, Thonicke et al., 2005). Trace gas and aerosol emissions can also be derived within these models via the aforementioned emissions factors.

Existing fire models display a wide variety of complexity in terms of how well they capture and/or abstract key fire-related processes. The Glob-FIRM model (Thonicke et al., 2001) in the LPJ Dynamic Global Vegetation Model (DGVM) (Sitch et al., 2003) predicts the fractional area burnt within a grid cell from the simulated length of fire season and minimal fuel load. However, it does not specify ignition sources explicitly and assumes a constant relationship between fire intensity and fire severity to describe fire effects. Fire resistance, a composite parameter to describe average fire intensity and fire severity, is defined as a parameter for each plant functional type (PFT) in the LPJ-DGVM. Reg-FIRM (Venevsky et al., 2002), an alternative regional-scale fire model in LPJ, treats climatic fire danger, wildfire ignitions and fire spread as distinct processes, but fire effects on vegetation mortality are prescribed parameters as in Glob-FIRM, and trace gas and aerosol emissions are not quantified. MC-FIRE, embedded in the MC1 DGVM, explicitly simulates fire spread (following Cohen and Deeming, 1985) and fire effects including post-fire mortality (Peterson and Ryan, 1986). However, it allows only one ignition per year per grid cell, and requires a drought index and information on time since last fire to estimate the fraction of the grid cell burnt (Lenihan and Neilson, 1998). Arora and Boer (2006) present a global simulation of fire activity and emissions from biomass burning within the Canadian Terrestrial Ecosystem Model (CTEM) (Verseghy et al., 1993); and Kloster et al. (2010) conducted a similar study having implemented CTEM-fire into the Community Land Surface Model (CLM) (Oleson et al., 2010). However, while CTEM-fire simulates the feedback between vegetation and fires, it adopts a simplified parameterized approach. Notably, it models fire rate of spread as a function of wind speed and soil moisture only, which ignores the influence of litter load and litter moisture. Also, fire-induced consumption of biomass and plant mortality are prescribed, and do not vary with changes in fire intensity. Scheiter and Higgins (2009) described a new vegetation model that was specifically developed for tropical vegetation. The model combines established components from existing DGVMs with novel process-based and adaptive modules for phenology, carbon allocation and fire within an individual-based framework. The fire model is semi-empirical, and for fire to spread, two conditions must be fulfilled: there must be an ignition source and the potential fire intensity must exceed a certain threshold. Potential number are limited by relative humidity only, and do not take into account socio-economic or demographic factors.

The fire model SPITFIRE (SPread and InTensity of FIRE) was designed to i) overcome many of the limitations in previous fire models set within DGVM frameworks, and ii) be flexible enough to permit simulation analyses at global scales as well as for any region, with minimal setup requirements (Thonicke et al., 2010). SPITFIRE was originally developed as an embedded module within the LPJ DGVM framework and is a successor to the RegFIRM fire model (Venevsky et al., 2002). RegFIRM explicitly simulates processes of climatic fire danger and wildfire lightning- and human-caused ignitions. SPITFIRE builds on this treatment with a more complete representation of ignitions and fire spread (if conditions are sufficiently dry) and comprises new process-based simulations of fire intensity and the risk of fire-damaged trees dying from either crown scorch or cambial death (the two most important causes of post-fire mortality), as well as emissions of trace greenhouse gases and aerosols from biomass burning.

SPITFIRE has been applied in coupled mode with the LPJ DGVM at global scales (Thonicke et al., 2010, Pfeiffer et al., 2013; Gomez-Dans et al., in review) and regional scales. Thonicke et al. (2010) focused on broad EO-based assessments of simulated burned area and emissions from biomass burning. Pfeiffer et al. (2013) did the same but from the perspective of developing improved fire modelling for pre-industrial applications. Gomez-Dans et al. (in review) used a combination of parameter calibration/optimization techniques, MODIS burned area data, and MODIS tree cover data to improve LPJ-SPITFIRE predictions of burned area at selected sites in different biomes. SPITFIRE has also been driven with L3JRC burned area data (Tansey et al., 2008) and MODIS burned area data (Roy et al., 2008; Roy and Boschetti, 2009) as part of the LPJ-GUESS vegetation model (Smith et al., 2001; Hickler et al., 2006) in a study examining emissions from biomass burning in Africa (Lehsten et al., 2008). Using LPJ-GUESS-SPITFIRE, Lehsten et al. (in review) examined how changes to fire frequency, including no fire, affects tree-grass ratios in Africa. Recently, Spessa et al. (2013) benchmarked LPJ-GUESS-SPITFIRE driven by a combination of monthly Global Fire and Emissions Database (GFEDv3) burnt area data (1997-2009) (Giglio et al., 2010; van der Werf et al., 2010) and long-term annual fire statistics (1901 to 2000) (Mouillot and Field, 2005) against EO-based tree biomass data for pan-tropical forests and savannas (Saatchi et al., 2011, Baccini et al., 2012). Finally, Spessa and Fisher (2010) completed the coupling of SPITFIRE to a global version of the Ecosystem Demography (ED) vegetation model (Moorecroft et al., 2001). ED has been run at global scale by Fisher et al. (2010) as part of the land surface model 'MOSES2.2' (Met Office Surface Exchange scheme) (Essery et al., 2001), and as part of the Community Land Surface Model (CLM) (Oleson et al., 2010). SPITFIRE is being implemented into the ED-CLM model (Spessa and Fisher, in progress).

LPJ-SPITFIRE simulates the number of fires, area burnt, fire intensity, crown fires, fire-induced plant mortality, and emissions of carbon, CO_2, CO, CH_4, VOC, NO_x, $PM_{2.5}$ and TPM at a daily, 0.5 degree resolution (Thonicke et al., 2010). In the model, the number of human-caused fires is modeled as a log-normal shaped function of population density, with the height of the curve dependent on the number of fires per capita per fire-season day. This parameter is empirically-derived from observed data on fires, the population density and the average fire danger conditions within a grid cell. The number of lightning-caused fires is currently prescribed and is sourced from flash rate data taken by the Optical Transient Detector (OTD) (Christian et al., 2003). Fire rate of spread (ROS) calculations are based on the USDA operational fire prediction models (Rothermel, 1972; Wilson, 1982), and are directly proportional to energy produced by ignited fuel, and also wind speed. ROS is inversely proportional to the amount of energy required to ignite fuels (fuel moisture and fuel bulk density, derived from the LPJ). Four dead fuel classes are considered in SPITFIRE: 1hr (dead leaves), 10hr (twigs/small branches), 100 (large branches) and 1000-hr (logs) classes. These values refer to the average time it takes for a fuel type to respond to equilibrium moisture conditions, which varies according to the surface area to volume (SAV) ratio of the fuel (e.g. leaves have high SAV and logs have very low SAV; Pyne et al., 1996). Area burnt is a function of ROS, and fire duration, assuming an elliptical shaped fire and the Canadian method for scaling the wind-directed long axis of a burn ellipse to the short axis (van Wagner and Pickett, 1985; CFFBG 1992). Litter moisture is simulated as a function of the fire 'danger' index, which in its current form is the Nesterov Index (Nesterov, 1949; Venevsky et al., 2002). Grass phenology (green-up and curing phases of annual grasses) is modeled as function of the upper soil moisture. Fuel combustion (by fine and coarse fuel classes) is simulated as a function of fuel moisture, while fire intensity is a function of both the calorific content of the fuels, the amount of fuel consumed and the fire ROS; and follows Byram (1959). Tree mortality and crown fires are modeled as a function of fire intensity, degree of cambial kill (which depends on fire residence time), and vegetation-specific attributes). Emissions are calculated using the Seiler and Crutzen equation (Equation1), with the emission factors of Andreae and Merlet (2001) and regular updates from the Max Planck Institute for Chemistry, Mainz.

Compared to the LPJ-DGVM, LPJ-GUESS and ED both represent a 'size and age structured' approximation of an individual based gap model (GUESS: Smith et al., 2001, 2011; Hickler et al., 2006, 2008; ED: Fisher et al., 2010). The major innovation of the LPJ-GUESS-SPITFIRE and ED-SPITFIRE models is the categorization of each climatic grid cell into a series of non-spatially contiguous patches. The patches can be thought of as analogous to different stages of the succession process, for example, after fire. Recently burnt patches in both LPJ-GUESS and ED tend to be dominated by shade intolerant vegetation, typically grasses; whereas less recently or undisturbed patches are generally dominated by shade-tolerant trees. These patterns reflect ecological reality. The age-class structure in LPJ-GUESS and ED further facilitates a more ecologically realistic representation of fire-induced mortality and light competition. By contrast, LPJ DGVM adopts an 'area-based approach' that implicitly averages individual and patch differences across 'populations' of vegetation types, and the climatic gridcell. As such, LPJ-DGVM cannot easily be used to simulate disturbance-based ecological succession.

Model Evaluation and Improvement using Earth Observation Data

For large-scale DGVM-fire models such as LPJ-SPITFIRE and ED-SPITFIRE, Earth Observation (EO) data, complimented by appropriate ground-based measures, are fundamentally important for model evaluation over the full range of eco-regions and climate regimes. LPJ-SPITFIRE has been validated at 0.5 degrees resolution against the GBS 1982 to 2000 burnt area series (available at 8 sq km resolution, Carmona-Moreno et al., 2005) (Thonicke et al., 2010). Comparisons with the satellite-derived Global Burnt Surface product (GBS, Carmona-Moreno et al., 2005) show that LPJ-SPITFIRE realistically detects area burnt over most of the globe (Fig. 14.2). However, the GBS product itself is known to underestimate burnt area in the boreal zone, and comparisons with a region-specific EO burnt area data-set indicate that LPJ-SPITFIRE actually produces a reasonable simulation of boreal fires recorded by Suhkinin et al. (2004) (Thonicke et al., 2010). Simulated biomass burning of actual vegetation, rather than potential, natural vegetation is, on average, about 2 Pg C per annum, which is compatible with estimates based on global inventories (e.g. van der Werf et al., 2010). LPJ-SPITFIRE has also been tested in selected regions using EO data on burnt area in southern Africa (Gomez-Dans et al., 2009), northern Australia, Borneo, western USA and Russia (Spessa et al., 2008) and Amazonia (Thonicke et al., 2009).

EO data are not only invaluable for testing model outputs (e.g. numbers of fires, and area burnt), but the increased sophistication of EO products in terms of the variables measured,

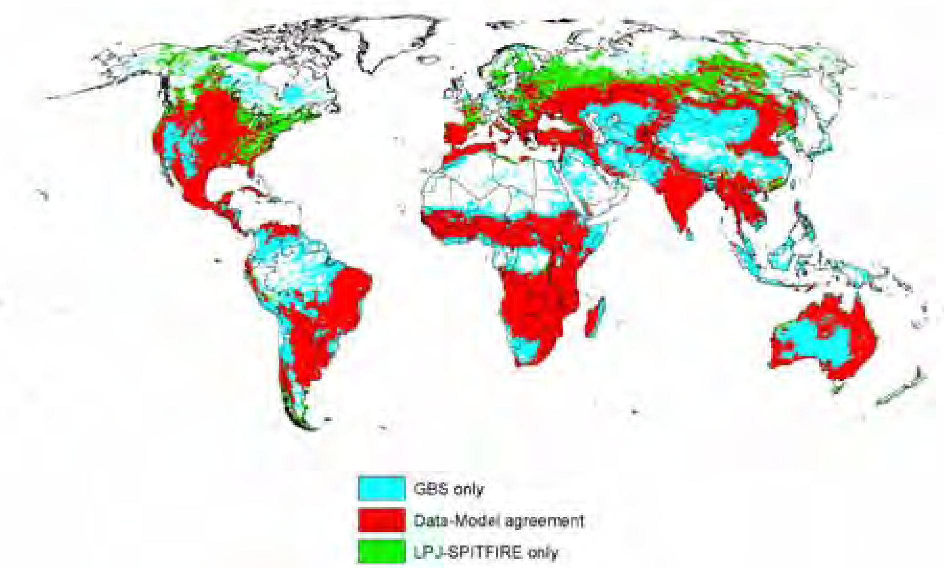

Figure 14.2. Comparison of simulated and observed area burnt based on a standard global LPJ-SPITFIRE simulation (Thonicke et al., 2010) and the GBS burnt area product covering 1982-99 (Carmona-Moreno et al., 2005). Data-model agreement (red): GBS detects fire and LPJ-SPITFIRE simulates area burnt greater than zero; area burnt detected by GBS only, but not LPJ-SPITFIRE (blue); area burnt simulated by LPJ-SPITFIRE only (green).

accuracy, temporal resolution and duration now enable the testing of individual components of the fire model, such as the simulation of fire rate of spread and fire intensity, in ways not possible only relatively few years ago (e.g. Dasgupta et al., 2006, 2007). Furthermore, many climate-related driving variables now have EO based analogues (e.g. land surface temperature, fuel moisture indices) that may assist greatly in the calculation of fire danger indices that currently rely on rather course scale interpolations of standard meteorological products or climate model outputs (Hao and Qu, 2007).

Wildland fires result in a wide variety of characteristic spectral signature changes that can be detected by remote sensing, including those related to the intense thermal emission from combustion (Lentile et al., 2006; Ichoku et al., 2003), to the albedo and spectral reflectance changes induced by burning, and to the presence of trace gas and aerosols smoke plumes (Jost et al., 2003; Trentmann et al., 2002, 2006). For these reasons, and because of the widespread, but highly variable, nature of global biomass burning activity, EO data are considered key to better characterizing the extent and influence of this phenomena and are amongst the key datasets capable of being used to test, constrain and improve models of global fire-climate-vegetation interactions. In recent years advances in using EO to better quantify and characterize biomass burning at scales from individual fire events to continental-scale fire episodes have come from the development of FRP measures from geostationary (and other) sensors in order to estimate fuel burned and emissions released (Roberts et al., 2005; Wooster et al., 2005), and (ii) new methods to estimate daily burnt area and severity (Roy et al., 2005, 2008). Furthermore, the lengthening data records from high quality instruments such as MODIS and the ATSR series of sensors are now capable of capturing the widely varying nature of fire activity and its response to variations in climate (van der Werf et al., 2010) making the validation and optimization of global-scale fire-climate vegetation models more feasible than was the case previously with the more limited EO data records.

In addition to these active fire and post-fire measures, the model-forcing data are now much improved in the EOS (post-2000) era, with remotely derived measures of LAI, soil and vegetation moisture and land surface temperature now routinely produced from optical, microwave and thermal infrared sensors. With improved processing of historical data and nearly seven years of EOS-era observations, it is now particularly timely to exploit these advances to further develop and test regional- and global-scale fire models. Whilst the long-term future of all such observations is not yet secured, coordinating bodies such as the GOFC-GOLD Fire Implementation Team are making particular efforts in this area, as well as coordinating products, protocols and validation efforts.

The NERC-funded FireMAFS (Fire Modelling and Forecasting System) project (2008-2010) focused on systematic evaluation of the SPITFIRE fire model (Wooster et al., 2010). The project used climate fields from monthly CRU TS 3.0[8] and daily ERA interim data[9] to drive LPJ-DGVM-SPITFIRE to predict fire activity, fire intensity and emissions from biomass burning in several case study regions notably southern Africa, northern Australia, Indonesia, Amazonia, Russia and Canada. The project utilized parameter calibration / optimization techniques to test and improve the fire model. However, poor prediction of vegetation cover and biomass by LPJ-DGVM in some regions challenged this work. A solution was found to circumvent these shortcomings in the LPJ-DGVM by using MODIS data on vegetation cover to help initialize and constrain the vegetation model, which resulted in improved predicted fuel dynamics and litter moisture from model. This constraint exercise further permitted an improved calibration of parameters in SPITFIRE (based on Markov Chain Monte Carlo (MCMC) techniques and using MODIS burnt area data). In turn, this calibration exercise led to an improved prediction of burnt area by SPITFIRE (Gomez-Dans et al., in review).

Future Priorities for Model Improvement from an Earth System Perspective

The need for process-based fire-vegetation models to assess future impacts of climate change and land cover/land use change on fire activity and emissions from biomass burning is clear. We should not only be striving to improve the accuracy of current models but also increase their bio-physical realism. Growing attention is being given to positive feedbacks in the

8 http://badc.nerc.ac.uk/data/cru/

9 http://www.ecmwf.int/research/era/do/get/era-interim

earth system because of their potential to accelerate the effects of CO_2-induced changes to global and regional climates (Denham et al., 2007). A good example is the burning of forests in Amazonia to clear for agriculture, which is likely to continue into the future. The consequences of these impacts will cause global CO_2 to rise and regional rainfall to decrease, which in turn, could lead to high temperatures and lower humidity- both of which are conducive to even more fire (Cochrane, 2003; 2009). In parallel, the strong coupling between drought and fire activity / deforestation in Indonesia points towards a positive climate-carbon feedback since climate change is thought to enhance drought conditions here in the future (Li et al., 2007), increasing future CO_2 and CH_4 levels (van der Werf et al., 2008). Potential natural vegetation may then adapt to a drier and more seasonal climate, implying that ecosystems developing towards a new climate-vegetation state will become more fire prone, possibly fire adapted, and characterized by a carbon storage potential lower than the rainforest ecosystems they replace.

To study such feedbacks and predict their consequences, increased effort should be directed at implementing and running fire-vegetation models within fully coupled earth system models (containing in one form or another: a land surface model, an atmospheric chemistry model, a global circulation model (GCM), a bio-physical model of the ocean and ice). Figure 14.3 illustrates the importance of fire is in terms of earth system functioning, and the broad range of complex processes involved.

However, earth system modeling is still in its infancy, and the range of fire feedbacks described in Figure 3, to the best of our knowledge, have never been previously analyzed as part of an earth system model. One example of an earth system model project in which fire features prominently is the EMAC-LPJ-GUESS-SPITFIRE project, started in mid-2011 and scheduled for completion in 2014. This project involves the Max Planck Institute for Chemistry in Mainz, the Biodiversity and Climate Research Centre (BiK-F) and University of Mainz. The main aim of this project is investigate how emissions from wildfires and vegetation affect the carbon cycle, reactive gases production, and aerosol production; and how these effects interact with atmospheric chemistry and climate. The project combines existing coupled climate-atmospheric chemistry-aerosols model (EMAC) (Joeckel et al., 2006, 2008, 2010; Tost et al., 2007)[10] with state-of-the-art process-based models of i) vegetation/ forest dynamics (LPJ-GUESS) (Smith et al., 2001, 2011; Hickler et al., 2006, 2008)[11]; and ii) fire disturbances and emissions of trace gases and aerosols from wildfires (SPITFIRE) (Thonicke et al., 2010).

To quantify and predict the range of potentially important feedbacks shown in Figure 14.3, we believe the following processes/components need to be implemented in future coupled fire-vegetation models set within an earth system model. This is not an exhaustive list but rather a list of key areas in which improvements to the modeling should focus. The key areas identified are based on our collective knowledge of working with EO fire data,

10 http://www.messy-interface.org

11 http://www.nateko.lu.se/lpj-guess/lpj_guess_main.html

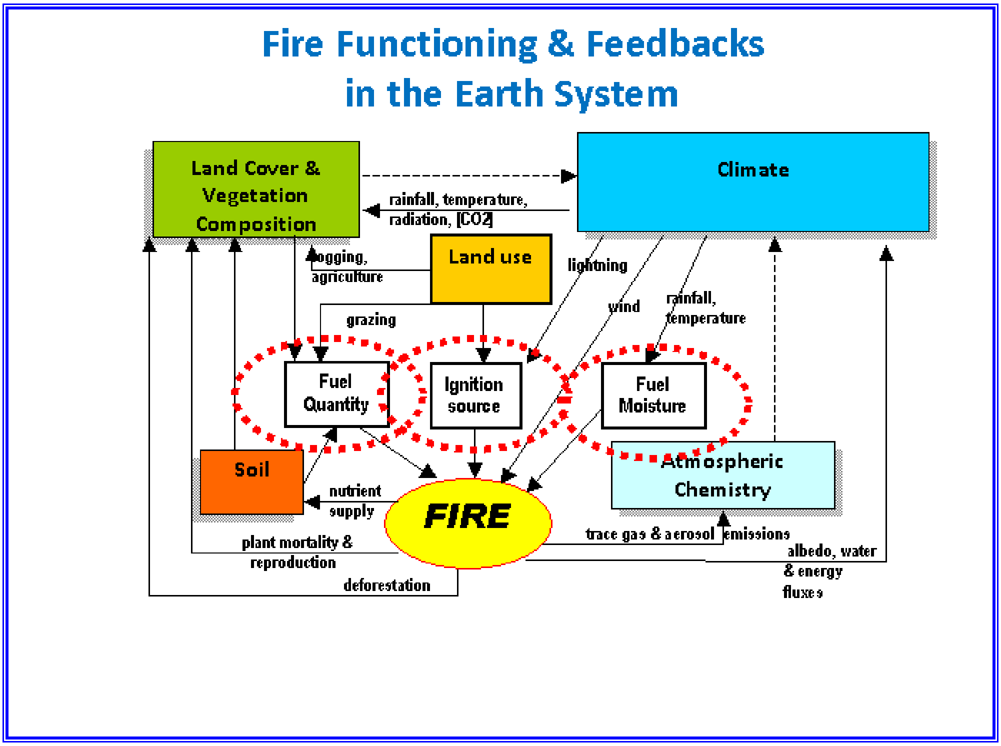

Figure 14.3. Fire functioning and feedbacks in the earth system, illustrating the three fundamental requisites for fire to occur: i) a sufficient amount of fuel, ii) sufficiently dry enough fuel; and iii) an ignition source.

process-based fire models, process-based vegetation models and earth system models. The principles discussed should generally apply to other modeling systems.

One, simulation of anthropogenic ignitions should take better account of the demographic and socio-economic factors driving them. Close to 100% of all wildfire in Africa are caused by humans (Saarnak, 2001), and a similar situation exists in respect of wildfires in the deforested areas of the tropics (van der Werf et al., 2008), Russia (Mollicone et al., 2006) and elsewhere. Currently the number of human-caused ignitions in SPITFIRE is simulated as a simple non-linear function of population density (Thonicke et al., 2010). The shape of this curve may be different for each gridcell, and is controlled by a single parameter derived from observed fire activity data (as opposed to burnt area data), and the observed length of the fire season. In future, however, ignitions forecasting should move towards a more explicit account of factors affecting ignitions – both proximate (e.g. land use, distance from secondary roads, population centres, logging coups (Cochrane et al., 1999; Chuvieco et al., 2008; Cardoso et al., 2009), and ultimate (e.g. agricultural and timber commodity prices) (Hooijer et al., 2006; Morton et al., 2006; Arima et al., 2007). One recent advance in this direction is the statistical analysis of Archibald et al. (2008). Although, this and similar analyses work at a different scale than typical DGVMs, and thus their results are difficult to directly incorporate into DGVMs. Another disadvantage is that statistical analyses often use land use parameter which are not available in projections for future climate scenarios which in turn further limits their applicability. Recently, Pfeiffer et al. (2013) describe a new representation in SPITFIRE for simulating anthropogenic biomass burning under preindustrial conditions that distinguishes the different relationships between humans and fire among hunter-gatherers, pastoralists, and farmers. While this new work resulted in improved fire simulations versus the original SPITFIRE model, it is largely empirical-based. Capturing the immense diversity of human–fire interactions at different spatio-temporal scales as part of future process-based models remains a major challenge.

Two, simulation of lightning-caused ignitions should always take into account that lightning flash frequencies are highly dependent on climate conditions. It is well known that lightning from dry thunderstorms can be a significant cause of fires in the tropical savannas during the dry-wet season transition (Williams et al., 2002) and in several other regions, notably western USA (Marlon et al., 2009), Russia (Suhkinin et al., 2004) and Canada (Fauria and Johnson, 2006). Further, climate model simulations suggest that lightning strike activity could, under certain conditions, become more prevalent in certain regions (Flannigan et al., 2005). Allen and Pickering (2002) reported a close relationship between flash rate and upward convective mass flux (MFLUX), and that MFLUX-based flash rates are most realistic compared with other indices of convective activity. Tost et al. (2007) assessed several combinations of state-of-the-art convection and lightning parameterizations used in simulations with the global atmospheric chemistry general circulation model ECHAM5/MESSy, against lightning observations. They concluded that a scheme based on cloud top height (CTH), which is related to convection, generally yielded more reliable results. Pfeiffer et al. (2013) implemented a new lightning-caused ignitions algorithm in SPITFIRE by scaling observed mean lightning flash rates (after Christian et al., 2003) with monthly anomalies of convective available potential energy (CAPE). This resulted in improved simulations natural fire occurrence compared with the original SPITFIRE. These studies indicate that simulating lightning flash rates as a function of convection-related variables is essential.

Three, landscape heterogeneity affects fire spread. A vast and growing body of remotely sensed data highlights the large-scale deforestation and fragmentation of natural forests that is occurring from the tropics to the boreal zone (Shvidenko et al., 2005). Further, the alarming prognosis is that this is likely to worsen in future as demand for agricultural and timber resources increases (Shvidenko et al., 2005). We know that as forest fragmentation changes, fire rate of spread and thus the amount of area burnt and emitted to the atmosphere is also likely to change (Siegert et al., 2001; Cochrane et al., 1999, 2002, 2003). Forest fragmentation can act as an impedance to fire spread, effectively reducing rate of spread. On the other hand, logging and fires in areas not usually subject to fires can create conditions that encourage future fires because of incursions by pyrophytic grass and woody shrubs which, in turn, lead to higher fine fuel loads and drier fuels surrounding the forest. Logging is also the first stage of land degradation from rain forest via a slash and burn culture to open areas with low productivity. Forest fragmentation also reduces the perimeter-to-area ratios of forest remnants further exposing them to fires from agricultural lands. Landscape fragmentation metrics derived from higher spatial resolution satellite data could be used to test how these affect rate of fire spread gained from MODIS or similar EO products. However, the quantification of these potential effects within a fire modeling framework remains a very complex and hitherto unexplored research question.

Four, previous fire modeling studies (either process- or inventory-based) have assumed constant emission factors (EFs) when simulating emissions of trace gases and aerosols from biomass burning (e.g. van der Werf et al., 2010; Thonicke et al., 2010). However, wildfires are characterized by two main forms of combustion– flaming and smoldering combustion; which implies that variable EFs should be used. It is the relative mix of these two types of combustion that generate the mix of species emitted from biomass burning. Flaming combustion or oxidation-type combustion reactions (e.g. production of CO_2, NOx) proceed at a faster rate when the fuel is dry and has a large surface-area-to-volume (SAV) ratio. The converse holds for smoldering combustion or reduction-type reactions (CO, CH_4 etc). A good example is the tropical savannas in which early dry season burns produce a higher CO/CO_2 ratio than those during the late dry season. If we are to realistically model trace gas and aerosol emissions from biomass burning, this problem needs to be resolved. Building on the methodology of Andreae and Merlet (2001), Korontzi (2005), van der Werf et al. (2010) and others, and recognizing that finer dry fuels burn more efficiently than coarser wetter fuels, first steps have been made towards to fixing this problem in SPITFIRE (Spessa et al., in progress) and in the GFED (van der Werf et al., in progress).

Five, forest crown fires are an important phenomenon in many regions in terms of its impact on tree mortality, and emissions of trace gases to the upper troposphere (Pyne et al., 1996). Further, pyro-cumulonimbus clouds associated with thunderstorms in the area of a severe forest fire can have its vertical lift enhanced to boost smoke, soot and other particulate matter as high as the lower stratosphere (Rosenfeld et al., 2007). While none of the current fire-vegetation models simulates active crown fires, LPJ-GUESS and ED unlike LPJ and other 'traditional' DGVMs are able to track heights of different patches of forests caused by different disturbance histories. Thus, in principle, LPJ-GUESS and ED would not need to be radically altered to account for crown fires. Nonetheless, crown fires are a complex phenomena, dependent on non steady-state weather conditions which are poorly resolved at the daily time step resolutions we normally run coupled fire-vegetation models in off-line mode, and which are often themselves caused by the large convective forces generated by such fires (van Wagner, 1977; Pyne et al., 1996; Finney, 1998; Scott and Reinhardt, 2001; Butler et al., 2004). Like other GCMs, HadGAM1 simulates weather on a half hourly time step- a scale that is more relevant to crown fires initiation and spread, but its resolution like most of its contemporaries is very low (~150kms). While this is likely to improve to 90 km with the next generation of models, fine scale weather changes remain a significant challenge to simulating crown fires as part of earth system models. Recent efforts to parameterize GCMs to better account for wind sheer and convective buoyancy fluxes at finer scales as part of extreme weather prediction (e.g. Shaffery et al., 2008) offers hope for the immediate future, however.

A coupled atmosphere-wildland fire simulation model has been developed in the last decade by the National Centre for Atmospheric Research (NCAR) to represent the complex interactions between fires and local winds (Clark and Hall, 1996; Clark et al., 2004; Coen, 2005). This coupled atmosphere-fire model is composed of a wildfire simulation model, based on the Rothermel fire rate of spread equation (Rothermel, 1972) driven by prescribed fuel load and structure, that has been embedded within the Clark-Hall atmospheric numerical model. The atmosphere and fire are fully coupled in that evolving modeled atmospheric information is used to drive the propagation of the fire line, and the sensible and latent heat from the fire model is released into the modeled atmosphere, greatly changing the atmospheric motions, creating strong convective updrafts, convergence near the surface, and strong near surface winds that, in turn, determine the spread rate and direction of the fire (Coen, 2005). Current work is focusing on embedding the atmosphere-fire model within the Weather Research and Forecasting Model (WRF), which is used for both research and operational weather prediction (Michalakes et al., 2000), by parameterizing weather processes at 1km resolution or less.

Six, none of the fire-vegetation models currently considers peat fires. This gap needs to be redressed because peat fires are emerging as a global threat with significant economic, social and ecological impacts. About 60% of the world's wetlands are peat, and the distribution of peats ranges from the tropics to the boreal zone (Flannigan and de Groot, 2009). Peat has high carbon content and can burn under low moisture conditions. Once ignited by the presence of a heat source (e.g. a wildfire penetrating the subsurface), it smolders. These smoldering fires can burn undetected for very long periods of time (months, years) propagating slowly through the underground peat layer.

Recent burning of peat bogs in Indonesia, with their large and deep growths containing more than 50-60 Pg C (Jaenicke et al., 2008), has contributed to increases in global CO_2 levels (Page et al., 2002; van der Werf et al., 2008, 2010; Spessa et al. 2010; cf. Page et al. (this volume, Chapter 7). Currently, peatland forests in Southeast Asia are at serious risk from unsustainable land use practices (notably drainage for agriculture and plantations, and wild fires); and could be completely degraded or destroyed over the next century (Hooijer et al., 2006). During the El Niño-induced drought of 1997, it is estimated that peat and forest fires released between 0.81 and 2.57 Pg C. This is equivalent to 13-40 percent of the average annual amount released by global burning of fossil fuels during the 1990s, and greater than the carbon uptake of the world's biosphere (Page et al., 2002). Recent work by van der Werf et al. (2008) show that other El Niño events during the past decade have also caused large spikes in emissions from peat fires in south east Asia. Spessa et al. (2010) highlight the complex interplay between El Niño-driven drought and deforestation in driving fire activity and emissions in the region, which have important implications for predicting climate change impacts there. Several global and regional climate modeling studies have reported that equatorial SE Asia, including Borneo, will experience reduced rainfall in future decades (e.g. Li et al., 2007). At the same time, demands for establishing pulp paper and palm oil plantations to replace native rainforests, especially on peat lands where tenure conflicts among land owners tend to be minimal, is forecast to increase. These joint scenarios imply even more fires and emissions in future.

Between 70-100 Pg of carbon are estimated to stored in circumpolar boreal peatlands (Flannigan and de Groot, 2009). Recent climate change projections concerning high latitude regions forecast increased melting of permafrost (Solomon et al., 2007) and decreased soil moisture (Dai, 2010). Although climate change projections for the high latitudes are subject to high levels of uncertainty, these projections suggest that peat fires in the boreal zone will become more common, and the associated emissions from such fires will increase (Flannigan and de Groot, 2009).

A wetlands/peat module would be a necessary precursor to implementing boreal and tropical peat fires in GUESS-SPITFIRE. Work has recently commenced on implementing wetlands in LPJ-GUESS, including new Plant Functional Types (PFTs) and processes pertaining specifically to their biogeochemistry and hydrology, based on studies by Woesten et al. (2008) and Wania et al. (2009a, b; 2010) (Ben Smith, pers. comm.). While accounting for depth of peat burning under different soil moisture conditions is not a straightforward task; previous work offers a guide. Frandsen (1987) calculated burn depth as a function of moisture, inorganic content and organic bulk density for a sample of organic soils in Canada. Ballhorn and Siegert (2009) have done similar work for the peatlands of Kalimantan and Sumatra. In both works, moisture content seems to be the main driving variable controlling burn depth. Since moisture content increases with increasing depth from surface, one could theoretically use SPITFIRE to simulate above ground spread of fire, and then, if a surface fire is simulated, use the moisture content of the organic soil at successive levels to determine depth of burn, and thus the amount of peat combusted. However, the challenge remains as to how best to simulate peat fires at the coarse resolution of an earth system model.

Conclusions

- Fires have been known to be a major source of trace gases and aerosols, for some species rivaling the amounts emitted by fossil fuel combustion.
- Improved satellite data and sophisticated biogeochemical modeling enables emissions assessments on a global scale with fine spatial and temporal resolution. Emissions estimates are still comparable to those based on older inventory-based techniques, but uncertainties remain large.
- Fires increase during El Niño periods because parts of the tropics where humans use fire as a tool for deforestation experience drought conditions. These spikes contribute to the inter-annual variability of CO_2 and CH_4 observed in the atmosphere.

- There is no alternative to the use of process-based coupled fire-vegetation models for the assessment of future fire regimes and emissions under changing climate, vegetation and/or land use, and the assessment of fire management strategies. Though their development is still at an early stage, this modeling approach is the only one that can be used in a predictive rather than a descriptive way.
- Recently developed dynamic fire-vegetation models are capable of simulating the extent of wildfires as well as their emissions of CO_2 and other greenhouse gases for ambient as well as for projected climatic conditions.
- The performance of fire-vegetation models however needs to be strongly improved and validated by field studies investigating the processes leading to emissions as well as by remotely sensed approaches linking recent climate with vegetation, fires and burned areas as well as by socio-geographic studies.
- Wildfires in their effect as well as in their origin can have a high socio-geographic component (e.g. in Africa, deforested areas of the tropics and Western Russia). On the other hand, lightning-caused fires can also be significant (e.g. in western USA, Canada, northern boreal Eurasia and northern Australia), and as such, also need to be taken into account by fire-vegetation models where appropriate.
- Further improvements to fire-vegetation models should not only focus on ignitions, but also: the way fire spreads through a heterogeneous landscape; fire-induced tree mortality and fire-induced ecological succession; crown fires; bio-climatically sensitive emission factors; and the mounting problem of peat fires in Indonesia and the boreal zone.

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15 Modeling Future Wildland Fire in the Circumboreal

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Abstract

Wildland fire is a key process influencing the structure and function of the circumboreal forest which covers 1.2 billion ha in northern Eurasia and North America. Fire activity in the circumboreal responds dynamically to the weather/climate, fuels, and people. Recently, our climate has been warming as a result of increases of radiatively active gases (carbon dioxide, methane etc.) in the atmosphere from human activities. Such warming is likely to have a rapid and profound impact on fire activity, as will potential changes in precipitation, atmospheric moisture, wind, and cloudiness. Vegetation patterns, and thus fuels for fire, will change in the future due to both direct effects of climate change and indirectly as a result of changing fire regimes. Overall, we expect that fire activity will continue to increase due to climate change. It appears that fire weather, area burned, and fire occurrence are generally increasing, but there will be regions with no change and regions with decreases in the circumboreal forest. Some of the increases in area burned are expected to be significant with increases of 6 times the observed area burned by the end of this century. The length of the fire season appears to be increasing already and should continue to lengthen in the future. Fire intensity and severity are more difficult to summarize and this is an area in need of further research. Humans will continue to be a crucial element of fire activity in the future through fire management, human-caused fire ignitions, and land-use. In the future, changes in weather/climate, fuels, and people and the non-linear, complex and sometimes poorly understood interactions among these factors will determine fire activity.

Keywords: Climate models, Canadian Forest Fire Weather Index System, fire weather, fire severity, lightning-caused fires

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Future Fire Activity

Fire activity responds dynamically to the weather/climate, fuels, and people. Recently, our climate has been warming as a result of increases of radiatively active gases (carbon dioxide, methane etc.) in the atmosphere from human activities (IPCC, 2007). Such warming is likely to have a rapid and profound impact on fire activity, as will potential changes in precipitation, atmospheric moisture, wind, and cloudiness (Flannigan et al., 2006; IPCC, 2007). Vegetation patterns, and thus fuels for fire, will change in the future due to both direct effects of climate change and indirectly as a result of changing fire regimes (Soja et al., 2007). Humans will continue to be a crucial element of fire activity in the future through fire management, human-caused fire ignitions, and land-use. In the future, changes in weather/climate, fuels, and people and the non-linear, complex and sometimes poorly understood interactions among these factors will determine fire activity. Table 15.1 (Annex) summarizes the literature with respect to the potential future fire weather, area burned, fire occurrence, fire season, fire intensity, and fire severity in the circumboreal forest, which covers 1.2 billion hectares in northern Eurasia and North America (Soja et al., 2007).

Fire Weather

Fire weather is defined as the weather variables that influence fire behaviour, ignition, and suppression. These variables include temperature, precipitation, humidity, and wind. These weather factors are predicted to change for much of the world (IPCC 2007), and thus fire weather can be expected to be affected by climate change.

More severe and extreme fire weather is predicted by $2\times CO_2$ and $3\times CO_2$ climate models in the circumboreal forest, with increases in the seasonal severity rating (SSR; a rating index to provide a measure of fire control difficulty and is a component of the Canadian Forest Fire Weather Index System) of up to 50% (Flannigan and Van Wagner, 1991; Stocks et al., 1998; Flannigan et al., 2000; Kochtubajda et al., 2006). Changes in fire weather are predicted to be highly variable depending on location. For example, Flannigan et al. (1998) predict that the fire weather index (FWI; a rating of fire danger that incorporates temperature, humidity, wind speed, and precipitation) may decrease in eastern Canada, western Canada, and most of northern Europe (Sweden, Finland, and western Russia); increases are expected in southern Sweden and Finland and throughout central Canada. Other studies focusing on the Canadian boreal forest found that the FWI will decrease for some of eastern Canada, but increase for most of the rest of the country in a $2\times CO_2$ climate (Bergeron and Flannigan, 1995; Amiro et al., 2001; Flannigan et al., 2001). In the Russian boreal forest, it has been predicted that areas of maximum fire danger risk will double by 2050, and changes will vary spatially across the country (Malevsky-Malevich et al., 2008). Hansen et al. (2012) show that the likelihood of extreme seasonal mean temperatures has increased significantly since the 1951-1980 base period and suggests that the extreme anomalies in Russia 2010 and Texas and Oklahoma in 2011 are a consequence of global warming. It is interesting to note that extreme fire activity was associated with this period of extreme heat in Russia and central U.S.A. Also, Dai (2012) demonstrates that increasing drought has been observed, and some GCMs suggest more severe and widespread droughts in the future under global warming.

Area burned

Flannigan and Van Wagner (1991) compared SSR from a 2×CO_2 scenario (mid 21st century) versus the 1×CO_2 scenario (approx. present day) across Canada. The results suggest increases in the SSR across all of Canada with an average increase of nearly 50%, translating roughly to a 50% increase of area burned by wildfire. Bergeron et al. (2004) suggest increases in area burned for most sites across Canada by the middle or end of this century, although some sites in eastern Canada were projected to have no change or even a decrease. Area burned was projected to increase by as much as 5.7 times the present values, but for many sites the historical area burned (1600s to near present) was higher than estimated future fire activity (Bergeron et al., 2004). This comparison emphasizes the need to temper our thoughts on changes in fire to include a broad temporal context. Flannigan et al. (2005) used historical relationships between weather/fire danger and area burned in tandem with two global circulation models (GCM) to estimate future area burned in Canada and suggest an increase of 74-118% in area burned by the end of this century (Fig. 15.1). Using a dynamic global vegetation model (DGVM) to examine climate, fire, and ecosystem interactions in Alaska, Bachelet et al. (2005) suggest area burned increases of 14-34% for 2025-2099 relative to 1922-1996. McCoy and Burn (2005) predict mean annual area burned in the Yukon to increase 33% and maximum annual area burned to increase 227%. In boreal Alberta, Tymstra et al. (2007) suggest area burned increases of about 13% and 29% for 2× and 3×CO_2 scenarios relative to the 1×CO_2 scenario using a fire growth model with output from the Canadian Regional Climate Model (RCM). Using air temperature and fuel moisture codes from the Canadian Forest Fire Weather Index System, Balshi et al. (2008) suggest decadal area burned for western boreal North America will double by 2041-2050 and will increase in the order of 3.5 to 5.5 times by the last decade of the 21st century as compared to 1991-2000. Amiro et al. (2009) predict that in a 3×CO_2 situation, area burned will double from current levels in the Canadian boreal forest. Other recent studies have shown that area burned may increase in the boreal forest from anywhere between 1.2 and 8 times (Drever et al., 2009; Krawchuk et al., 2009b).

Numerous studies suggest that temperature is the most important variable affecting annual wildland fire activity, with warmer temperatures leading to increased fire activity (Parisien et al., 2011). Gillett et al. (2004) suggest that the increase in area burned in Canada over the past four decades is due to human-caused increases in temperatures. The reason for the positive relationship between temperature and wildland fire is three-fold. First, warmer temperatures will increase evapotranspiration, as the ability for the atmosphere to hold moisture increases rapidly with higher temperatures, thereby lowering water table position and decreasing fuel moisture unless there are significant increases in precipitation. Second, warmer temperatures translate into more lightning activity that generally leads to increased ignitions (Price and Rind, 1994). Third, warmer temperatures may lead to a lengthening of the fire season (Westerling et al., 2006). While testing the sensitivity of landscape fire models to climate change and other factors, Cary et al. (2006) found that area burned increased with higher temperatures. This increase was present even when precipitation was increased, although the increase in area burned was greatest for the warmer and drier scenario. The bottom line is that we expect more area burned in a warmer world.

Fire occurrence

Similar to area burned, changes in climate will influence future fire occurrence5 through myriad pathways that involve weather conditions conducive to combustion, fuels to burn, and ignition agents. The majority of wildfires are ignited by lightning strike or by humans; volcanoes start few fires and only in select parts of the world. Lightning-caused fire contributes to the majority of fire occurrence in relatively few parts of the world, such as remote areas of boreal North America (Stocks et al., 2003). This high relative proportion of lightning-caused fires in these remote northern landscapes is simply a result of extremely low population density; overall both lightning strike density and resulting lightning fire density tend generally to decrease within increasing latitude through much of the boreal forest zone following the general trends of decreasing average air temperature. Humans are the main agents of fire across most of the planet. Changes in climate may have little direct influence on human behaviour, however changes in vegetation, fuel moisture and fire weather caused by climate change may alter the ease of fire ignition and success of fire suppression by humans. Changes in fire-related policy including development in the wildland-urban interface, fire management in wilderness areas, social awareness of fire risks, forest and agricultural management will have very large impacts on human-caused fire occurrence alongside global climate change (Moritz and Stephens, 2008).

In regions of the globe where fuels to burn are abundant such as forests or shrublands, a reasonable method to project future fire occurrence is to relate observed fires (either human-caused or lightning caused) to fire weather conditions using statistical models, then use these models with climate data from GCMs or RCMs to project fire occurrence in the future. Many studies have examined the influence of fire weather and fuel moisture on fire occurrence itself (e.g. Martell et al., 1987, 1989; Wotton and Martell, 2005; Drever et al., 2006; Krawchuk et al., 2006). There are few studies that have used these fire-weather relationships to then project future fire occurrence. For example, in the mixedwood boreal forest of central-eastern Alberta, Krawchuk et al. (2009b) projected regional increases in lightning-caused fire occurrence through the 21st century, showing an expected 80% increase in initiation. Wotton et al. (2003) projected an increase in human-caused fires in Ontario of 50% by the end of the 21st century in association with climate change; though an overall increase

5 Fire occurrence is a relatively simple measure of fire activity that quantifies the presence or absence of an event. Here, we define fire occurrence analogously to fire initiation: the sustainability of flaming ignition that results in the origin and detection of a fire.

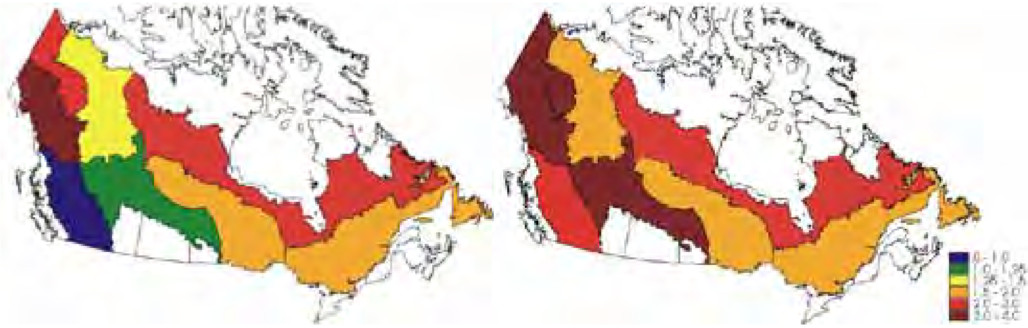

Figure 15.1. Ratio of $3\times CO2/1\times CO_2$ area burned by Ecozone using the Canadian General Circulation Model (GCM), and Hadley GCM respectively. The area burned model did not work for Ecozone 14 with the Canadian GCM.

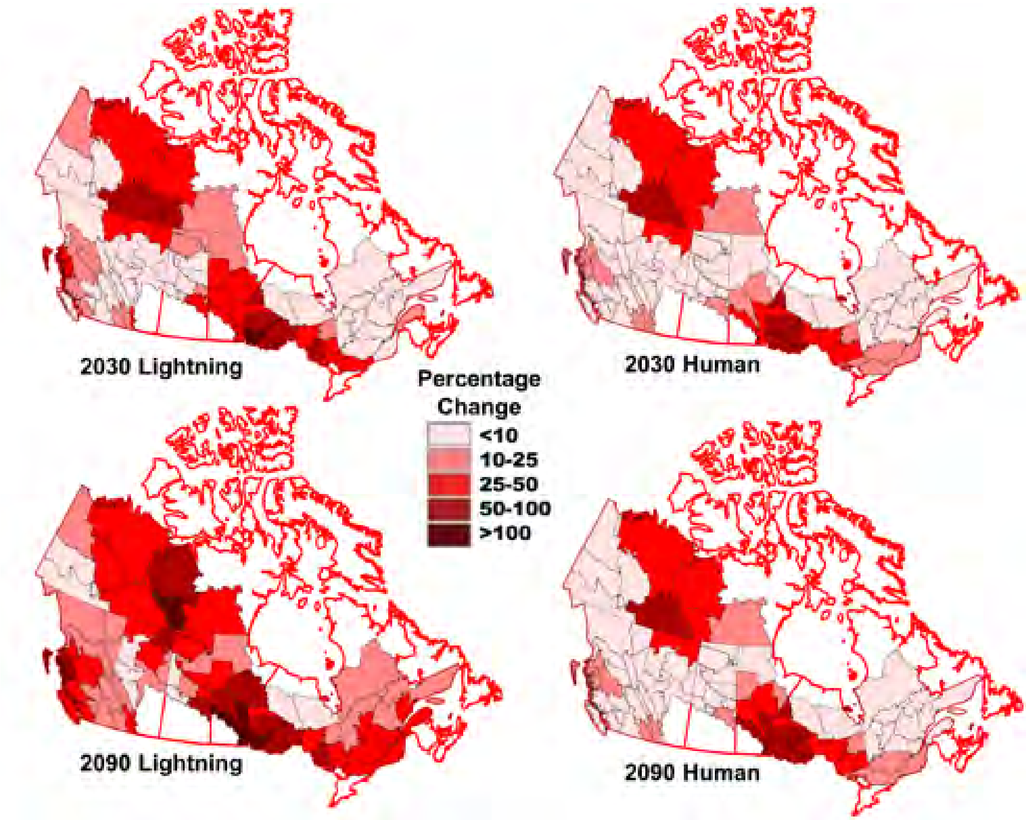

Figure 15.2. Relative change (percentage increase) in fire occurrence between future and baseline scenarios for the Canadian Climate Centre GCM. Relative change is given as the percentage increase in number of fires predicted by the GCM (future scenario minus baseline scenario) divided by the total number of fires in the baseline scenario (i.e., (N2020-2040 – N1975-1995) / N1975-1995); "no data" is shown in white.

in fire was projected, there were areas where less severe conditions and reduced fire occurrence were projected. At a much broader scale, both human and lightning-caused fire was examined across the entire forested area of Canada (Wotton et al., 2010). Those results suggest that there was general consistency in the prediction that temperature increases typically balance or outweigh precipitation increases leading to overall drier fuels and increased fire occurrence; there was however also significant regional variation in the change in future fire occurrence rates compared to current levels (Fig. 15.2). Fire occurrence in the boreal forest of Russia has been predicted to increase, with up to 12 more days per year with high fire danger (a component of which is fire occurrence) (Malevsky-Malevich et al., 2008). Overall, there is significant spatial variability in predicted changes in fire occurrence, with areas of increases, decreases, or no change expected across the circumboreal forest (Bergeron et al., 2004; Scholze et al., 2006; Balshi et al., 2008; Krawchuk et al., 2009a).

Fire season

In boreal and many temperate forests there is a distinct fire season during spring and summer. Most fire agencies in Canada consider the fire season to operate from the start of April until the end of October, but expect little activity past the end of August. Climate change research using General Circulation Models (GCM) outputs in the boreal forest of North America and Russia have shown an extension of conditions conducive to fire ignition and spread at both the start and end of the fire season (Wotton and Flannigan, 1993; Stocks et al., 1998; Kochtubajda et al., 2006). These studies have shown that the fire season may increase by up to 50 days in some areas of the boreal forest, depending on the model and climatic scenario used (Wotton and Flannigan, 1993; Kochtubajda et al., 2006). Changes in fire season will have implications for fire management, fire behavior, and fire ecology. More research needs to be done to better predict future changes.

Fire intensity

Fire intensity is a measure of energy output and is a function of the fuel load burning and the fire weather conditions under which this occurs. Given that changes in climate will affect the growth and distribution of vegetation to burn as well as weather conditions, the net result on intensity is a challenge to predict. The importance of future projections of fire intensity lies in the relationship to fire behaviour, suppression effectiveness, emissions, effects (e.g., fire severity) and feedbacks to vegetation dynamics through soil conditions and via the life history strategies of flora. In areas dominated with long-lived flora, such as trees, the effects of climate change on fire intensity are more likely to manifest through changes in fire weather conditions rather than changes in fuel load or biomass to burn. However in grassland, savanna or deserts dominated by short-lived or more episodic flora, changes in climate could promote rapid changes in biomass availability such that fire intensity of an area could be altered even with relatively little change to weather conditions of the fire season.

Relatively little work has been done to study possible changes in the intensity of fires under future conditions, and those studies demonstrate the complexity arising from the interaction of changes in biomass and weather conditions. In the western Canadian boreal forest, de Groot et al. (2003) showed that more severe burning conditions led to higher intensity fires in all forest types, using climate data from the Canadian GCM and a fire effects model of forest dynamics. In a comparison between 2080-2100 versus 1975-1990 conditions, de Groot et al. (2003) determined that increased fire intensity gave a small advantage to thicker-barked species but also led to an increase of deciduous species that resprout after fire. The latter generated a negative feedback to fire regime since a shift towards these deciduous species promotes a reduction in fire intensity, even under more severe fire weather conditions. Taking a simpler approach, Kafka et al. (2001) studied changes in fire intensity for boreal forests of Saskatchewan using static fuel data and changing fire weather projected from the Canadian RCM. Similar to de Groot et al. (2003), Kafka et al. (2001) calculated an overall increase in fire intensity in $2\times CO_2$ conditions with significant spatial variation due to the interaction and heterogeneity of fuel types and weather. Alongside climate-mediated changes, future fire intensity will also be influenced by management decisions through the reduction or accumulation of fuel load (Shang et al., 2007).

Fire severity

Very little research has been done on the effects of climate change on fire severity6. Under future climate scenarios of $2\times CO_2$ (Amiro et al., 2009) and $3\times CO_2$ (de Groot et al., 2003; Amiro et al., 2009) using the Canadian GCM fire severity in boreal Canada was found to be greater than the $1\times CO_2$ scenario. However, Amiro et al. (2009) found the increase in ground fuel consumed due to increased severity (0-18%) was small in comparison to the total increase in fuel consumption due to the increase in future area burned. Future fire severity could additionally increase or decrease if there is a shift in the fire season. Ground fuels are generally wettest early in the fire season and driest late in the fire season, leading to low fire severity in the spring and higher fire severity in the autumn (de Groot et al., 2012). A general expansion in the fire season length is expected (Wotton and Flannigan, 1993), but it is not known whether this would significantly affect the seasonal timing of the majority of area burned. Another factor that could substantially influence future fire severity is fuel load (Amiro et al., 2009), which may be affected by climate change and future human activities, but the net impact of these many factors contributing to future fuel load is unknown.

Fire Management

Wildland fire management problems are increasing globally for numerous reasons. Common global problems include the expansion of the wildland-urban interface (Cottrell, 2005; Zhang et al., 2008; Theobald and Romme, 2007), increasing fire suppression costs, and

6 The term 'fire severity' is used in different ways in the published literature. Here, it is defined as a component of the fire regime: indicating depth of burn or fuel consumption of the ground layer.

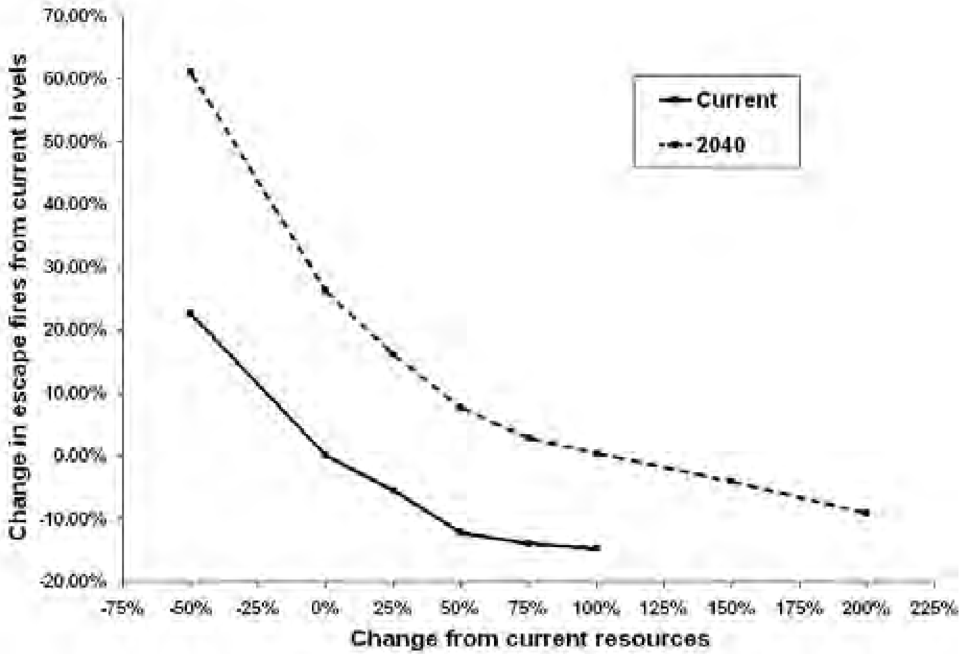

Figure 15.3. Change in the number of escape fires (from current level) with changes in resource levels for both current and 2×CO_2 climate.

increased hazardous emissions causing greater negative human health impacts. Fire management agencies worldwide also recognize the consequences of, and the contribution of fire to, climate change. Impacts of climate change on the fire environment are generally seen with the trend of increasing fire activity, particularly in the circumboreal forest (Tab. 15.1; Annex). The obvious question that arises is: can forest fire management agencies adapt and mitigate the impacts of this potential increase in fire activity through increasing resource capacity? Under climate change a disproportionate number of fires may escape initial attack, resulting in very significant increases in area burned; the reasoning behind this hypothesis is that there tends to be a very narrow range between the suppression system's success or failure (Stocks, 1993). Detailed simulation of the initial attack system of Ontario's fire management agency, which actively manages fire across approximately 50×10^6 ha of boreal forest in Canada, showed that to move the escape fire threshold down from current levels, very significant investment in resources would be required (McAlpine and Hirsch, 1998); that is, incremental increases in fire suppression resource lead to diminishing gains in initial attack success. A further study using Ontario's initial attack simulation system with future climate change scenarios of fire weather and occurrence showed that current resource levels would have to at least than double to meet even a relatively small increase (15%) in fire load

(Fig. 15.3; Wotton and Stocks, 2006). An agency's fire load threshold is not the only physical limit that might play a role in future success and failure of fire management objectives under a changed climate. Direct fire suppression methods, including high volume airtanker drops, become relatively ineffective once fires become somewhat intense crown fires. Thus, if fire intensities are to increase as suggested earlier in this paper, one can expect the number of situations when direct fire suppression activity is ineffective to increase as well. Podur and Wotton (2010) found that it was the high intensity fires that lead to strong increases in area burned. Adaptation to new fire climates may require fire agencies and the public to re-examine their current tolerance of fire on the landscape, or think beyond fire management practices of the 20th century to mitigate unwanted fire. Options such as treating fuels in the immediate vicinity of values at risk may be one of the few viable solutions available (e.g., Cary et al., 2009), along with strategically-placed landscape fuel treatments (Finney, 2007).

In the areas of the circumboreal dominated by human-caused fire, one might think increased fire prevention campaigns and enforcement of restricted fire zones might help to reduce the number of starts during high fire-potential periods. However, areas with well established fire prevention programs such as southern California still tend to have a significant human-caused fire load, though this may be due in part to the rise of arson in recent years. It is difficult to predict what changes in societal values or demographics might occur over the next century that will have a direct impact on the number of human ignition sources on the landscape. What does seem clear is that in areas where fuel is available, environmental conditions (i.e. fuel moisture) will be more conducive to ignition in the future. Without major changes in patterns of human activity or fuels, the number of fires occurring from human causes will likely increase and thus the presence of fire in high value areas, and the consequent pressure on fire management agencies to deal with this fire, will likely increase. Throughout most of the 20th century in most of the world, 'fire management' organizations tended to be fire suppression organizations, focused on fire exclusion. Today there is a recognition of the need to balance fire suppression to protect values (e.g., in the wildland-urban interface, or in high value timber production areas) with the need to let fire in wilderness areas burn. Increased fire activity due to climate change, and increased awareness of carbon emission from wildfire as well as potential newly available sources of carbon emissions, such as boreal peatlands (Flannigan et al., 2009), are added pressures that will make achieving a balance between value protection and the ecological needs for fire even more difficult for fire management agencies.

Summary

A great deal of research has been completed on wildland fire and we are beginning to understand the relationships between various aspects of fire activity and the key factors such as weather/climate, fuels, and people, along with their interactions. These factors are dynamic and will continue to change as the climate, fuels, and people respond to global change and other influences. Overall, we expect that fire activity will continue to increase due to climate change. It appears that fire weather, area burned, and fire occurrence are generally increasing, but there will be regions with no change and regions with decreases in the circumboreal forest. This spatial variation highlights the need to view the impact of climate change on fire activity in a spatially-dependent context. The length of the fire season appears to be increasing already and should continue to lengthen in the future. Fire intensity and severity are more difficult to summarize and this is an area in need of further research. There could be surprises in the future, perhaps even the near future, with respect to fire activity and this is due to our limited understanding of the interactions between weather/climate, fuels, and people.

The role of people in global fire regimes needs much more work as policy, practices, and behaviour vary across the circumboreal and with time. The more physical aspects of wildland fire have received greater attention by the research community but there are still areas that need further work including global studies that dynamically model weather, vegetation, people, fire, and other disturbances. Lastly, we require accurate data sets of fire activity. The advent of satellite sensors appropriate to monitor wildland fire has been a significant advance in terms of area burned but even those data provide a wide range of estimates, and we still do not have an accurate estimate of circumboreal fire occurrence.

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Annex: Table 15.1. Display of the generalized results of future fire studies including the fire activity metric(s) (fire weather, area burned, fire occurrence, fire season, fire intensity, and fire severity) used, the location of the study area, the projected change in the fire activity and the time period the change is expected, and the general trend (increase, +; or decrease, -) exhibited by the predicted fire activity. *For the purposes of this Table, fire danger has been included as fire weather and fire occurrence.

Fire Activity Metric	Location	Projected Change	Time Period / Scenario	General Trend	Reference
Fire weather, area burned	Canada	~40% increase due to 46% increase in severe fire weather (seasonal severity ratio, SSR).	2×CO_2	+	Flannigan and Van Wagner (1991)
Seasonality	Canada	Length will increase by an average of 22% (range of 16-39% depending on area) which is equal to 30 days (range of 24-51, depending on area).	2×CO_2	+	Wotton and Flannigan (1993)
Fire weather	Canada	Southeastern boreal forest will show a decrease in FWI; western Canada FWI will increase dramatically	2×CO_2	+/-	Bergeron and Flannigan (1995)
Fire weather	North America, Northern Europe	FWI will decrease in eastern and western Canada; FWI will increase in central North America; FWI will increase over southern Sweden and southeast Finland; remainder of northern Europe shows decreased FWI values.	2×CO_2	+/-	Flannigan et al. (1998)
Fire weather, seasonality	Canada and Russia (boreal forest)	Fire season: earlier start. Fire weather: increase in severity (monthly severity ratio (MSR) and SSR); more extreme MSR and SSR expected.	2×CO_2	+	Stocks et al. (1998)
Fire weather	North America	SSR will increase by 10–50% over most of North America.	2×CO_2	+	Flannigan et al. (2000)
Fire weather	Canada (western)	Fire weather index (FWI) predicted to increase in most of western Canada by more than 20%, with some areas of no change, and some areas of decreases	1×CO_2 vs. 2×CO_2	+/-	Amiro et al. (2001)
Fire weather	Canada (boreal forest)	Fire weather index (FWI) will decrease for some of eastern Canada, but increase for most of the rest of the country.	2×CO_2	+/-	Flannigan et al. (2001)
Intensity	Canada (boreal forest in Saskatchewan)	Increase in fire intensity at 2×CO_2; little additional change detected under 3×CO_2conditions.	2×CO_2; 3×CO_2	+	Kafka et al. (2001)
Area burned, occurrence, intensity, severity	Western Canada	Area burned: 14-137% increase (depending on location). Fire occurrence: shorter fire cycle. Fire severity: greater DOB, greater total fuel consumption. Fire intensity: greater intensity.	1975-1990 vs. 2080-2100	+	de Groot et al. (2003)
Occurrence	Canada (Ontario)	Human-caused fires could increase 18% or 50%.	Recent history vs. 2020-2040; end of 21st century	+	Wotton et al. (2003)

Fire Activity Metric	Location	Projected Change	Time Period / Scenario	General Trend	Reference
Area burned, Occurrence	Canada	Burn rate will increase on average; most areas will increase, some will decrease.	$2\times CO_2$; $3\times CO_2$	+/-	Bergeron et al. (2004)
Area burned	U.S.A. (Alaska)	Area burned to increase 14-34% (depending on scenario).	1922-1996 vs. 2025-2099	+	Bachelet et al. (2005)
Area burned	Canada	74-118% increase (range varies with location and model used).	Reference 1959-1997 vs. 2080-2099 ($3\times CO_2$)	+	Flannigan et al. (2005)
Area burned, occurrence	Canada (Yukon)	Fire occurrence: mean number of fires per year to increase 77%, maximum annual number of fires to increase 68%. Area burned: mean annual area burned to increase 33%, maximum annual area burned to increase 227%.	1960-2000 vs. 2040-2069	+	McCoy and Burn (2005)
Area burned, occurrence	Canada (Ontario)	Area burned: 31% or 78% increase. Fire occurrence: 15% or 50% increase.	Reference 2000 vs. 2040/2090	+	Wotton et al. (2005)
Area burned, occurrence	Canada (southern Quebec)	Burn rate for Quebec will increase.	$2\times CO_2$; $3\times CO_2$	+	Bergeron et al. (2006)
Fire weather, seasonality	Canada (NWT, northwest Canada)	Fire season length: average increase of 30-50 days (depending on model). Fire weather: seasonal severity rating (SSR) to increase on average 19-44% (depending on model); large spatial variability with areas of increases and some areas of no change or decreases.	$3\times CO_2$	+/-	Kochtubajda et al. (2006)
Occurrence	Global	Fire frequency will increase in some areas and decrease in others (highly variable – see paper); changes are more extreme with greater increase in temperature.	1961-1990 vs. 2071-2100	+/-	Scholze et al. (2006)
Area burned	Canada (boreal forest in Alberta)	12.9 or 29.4% increase.	$2\times CO_2$; $3\times CO_2$	+	Tymstra et al. (2007)
Area burned, occurrence	U.S.A. (Alaska) and western Canada	Area burned: 2 or 3.5-5.5 times. Fire occurrence: fire return intervals will decrease 50% in Alaska (87-103 years less between fires) and 40% in western Canada (64-69 years less).	Reference 1970-2000 vs. 2041-2050/2091-2100 for area burned; 2070-2100 for occurrence	+	Balshi et al. (2008)
Occurrence	Canada (Southern Boreal Shield)	Increase of 34-61% in the typical number of large fires.	1795-1998 vs. 1999-2100	+	Girardin and Mudelsee (2008)
Fire weather, occurrence	Russia (boreal forest)	Increase in the number of days with high fire danger* of up to 12 days, depending on location; areas of maximum fire danger risk will double by 2050.	1981-2000 vs. 2100	+	Malevsky-Malevich et al. (2008)
Area burned, severity	Canada (boreal forest)	Area burned: increase by 1/3 ($2\times CO_2$); double ($3\times CO_2$). Fire severity: increase 0-18%.	$2\times CO_2$; $3\times CO_2$	+	Amiro et al. (2009)
Area burned	Canada (Quebec)	Increase in area burned of about 1.2 to 8.0 times (depending on scenario).	1959-1999 vs. 2100	+	Drever et al. (2009)

Fire Activity Metric	Location	Projected Change	Time Period / Scenario	General Trend	Reference
Occurrence	Global	Fire-prone areas will increase in some areas and decrease in others (highly variable – see paper).	1996-2006 vs. 2010-2039, 2040-2069, 2070-2099	+/-	Krawchuk et al. (2009a)
Area burned, occurrence	Canada (mixedwood boreal forest of central-eastern Alberta)	Area burned: 1.9 ($2{\times}CO_2$) and 2.6 ($3{\times}CO_2$) fold increases. Fire occurrence: 1.5 ($2{\times}CO_2$) and 1.8-fold ($3{\times}CO_2$) increase of lightning fire initiation.	Reference 1975-1985 vs. 2040-2049 ($2{\times}CO_2$)/2080-2089 ($3{\times}CO_2$)	+	Krawchuk et al. (2009b)
Fire risk, seasonality	Canada (central Quebec)	Increases in fire risk in August (110%) but a 20% drop in risk in May. Increases in area burned, 4% 2030-2060 and 7% 2070-2100	Reference 1975-2005 vs. 2030-2060 and 2070-2100	+	Le Goff et al. (2009)
Fire weather	Canada (study area in boreal forest of Ontario/ Quebec)	Increase in monthly drought code and subsequent increases in burn rate and area burned.	1961-1999 vs. 2046-2065, 2081-2100	+	Bergeron et al. (2010)
Fire weather	Finland	Up to a 30% increase in the Finnish forest fire alarm days (based on soil moisture).	1961–1990 vs. 1991–2020, 2021–2050, 2070–2099	+	Kilpeläinen et al. (2010)
Fire season	Global	Increases in fire season length around the world.	1961-1990 vs. 2070-2100	+	Liu et al. (2010)
Area burned	Canada (Ontario)	Area burned doubling by 2040 and eight increase for the end of the 21St century	Reference 2000-2009 vs 2040-2049($2{\times}CO_2$)/2080-2089 ($3{\times}CO_2$)	+	Podur and Wotton (2010)
Occurrence	Canada	Increases of 25% by 2030 and 75% (Canadian GCM) – 140% (Hadley GCM) by the end of the 21st century.	Reference 1975-1995 vs. 2020-2040 and 2080-2100	+	Wotton et al. (2010)

16 Social Dimensions of Fire

Stephen J. Pyne[1]

Abstract

People have used fire in every setting to improve their lives. They have adapted fire for homes, buildings, factories, fields, pastures, and public wildlands. Whatever they could enhance by fire they did. They have also used fire destructively as arson, warfare, and accident. There are regular patterns to human fire practices, both geographically and historically. These remain understudied, however, for fire lacks an intellectual discipline of its own and exists as a subset of other fields. Still, there are typical patterns associated with aboriginal economies, agricultural (and pastoral) economies, and industrial economies. The latter is prime driver of fire dynamics on Earth today, as the planet divides into two grand combustion realms, one fed by surface fuels and the other by fossil fuels. The link between the various expressions of fire remains humanity.

Keywords: Aboriginal fire, industrial fire, anthropogenic fire, traditional burning, fossil biomass

Uses of Fire

There is a simple reply to the question, how has humanity used fire? People have has used fire every way imaginable in order to improve their many habitats.

They have used it in homes and factories, in fields and forests, in pastures and nature preserves. They have organized ceremonies around it, and invented myths and philosophies. The world of early hominids was a cave or *domus* illuminated and heated by fire. That remains true for industrial humanity today, although that firepower is routed through machinery. Humanity's dwellings, whether open or closed, have been worlds informed by fire.

Not all usage has been constructive. People have also used fire destructively as arson, warfare, and carelessness. Moreover, what is a good fire for one group may be condemned as a bad fire by another group that has different intentions for a landscape.

The following schema suggests some of the ways fire has been applied to the land.

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Aboriginal fire practices

Aboriginal fire is defined by control over ignition alone. People can start, and within limits, stop fires. They must reorganize their setting through such means alone through timing, frequency, location, and patterns of ignition.

Its uses:

- to hunt; by driving game or by relying on freshening vegetation to attract the sought after fauna
- to forage; by stimulating preferred plants, especially tubers and berries, and by clearing the surface of debris that makes collecting of nuts and other fallen edibles easier
- to fish; by attracting fish at night to boats or shorelines, where they can be caught
- to smoke out animals from dens and bees from hives
- to open routes of travel and to "clean up" landscapes, considered by many peoples as a duty owed their habitat
- to wage war; by attacking villages, burning landscapes of economic value to others, by obscuring fields of battle
- to protect against wild fire, whether natural or anthropogenic
- to cook foodstuffs, which enhances the nutritional value of many items and detoxifies others, and to preserve foods; by smoking, curing, or otherwise retarding spoilage

In addition, a considerable amount of "fire littering" occurs, as a byproduct of fire's attachment to human activities. Accidental burning can be a significant source of ignition. In boreal landscapes, for example, it can propagate widely and alter the mosaic of burning. In Africa and India, dropping torches used to flush bees from hives, subsequently spread through the scene, providing a regular source of benign burning.

Agricultural fire practices

Agricultural fire adds a control over fuels to control over ignition: it means people can create fuels as much as they can start fires. Such control can occur by slashing and drying vegetation, from forests to organic soils to fallowed fields; by draining wetlands, and exposing combustibles; and by otherwise altering the availability of fuels.

What water does within floodplains, fire does outside of them. It purges and promotes, which is to say, it temporarily drives off competing species and fertilizes a site. The effect is typically ephemeral – one or two years; by the third year, in the absence of aggressive weeding or other measures, the site must be abandoned or left to fallow. The rhythm of fuels determines the rhythm of burning.

Two patterns are most common. In one, shifting cultivation, the farm moves through the landscape, with a site used for one or two years before being abandoned. In the other, field rotation, the landscape (as it were) moves through a fixed site; that is, there is a cycling of crops with a period of fallow (followed by burning) at some stage. Which pattern prevails is largely a matter of land ownership.

Pastoralism adds other variants, including some that, much as with floodplains, do not rely on fire. But most do. The herds move from infields to outfields, or seasonally graze on outlands, or migrate systematically with the seasons (Mediterranean transhumance is a good example, although variations exist for the Alps and the *saeter* system in Scandinavia). Lands are burned according to customary regimes, most often in the spring or autumn.

Industrial fire practices

The defining feature of industrial fire is the combustion of fossil biomass, which, to be effective, must occur in special chambers and its power transmitted through machines to its destined applications. Through processes of technological substitution and outright suppression industrial combustion competes against other forms of anthropogenic fire.

The arrival of industrial fire comes with a recession of traditional burning. Fire leaves the built environment; it disappears from homes, offices, and factories, and their immediate landscaping. It leaves agriculture, as the "fossil fallow" from subsurface biomass does the work of fertilizing, weeding, and purging previously done by flame. Instead of rough pasture openly burned to provide forage for draft animals, diesel powers tractors, and the fields are left unburned. Fallowing disappears. Flocks and herds move by rail or truck rather than over trails; the land, again, lies unburned.

The paradox, however, is that industrial societies tend to create nature preserves; and where industrialization coincided with colonization, notably in the 19th century, the two have led to vast domains of public land. This experiment in state-sponsored conservation was intended to prevent free-burning fires; instead, it established a permanent habitat for maintaining them, and in recent decades has become the scene for fire's restoration. While the preponderance of the Earth's burned landscapes continue to remain embedded in agriculture, the most studied and intensively managed lie in the public forests and preserves of industrial countries, especially the U.S.A., Canada, Australia, and Russia.

Fire Science

A formal scholarship of fire has followed a similar trend. In the past, fire was a universal presence, and often a means of explanation. With industrialization, however, it has become a subset of other disciplines. Alone among the ancient elements it does not claim an academic discipline or university department. There is no coherent theory of fire; instead, it gets judged by how it relates to other topics.

There is an old saying that fire makes a good servant but a bad master. That split in perception is a very old in Western civilization. Those who work on the land (the servants) tend to value fire; those who don't (the masters) condemn it as primitive. Those who denounce it are typically academics, ministers of agriculture, or officials charged with maintaining public order, who see fire as wasteful, dangerous, and an outcome of ignorance and superstition. Only in recent decades has a counter-perception evolved in which fire is seen as natural, and in some circumstances (such as nature preserves) as useful and necessary. Still, such understanding does not lie within a field of fire so much as it is a byproduct of other disciplines.

This lack of coherence – of a standard by which fire might again serve as a focus itself – seriously compromises our ability to integrate its global presence and to evaluate desirable from undesirable burning. In seeking ways to prevent the fires we don't want, while promoting the ones we do, we must also look to reforming the scholarship that we use to make such judgments. That scholarship must extend beyond the natural sciences – as fire does.

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17 The Economic Dimension of Wildland Fires

Armando González-Cabán[1]

Abstract

The economic relevance of wildland fire management and protection programs is ever growing, particularly considering mounting wildfire costs and losses globally, and the justifications required for budget allocations to management and protection of forest ecosystems. However, there are major difficulties in grappling with the problem of rapidly increasing wildland fire management costs. For example, in the U.S., the U.S. Department of Agriculture Forest Service from 1997-2008 has spent more than $US11.5 billion on fire suppression alone, on wildfires affecting more than 26 million ha of land. It is important to keep in mind that inclusion of the expenditures for the other four federal agencies with fire protection responsibilities and the expenditures of all other states with wildland fires could possibly put the figure in the realm of hundreds of billions. Canada spends an average of between $US531 million annually on fire suppression, prevention, and prescribed burning alone. Mexico and the Central America region are also suffering tremendous losses to forest fires. For example, during 1998 more than 7.7 million ha of forest and agricultural were affected. In the South American continent, during the 1990s Brazil, Argentina, and Bolivia had wildfires that burned annually an average of 1.03, 1.5 and 0.92 million hectares respectively of forest lands. Suppression expenditures and financial losses due to wildfires in the South American region are difficult to obtain. However, some estimates of the financial losses of forest fires in South America go as high as $US1.6 billion annually in the 1990s. The five most southern countries of the European Union during the period from 2000 to 2007 suffered on average 60,000 fires affecting 476,000 ha of forest lands. Unfortunately, there is not yet an estimate of the suppression expenditures or the economic impact of those fires in the individual countries and the Mediterranean basin region. In 2009 Australia experienced large wildfires affecting more than 430,000 ha, wiping out complete towns, killing 173 persons, destroying over 2000 homes, leaving more than 7,500 people homeless and creating havoc in the local economies. Recent estimates place the cost of bushfires to Australia at $US6,625 million.

Keywords: Wildland fire management costs, wildland fire fatalities, fire suppression expenditures, wildfire disasters

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The economic relevance of wildland fire management and protection programs is ever growing, particularly considering mounting wildfire costs and losses globally, and the justifications required for budget allocations to management and protection of forest ecosystems. However, there are major difficulties in grappling with the problem of rapidly increasing wildland fire management costs. For example, in the U.S.A., the U.S. Department of Agriculture Forest Service from 2000-2011 has spent more than $US 16 billion on fire suppression alone, on wildfires affecting more than 33×10^6 ha of land (González-Cabán, 2008; González-Cabán and Omi, 1999; González-Cabán, 2009) (Tab. 17.1). In 2003, in California alone, 300,000 ha were burned, more than 3,500 homes destroyed, 22 people killed, and more than $US3.5 billion worth of property losses (González-Cabán, 2008). It is important to keep in mind that inclusion of the expenditures for the other four federal agencies with fire protection responsibilities and the expenditures of all other states with wildland fires could possibly put the figure in the realm of hundred of billions. For example, recent estimates for the state of California put the economic impact of wildfires during 2008 conservatively upward of $10 billion (pers. comm. with Bob Zybach on 5 May 2009). Suppression expenditures alone were estimated in excess of $US1 billion (Boxall, 2008). Lately there has been a growing concern on the disparity between reported costs by the USDA Forest Service and actual damages and losses (Morton et al., 2003; Lynch, 2004; Dunn et al., 2005, Calkin et al., 2005; Mason et al., 2006; Western Forestry Leadership Coalition, 2009; Mowery, 2013). Some attempts have been made to try and figure out the factors contributing most to wildland fire costs, and estimating individual fire suppression costs, although more research is needed (González-Cabán, 1984, 1985; McKetta and González-Cabán, 1985; González-Cabán and McKetta,1986; González-Cabán et al., 1986; Smith and González-Cabán, 1987; Liang et al., 2008).

Canada spends an average of between $US531 million annually on fire suppression, prevention, and prescribed burning alone. This does not account for timber, recreation, health and personal property losses. The mean annual area burned associated with these expenditures is 2.043×10^6 ha and an average of almost 8,000 wildfires annually (Tab. 17.2).

Mexico and the Central America region are also suffering tremendous losses to forest fires. For example, one of the worst forest fires year in record in the area was 1998 when more than 2.3×10^6 ha of forest lands was affected; Mexico bearing the brunt of it with 0.85×10^6 ha burned. Adding the area burned to agricultural uses in the region (5.3×10^6 ha) bring the total for 1998 to 7.7×10^6 ha. That is the equivalent of the entire country of Panama! Recent estimates of the number of fires and area affected annually in the combined Caribbean and Central American regions was estimated as 41,540 fires and 1.1223×10^6 ha respectively (Julio Alvear, 2008). Unfortunately, fire suppression expenditures information is not readily available in many of the Central America and Caribbean region countries. However, just three of the region countries (Guatemala, Honduras, and Mexico), spend over $US21 million a year in personnel and equipment. The fire management budget for Mexico in 2012 is estimated at close to $US67 million (Juan Arturo Raygoza, pers. comm., 2 May 2012).

Table 17.1. US Department of Agriculture Forest Service Area burned and associated suppression costs for the period 2000-2011. Source: National Interagency Fire Center Wildland Fire Statistics and the USFS Wildland Fire Management budget FY2000 - FY2011, and Mark Lichtenstein, Branch Chief, Budget and Planning, FS.

Year	Area Burned (million ha)	Suppression costs ($US billion)
2011	3.53	1.414
2010	1.39	0.898
2009	2.41	1.018
2008	2.21	1.980
2007	3.78	1.800
2006	4.00	1.900
2005	3.52	0.876
2004	2.75	0.890
2003	1.99	1.326
2002	2.81	1.661
2001	1.45	0.918
2000	3.41	1.362
Total	**33.25**	**16.043**

Table 17.2. Canada number of fires, area affected, and total fire protection expenditures for the period 2000-2010: Source: Canadian Interagency Forest Fire Centre (CIFFC), Canada Report 2011, and Mr. Serge Poulin, Operations Manager CIFFC.

Year	Number of fires	Area affected (million ha)	Total expenditures ($US million)
2010	7,319	3.156	636.169 [1]
2009	7,167	0.755	1,001.951
2008	6,036	1.310	713.720
2007	7,581	1.301	498.107
2006	9,713	2.055	139.018
2005	7,438	1.706	449.777
2004	6,647	3.275	539.275
2003	8,243	1.635	885.081
2002	7,847	2.758	477.002
2001	7,714	0.630	300.651
2000	5,469	0.648	269.176
Total	**81,174**	**19,229**	**5,909.927**

[1] Incomplete; missing information from some agencies.

In the South American continent, during the 1990s Brazil, Argentina, and Bolivia had wildfires that burned annually an average of 1.03, 1.5 and 0.92×10^6 ha of forest lands. These three countries alone account for about 88 percent of the total annual area burned in the decade. As in the Caribbean and Central American regions suppression expenditures and financial losses due to wildfires in the South American region are difficult to obtain. However, some estimates of the financial losses of forest fires in South America go as high as $US1.6 billion annually in the 1990s (Julio Alvear, 2004). During the recent decade it is estimated that the number of fires and area affected annually in all South America is 278,460 ha and 21.276×10^6 ha respectively. Despite scant studies and information on suppression expenditures and economic impact of these fires (other than Chile, cf. Tab. 17.3) the financial burden of that level of wildfires has been estimated to be more than the $US1.6 billion during the 1990s (Julio Alvear, pers. comm., 28 April 2009). This is a significant figure, particularly when the social and ecological consequences of the fires are not even considered.

Table 17.3. Chile number of fires, area affected, and total fire protection expenditures during the period 1998-2007. Source: Julio Alvear (2008) and Fernando Maldonado, CONAF (pers. comm. 3 May 2012).

Year	Number of fires	Area affected (ha)	Total expenditures ($US million)
2011	4,952	47,035	26.296
2010	4,069	58,364	24.101
2009	6,157	64,222	26.707
2008	6,975	42,037	14.344
2007	5,143	43,384	9.104
2006	5,396	19,322	5.461
2005	6,653	65,300	7.879
2004	6,430	50,687	8.907
2003	7,572	41,988	6.359
2002	6,701	90,069	16.174
2001	5,376	10,921	3.824
2000	5,252	17,183	4.100
Total	**70,676**	**550,512**	**153.256**

Every year, on average, Europe experiences 45,000 forest fires, burning approximately 0.5×10^6 ha of forest and woodlands. Between 1989 and 1993 close to 2.6×10^6 ha of land were burned. 2003 was a particularly significant year for Europe. In Portugal more than 0.45×10^6 ha were affected by wildfires; France saw an increase in area burned of more than 30 percent from the previous decade. During 2007 Greece experienced significant forest fires that affected more than 0.27×10^6 ha of forests and other lands, burned more than 3000 homes and killed more than 78 people (Xanthopoulos, 2008, 2009). Italy also experienced significant fires affecting almost 0.23×10^6 ha of forest lands. The five most southern countries of the European Union during the period from 2000 to 2007 suffered on average 60,000 fires affecting 0.476×10^6 ha of forest lands (Joint Research Centre, 2007). Unfortunately, we still don't have a good estimate of the suppression expenditures or the economic impact of those fires in the individual countries and the Mediterranean basin region. In 2009 Australia again experienced extremely large and severe wildfires affecting more than 0.43×10^{-6} ha, wiping out complete towns, killing 173 persons, destroying over 2000 homes, leaving more than 7500 people homeless and creating havoc in the local economies (Rees, 2009a, 2009b). A seminal paper by Ashe (2009) estimates the cost of bushfires to Australia at $US6,625 ($AU8,500) million. The author also determined "…that Australia is investing approximately $US5,612 ($AU7,200) million (or 85% of the total cost of fire) to manage a loss of approximately $US1,013 ($AU 1,300) million (or 15% of the total cost of fire). He further questions the effectiveness and efficiency of such investment given the amount of losses.

Large forest fires in China (1987), Mongolia (1996-1998), Russia (1998, 2003), and other parts of the world demonstrate that wildfire disasters are affecting many countries. There are only a few detailed studies on ecological and economic impacts of fires. In 2003 the Russian Federation was affected by wildfires affecting 20.2×10^6 ha of forest and non-forest lands in the region around Baikal lake alone (Huang et al., 2009; Goldammer, 2010; Goldammer et al., 2012). Considering that the export value of forest products from global boreal forests is close to 47% of the world total (Kuusela, 1990, 1992) the economic impact of fires in the boreal forests could be enormous, although not yet quantified.

The economic impact of the Indonesian fires and haze in 1997-98 have been estimated conservatively at about $US4.5 billion to the economies of Indonesia, Malaysia, and Singapore (EEPSEA, 1997; Rowell and Moore, 1998; Buttler, 2006). And this did not include long-term health damages, loss of life, reduced crop productivity, etc.

Based on a worldwide study it is estimated that approximately 350×10^6 ha of vegetated land (forest and non forest) are burned annually (Tansey et al., 2004). This is equivalent to burning the area of the Indian subcontinent every year! Yet, we are still struggling with the problem of lack of good statistical data on suppression expenditures and economic impact of wildfires in the majority of the countries of the world. Not enough is being done to develop a better system of collecting economic data uniformly.

However, the Global Fire Monitoring Center (GFMC) initiative to systematically collecting statistical data and narratives from government sources, correspondents and the media, on human and economic consequences of wildfires is pointing to the right direction. The Global Wildland Fire Fatalities Reports of 2008 to 2010 revealed 998 fatalities for the period including wildland firefighters, military and civilians. Their 2011 report included worldwide data on structural damages and other losses caused by wildfires, and evacuations due to wildfire threat (GFMC, 2012a). However, the numbers of fatalities and damages include only those reported in the media and by GFMC correspondents. Thus, due to the lack of a comprehensive national / international reporting system the statistical dataset is likely to be incomplete, especially considering the numerous unreported numbers of wildfires and associated fatalities in remote regions of the developing world. However, considering that in 2011 over 85,000 evacuations were recorded, and more than 7,000 homes lost globally, and the preliminary 2012 assessment by GFMC, showing that in the U.S.A. alone more than 80,000 people had been evacuated and more than 1300 homes lost, indicate the magnitude of the socioeconomic significance of wildfires affecting society; and underscore the importance of collecting complete global statistical data (GFMC, 2012b).

It has become evident in the recent years; we have a public and governmental oversight that demands greater accountability for fire management actions and expenditures. A diversity of wildland uses is affected, from recreation and wildlife interests, and ecosystem sustainability to traditional commodity outputs. There are multiple competing demands on the limited financial resources of governments. To achieve a balanced distribution of budget funds according to the priorities established in strategic and economic planning processes, appropriate analytical tools and methodologies that allows us to measure the direct suppression expenditures and the financial and economic impacts of wildfires worldwide are needed.

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18 Vegetation Fire Smoke Emissions and Human Health

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Abstract

Air pollution generated by vegetation fire smoke is a phenomenon that has influenced the global environment in prehistoric and historic time scales. Although historic evidence of the impacts of VFS on societies is scarce, there are indications that VFS has been a factor that influenced society significantly since the Middle Ages. In recent decades, increasing application of fire as a tool for land-use change has resulted in more frequent occurrence of extended fire and smoke episodes with consequences on human health, and security. Some of these events have been associated with droughts that are attributed to inter-annual climate variability or possible consequences of regional climate change. In metropolitan or industrial areas, the impacts of VFS may be coupled with the emission burden from fossil fuel burning and other technogenic sources, resulting in increasing adverse affects on the human population. Exposure and vulnerability of humans to fire emissions is a subject that needs more information on options for limiting smoke impacts on human health and security. A number of recent vegetation fire smoke pollution episodes have caused public concerns and alerted policy makers. Some responses, such as calls or laws for eliminating the use of fire in land management, have resulted in conflicts, contradicting effects, or are difficult – if not impossible – to enforce. The consequences of fire burning on radioactively contaminated lands and its consequences on redistribution of radioactive particles lifted by fire smoke is another serious issue that needs to be addressed.

Keywords: Vegetation fire smoke, fire smoke compounds, fire smoke toxicity, radioactivity, smoke impacts on human mortality

Introduction

Air pollution generated by vegetation fire smoke (VFS) is a phenomenon that in many cases it has influenced the global environment. Increasing application of fire as a tool for land-use change has resulted in more frequent occurrence of extended fire and smoke episodes with consequences on human health and security. Some of these events have been associated with

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Table 18.1. Chemical composition of smoke of vegetation fires burning in the interface of rural, urban, or industrial areas, based on the flame-front and smoke dispersion pathway.

	Vegetation fire flame-front pathway	**Rural fields**	**Rural or urban constructions**
Physical/ Chemical processes:	Pyrolysis and combustion of forest fuel	Pyrolysis and combustion of agricultural fields, fungicides, fertilizers, pesticides e.g. 4-chloro-2-methyl phenoxy acetic acid (MCPA)	Pyrolysis and combustion of paint, glue, wood, plastics) Glass, cement, plaster, asbestos can be contained in the smoke produced
Chemical components:			
a) Organic	a) VOCs (Hydrocarbons, Aldehydes, furans, carboxylic acids, BTEX), SVOCs (PAHs)	a) VOCs, SVOCs (PAHs), PCDDs, PCDFs	a) Non polar VOCs (e.g BTEX, styrene), SVOCs (PAHs), PCDDs, PCDFs, PCBs
b) Inorganic	b) CO, CO_2, NO_X, SO_x, trace elements (e.g. S, Cl, K, Na, Mg, Cu, Ni, Cu, Zn)	b) CO, CO_2, CH_4, HCl, SO_2, NO_X, PO_x, NH_3, CS_2, H_2S, HCN	b) CO, CO_2, metals (e.g. Ca, Mg, Ti, Al)
Physical properties:			
a) particle size	a) Coarse (PM_{10}) & fine ($PM_{2.5}$)	a) Coarse (PM_{10}) & fine ($PM_{2.5}$)	a) Coarse (PM_{10}) & fine ($PM_{2.5}$)
b) particle shape	b) Spherical, fibrus		
Chemical properties:			
a)Alcalinity / acidity			a) Alkaline pH
b)Photo-chemical reactions			

Landfills	Illegal waste disposal	Forest fire retardants	Smoke pathway	Urban or Industrial areas
Pyrolysis and combustion of household waste, plastic, rubber, paper, Glass and metals can be contained in the smoke produced	Pyrolysis and combustion of organic residues, lead-acid vehicle batteries, electric appliances, radioactive materials	Pyrolysis and combustion of diammonium phosphate (DAP), ammonium sulfate & other commercial retardants	Mixture of gases, liquids & solids	Mixing of forest fire smoke with urban and industrial pollutants, possible photochemical reactions
a) VOCs, chloro-benzenes, chloro-phenols, SVOCs (PAHs), Carbonyls, PCDDs, PCDFs, PCBs	a) PCDDs, PCDFs, Co-PCBs			a) Aliphatic H/C, VOCs, BTEX, Styrene, PAHs, Saturated hydrocarbons (PAR), mercaptans
b) CO, CO_2, heavy metals (e.g. Pb, Cd, Cr, Cu, Zn)	b) CO, CO_2, radionuclides (I-29, Cs-137, Cl-36)	b) NH_3, SO_2		b) CO, CO_2, NO_X, SO_2, H_2S, O_3
a) Mainly fine particles ($PM_{2.5}$<)		a) Mainly fine particles ($PM_{2.5}$<)		a) Coarse (PM_{10}) & fine ($PM_{2.5}$)
				b) Irregular
				b) PAH photo-degradation, photo-chemical O_3

droughts that are attributed to inter-annual climate variability, or are possible consequences of regional climate change. In metropolitan or industrial areas, the impacts of VFS may be coupled with the emissions burden from fossil fuel burning and other technogenic sources, resulting in increasing adverse affects on the human population. Possible chemical synthesis of the smoke produced in different scenarios of a forest fire, burning near rural, urban or industrial areas is given in a format of a road-map for air-quality assessment (Tab. 18.1) (Statheropoulos and Karma, 2007). Special emphasis should be given on radioactive emissions generated by fires burning in peatlands and on terrain contaminated by radionuclides.

A global perspective regarding the impacts of vegetation fire emissions on the environment, human health and security has been presented recently (Goldammer et al., 2009). Generally, during vegetation fires, high peak concentrations of VFS components can be observed, especially near the flame-front. Table 18.2 presents mean concentrations of VFS components measured under “smoky” conditions in the field (sampling duration 20-30 min) that have been reported in the literature (Miranda et al., 2005; Pinto and Grant, 1999; Reinhardt et al., 2000; Statheropoulos and Karma, 2007).The respective quideline values. for outdoor environment, as published by the Word Health Organization (WHO Guidelines for Air Quality, 2000 and WHO Air Quality Guidelines Global Update, 2006) are also given. However, these values could be more appropriate in order to evaluate exposure of the general population. Only the BaP recommended exposure limit provided by the U.S. National Institute for Occupational Safety and Health (NIOSH) refers to occupational health.

Table 18.2. Mean concentrations measured in smoky conditions in the field and respective guideline values given by WHO (2000)

Compound	Concentration	Guideline value (ppm)	Averaging time
[1]CO	54 ppm	50	30 min
[2]Benzene	0.22 ppm	[a]0.0016	1 year
[2]Toluene	0.12 ppm	0.27	30 min
[2]Xylene	0.08 ppm	1.1	24-h
[1]Acroleine	0.071ppm	0.02	30 min
[1]Formaldehyde	0.468 ppm	0.08	30 min
[3]BenzoPyrene (BaP)	7.1 ngm^{-3}	[b]100 $\mu g\ m^{-3}$	8-h
[1,4]$PM_{2.5}$	[1,2]7,000 $\mu g\ m^{-3}$, [4]2,300 $\mu g\ m^{-3}$	[c]25 $\mu g\ m^{-3}$	24-h

[1]Reinhardt et al. (2000); [2]Statheropoulos and Karma (2007); [3]Pinto and Grant (1999), [4]Miranda et al. (2005)

[a]Directive 2008/50/EC, [b]NIOSHREL (2012), [c]WHO (2006)

VFS produced by large vegetation fires is usually transported many kilometres away from the source. Usually, fine particles can be transported to long distances (cross border transfer). During the El Niño episode in Southeast Asia in 1997-98, the smoke-haze layer covered an area up to 10×10^6 km^2 (Nakajima et al., 1999; Heil and Goldammer, 2001). Moreover, during 2002, the Canadian forest fires in a province of Quebec affected the PM levels of the city of Baltimore in the United States, which is located hundreds of kilometres from the source (Sapkota et al., 2005). Fires in Canada were also found to cause high concentrations of CO and O_3 over a period of two weeks in the southeastern and eastern coastal United States during the summer of 1995 (Wotawa and Trainer, 2000).

Toxicity of the VFS mixture can be the additive or the synergistic result of all the possible hazardous smoke components, depending on the fuel types burned and the possible materials contained in the VFS. Additive toxicity is defined as the toxicity of a mixture of contaminants that is equal to the summation of the toxicities of the individual components. Synergistic toxicity is defined as the toxicity of a mixture of contaminants that may result in a total toxicity greater than the summation of the toxicities of the individual components. VFS may contain toxic compounds such as (Statheropoulos and Goldammer, 2007):

- Respiratory irritants: Irritants can cause inflammation of mucous membranes. Ammonia (NH_3) and nitrogen dioxide (NO_2) are indicative examples. Irritants can also cause changes in respiration and lung function, such as sulphur dioxide, formaldehyde, and acroleine. According to specific studies, formaldehyde and acroleine were suspected of causing respiratory problems to the exposed firefighters
- Asphyxiants: Asphyxiants prevent or interfere with the uptake and transport of oxygen. An example is carbon monoxide, which in high concentrations can result in immediate collapse and death. Methane and carbon dioxide are also considered asphyxiants. The Safety Booklet of Jefferson Lab, 2008 quotes the following table of health impacts of oxygen deficiency (Tab. 18.3)

Table 18.3 Oxygen deficiency and the relevant health effects

Percent Oxygen	Health Effects
17	Night vision reduced; Increased breathing volume Accelerated heartbeat
16	Dizziness; Reaction time for new tasks is doubled
15	Poor judgment; Poor coordination; Abnormal fatigue upon exertion; Loss of muscle control
10-12	Very faulty judgment; Very poor muscular coordination; Loss of consciousness
8-10	Nausea; Vomiting; Coma
< 8	Permanent brain damage
< 6	Spasmodic breathing; Convulsive movements; Death in 5-8 minutes

Carcinogens: A carcinogen is a chemical, known or believed to cause cancer in humans. The number of proven carcinogens is comparatively small, but many more chemicals are suspected to be carcinogenic. International Agency on Research on Cancer (IARC) have classified the chemical agents into different groups depending on their impact on humans. Group 1 includes agents carcinogenic to humans, Group 2A are probably carcinogenic to humans, Group 2B are possibly carcinogenic to humans, Group 3 are not classifiable as to its carcinogenicity to humans and Group 4 are probably not carcinogenic to humans. According to IARC, benzene, benzo[a]pyrene and formaldehyde are Group 1 carcinogens ('Sufficient evidence in humans or sufficient evidence in animals and strong mechanistic data in humans'). Usually guideline values are given by WHO in terms of unit risks which refer to lifetime exposure.

- Mutagens: A mutagen is an agent that changes the hereditary genetic material. Such a mutation is probably an early step to the development of cancer, for example, formaldehyde, acroleine.
- Teratogens may cause non-heritable genetic mutations or malformations in the developing fetus, for example, toluene
- Systemic toxins: These are chemicals, which can cause toxic effects, as a result of their absorption and distribution to a site distant from their entry point. Examples are heavy metals, such as lead, mercury, and cadmium, which may be contained in the VFS particles, especially when the flame-front expands to waste disposals (landfills).

In order to achieve a more representative assessment of VFS health impacts, VFS exposure should be considered as combined exposure to multiple chemicals. Combined exposure to multiple chemicals is defined in the context of whether or not the components act by similar or different modes of action in induction of critical effect (WHO/IPCS, 2011).

The exposure of firefighters to VFS is characterized mostly by a standard periodicity (every summer) and duration (e.g., long-lasting fires). Hence, the ability to measure online their exposure is considered critical. Exposure of the firefighters to CO and formaldehyde can exceed legal and short-term exposure limits, occasionally, in smoky conditions; CO level has been noted as exceeding the 200 ppm ceiling set by the NIOSH (Reinhardt et al., 2000). Exposure of general populations to VFS is not a continuous situation. However, susceptibility of the receptors should also be taken into consideration during exposure assessment, as sensitive groups, such as children, pregnant women, people with respiratory problems, and the elderly are considered more vulnerable (USEPA, 2001).

Emissions from Fires Burning on Contaminated Terrain

In some countries forests and other lands are contaminated by various types of hazardous chemical and radioactive pollution. Wildfires occurring in such contaminated terrain may result in secondary air pollution. The territories most affected by radioactive pollution have been contaminated by the release of radionuclides during the failure of the Reactor Number Four of the Chernobyl Nuclear Power Plant in 1986. Among the total 6×10^6 ha of

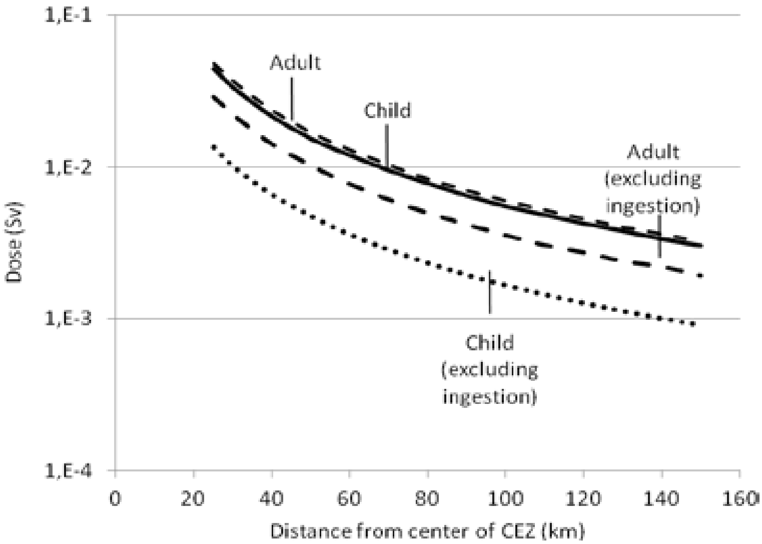

Figure 18.1. Estimated total dose (Sv) (with and without ingestion), as a function of distance from the center of the CEZ, that could be received by children (1 year old) and adults during the year following a catastrophic wildfire (Hohl et al., 2012).

radioactively contaminated terrain in Ukraine, Belarus and Russia the most polluted forest area covers over 2×10^6 ha in the Gomel and Mogilev regions of Belarus, the Kiev region of Ukraine, and the Bryansk region of the Russian Federation. The main contaminator was found to be caesium-137 (^{137}Cs); in the core zones of contamination, strontium-90 (^{90}Sr) and plutonium-239 (^{239}Pu) were found in high concentrations. Generally, below average dry conditions, the surface fuels contaminated by radionuclides – the grass layer and the surface layer of peatlands – are consumed by fire. Most critical is the situation in peat layers, where the radionuclides are deposited. The long-range transport of radionuclides lifted in the smoke plumes of wildfires and their fallout on large areas were investigated in detail in 1992 (see reviews by Goldammer et al. [2009] and Hao et al. [2009]).

The Chernobyl Wildfire Project, consisting of scientists from the Ukraine, U.S.A., and Germany, developed a model to assess the potential implications of a catastrophic wildfire the Ukrainian portion of the Chernobyl Exclusion Zone (CEZ) on populations living and working near the CEZ. The complete model consists of a source model, a transport model, and an exposure model. As a worst case scenario, it is assumed that a fire would consume the biomass of pine forests and former agricultural lands and release any associated radionuclides into the atmosphere. The transport model assumes that the wind would blow primarily towards Kiev throughout the fire event.

The exposure model estimates adult and child (1 year old) external exposures and doses via five exposure pathways. Excluding the food ingestion pathways, calculated doses to populations at distances 30 km or greater from the release point are less than the critical thresholds that would require evacuations. However, Ukrainian law would require limiting consumption of certain foodstuffs to avoid exposure through ingestion.

Recent research reveals that, as a consequence of climate change, mercury deposits once protected in cold northern forests and wetlands will increasingly become exposed to burning. Mercury is released to the atmosphere with fire smoke. Turetsky et al. (2006) quantified organic soil mercury stocks and burned areas across western boreal Canada; it was assumed that, based on ongoing and projected increases in boreal wildfire activity due to climate change, atmospheric mercury emissions will increase and contribute to the anthropogenic alteration of the global mercury cycle and to the exacerbating mercury toxicities of food chains in the northern hemisphere.

Other contaminated terrains are former gold mining areas, e.g. calcine sand deposits in Victoria (Australia), which are a by-product of past gold mining methods and contain small amounts of arsenic and mercury. They became airborne after vegetation cover was burnt by a wildfire in February 2009 ("Black Saturday Fire"). The threat of uncontrolled airborne distribution of arsenic and mercury was controlled by site rehabilitation a year later (Anonymous, 2010).

Evidence of Smoke Impacts on Human Mortality

Although the land-use fire and smoke pollution episode in South East Asia in 1997-98 created an interest of the scientific community to assess the impacts of vegetation fire smoke pollution on human health and mortality and prompted the United Nations to evaluate the state-of-the-art knowledge on the scientific base of VFS and measures of health protection (Schwela et al., 1999 a, b, c; Heil and Goldammer, 2001), only occasional narratives and evidence are available. While general narratives described extended smoke pollution episodes in all continents during recent years, these episodes have not been utilized sufficiently for in-depth research, clinical studies and collection of statistical information on hospital admissions, immediate consequences on public health or premature deaths.

Recently reported numbers of populations affected by smoke pollution include government reports published in the media, e.g. those reported after the fire and smoke episode in Western Russia in 2010 or in Thailand in 2012. According to official statistics of the Economic Development Ministry of the Russian Federation the number of deaths during the months July and August 2010 in Russia exceeded the number of deaths in the same period of 2009 by 55,800.[3] While an increase of premature deaths could be attributed to both of combined impacts of the extreme heat wave and the long-lasting VFS pollution, a study of daily fine particulate matter ($PM_{2.5}$) concentrations using MODIS satellite observations of aerosol optical depth (AOD) led to the conclusion that that exposure to air pollution from the 2010 wildfires "*may have caused hundreds of excess deaths*" in Moscow Region (van Donkelaar et al., 2011). An evaluation of the daily number of deaths by age group (all ages, <75 and ^{3}75 years) provided by the Hellenic Statistical Authority for all natural, cardiovas-

3 Report of the Economic Development Ministry of Russia, published in The Moscow Times, 27 October 2010, on file at the GFMC repository: http://www.fire.uni-freiburg.de/media/2010/10/news_20101027_ru.htm

cular and respiratory causes during a large fire episode in Greece in 1998 by Analitis et al. (2011) showed that the fires were associated with a significant increase in the daily number of deaths: 50% increase in the total daily number of deaths, 61% increase in the number of cardiovascular deaths (78% for those <75 years old and 55% for those ^{3}75 years old) and 92% increase in the daily number of respiratory deaths (72% for those <75 years old and 101% for those $75 years old). The effects on total and cardiovascular mortality were higher during the days of the fires, while the lagged effects are larger for respiratory mortality (Analitis et al., 2011).

The annually recurring episode of agricultural burning in mainland Southeast Asia during the dry season (between January and April) is regularly resulting in extended near-ground VFS pollution. In early 2012 extended smoke pollution affected the North of Thailand. The Provincial Disease Control Office in Chiang Mai reported that in February-March 2012 more than 240,000 people sought medical treatment for haze-related illnesses at 87 hospitals in the eight northern provinces of Thailand. The official tally recorded over 100,000 patients with coronary heart disease, another 100,000 patients with respiratory diseases and about 20,000 persons suffering from eye inflammation and dermatitis.[4]

A first attempt to model global mortality attributable to VFS by Johnston et al. (2012) involved combining outputs from a chemical transport model with satellite-based observations of aerosol optical depth to estimate daily and annual exposure to $PM_{2.5}$ globally. In World Health Organization (WHO) subregions classified as sporadically impacted by VFS, the daily burden of mortality was estimated using previously published concentration-response coefficients for the association between short-term elevations in $PM_{2.5}$ from VFS and all-cause mortality. In subregions classified as chronically impacted, the annual burden of mortality was estimated using the American Cancer Society study coefficient for the association between long-term $PM_{2.5}$ exposure and all-cause mortality. Strong La Niña and El Niño years were compared to assess the influence of inter-annual climatic variability. The principal estimate for the average mortality attributable to VFS exposure was 339,000 deaths annually. In sensitivity analyses the interquartile range of all tested estimates was 260,000 to 600,000. The regions most affected were Sub-Saharan Africa (157,000) and Southeast Asia (110,000). Estimated annual mortality during La Niña was 262,000 compared with 532,000 during El Niño.

While the authors of the study are anticipating that subsequent estimates will be improved by better exposure assessment (particularly as empirical PM data become more globally available) and further epidemiologic studies on mortality and morbidity associated with landscape fire smoke (particularly in regions with high exposure), this assessment will require an in-depth review. Guidelines for reducing VFS impacts on human health, however, are available and will support decision making for policy and response (Schwela et al., 1999a; OEHHA and USEPA, 2008).

4 Report of the Economic Provincial Disease Control Office of Chiang Mai, published on 24 March 2012, on file at the GFMC repository: http://www.fire.uni-freiburg.de/media/2012/03/news_20120322_th.htm

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19 Effects of Increasing Atmospheric CO_2 on Flammable Ecosystems

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Abstract

Increasing CO_2 in the atmosphere can influence vegetation directly by increasing photosynthetic rates and by reducing plant water use because plants transpire less. These CO_2 fertilization effects are greatest where other plant growth requirements, especially light and nutrients, are well supplied. Where they are not, as in mature forests, plants will be less responsive to increasing CO_2 since shade inhibits photosynthesis. Burnt forest and shrublands in the early recovery stages may be most responsive because they are well lit and fertilized by ash. Rapid regrowth rates under elevated CO_2 are likely to favour plants that have 'sinks', where they can use the extra carbon, such as swollen roots that store starch promoting resprouting after fire. CO_2 fertilization should promote rapid post-burn recovery of burnt shrublands and forests. Increasing CO_2 may cause the reverse trend with forests expanding at the expense of savannas. The general tendency to more wooded vegetation under high CO_2 scenarios may, at first sight, seem beneficial. But a full accounting has yet to be made. Grasslands and savannas include wilderness areas hosting some of the last populations of free-roaming large herbivores and pastoral lands which support the livelihood of millions of people. Increase in trees will be accompanied by reduced grass and grass-fuelled fires, changed albedo, hydrology, aerosol content of the atmosphere, NO_X emissions and other disruptions along with increases in above-ground carbon. The net effect on climate change is uncertain and poorly understood.

Keywords: Atmospheric CO_2 concentration, C4 photosynthetic efficiency, C3 photosynthetic efficiency, available fuel, grass-fuelled fires

Introduction

Anthropogenic activities have driven atmospheric CO_2 concentrations to levels exceeding anything plants have had to deal with for at least the last 650,000 years and probably the last twenty five million years (Royer, 2006). The effects of CO_2 enrichment on plants and

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ecosystems has been the focus of intense research effort, much of it in artificial glasshouse settings (Poorter and Navas, 2003; Ainsworth and Long, 2004; Nowak et al., 2004). There are still many uncertainties in extrapolating short-term glasshouse studies to field situations and to longer-term consequences of elevated CO_2 (e.g. Korner, 2006; Millard et al., 2007). Free Air CO_2 (FACE) experiments are conducted in the field under the most natural conditions devised thus far (Nowak et al., 2004; Korner, 2006). They are also the most expensive and least replicated across geographic regions. FACE experiments in temperate forests have shown that trees respond most to elevated CO_2 in the early stages of forest growth and not after the canopy closes. In grasslands, elevated CO_2 promoted grass productivity, an effect attributed to CO_2 -induced reduction in water use resulting in effectively moister soils (Morgan et al., 2001). There are no field experiments incorporating fire and CO_2 responses. Thus this report is based on physiological studies, glasshouse experiments and simulations and is necessarily speculative.

Responses to Increasing CO_2

Physiological responses

Changes in atmospheric CO_2 can influence the physiological ecology of plants in three major ways. The first is reduced transpiration with increasing CO_2 as stomata adjust to higher CO_2 concentrations. This results in precipitation becoming more effective for plant growth so that arid areas effectively become less arid. The result can be deeper percolation of moisture into soils favoring woody seedling establishment in grasslands (Polley et al., 1999). The second is the direct effects of CO_2 on photosynthesis. Elevated CO_2 can promote photosynthetic rates, especially if other factors are not limiting such as light, nutrients and water. The positive photosynthetic response is greatest where there is a sink for the extra photosynthates, such as the swollen underground roots of resprouting species that are common in many fire-prone ecosystems. The third major effect is on the relative physiological advantages of C3 and C4 photosynthesis. Increasing CO_2 will favour plants with a C3 photosynthetic pathway more than those with a C4 pathway with the magnitude of the response varying with the temperature of the growing season (Ehleringer et al., 1997; Sage, 2004; Ehleringer, 2005).

Ecological responses

These physiological responses have important consequences for plant ecology and may therefore trigger land-cover changes. Reduced water use of grasslands at higher CO_2 is likely to favour woody plant establishment, especially in more arid ecosystems, because there is more soil moisture available for deep-rooted seedlings. Morgan et al. (2007) reported a five year CO_2 enrichment study showing a 40 fold increase in aboveground biomass of a woody shrub in a semi-arid short grass prairie consistent with this argument. Direct effects of CO_2 on photosynthesis are likely to promote growth rates, resprouting ability, and herbivore defense especially of carbon-rich woody seedlings and saplings (Bond and Midgley, 2000; Hoffmann et al., 2000). The expected result would be faster regrowth rates of woody vegetation after a fire. The CO_2 fertilization effect is likely to be greatest soon after a burn when light, water and nutrients are least likely to be limiting regrowth. As the canopy recovers, shade, nutrients and soil moisture are likely to be more important than CO_2 in limiting growth (Korner, 2006).

CO_2 induced changes in the relative photosynthetic performance of C4 and C3 plants could have major consequences for savannas of the world which occupy vast areas of the tropics and sub-tropics. C4 grasses have a higher quantum yield than C3 grasses at low CO_2 and in warmer climates. Indeed the C4 photosynthetic pathway is thought to have evolved in response to low CO_2 conditions in the past. The corollary is that C4 grasses should lose their photosynthetic advantage as CO_2 increases in the future to favour C3 plants. Collatz et al. (1998) explored the magnitude of these responses for future CO_2 scenarios (Fig. 19.1). They simulated C4 vs. C3 photosynthetic efficiency under different CO_2 and climate scenarios. From these simulations they determined the fraction of the world's land area in which C4 grasses would have the greater photosynthetic efficiency. Under 20th century climate conditions and CO_2 levels (350 ppm), C4 grasses would outperform C3 grasses over about 45% of the world's land area. Areas favorable for C4 plants are expected to decline steeply in the coming decades falling to half their present area by mid-century and almost disappearing by the end of the century (2x CO_2) (Fig. 19.1; Collatz et al., 1998). It is interesting to note that global warming is predicted to have less of an effect than increased CO_2 on the future status of C3 vs. C4 grasses. These simulations imply major disruption to grasslands over the next few decades. However it is far from clear how changes in photosynthetic performance will translate to changes in land cover. We do not know how photosynthetic efficiency relates to ecological dominance and, even if there is a direct relationship, switches in grass composition are likely to lag far behind changes in CO_2 because of delays in dispersal and competitive displacement. Sage and Kubein (2003), in one of the very few attempts to look into the future of the C4 grass systems, concluded that C4 grasses may even increase in future if fires become more common at high human population densities. Either way, we can expect significant disruptions to one of the world's most extensive biomes in response to increasing CO_2, with complex and potentially globally significant consequences for their structure, functioning, biodiversity and land surface-atmosphere feedback effects.

Implications for Flammable Vegetation, Fire Regimes and Land Cover

Flammable shrublands and woodlands

CO_2 fertilization may promote more rapid recovery of vegetation after fire. In woody vegetation subject to recurring crown fires, such as chaparral and matorral, fuels might accumulate more rapidly and promote more frequent fires. Given the strong dependence of crown fires on extreme weather conditions (e.g. Moritz et al., 2004), the effects of fuel dynamics on the

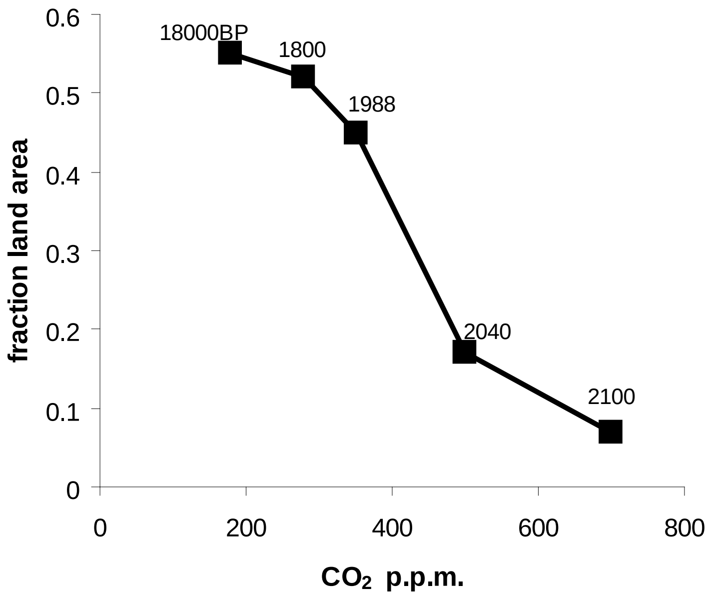

Figure 19.1. Simulated changes in global land area classified as suitable for C4 grasses in response to changing atmospheric CO_2. Fraction land area is the proportion of the world's land area where the climate allows C4 grasses to have a higher CO_2 fixation efficiency than C3 grasses. The numbers above the points indicate years thought to match the CO_2 concentrations starting with 18,000 years ago when CO_2 was ~180 ppm and ending in 2100 when CO_2 may reach 700 ppm. Simulations include simulated climate change (derived from Collatz et al., 1998).

fire regime may prove negligible relative to changes in the frequency of extreme fire weather events and ignition activity.

C4 grassy biomes of the tropics and sub-tropics

Increasing CO_2 and tree cover in savannas

Grasslands, including savannas, occupy vast areas of the tropics and sub-tropics. Fire is a very frequent disturbance in savannas which are estimated to account for >80% of the global area burnt annually (Mouillot and Field, 2005). To establish in frequently burnt grasslands, woody seedlings must rapidly acquire the ability to resprout. Once established, saplings then have to grow above the flame zone between successive fires before they can emerge as relatively fire-proof adult trees. Saplings may be trapped in the flame zone for decades, resprouting after repeated fires. Resprouting is made possible by the presence of large underground storage organs with high starch content in many savanna plants (Hoffmann et al., 2004; Schutz et al., 2009). The probability of saplings escaping the flame zone is influenced both by the fire regime and by sapling growth rates to escape height (Higgins et al., 2000). Elevated CO_2 is expected to promote woody seedlings by reducing the time required to acquire starch reserves to make them fire-proof. Saplings are expected to grow taller faster increasing the probability of escaping the flame zone which will result in denser tree cover (Bond et al., 2003). Thus the overall effect of CO_2 in grassy ecosystems is likely to be promotion of woody plants and denser tree cover n savannas.

Increasing CO_2 and savannas vs. forests

Savannas are far from steady-state systems. Both fire and herbivore exclusion experiments have shown large increases in woody biomass, sometimes resulting in complete replacement of the grasslands by closed forests where C4 grasses are shaded out (e.g. Louppe et al., 1995; Woinarski et al., 2004; Briggs et al., 2005). Large areas of C4 grasslands and savannas occur in climates that can support forests. Mosaics of savanna and forest are common in all tropical and sub-tropical regions. Fires occasionally burn from grasslands into forests providing opportunities for the shade-intolerant C4 grasslands to expand. If forest recovers rapidly after a fire, grasses will be shaded out and the forest becomes less vulnerable to burning. Increased CO_2 is likely to favour rapid recovery of woody plants so that forest margins may become more fire-proof than under low CO_2 and advance into grasslands.

The overall effect of CO_2 in grassy ecosystems is thus to promote woody plants within savannas leading to increased woody cover and, where forest patches occur, to favour forest expansion at the expense of grasslands. Increases in woody plants have been widely observed in both arid and mesic savannas over the past century (Archer et al., 1995; van Auken, 2000; Roques et al., 2001; Asner et al., 2003; Bowman et al., 2008). There are also reports of forest advance into grasslands, including frequently burnt grasslands. For example, Brook and Bowman (2006) reported a landscape-wide expansion of forest (42% increase) in the Australian monsoon tropics over the last five decades while Russell-Smith et al. (2004) reported a near doubling of forest patches in savannas in north-east Queensland from 1943 to 1991. In Kansas prairies, gallery forest increased in area by 69% from 1939 to 2002, fragmenting the prairie landscape (Briggs et al., 2005). In South Africa, scrub forest has invaded savannas in conservation, commercial ranching and communally farmed areas, with increases from 12 to 68, 5 to 55 and 3 to 27 % respectively from 1937 to 2000 (Wigley et al., 2010). The reverse pattern of rapid loss of tropical forest due to frequent intense fires (excluding deforestation fires) has also been reported (Cochrane and Laurance, 2002). Catastrophic fires that transgress from savannas into forests may increase with global warming. The net effect of these two processes in altering forest/savanna boundaries has been little explored as a driver of land-cover change in the tropics.

Savanna dynamics are complex, with tree cover varying with the interaction of climate, soil, fire, herbivory, and direct and indirect human use of woody and herbaceous plants (Bond, 2008). Thus, while increasing CO_2 may be causing a general tendency towards greater woodiness, changes in land use can promote or retard this tendency. The causes of woody increase are much debated with many scientists arguing for the prime importance of changes in land use (especially increased grazing and decreased use of fire) (Archer et al., 1995), while evidence for global drivers, particularly the effects of increasing atmospheric CO_2 on the tree/grass balance, remain controversial. We need a much better understanding of the dynamics of grass-forest boundaries to be able to predict which parts of the world have the potential for rapid biome shifts and what may trigger them.

In more arid grasslands, fire activity is limited by available fuel which is largely governed by precipitation in the previous wet season. In wet ecosystems, where forest dominates, fires occur in years that have extended dry seasons, allowing fuels to dry out whereas in savanna–dominated areas, fires show little inter-annual variation (van de Werf et al., 2008).

Consequences of Changes in Tree Cover in Savannas and Grasslands

Changes in tree cover can have important ecosystem consequences with feedbacks to the earth-atmosphere system (Beerling and Osborne, 2006). Even small increases in woody biomass in savannas represent a substantial carbon sink because of their large spatial extent (Asner et al., 2003; Williams et al., 2005). However grasslands differ from forests not only in carbon stocks but also in their energy budget and hydrology (Hayden, 1998). They typically have a higher albedo than forests, partly because they retain dead, reflective leaves over the dry season. Trees generally transpire more water than grasses because of their more extensive root system, greater leaf area, and greater canopy roughness. Consequently reduction in trees reduces evapotranspiration and increases runoff with feedbacks to the regional climate (Hayden, 1998). Extensive grass-fuelled fires also have feedbacks to climate (Hoffmann et al., 2002). Black aerosols alter energy budgets and reduce the size of cloud droplets causing precipitation to be less frequent but more intense (Koren et al., 2004; Andreae et al., 2004) while savanna fires are important sources of NO_X which influences tropospheric ozone formation (Hobbs et al., 2003). It is important to note that changes in tree cover have effects on radiative forcing far beyond those of carbon sequestration alone. Evaluating the multiple atmospheric effects of large-scale shifts in tree abundance and/or grass-fuelled fire frequencies on the earth-atmosphere system poses a significant challenge to earth system scientists.

The costs and benefits of changes in woody cover in the tropical grassy biomes vary depending on ecological and socioeconomic context and spatial scale. Carbon sequestration projects have become a source of income in some regions where increased tree cover is a desirable goal. Elsewhere tree increase is undesirable, as in African savanna parks and livestock farming areas, where tree thickening has negative impacts on grazer ecology. Some savanna and associated grassland floras are very rich in biodiversity. Plants and animals in the grassy biomes are different from those in adjacent forests so that forest spread into grasslands could cause cascading changes in biodiversity. However the scale of forest spread into grasslands is still largely a local phenomenon, important where it occurs, but not yet a global challenge.

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20 Satellite Monitoring and Inventory of Global Vegetation Fire

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Abstract

Remote sensing instruments on-board polar and geostationary satellites are capable of monitoring of vegetation fires at varied spatial scales. Observations from the coarse and medium resolution sensors are complemented by moderate to high spatial resolution narrow-swath sensors in detecting, monitoring as well as validating fire products. Currently, three different fire products are derived from the satellite sensors a). Active fires that can be detected through the elevated thermal radiance signal typical of flaming and smoldering conditions; b). Fire radiative power product based on the measured rate of radiant energy output of detected fires; c). Burned area product derived mostly through measuring changes in surface reflectance before and after the fire from red, near infrared and short-wave infrared channels. We argue that these satellite derived products can provide useful insight to both operational and policy formulation settings for climate change research. More specifically, for programs such as the implementation of Reducing Emissions from Deforestation and Degradation (REDD), satellite fire monitoring could contribute to emissions estimation, detection of fires in fire-exclusion areas, monitoring fire type, identifying illegal forest clearance, etc. Further, satellite data can be useful for generating long-term essential climate variables (ECVs), including fire disturbance. We also stress on the need to validate satellite products at multiple scales and geographical settings. To address the validation issues, an international coordination effort is currently underway through the Land Product Validation (LPV) subgroup of the Committee on Earth Observation Satellites (CEOS), in cooperation with the Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) Fire Implementation Team. The first international protocol for the production of reference (validation dataset) for the coarse resolution continental and global burned area products is being developed by GOFC-GOLD Fire Implementation Team. In addition, GOFC-GOLD fire teams at the University of Maryland, U.S.A., as well as Global Fire Monitoring Center (GFMC), Germany, through their outreach activities have been providing several web-links on satellite derived fire products.

Keywords: Fire remote sensing, global burned area product, fire radiative power product, essential climate variables, Global Observation of Forest and Land Cover Dynamics

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Introduction

Satellite monitoring of fires has been receiving increasing attention, partly due to a number of international observation coordination efforts to elevate the importance of such monitoring and identify observation requirements, initially by IGBP-DIS in the 1990s and more recently by the Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) Fire Implementation Team, the International Wildland Fire Conferences and the Group on Earth Observations (GEO) (Justice, 1994; Ahern et al., 2001; Townshend et al., 2004; Csiszar et al., 2010). Fire special interest groups and the GOFC-GOLD and UNISDR regional fire networks have also held a number of regional outreach workshops which have provided outreach for the new satellite products and analysis methods, resulting in the setting of regional priorities with respect to fire observations and a number of coordinated fire-related activities (Gitas et al., 2008; Chuvieco and Justice, 2004; Justice et al., 2003; Chuvieco et al., 2008; Roy et al., 2005). A maturing of the field of satellite fire monitoring has led to a range of derived products at the global scale, targeting different user communities, from science to applications (Justice et al., 2002). The increased availability of the data has led to a growth in user community and a greater diversity of use of the available data products. However, we are still a long way from the desired global fire monitoring system that would serve a range of satellite fire data users, from fire scientists to fire managers and the general public.

Fires have a range of impacts on different ecosystems as a function of severity and management (Cochrane, 2003; Bowman et al., 2009). They also are a hazard and can lead to the destruction of property and life. Climate variability and change are leading to changing fire regimes (Kasischke and Turetsky, 2006; Westerling et al., 2006). Climate projections indicate the possibility of greater changes in fire regimes in years to come (Stocks et al., 1988; Flannigan et al., 2005). Fires also contribute to climate change in terms of emissions (IPCC, 2007). Biomass burning fires account for 50% of emissions from fossil fuels (van der Werf et al., 2006; Andreae and Merlet, 2001). Fires can also change the surface albedo, resulting in a change in radiative forcing (Jin and Roy, 2005). The products of fire also have an impact on cloud formation and atmospheric radiative forcing (Reid et al., 2004). Wildfires and controlled fires for forest management or agricultural fires impact regional air quality (Yevich and Logan, 2003). With increasing extreme weather events, management of uncontrolled fires has become an extremely expensive undertaking in a number of countries. Fire regimes are also changing as a result of human population, dynamics as land is either abandoned, traditional fire and land management practices are modified or lands are cleared for agricultural expansion. Agricultural fires used to clear crop residue or prepare land for planting are widespread (Korontzi et al., 2006; Fig. 20.1).

With these various important concerns about fire, there is a growing need for effective inventory and monitoring of fires. The transient and pervasive nature of fire, makes comprehensive ground-based inventory and monitoring prohibitively expensive. Satellite observations provide a means for consistent and rapid synoptic monitoring at the global scale.

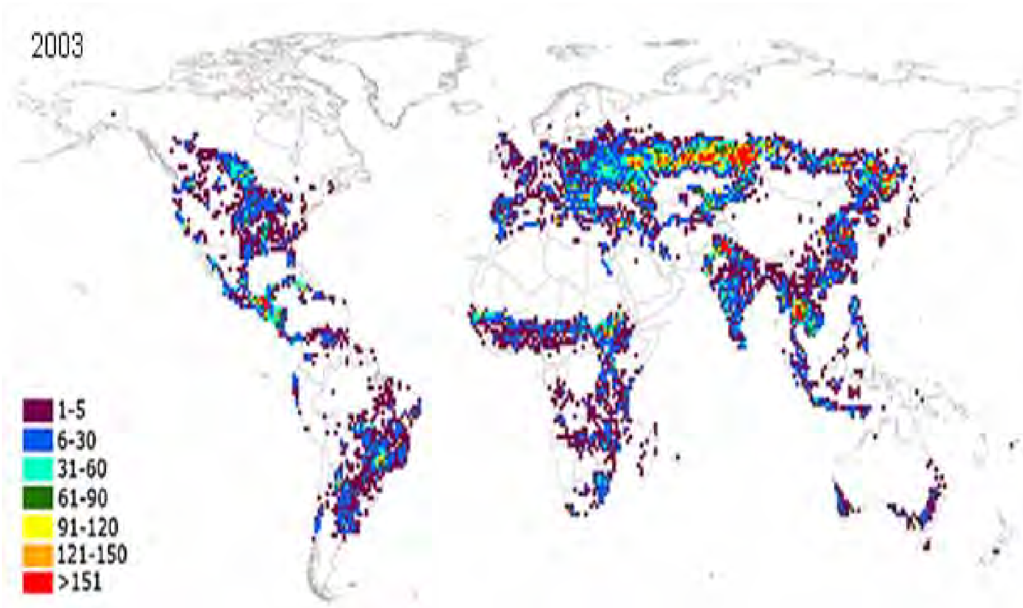

Figure 20.1. Global agricultural fires detected in 2003 (Korontzi, 2006).

Satellite Systems for Fire Monitoring

Most earth observation satellites can be used for studying some aspect of fire (Tab. 20.1). Coarse spatial resolution satellites provide daily global coverage while fine spatial resolution systems require targeted acquisitions. Over the last decade, the space agencies have made considerable investments in deriving geophysical products from the raw satellite data, reducing the burden on data users and moving towards a set of standardized global products (Justice et al., 2002). There are currently three major types of satellite fire products: active fire, fire radiative power and fire affected area (burned area or fire scars). A number of approaches are also being explored to assess burn severity[5] (Roy et al., 2006; De Santis and Chuvieco, 2007). In addition there are a number of satellite systems and products which are used to monitor fire related conditions e.g. vegetation/land cover type, vegetation condition (e.g. moisture content) or fire emission products e.g. particulates and gases (Randerson et al., 2007).

Global vegetation fire monitoring is undertaken primarily by remote sensing instruments on polar orbiting and geostationary satellites. Sensors with broad swaths on polar orbiting satellites provide coarse-to-medium spatial resolution observations (0.25-1 km) over the entire globe, typically twice a day, with higher temporal frequency at high latitudes. Coarser spatial resolution (1-4 km) sensors on geostationary satellites provide hemispheric observa-

5 http://mtbs.gov/

tions every 15-30 minutes. Currently such geostationary systems provide regional coverage. Potentially, however, a coordinated network of such sensors could provide global coverage, except at high latitudes. Observations from the coarse and medium resolution sensors are complemented by moderate to high spatial resolution (<10 m – 100 m) narrow-swath sensors, which have longer revisit intervals, but are useful for local scale applications as well as for the validation of global products.

Table 20.1. Examples of recent, current and planned Earth Observation Systems which can be used for different aspects of Fire Monitoring (planned systems are in italics). *Note:* Acronyms are defined in the text below.

Fire monitoring aspects	**Earth Observation Systems and Sensors**
Active Fire Detection and Characterization (mi-IR)	- AVHRR, GOES DMSP-OLI, MSG, VIIRS, *SLSTR, GOES R* (operational sensors) - TRMM, MODISAM/PM, AATSR, TET-1, ASTER, *BIROS* (experimental)
Burned Area, Fire Danger, Post Fire Assessments (Vis, NIR, thermal)	Coarse / Moderate Resolution (4km-250m) - AVHRR/METOP (operational) - MODIS AM/PM, SeaWiFs, ATSR, VEGETATION (experimental)
	Moderate / High resolution (60m-10m) - Landsat 5/7/8(LDCM), SPOT, IRS, AWiFs, CBERS, Formosat - ASTER (thermal) - Radarsat (C band synthetic aperture radar) - EO 1 Hyperion (hyperspectral)
	Hyperspatial / Fine Resolution - Ikonos, Quickbird, RapidEye, DMC - Surreysat, etc.
Emission Products (optical and sounding)	- MODIS, VIIRS, MISR (Aerosol Optical Depth) - AIRS, MOPPITT (CO, etc.)

Active fires

Active fire mapping algorithms take advantage of the elevated thermal radiance signal from hot fires. Currently, several sensors carry bands in the mid-infrared near 4 μm, which is most sensitive to radiance signal from typical flaming and smoldering fires. The Moderate Resolution Imaging Spectroradiometer (MODIS) on board the morning descending Terra and afternoon ascending Aqua polar orbiting NASA satellites has bands specifically designed to measure thermal radiance from fires and is currently the most widely used polar sensor

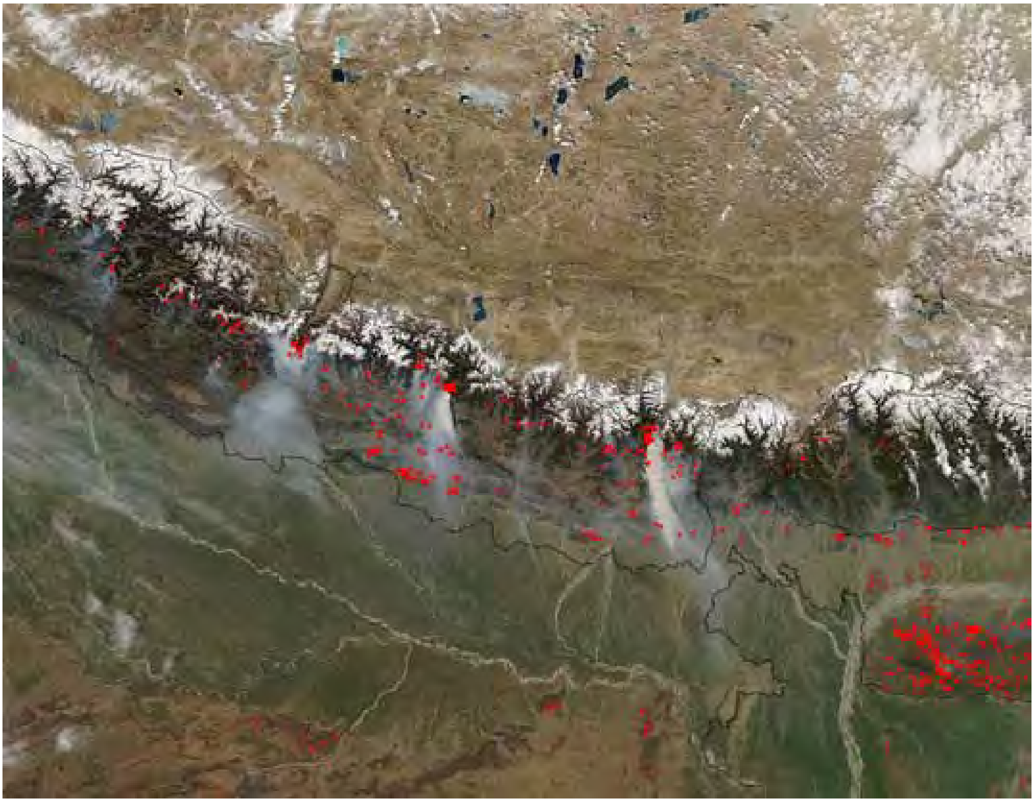

Figure 20.2. Active biomass burning (red dots) in the Himalayan foothills (MODIS Terra, 12 March 2009) (Courtesy: MODIS Rapid Response System).

for near-real-time fire monitoring (Fig. 20.2). MODIS is currently the most mature system providing global daytime monitoring, when fire activity is greatest. Visible Infrared Imager Radiometer Suite (VIIRS) on board the new generation Suomi National Polar-orbiting Partnership (S-NPP) and Joint Polar Satellite System (JPSS) satellites provides continuity with MODIS, with specific fire detection features and good geometric and radiometric characteristics[6]. Additionally, a number of national and regional monitoring systems have been developed using AVHRR,MODIS, and most recently VIIRS data from direct-readout receiving stations.[7]

The heritage sensors on polar orbiting satellites include the Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) operational satellite series, which provide more than 25 years of global daily observations. AVHRR data are also used in numerous near-real-time systems, but are less ad-

6 http://www.jpss.noaa.gov/viirs.html
7 http://directreadout.sci.gsfc.nasa.gov/

equate for fire detection because the instrument lacks dedicated fire bands. The mid-infrared channels of the European Space Agency Along-Track Scanning Radiometer (ATSR) and Advanced ATSR (AATSR) series, which also have sub-optimal daytime fire detection capabilities, have been applied successfully for monitoring fires at night. Nighttime fire observations are also possible using the visible band of the Operational Linescan System (OLS) on board the Defense Meteorological Satellite Program (DMSP) series (Elvidge et al., 2001), and the Day/Night Band of the new VIIRS sensor. The Visible and Infrared Scanner (VIRS) on board the NASA Tropical Rainfall Measuring Mission (TRMM) satellites provide fire observations in the tropics, and, due to its special orbital characteristics, allows for sampling of the diurnal fire cycle (Giglio et al., 2000).

On a geostationary platform located over Africa, the SEVIRI instrument on the Meteosat Second Generation (MSG) satellite provides an improved capability for fire monitoring over the hemisphere that includes Africa and Europe. The Geostationary Operational Environmental Satellite (GOES) Wildfire Automated Biomass Burning Algorithm (WF_ABBA) is providing half-hourly fire observations for the Western Hemisphere. Improved fire detection capabilities will be available from the Advanced Baseline Imager (ABI) on the new generation GOES-R satellites. These and other current (MTSAT-1R – Japan, FY-2C/2D – China) and future (Indian INSAT-3D, Russian GOMS Elektro L MSU-GS, Korean COMS) geostationary platforms will enable nearly global geostationary fire monitoring.

Fire Radiative Power

In addition to the detection of the presence of active fires, some recent and planned sensors also allow for the characterization of the burning process. The fire radiative power (FRP) product provides information on the measured rate of radiant energy output of detected fires. From small-scale experimental fires, it has been demonstrated that the amount of radiant energy released per unit time (the FRP) is related to the rate at which fuel is being consumed. Therefore, measuring this FRP and integrating it over the lifetime of the fire provides an estimate of the total fire radiative energy (FRE), which for wildfires is proportional to the total mass of fuel biomass combusted (Wooster et al., 2005). FRP products are currently derived from MODIS, SEVIRI and GOES and are planned or considered to be included in product suites from SLSTR, VIIRS and ABI.

Fire-affected areas (burned areas)

Algorithms to map fire-affected areas typically take advantage of the temporal persistency of fire effect (removal of vegetation, exposure of bare soil, presence of char or ash, etc.) and the corresponding signal in reflected or emitted radiation. The methodologies are based on satellite image classification using multi-spectral information in the visible, shortwave-infrared and infrared bands and the analysis of multi-temporal satellite imagery. Burned area maps are built using multi-spectral analysis of reflectance or various spectral indexes, such as the Normalized Difference Vegetation Index (NDVI), the Global Environment Monitoring Index (GEMI) or the Normalized Burn Ratios. Some algorithms account for the bi-directional effects of wide swath satellite data, which can impact burned area detection (Roy et al., 2008). Some approaches combine active fire information in the burned area mapping, e.g. Giglio et al. (2009). Recent global products include L3JRC using SPOT VEGETATION data[8]; the GLOBCARBON project[9] using VEGETATION and (A)ATSR data (also included in the framework of the GEOLAND project[10] and the MODIS Burned Area Product[11] (Fig. 20.3).

Fire Product Validation

If satellite derived fire products are to be used in scientific studies, to provide national inventories or in the context of the international conventions then there is a need to understand their accuracy (Morisette et al., 2006). Inter-comparison of products made with different satellite data and/or algorithms provides an indication of gross differences and possibly insights into the reasons for the differences, however product comparison with independent reference data are needed to determine accuracy (Justice et al., 2000). Validation is the term used here, and more generally, to refer to the process of assessing satellite product accuracy by comparison with independent reference data. Validation is required to provide accuracy information to help users decide if and perhaps how to use a product, and, combined with product quality assessment (Roy et al., 2002), to identify needed product improvements (Morisette et al., 2002; Strahler et al., 2006). International coordination to address these issues and to establish and promote a standard protocol for the products is being developed by the Land Product Validation (LPV) Subgroup of the CEOS Working Group on Calibration and Validation[12], in cooperation with the GOFC-GOLD Fire Implementation Team. Given the cost of validation, international cooperation and sharing of validation data are highly desirable.

The first international protocol for the production of reference (validation) dataset for the validation of coarse resolution continental and global burned area products was developed by Boschetti et al. (2009), building on a method developed by Roy et al. (2005).[13] The protocol requires that burned areas are mapped at a higher spatial resolution (i.e. the Landsat class of observations 30-60m) between two dates acquired a few weeks apart and compared to the same period from the coarse resolution data (Roy et al., 2005; Boschetti et al., 2006; Roy and Boschetti, 2009).

Validation of active fire detection is more problematic due to the dynamic and often short-lived nature of fire events. However the unique, simultaneous acquisition of ASTER

8 www-tem.jrc.it/products_complete.htm
9 dup.esrin.esa.it/projects/summaryp43.asp
10 www.gmes-geoland.info
11 modis-fire.umd.edu/MCD45A1.asp
12 http://lpvs.gsfc.nasa.gov/
13 http://lpvs.gsfc.nasa.gov/fire_background.html

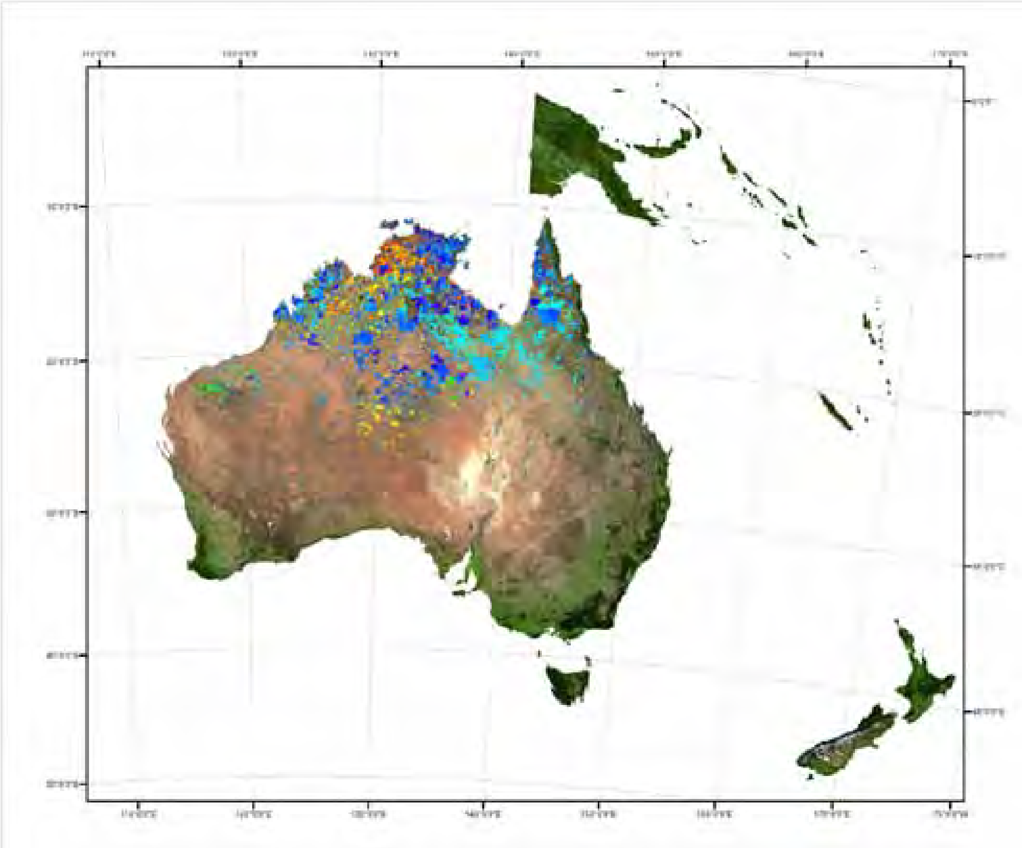

Figure 20.3. One year of burning in Australia (July 2001- June 2002) as mapped by the MODIS (MCD45) product. The rainbow color scale indicating the day of burning, overlaid on MODIS surface reflectance to provide geographic context (Roy et al., 2008).

30m and MODIS 1km data on the EOS Terra platform has enabled a comprehensive global validation of the MODIS Terra Fire product (Morisette et al., 2005). To this end, an automated fire detection algorithm was developed for ASTER (Giglio et al., 2008). Efforts have been made to validate coarse resolution active fire products by locating the burn scar after the fire but location can be problematic given the sub-pixel nature of the fires and that errors of omission of undetected fires cannot be well addressed.

Data Availability and Accessibility

As noted above, there are several satellite systems which provide fire related information, however there is no standard approach to data provision and data providers have very different data policies. Similarly there is no standard system for determining data coverage or availability. Generally, coarse resolution satellite data are freely available. Some moderate/high resolution data are only available for purchase, e.g. SPOT and IRS AWiFS, while others, such as Landsat data are available for free electronic download. (It should be noted though that Landsat 7 has been experiencing a serious line-scan problem since 2003.) Virtually all fine spatial resolution data are in the commercial domain and prices vary. The cost of satellite data remains a significant obstacle to uptake of the data. The failure to transition successful sensor missions to operational status has also limited the greater use of the data by operational resource management agencies.

Although there are several moderate/high resolution systems, there is currently no global coordination of moderate/high resolution data acquisition and high resolution data coverage for specific locations often needs to be requested. For large parts of the world, some systems e.g. Landsat 5, CBERS and IRS require a direct readout (ground) station for coverage.

Access to derived fire products is often easier than obtaining the raw satellite data and less overhead in terms of data processing. Active fire products from various sensors can be viewed simultaneously using the Internet and Web-Geographical Information System technology. Examples include the NOAA Hazard Mapping System, which displays data from AVHRR, GOES and MODIS[14] or the Brazilian CPTEC/INPE fire mapping system, which includes data from AVHRR and MODIS.[15] A number of such monitoring systems are listed on the websites of the Global Observation of Forest and Landcover Dynamics (GOFC-GOLD) Fire theme[16] and the Global Fire Monitoring Center (GFMC).[17] One easily accessible and much used web-based system for distributing MODIS-based fire information is Fire Information for Resource Management (FIRMS) (Davies et al., 2009).[18]

Fire Emissions and REDD

Estimates of atmospheric emissions from biomass burning have conventionally been derived adopting ‘bottom up’ inventory based methods (Seiler and Crutzen, 1980). These generally multiply the area burned by the fuel load, factoring in the combustion completeness and an emission factor for the fuel type and the emission species (Andreae et al., 2001, Korontzi et al., 2003). Since burned area products derived from satellite data have become available, the largest uncertainty lies in the dynamic estimation of fuel load. Fuel load has been estimated using various methods from sample field data, satellite data and models (including those partially driven by satellite data) calculating Net Primary Production to provide biomass increments and partitioning between fuel classes (Van der Werf et al., 2003).

The direct estimation of FRP from satellite data, as described above, provides an alternative to the conventional bottom up approaches. The FRP is a geophysical variable potential-

14 www.osdpd.noaa.gov/ml/land/hms.html
15 http://sigma.cptec.inpe.br/queimadas
16 http://gofc-fire.umd.edu
17 http://www.fire.uni-freiburg.de
18 http://maps.geog.umd.edu/firms/

ly directly related to the rate at which the fire is consuming biomass, and thus releasing CO_2 and other trace gases and aerosols; the FRE, obtained through the temporal integration of the FRP, is potentially related to the total biomass consumed and thus to the total emissions. However, these methods are currently being developed in the research domain (Wooster et al., 2005) and have yet to transition to the operational domain.

Policy attention is currently being given to the instrument Reducing Emissions from Deforestation and Degradation (REDD) in the context of mitigating climate change by reducing greenhouse gas emissions. The role of fire monitoring in the implementation of REDD is still under consideration. However there are a number of ways in which satellite fire monitoring could contribute, including calculation of fire emissions from national to local scales, detection of fires in fire-exclusion or forest management areas, identifying illegal forest clearance, monitoring fire type, impact and subsequent vegetation recovery and providing fire danger rating. Limiting fires in forest areas that naturally would burn requires careful management and often a program of controlled burning. Information leading to better forest/fire management to reduce the frequency of stand replacement fires would also lead to a reduction in emissions and a net increase in carbon sequestration. The FAO definition of forests, namely areas with greater than 10% tree cover, includes large areas of savannah woodlands. Managing savannah fires from the perspective of reducing emissions would need to be carefully balanced by consideration of land use and ecosystem impacts and especially the longer term consequences. The implementation of Fire and REDD warrants close involvement of the science community in the evaluation of potential impacts of the different management intervention options.

Long-term Satellite Data Records and Essential Climate Variables

The international community recognizes the need for consistent long term observations with which to study the impacts of climate and global change (GCOS Implementation Plan 2004). Fire disturbance has been identified as one of 44 Essential Climate Variables (ECVs). The space agencies are now charged with coordination to generate these long term data records, which in some cases require data from different agencies. The development of a consistent long-term satellite record is a challenge for the remote sensing community as it always involves using data from different instruments and requires careful attention to calibration, geolocation, and atmospheric correction. Often new sensors provide improvements over previous instruments, which creates a dynamic, product continuity, e.g. the progression from the AVHRR, to the MODIS and then to the VIIRS sensors with improvements in spatial resolution and radiometry. NASA and NOAA are currently supporting the development of land long term data records[19] and ESA is also embarking on a program of ECV development. It is critical that the ECVs, be community endorsed and undergo an extensive program of validation.

19 http://ltdr.nascom.nasa.gov/ltdr/ltdr.html

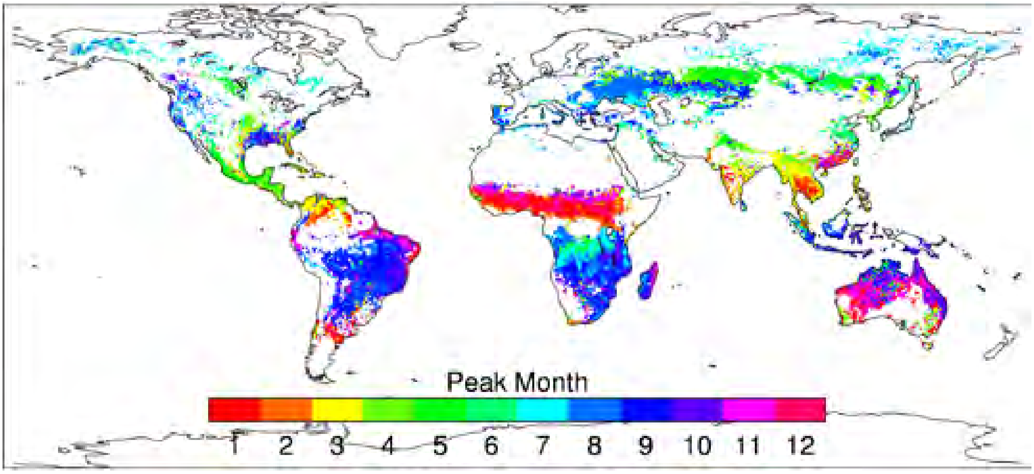

Figure 20.4. Mean peak month of fire occurrence from 2000-2005 (1 = January, 12 = December) (Giglio et al., 2007)

A Satellite-based Global Fire Assessment

The UN FAO Forest Resource Assessment 2005 was complemented by a Global Fire Assessment, a narrative consisting of 12 regional descriptive working papers prepared by the Global Wildland Fire Network. With the availability of a consistent satellite data record from MODIS it is now possible to provide a more quantitative assessment of the global extent of fire and trends over the last decade. The GOFC-GOLD Fire Implementation Team (co-chairs: Justice and Goldammer) in conjunction with the Global Fire Monitoring Center is currently embarking on a Global Fire Assessment using the available satellite data. The assessment which will be for the last ten years, will utilize the available satellite records and will include a number of metrics associated with fire location, timing and spatial characteristics (Fig. 20.4). Analysis and interpretation of the results will be undertaken in cooperation with the regional fire networks of GOFC-GOLD and the UNISDR. Reporting will be undertaken at the national and continental scale.

Observation Requirements and Future Missions

The fire data user community could benefit from refining the requirements for satellite derived fire information and working with the space agencies to ensure that the necessary observations are collected. The future for operational coarse resolution imaging will depend on the United States JPSS and European Sentinel programs which are designed to serve the operational community. VIIRS is supposed to provide continuity with MODIS, and fire detection capability will also be provided by the SLSTR (Sea and Land Surface Temperature Radiometer) on board the GMES (Global Monitoring for Environment and Security)

Sentinel-3 satellite.[20] The situation with respect to future moderate/high resolution sensing is less clear as there are multiple systems being proposed, including the European Sentinel 2 planned for launch in 2014.[21] The major challenge with this class of system, as discussed above, is associated with developing a coordinated international data acquisition strategy leading to an increased temporal resolution of Landsat class observations with 2-3 day global coverage.

International Coordination Efforts

There is a clear need for increased international coordination with respect to fire observations both in terms of the satellite observations as well as consistent national reporting of in-situ observations. The satellite observations are currently being coordinated through the Coordination Group for Meteorological Satellites (CGMS) and CEOS. Input to the space agencies from the scientific and satellite data user community is being coordinated through the GOFC-GOLD program and the regional fire networks. The GFMC has taken the lead in coordinating the broader needs of the fire monitoring community in the context of the UNISDR through the United Nations International Strategy for Disaster Reduction (UNISDR)[22] Global Wildland Fire Network[23] and its participation and sponsorship of the series of International Wildland Fire Conferences. The validation protocols for the satellite fire products and the standards for validation reporting are being developed by the CEOS CVWG LPV, as discussed above. These coordination efforts are helping to realize the full potential of what satellite monitoring could bring to the improved understanding and management of fire.

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20 http://www.esa.int/esaLP/SEM097EH1TF_LPgmes_0.html

21 http://ldcm.nasa.gov/

22 http://www.unisdr.org

23 http://www.fire.uni-freiburg.de/GlobalNetworks/globalNet.html

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21 The Global Early Warning System for Wildland Fire

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Abstract

Wildland fires burn several hundred million hectares of vegetation every year, and increased fire activity has been reported in many global regions. Many of these fires have had serious negative impacts on human safety, health, regional economies, global climate change, and ecosystems in non-fire-prone biomes. Worldwide fire suppression expenditures are rapidly increasing in an attempt to limit the impact of wildland fires. To mitigate fire-related problems and costs, forest and land management agencies, as well as land owners and communities, require an early warning system to identify critical periods of extreme fire danger in advance of their potential occurrence. Early warning of these conditions allows fire managers to implement fire prevention, detection, and pre-suppression plans before fire problems begin. Fire danger rating is commonly used to provide early warning of the potential for serious wildfires based on daily weather data. Fire danger information is often enhanced with satellite data, such as hot spots for early fire detection, and with spectral data on land cover and fuel conditions. Normally, these systems provide a 4- to 6-hour early warning of the highest fire danger for any particular day that the weather data is supplied. However, by using forecasted weather data, as much as two weeks of early warning can be provided. This short paper presents the first products of a Global Early Warning System for Wildland Fire to provide advanced early warning capabilities at local to global levels. This system will provide 1) new longer term predictions of fire danger based on advanced numerical weather models, 2) a common international metric for implementing international resource sharing agreements during times of fire disaster, and 3) a fire danger rating system for the many countries that do not have the financial or institutional capacity to develop their own system. Because the system can be used at the local level, it can support local capacity-building by providing a foundation for community-based fire management programs.

Keywords: Wildland fire early warning, global fire danger forecast, fire danger rating, numerical weather prediction, fire weather

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A publication of the Global Fire Monitoring Center (GFMC)

Introduction

Fire is an increasingly prevalent disturbance on the global landscape with several hundred million hectares of vegetation burning every year. Land and forest fires (collectively referred to as wildland fires) occur annually in all vegetation zones and most global fire is unmonitored and undocumented. Increasing trends in wildland fire activity have been reported in many global regions. Uncontrolled wildfires can have many serious negative impacts on local human safety, health, regional economies and global climate change. To mitigate these fire-related problems, forest and land management agencies, as well as land owners and communities, require an early warning system to identify critical periods of extreme fire danger in advance of their occurrence. Early warning of these conditions with high spatial and temporal resolution, allows fire managers to implement fire prevention, detection, and pre-suppression plans before fire problems begin. Considering that most uncontrolled and destructive wildfires are caused by humans as a consequence of inappropriate use of fire in agriculture, pastoralism, and forestry, it is crucial that international wildland fire early warning systems are developed to complement national fire danger rating systems where they exist, to provide early warning where national systems do not exist, and to enhance warnings applied or generated at the local community level. This will ensure delivery of targeted information reflecting specific local conditions and allow the involvement of local communities in wildland fire prevention.

System Objectives

The goal of the Global Early Warning System for Wildland Fire (EWS-Fire) is to provide a scientifically supported, systematic procedure for predicting and assessing international fire danger that can be applied from local to global scales. The system is not intended to replace the many different national fire danger rating systems currently in use, but rather to support existing national fire management programs by providing:

- new longer term predictions of fire danger based on advanced numerical weather models
- a common international metric for implementing international resource sharing agreements during times of fire disaster
- a fire danger rating system for the many countries that do not have the financial or institutional capacity to develop their own system. Because the system can be used at the local level, it can support local capacity-building by providing a foundation for community-based fire management programs.

System Overview

The EWS-Fire has two distinct requirements in order to function: (1) it must provide predicted fire danger based on forecasted fire weather conditions, and (2) it must also provide a means of interpreting the fire danger in practical and locally relevant fire management terms. These criteria imply that the fire danger rating systems used by the EWS-Fire must have fairly simple and reasonably predictable weather inputs over the forecasted range, and it must be possible to locally calibrate the fire danger indices.

The EWS-Fire provides both current and forecasted fire danger information because both are important for fire management decision-making. Current fire danger indicates the actual fire potential and provides a quantitative method to compare and prioritize areas when suppression resources are limited. Forecasted fire danger provides early warning of future trends in fire potential, allowing fire and land managers to plan and implement fire management strategies in advance.

By overlaying current fire danger maps with hot spot data, the EWS-Fire indicates areas where ongoing fires combine with high fire danger to create the greatest current priority. Combining forecasted fire danger maps with hot spot data indicates critical areas where serious fire problems will occur if current fire activity persists. The international panel for Global Observation of Forest Cover and Global Observation of Landcover Dynamics (GOFC-GOLD) has developed several fire monitoring and mapping products that make use of hot spot data and are included in the EWS-Fire.

Daily current fire danger products are already being generated for many countries and some global regions on an operational basis. Linking or networking these agency products within the EWS-Fire provides a globally-compiled product of current fire danger. The advantage of building on existing national and regional systems is that it ensures direct connection and applicability of the EWS-Fire between local, national, and global scales. In some global regions where there are few national systems in place, 'Regional Network' agencies can assist in providing and implementing national-level fire danger and early warning information. In Africa, for example, the GOFC-GOLD Southern African Fire Network (SAFNET) will provide daily fire danger and early warning for the Southern Africa region and the UNISDR Regional Sub-Sahara Wildland Fire Network (AfriFireNet) will provide technical advice in the operational use of fire danger and early warning information.[3]

Global EWS-Fire Products and Dissemination

All early warning products can be accessed via the Global Early Warning System for Wildland Fire website[4], which is hosted by the Global Fire Monitoring Center. The EWS-Fire website is fully operational since 2010 and producing daily global early warning products at that time. Current global fire danger will be compiled from national and/or regional agencies and aggregated with EWS-Fire generated products for countries that do not have a national fire danger rating system in place. Several forecasted fire danger products (see Fig. 21.2 as an example) will be presented using different sources of numerical weather predic-

3 A collaborative arrangement resulting from the recent 'Regional Consultative Workshop for the Development of a Southern African Development Community (SADC) Cross-border Fire Management Programme' (25-27 January 2010, Maputo, Mozambique).

4 http://www.fire.uni-freiburg.de/gwfews/index.html

tions (ensemble forecasts) to represent a range of possible future fire weather conditions. National fire danger rating systems will be linked to the global system to exchange information, and regional systems will be setup to assist or provide national-level systems where there currently are none. Local communities will be integrated with national and global systems, and will also be capable of calculating local fire danger and implementing appropriate fire management actions. A summary of operational activities from local to global levels is summarized in Table 21.1.

All EWS-Fire products will be updated several times each day in blocks of time zones so that regional, national, and local fire management agencies will have access to information in the morning that is valid for the afternoon peak burning period of the day. Specially-designed global level products can be prepared for specific disaster and health and safety management agencies as requested, e.g., for the United Nations International Strategy for Disaster Reduction (UNISDR), Food and Agriculture Organization (FAO), United Nations Environment Program (UNEP), World Health Organization (WHO), or the World Meteorological Organization (WMO).

Dissemination of wildland fire early warning products must be directed to various user levels from global to local scale using multiple channels. A dedicated GFMC Wildland Fire Early Warning Portal provides access to the EWS-Fire as well as global, regional, and national early warning systems.[5] These users, however, must have regular access to the Internet. Advance information tools must be developed to disseminate fire warning alerts to targeted users. This technology is already in use for rapid alerts of satellite-detected wildland fires, such as the Advanced Fire Information System (AFIS)[6]. AFIS is the first near real-time operational satellite fire monitoring system in southern Africa. The system is based on technology developed at the University of Maryland and NASA over the last few years. Funding for the development, installation, and operational running of the system has been made possible through ESKOM, the Department of Agriculture, and the Council for Scientific and Industrial Research (CSIR) Satellite Application Centre (SAC). The CSIR SAC is in the process of customizing and further developing AFIS to enable not only the detection of fires but also the prediction and assessment of future fire events.[7]

Community-based Fire Management – Reaching the Last Mile

For many countries, fire management happens at the local level. As previously mentioned, this means communication networks need to be established so that early warning reaches local communities. Such networks are not always stable, therefore communities also need to be prepared to determine their own local fire danger conditions, independent of global or national networks when necessary. Additionally, communities need to be trained to use fire danger information to make fire management decisions. For these reasons, technology trans-

5 http://www.fire.uni-freiburg.de/fwf/fwf.htm
6 http://afis.meraka.org.za/afis/
7 http://www.fire.uni-freiburg.de/GlobalNetworks/Africa/Afrifirenet_4e.html

Table 21.1. Daily operational activities in the Global Early Warning System for Wildland Fire.

	Current fire danger information	**Future fire danger information**	**Fire management activity**
Global	1. Collect and present current global fire danger from available national sources 2. Collect daily global fire weather data from WMO network 3. Calculate and present daily fire danger for countries that do not produce national summaries	Provide 1-14 day forecast fire danger using global numerical weather models	Provide early warning of fire danger to national and international wildland fire and disaster management organizations (e.g., all countries via GFMC website, UNISDR, FAO, WHO, UNEP, WMO etc.)
Regional	Assist with national-level activities for countries where a national fire danger rating system is not in place		
National	1. Collect data from national synoptic and fire weather station networks 2. Calculate fire danger once or twice daily	1. Calculate1-3 day national fire danger forecast 2. Receive 1-14 day general forecast from global level	1. Determine resource-sharing within country, and bi-laterally with other countries 2. Fire management decisions based on nationally-derived guidelines
Local	1. Collect local fire weather data 2. Calculate daily or hourly fire danger, as necessary	1. Receive1-3 day national forecast from national or regional level 2. Receive 1-14-day general forecast from global level	1. Determine daily fire prevention, detection, and suppression activities at local level 2. Field-level decisions based on locally-derived prescribed fire management guidelines

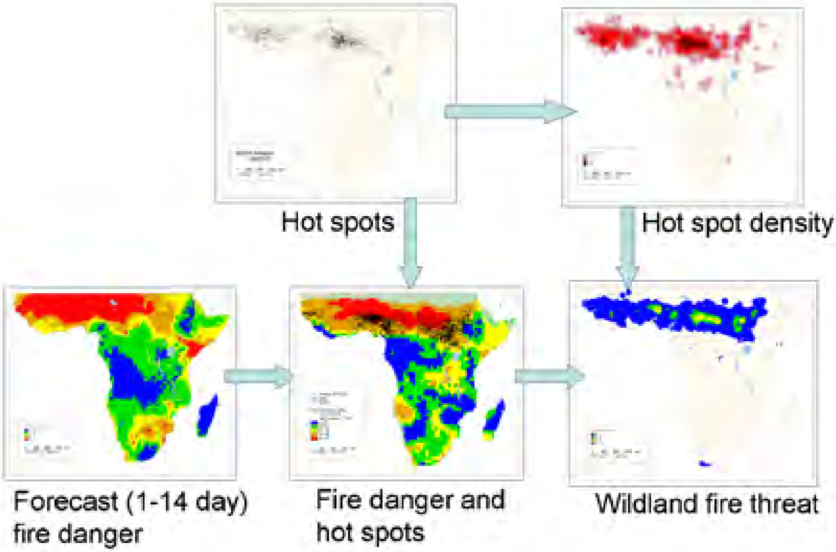

Figure 21.1. Examples of fire early warning products from the sub-Saharan demonstration study presented at the GOFC-GOLD fire early warning workshop (University of Ghana, Accra, Nov. 2007). Future fire danger (in this case, represented by the Fine Fuel Moisture Code of the Canadian FWI System) is overlaid by current hot spot data to indicate areas where prescribed fire use may need to be restricted due to threat of escaped fire or potential fire damage. Data of active fires can also be overlaid on current fire danger to indicate areas of greatest current priority.

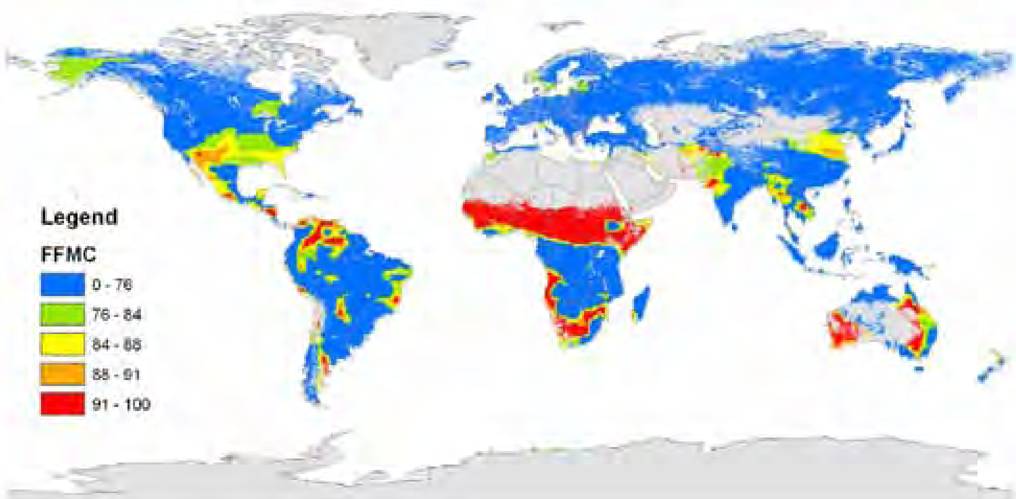

Figure 21.2. Example of a forecasted global fire danger product using the Fine Fuel Moisture Code (increasing values indicate higher fire danger). Other fire danger indices can be presented, depending on user requirements.

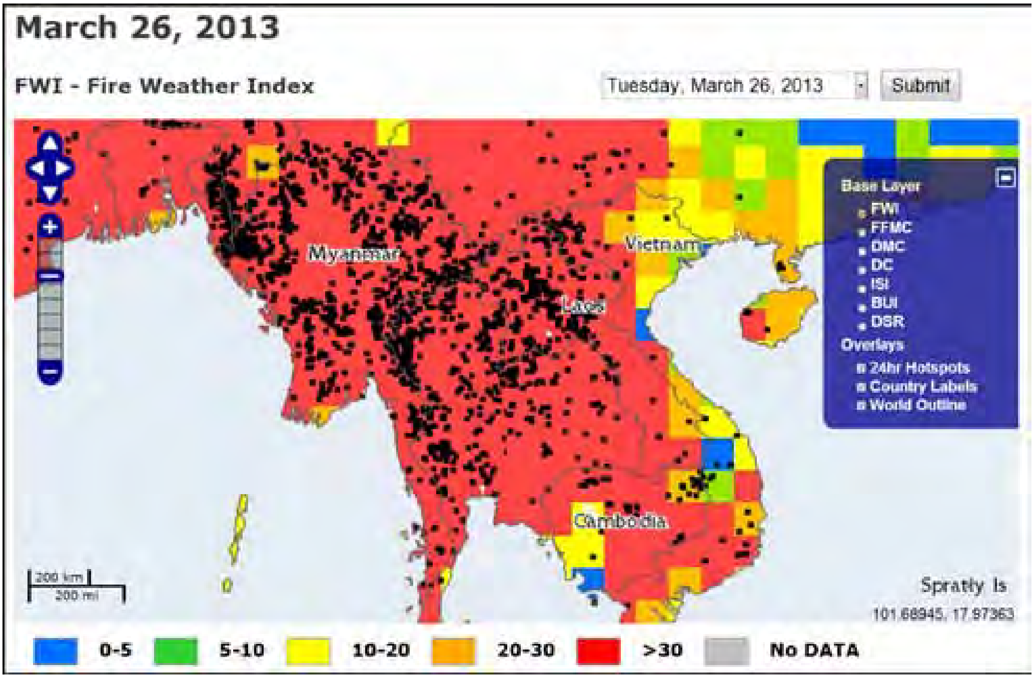

Figure 21.3. Example of a selected region of forecasted global fire danger product using the Fire Weather Index on 26 March 2013. Satellite-derived locations of active fires burning during the last 24 hours (in this case: 25 March 2013) are marked by black dots.

fer is critical to the success of community based fire management. Due to the huge number of fire-prone communities that need this training (mostly located in developing nations), this will be a long-term effort that will likely occur as funding sources, such as international aid programs, are available.

Technical training in the application of early warning information to fire management planning and actions will be done through various training programs and educational institutions such as the United Nations University (UNU), now associated with the GFMC.[8] The Global Wildland Fire Network, through the participation of government and non-government institutions of countries organized in Regional Wildland Fire Networks, is offering a suitable platform for regional training.[9] The first fire technology transfer programs in Africa[10] and Southeast Asia have been very successful. For the EWS-Fire, training would include course instruction on basic fire weather, fire behavior, fire danger, and early warning,

8 http://www.fire.uni-freiburg.de/programmes/un/unu/unu.htm
9 http://www.fire.uni-freiburg.de/GlobalNetworks/globalNet.html
10 http://www.fire.uni-freiburg.de/GlobalNetworks/Africa/Afrifirenet_3.html

and calculation of fire danger indices using simple computer programs and manually with tables.

Finally, assistance in the development of local fire management decision-aids based on EWS-Fire products will be done through facilitated workshops. This will help local communities develop criteria for determining when specific fire prevention, detection, and suppression actions are taken based on early warning information. The UNISDR, the Global Wildland Fire Network and the GOFC-GOLD Regional Fire Implementation teams and networks would jointly work in technology transfer and training to develop local expertise and capacity building in wildland fire management.

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22 Beyond Climate Change: Wildland Fires and Human Security in Cultural Landscapes in Transition – Examples from Temperate-Boreal Eurasia

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Abstract

In many regions of Eurasia cultural landscapes that were formed by traditional agrarian societies over centuries are changing rapidly. The process of rural exodus and the rapidly accelerating trend of urbanization is associated with abandonment of land cultivation and thus directly or indirectly affecting cultural and wildland fire regimes. This chapter looks at the specific issues linked with wildland fire, land use and land-use change in Eurasia, and to wildfires and threats emerging from the heritages of civilization. While the temperate-boreal zone of Eurasia is in the focus of this chapter, some views to the cultural landscapes of North America reveal comparability and similarities between continents. An increasing awareness of newly arising or newly perceived fire-related problems by the general public and by policy makers is apparent. However, development of fire management solutions such as the adjustments to public policies affecting land management and operational fire management to the changing land use conditions and society's vulnerability are lagging behind. Changing paradigms in ecology and nature conservation have recently led to reconsidering fire-exclusion policies in certain sectors of land / landscape management, nature conservation and forestry. However, the use of prescribed fire in ecosystem management in Europe may not exclusively target those vegetation types that have been shaped by fire over historic time scales, but rather to introduce fire as a tool to substitute abandoned cultivation practices. However, use of fire in agriculture is being questioned where new insights into the side effects of burning are revealed by recent research. For example, there are indications that deposition of black carbon emitted from agricultural spring fires in Northern Eurasia are impacting the albedo of the Artic environment, leading to acceleration of warming and melting of snow and ice cover. As a symptom of these developments the terms "necessary" and "unnecessary" burning in the agricultural sector in temperate-boreal northern Eurasia are entering the wildland fire terminology.

Keywords: Cultural landscape fire, rural exodus, land cultivation abandonment, radioactive pollutants, prescribed burning

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Introduction

In many regions of Eurasia cultural landscapes that were formed by traditional agrarian societies over centuries are changing rapidly. The process of rural exodus and the rapidly accelerating trend of urbanization is associated with abandonment of land cultivation and is thus directly or indirectly affecting cultural and wildland fire regimes. This chapter identifies the specific issues linked with wildland fire, land use and land-use change in Eurasia, and the wildfire threats emerging from the heritages of civilization. While the temperate-boreal zone of Eurasia is the focus of this chapter, some analyses of the cultural landscapes of North America reveal comparability and similarities between continents.

Socio-economic Changes, Industrial Heritages and Emerging Fire Threats in Eurasia

Temperate-boreal Eurasia extends from Western Europe to Asia's Far East and spans more than 200 degrees of longitude. While the region contains a large variety of ecosystems and land-use systems, there exist commonalities of determinants of wildland fire between these countries and subregions that share similar historic and contemporary natural, cultural and social conditions.

Some hazards and risks associated with wildland fires have been perceived as threats only recently due to a better scientific understanding of conditions influencing wildland fire. The public perception of wildland fire throughout the region has been stirred significantly by the discussion of the anticipated consequences of climate change on forest fire occurrence and impacts. However, some recent wildfire episodes also revealed the vulnerability of society to direct and secondary effects of fire such as the impacts of fire smoke pollution on human health and security.

Wildland fires burning at the interface of, or even inside residential, urban and industrial areas, and fires burning on terrain contaminated by industrial deposits and heritages of armed conflicts are perceived as new, unprecedented threats – although they have existed before, albeit unnoticed publicly and politically. It is also becoming evident that the alteration of fire regimes in the cultural landscapes of Eurasia is driven fundamentally by land-use change.

Recent wildfire episodes in temperate-boreal Eurasia have resulted in severe environmental damages, high economic losses and considerable humanitarian problems. After the Mediterranean fire crisis in 2007, followed by the fire and smoke episode in Western Russia in 2010, several key issues affecting wildland fire in the cultural landscapes of temperate-boreal Eurasia have been identified:

- Increasing rural exodus and urbanization, resulting in abandonment of traditional land cultivation (agriculture, pastoralism, forestry) resulting in an increasing wildfire hazard;
- Urbanization resulting in a reduced rural work force, including availability of rural firefighters;

- Re-privatization of formerly nationalized forests resulting in the absence of forest and fire management in smallholder forest estates;
- Weakened governance over forestry and decreased fire management capabilities in many Eastern European and Central Asian countries as a consequence of the transition of national economies, often associated with the uncontrolled or illegal forest use and increase in related wildfires;
- Increasing occurrence of wildfires affecting the perimeters of metropolitan areas, settlements and developments dispersed throughout wildlands;
- Secondary problems associated with wildfires, e.g., those burning in territories contaminated by radioactivity and remnants from armed conflicts (e.g., unexploded ordnance, land mines, uranium-depleted ammunition); or wildfires affecting agricultural lands treated with pesticides; landfills, other industrial waste and structures containing hazardous materials, especially at the urban / residential perimeters;
- Consequences of climate change on cultural fire regimes and ecosystem vulnerability (e.g., climate-driven transformation of former fire-free or fire-protected natural ecosystems and land-use systems such as peat bogs and high-altitude mountain ecosystems to ecosystems becoming vulnerable to and increasingly affected by wildfires).

The assessment of changing fire regimes and the increasing vulnerability of society and subsequent public policy responses are influenced by new scientific insights into the composition of fire emissions and their impacts on the environment and human health and must address the following considerations:

- Effects of gas and particle emissions from open burning vegetation fires on human health;
- Vulnerability of industrial and rural societies to air pollution generated by vegetation fires;
- Impacts of radiatively active trace gases and particle emissions from vegetation fires affecting the functioning of the atmosphere and contributing to climate change;
- Impacts of fire emissions on ecosystems, e.g. the consequences of deposition of fire-emitted black carbon in the arctic environment;
- Resulting conflicts in fire management, e.g., controversial views on the acceptance of prescribed burning.

While a growing acknowledgment of these issues by the public and by policy makers can be noted, there is a lack of review, adjustment or development of appropriate fire management policies.

The recently published *White Paper on Use of Prescribed Fire in Land Management, Nature Conservation and Forestry in Temperate-Boreal Eurasia* (Goldammer, 2010a) is an example for changing perceptions of the role of fire in cultural landscapes. The white paper reveals that the use of fire – including disturbance related to swidden (shifting) agriculture and other land cultivation practices – have contributed to shaping landscape patterns of high ecological and cultural value and diversity across temperate-boreal Eurasia in areas such as heathlands, open grasslands and meadows. In the eastern Euro-Siberian biota, e.g. in the light taiga, natural fires have shaped open and stress-resilient forest ecosystems (Sannikov and Goldammer, 1993).

Changing paradigms in ecology and nature conservation have recently led to reconsidering fire-exclusion policies in certain sectors of land / landscape management, nature conservation and forestry. However, the use of prescribed fire in ecosystem management in Europe may not exclusively target those vegetation types that have been shaped by fire over historic time scales, but rather may introduce fire as a tool to replace abandoned cultivation practices (Goldammer, 2010a).

A sound understanding of the "pros and cons" of prescribed fire application is as necessary as consideration of the side effects of fire use. Large areas threatened by land abandonment are embedded in industrialized regions in which society is becoming increasingly intolerant of fire emissions. The fire and smoke episode in Western Russia in 2010 is a striking example of both increased perception and vulnerability (Goldammer, 2010b). Legal restrictions for open burning are included in clean-air rules and the obvious general necessity to reduce those gas and particle emissions that are threatening human health (cf. chapter 18 of this volume). Concerns of those parties that consider prescribed fire emissions a contribution to the increase of the anthropogenic *greenhouse effect* and thus global warming complicate the debate. The traditional use of fire in agriculture is being questioned due to new insights into the side effects of burning emerging from recent research. For example, there are indications that deposition of black carbon emitted from agricultural spring fires in Northern Eurasia are impacting the albedo of the Artic environment, leading to acceleration of warming and melting of snow and ice cover (Clean Air Task Force, 2009; Doherty et al., 2010; Hegg et al., 2010; McCarty et al., 2012). As a symptom of these developments the terms "necessary" and "unnecessary" burning in the agricultural sector in temperate-boreal northern Eurasia are entering the wildland fire terminology.[2]

On the other hand it is noted that nature conservation agencies, non-government actors and the general public have developed a rather sound understanding and perception of the "nature of fire" compared to the situation two to three decades ago. International (regional) dedicated networks and research projects such as the *Eurasian Fire in Nature Conservation Network* (EFNCN)[3], within which the *White Paper on Use of Prescribed Fire* was developed, and particularly the European Integrated Project *Fire Paradox*, have significantly contributed to the acceptance of fire use in wildfire hazard reduction and fire suppression (Sande Silva et al., 2010; see also Birot, 2009).

2 The *International Conference on Open Burning and the Arctic* (Russia, November 2010), which explored the impacts of emissions from open fires on Arctic climate, particularly black carbon emissions from set fires in Northern Eurasia, provide a critical view of the escalating fire use in the agricultural sector (Clean Air Task Force, 2009; Clean Air Task Force / Bellona, 2011).

3 http://www.fire.uni-freiburg.de/programmes/natcon/natcon.htm

Pressing Issues

Some of the newly arising or recently perceived wildland fire problems in the Eurasian region are strongly related to cultural and industrial heritages and recent changes in the cultural landscapes. The examples given in the following reveal that the most immediate impacts of wildland fires on society are determined by human activities, rather than by nature or climate change. Some of the examples highlight events that have been influenced or generated by policies and politics. While some cases may uncover some unspoken problems, there is no intent to blame or accuse any party, nation or country.

Rural Exodus

The interest and insight into cultural landscape ecology has been driven by the increasingly visible socio-economic changes in the past four decades – notably the rural exodus all over Eurasia, which has resulted in abandonment of traditional land-use methods over wide areas (Dimitrakopoulos and Mitsopoulos, 2005). With the elimination of land cultivation, including traditional burning practices, large areas of Europe are reverting to fallow lands – a process that is associated with ecological succession towards brush cover and forest and an overall loss of open habitats. Besides the loss of valuable biodiversity the fire regimes of abandoned lands are transitioning from fuel-limited to water-limited (Pausas and Fernández-Muñoz, 2011), resulting in an increased wildfire hazard.[4] This trend is evident in a number of extremely severe wildfires such as in Southern Mediterranean Europe and the Balkans in 2007 (Xanthopoulos, 2008) and Western Russia in 2010 (Goldammer, 2010b). Similarly, the exclusion of fire in natural ecosystems such as northern boreal and sub-boreal coniferous forests in Eurasia has resulted in changing vegetation composition and an increase of wildfire hazard, notably in Central-Eastern Eurasia.

The country with the highest rate of abandoned villages and agriculture is Russia (Ioffe, 2005; Ioffe et al., 2006, 2011). Between 1939 and 1989 the rural population of the USSR declined from 130.2 to 97.7 million. Within the Russian Soviet Federative Socialist Republic (RSFSR) alone the decline averaged 100,000 people per year between 1979 and 1988.[5] In 2010 alone more than 3,000 villages in Russia became deserted[6], a development obviously supported by government policy aimed at relocating people from rural areas and impoverished towns to larger metropolitan areas in order to improve living conditions.[7]

4 Recently the consequences of rural exodus on increasing wildfire hazard and occurrence has been investigated and proven for the Western Amazon region (Peru) (Uriarte et al., 2012)

5 Data provided by „Seventeen Moments in Soviet History“: http://www.soviethistory.org/index.php

6 See report „Exodus leaves Russia's villages to ghosts", published on 30 August 2011 by http://rt.com/news/rural-russia-dying-villages-411/.

7 See report „Russia Plans Mass Exodus", published on 17 November 2010 by http://www.nodeju.com/5449/russia-plans-mass-exodus.html.

The consequences of rural exodus in Russia and its neighboring countries of temperate-boreal Eurasia on changing fire regimes have not yet been subject to dedicated research. After the collapse of the former Soviet Union the decreasing support of the agricultural sector by the Russian government resulted in abandonment and fallow of 27 million ha of agricultural lands between 1990 and 2009 (Schierhorn and Müller, 2011). Empirical observations suggest that abandonment of agricultural lands, coupled with uncontrolled succession towards bush encroachment and natural reforestation constitute an increasing wildfire hazard – at least during the transition phase to forest formation. At the same time it seems that intentionally set fire is increasing – to keep agricultural lands open or to dispose of crop residue – with the consequence of uncontrolled wildfires spreading to surrounding vegetation, including forest and peat swamps. Recent studies of agricultural burnings at the global scale (e.g., Korontzi et al., 2006) are revealing the magnitude of occurrence but cannot yet prove long-term changes of agricultural fire regimes in temperate-boreal Eurasia related to the historical and current trend of rural exodus.

Increasing vulnerability of urban and peri-urban populations

The weakening or depletion of the rural work force is another factor aggravating the newly arising fire problems in these cultural landscapes in transition. Abandoned villages, along with those with aging populations are increasingly unprotected. As witnessed in 2010, the risk of wildfires spreading uncontrolled into villages and the resultant damage appears to be becoming a serious problem.

The problems and vulnerabilities of infrastructures and populations neighbouring or interspersed with wildlands have received increasing interest by the Western European research community and led to some policy response.[8] Many countries have created guidelines and legal instruments obliging owners of properties at risk of wildfire to take precautionary and preventive measures for wildfire hazard reduction, and jurisdictions to enforce these policies (Xanthopoulos, 2004).

Secondary effects of wildland fire, however, have been largely neglected in the past, notably vegetation fire smoke pollution impacts on human health and security. The episode of drought, wildfires and smoke pollution in Western Russia in July-August 2010 revealed the humanitarian problems arising in metropolitan areas from smoke emitted by burning of natural vegetation in the rural landscape as well as through long-distance smoke transport (Goldammer, 2010b).

Other threats have also been largely ignored. Wildfires burning houses, industrial infrastructure, agricultural lands treated with pesticides, fungicides, and fertilizers and fires affecting landfills (residual waste) and other waste (e.g. batteries, radioactive materials) generate substantial amounts of hazardous pollutants (Statheropoulos and Goldammer, 2007; Goldammer et al., 2009). The Frio Fire in the Pinal Mountains near in Arizona, which

8 For comprehensive literature on the wildland-urban fire research, including modeling, see: http://www2.bfrl.nist.gov/userpages/wmell/public.html#sec_publications.

burned between August and October 2011 and assumedly affected an area treated with *Agent Orange* in 1965, fuelled public concerns about the consequences of smoke pollution containing dioxins on human health.[9]

Vegetation fires have the potential to release and transport toxic industrial and agricultural substances that have been previously deposited in ecosystems (Genualdi, 2008).[10] In the case of pesticides and polychlorinated biphenyls (PCBs) these persistent organic pollutants can land in regions where the compounds are now banned – or even in the Arctic, where they were never applied. One of the studies uses satellite imaging of smoke plumes and modeling of air mass trajectories to track the source of pollutants emitted by Siberian wildland fires in 2003 and transported to the Pacific Northwest of the U.S., including dieldrin and alpha-hexachlorocyclohexane (alpha-HCH) (Genualdi, 2008).

Recent research reveals that as a consequence of climate change, mercury deposits previously protected in cold northern forests and wetlands will increasingly become exposed to burning. Mercury is readily released into the atmosphere with fire smoke. Turetsky et al. (2006) quantified organic soil mercury stocks and burned areas across western boreal Canada. It was assumed, that based on ongoing and projected increases in boreal wildfire activity due to climate change, atmospheric mercury emissions will increase and contribute to the anthropogenic alteration of the global mercury cycle and to the exacerbation of mercury toxicity in northern food chains.

Fires Burning on Radioactively Contaminated Terrain

In some countries forests and other lands are contaminated by a variety of hazardous chemical and radioactive pollutants. Wildfires occurring in such contaminated terrain may result in hazardous secondary air pollution. The territories most affected by radioactive pollution are those contaminated with radionuclides released during the failure of the Reactor Number Four of the Chernobyl Nuclear Power Plant in 1986. Among the total 6 million ha of radioactively contaminated terrain in Ukraine, Belarus and Russia, the most polluted forest area covers over 2 million ha in the Gomel and Mogilev regions of Belarus, the Kiev region of Ukraine, and the Bryansk region of the Russian Federation. The main contaminant is reported as caesium-137 (^{137}Cs) but in the core zones of contamination strontium-90 (^{90}Sr) and plutonium-239 (^{239}Pu) were also found in high concentrations. Under average dry conditions the contaminated surface fuels – the grass layer and the surface layer of peatlands – are consumed by fire. Most critical is the situation in peat layers, where radionuclides are deposited. The long-range transport of radionuclides lifted in the smoke plumes of wildfires

9 EPA Study finds Agent Orange Dioxins in Pinal Mountains. Hazardous? You decide", published on 15 October 2011 by http://www.examiner.com/public-policy-in-mesa/epa-study-finds-agent-orange-dioxins-pinal-mountains-hazardous-you-decide and extracts in the GFMC repository http://www.fire.uni-freiburg.de/media/2011/10/news_20111015_us2.htm

10 See also summary report "Forest fires could spread pollutants", released by www.usnews.com on 3 December 2009, available at GFMC repository: http://www.fire.uni-freiburg.de/media/2009/12/news_20091204_us2.htm.

and their fallout on large areas were investigated in detail in 1992 (c.f. review by Goldammer et al., 2009b). A recent study presented at the conference "Twenty-Five Years after Chernobyl Accident: Safety for the Future" (Kiev, Ukraine, 20-22 April 2011) concluded that radioactive fallout from a large forest fire occurring in the Chernobyl Exclusion Zone could affect the food chain and thus be considered threat to human health and security (Hohl et al., 2012; see also chapter 18 of this White Paper).

Wildfires Collateral Damages during Armed Conflicts

Fires occurring during or after armed conflicts or during political unrest constitute a major humanitarian and security issue. The history of fire use as a weapon during wars is as long as the history of armed conflicts of humankind (Pyne, 1995). In World War I the Turkish Army burned extended areas in the Rhodopi mountains of Bulgaria to clear the vegetation cover and the hideouts of the Bulgarian resistance fighters (Müller, 1929); in 1922 Greece suffered large wildfires due to similar reasons (Xanthopoulos, 2010). Most prominent examples of fire use in the 20th Century were the attempts by conflicting parties during World War II to ignite the enemy's hinterland forests in order to distract its military operations. More than 9,000 balloon-carried incendiary devices were launched by the Imperial Japanese Army in 1944 and 1945 (operation *Fusen Bakudan*) to be carried by the high-altitude jet stream to North America, with several hundreds reaching U.S. airspace and soil (Webber, 1975). The Allied Forces on the other hand sent more than 53,000 balloon-carried incendiary devices to ignite forests in Germany at the late stage of the war (Peebles, 1991). In Greece German military forces ignited forests in Central Greece (Pertuli, Thessaly) to drive out members of the resistance movement (Xanthopoulos, 2010). The war in Viet Nam in the 1960s did not only involve large-scale chemical spraying to defoliate forests to destroy the cover of the Viet Cong ("Operation Ranch Hand"), but the Military Assistance Command-Vietnam (MACV) also ordered "Operation Pink Rose", which attempted (in vain) to burn herbicide-treated forests and the hideouts of the enemy forces (Shapley, 1972; Westing, 1975; Lewis, 2005).[11]

Most recent occurrences of wildfire during armed conflicts cannot clearly be assigned to intentional tactical or strategic intentions. Most of the fires highlighted in the following are rather collateral damages during conflicts, or fires that were otherwise started at times of armed conflict. Warring parties often used wildfires as an opportunity and reason for mutual accusations. The most recent conflict-related wildfires occurred mainly in the South Caucasus, Near East and the Central Asian Hindu Kush regions.

South Caucasus: The Nagorno-Karabakh conflict (2006): During the period of June to September 2006, extended wildfires affected territories situated close to the Line of Contact (LoC) in and around the Nagorno-Karabakh region. Countries involved in the unresolved conflict around Nagorno-Karabakh accused each other of having ignited the fires intentionally. The fires affected large areas of abandoned lands around the LoC as well as adjoining ag-

11 See a review of the emerging field of warfare ecology by Machlis et al. (2011).

ricultural and forest lands. Impediments to controlling the fires included the threat of landmines and unexploded ordnance, as well as ongoing tensions between armed forces along the LoC. Concerns over the fires in the affected territories resulted in the UN General Assembly Resolution A/RES/60/285 "The Situation in the Occupied Territories of Azerbaijan" (15 September 2006).[12] A joint mission of the Organization for Security and Cooperation in Europe (OSCE), the United Nations Environment Programme (UNEP) and the Global Fire Monitoring Center (GFMC), assessed the short- and long-term impacts of the fires on the environment. In his report to the UNGA the OSCE Chairman-in-Office recommended a number of short- to long-term measures aimed at improving fire management capability in the countries concerned and to contribute to peace building in the region (UN General Assembly, 2007).[13] Between 2007 and 2012 the recommendations were implemented by the GFMC with funding from the Environment and Security (ENVSEC) Initiative[14] and the Secretariat of the Euro-Mediterranean Major Hazards Agreement (EUR-OPA) of the Council of Europe.[15]

Afghanistan / Pakistan (2006): In 2006 the armed conflict in the border region between Afghanistan and Pakistan escalated. Afghanistan-based NATO forces entered Pakistan's airspace from the neighboring Nooristan province. The air raids on two border villages Daroshot and Azo (Arandu) involved dropping of bombs, which ignited wildfires in the surrounding forests.[16]

Israel-Lebanon (2006): During the armed conflict shelling, air raids and rocket attacks started numerous fires on the territories of Israel and Lebanon at a time of drought and extreme wildfire risk (Achiron-Frumkin and Frumkin, 2006). In Israel 800 forest fires were induced by rockets (400 of which required response) affecting 1,200 ha of forests (mainly coniferous). In addition about 6,600 ha of nature reserves, national parks and landscapes proposed as nature reserves, as well as ca. 7,000 ha pasture lands were burned. In Lebanon

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12 UNGA Resolution A/RES/60/285 "The Situation in the Occupied Territories of Azerbaijan": http://www.fire.uni-freiburg.de/GlobalNetworks/SEEurope/UNGA%20Resolution%207%20September.pdf

13 61st UN General Assembly Session, Agenda item 17 „The situation in the occupied territories of Azerbaijan", Letter dated 20 December 2006 from the Permanent Representative of Belgium to the United Nations addressed to the Secretary-General: http://www.fire.uni-freiburg.de/GlobalNetworks/SEEurope/N0720860-OSCE-UNGA-ENG.pdf

14 The Environment and Security (ENVSEC) Initiative transforms environment and security risks into regional co-operation. ENVSEC comprises the Organization for Security and Co-operation in Europe (OSCE), Regional Environmental Centre for Central and Eastern Europe (REC), United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP), and the North Atlantic Treaty Organization (NATO) as associate partners.

15 The ENVSEC project „Enhancing National Capacity on Fire Management and Wildfire Disaster Risk Reduction in the South Caucasus" is operational since 2008 and includes Armenia, Azerbaijan and Georgia, as well as a regional component on cooperative capacity building in fire management.

16 http://www.fire.uni-freiburg.de/media/2006/10/news_20061019_pak.htm

the total area of burned forests was 712 ha and that of burned productive trees was 308 ha.[17] The use of white phosphorous as marker bombs or smoke screens in the Gaza War of 2008-2009 carried a high risk of igniting structural and wildland fires.[18]

Georgia (2008): During the armed conflict in Georgia in August 2008 a number of forest fires occurred as a consequence of military activities and caused collateral damages in several sites in the country. According to reports by government authorities and non-government organizations the fires burned between 13 August and the end of August 2008. Starting on 13 August 2008 two forest fires in the Ateni Gorge (Ateni and Ormotsi compartments of the Inner Kartli Regional Forest District) affected around 60 ha of forests. Fires affected approximately 950 ha in the Borjomi Gorge in Samtskhe-Javakheti Region, of which approximately 150 ha of the Borjomi area burned in the buffer zone of the Nedzvi Nature Sanctuary. Several fires also affected two national parks and one nature reserve. Three fires burned within the Borjomi-Kharaguali National Park. A joint mission of OSCE and UNEP to assess the environmental impacts of the conflict in Georgia confirmed the damages caused by fires in Borjomi Gorge and noted that additional areas had burned along the main corridors of combat activities (roads between South Ossetia and Gori Region).[19] Starting in 2009 the ENVSEC programme included Georgia in the above-mentioned regional fire management project.

Asymmetric Conflicts: The Forest Fire Jihad

In November 2008 a website carried the first known posting calling for *Forest Jihad*. According to a U.S. intelligence report published in January 2009 the statement, in Arabic, said that "summer has begun so do not forget the *Forest Jihad*." The writer called on all Muslims in the United States, Europe, Russia and Australia to "start forest fires".[20] The posting quoted an imprisoned Al Qaida member:

- "*Jihad* is an art just like poetry, music, and the fine arts. There are people that draw and there are others that are *jihadists*. They both act upon inspiration".
- "The idea of forest fires is attributed to him, may God set him free, as is in this short clip".
- The posting said that setting forest fires was legal under extremist Islamic law as part of "an eye for an eye" and can produce "amazing results".

17 Report of Association for Forests, Development and Conservation (AFDC) is archived in the GFMC repository.

18 „Did Israel use a banned weapon?", published on 22 January 2009 by CBS: http://www.cbsnews.com/stories/2009/01/22/eveningnews/main4748346.shtml?tag=currentVideoInfo;videoMetaInfo

19 Report of the Joint OSCE / UNEP Environmental Assessment mission to Georgia (29 September to 3 October 2008): http://www.fire.uni-freiburg.de/GlobalNetworks/SEEurope/OSCE-UNEP-GFMC-Env-Assessment-Georgia-Oct-2008-OSCE-34577_en.pdf

20 "U.S. intelligence alerted to threat of ‚Forest Fire Jihad'", published on 15 January 2008 by www.worldtribune.com (http://www.worldtribune.com/worldtribune/WTARC/2008/me_terror_01_15.asp, and http://www.fire.uni-freiburg.de/media/2008/01/news_20080117_us2.htm)

- The writer stated that it was permissible to burn trees in carrying out jihad. "Scholars have justified chopping down and burning the infidels' forests when they do the same to our lands," the writer said.
- The writer stated that "targeted forests" are in the nations that "are at war with Muslims," including the United States, Europe, Russia, and Australia.
- "Smoke caused by the fires will create pollution and military forces could be tied up fighting fires". The report noted that U.S. military forces in Iraq or Afghanistan "could even be recalled" as occurred following hurricane Katrina, which, in fact did not occur.
- The report urges terrorists to use sulphuric acid to start a forest fire, as well as gasoline.

While Australian authorities have revealed no evidence linking any recent wildfires to extremists, terrorism experts say "the large death toll, the huge swath of destruction and the massive financial blow to the country are proving to Islamic terrorists that arson can be a highly effective – and simple – tool of holy war".[21]

In December 2010 Israel's police, fire brigades and press intentionally covered up an Arab arson offensive that took place while fires raged on Carmel Mountain on the first week of December 2010, an Israeli media report claimed.[22] Police and the Fire Commission decided not to spread the information about the arson "so as not to wake into action more potential terrorists". The press report listed the locations of about 25 arson attacks that the fire brigades fought in the early days of the month. In November 2010 eighteen acts of arson were recorded in the *Forest of Peace*, the press report noted.

The tensions are reflected by recent events that are not yet finally evaluated. In February 2011 the leader of a major Muslim movement in Israel was arrested for allegedly damaging and setting fire to a eucalypt forest in Southern Israel.[23] The attack was allegedly in protest of a Jewish National Fund project in the area. The Jewish National Fund is working to plant forest on parts of the Negev, a plan opposed by some Bedouin residents of the region. Residents of the town of El-Araqib in particular had condemned the project out of concern that it will use land that they hope to use in the future to house Arabs "returning" to Israel from the rest of the Arab world.

In May 2012 Al Qaida called upon its followers to unleash massive forest fires upon the United States and published graphic instructions for the creation and ignition of "ember

21 „Australian wildfires could fuel 'Forest Jihad' terrorists, experts say", published on 09 February 2009 by http://www.foxnews.com/story/0,2933,490306,00.html

22 "Cover up of Arab arson offensive exposed", published on 15 December 2010 by http://www.israelnationalnews.com/news/news.aspx/141167

23 "Islamist leader arrested for forest fire arson", published on 22 February 2011 by http://www.israelnationalnews.com/News/News.aspx/142464

bombs". Detailed in the memorably titled, "It is of your Freedom to Ignite a Firebomb" the call targeted Montana because of its rapid population growth in the wooded areas.[24]

Later in 2012 the Russian Secret Service FSB claimed to possess information that terrorism tactics of Al Qaida included setting fire to European forests, an allegiation which could not be proved.[25]

The U.S. Department for Homeland Security (DHS, 2012) released an internal note (unclassified but for official use only) "Terrorist Interest in Using Fire as a Weapon" aimed at "providing awareness of terrorist interest in the tactic of intentionally setting fires to cause casualties, economic damage, and resource depletion".[26]

Civil Unrest and Wildfires

Wildfire outbreaks have also occasionally been attributed to domestic civil unrest in some countries. Kailidis (1992) intended to prove that wildfires in Greece were started purposely during times of elections and political crises between the 1920s and 1980s. Xanthopoulos (2010) rejected this direct link of high-fire occurrence years with political unrest and attributed the underlying causes to poor performance of government agencies. In this regard he also rejected the hypotheses developed by Christodoulakis and Skouras (2009), who developed theories suggesting that around elections, wildfires and tax evasion increase significantly in Greece, with important economic implications. However, Xanthopoulos (2010) confirmed the use of fire during the civil war between the nationalistic and communist movements.

Political motivations and accusations for arson can hardly be proven, for example blaming the ETA in Spain or the Mafia in Italy for political arson (Xanthopoulos, 2010). However, there is occasional evidence indicating such motivations such as the series of arson fires in and around Athens (Greece) in 1981. In August 1981 the right-wing movement *Galazios Toxotis* ("*Blue Archer*") was accused having lit fires in the residential area *Nova Politeia* of Athens – home to many political leaders, as well as trying to blackmail the government into releasing political prisoners (members of the former military junta).[27]

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24 „Unleash Hell: New Al Qaeda magazine describes in detail how to start huge forest fires across the U.S. with instructions on how to make 'ember bombs'", published on 3 May 2012 by http://www.dailymail.co.uk/news/article-2138758/Unleash-Hell-New-Al-Qaeda-magazine-describes-start-huge-forest-fires-U-S-instructions-make-ember-bombs.html

25 „Forest Jihad: Al-Qaida Turns to Eco-Terrorism says Russian Security Chief", published on 3 October 2012 by http://www.ibtimes.co.uk/articles/390777/20121003/russia-terrorists-forest-jihad-alexander-bortnikov-al.htm

26 For more information on the concept of „pyro terrorism" see Baird (2006) and Deshpande (2009)

27 „Blauer Bogenschütze. Der Großbrand, der Athen bedrohte, ist anscheinend das Werk von Rechtsextremisten, die ihre Idole aus dem Gefängnis pressen und das Volk kurz vor den Wahlen in Unruhe versetzen wollen", published on 10 August 1981 by http://www.spiegel.de/spiegel/print/d-14335960.html

A case of collateral damages of civil protest involving wildfires has been noted during demonstrations in Israel in May 2010 when brush fires started by tear gas canisters were fanned by the wind and engulfed the land in a massive brushfire.[28] In June 2011 Jewish settlers were accused of setting fire to fields belonging to Palestinian inhabitants of the West Bank village of Burin.[29]

It is alleged that in December 2011 former Turkish Prime Minister Mesut Yilmaz officially admitted that Turkish secret agents intentionally started forest fires in Greece in the 1990s as part of state-sponsored sabotage. This followed earlier claims that the blazes were a retaliation for Greece's alleged hosting of training camps for Kurdish rebels of the Kurdistan Workers' Party (PKK) and urban underground leftist group Devrimci Sol and even a retaliation for forest fires in Turkey's tourism areas during the 1990s allegedly set by Greek secret service agents.[30]

Wildfires and other Remnants of Armed Conflicts: Land Mines and Unexploded Ordnance (UXO)

The countries in the region most affected by land mines are Bosnia and Herzegovina, Croatia, Serbia, Macedonia, Georgia, Ukraine, and Armenia. The origin of the land mines and unexploded ordnance (UXO) in Bosnia and Herzegovina, Croatia and Serbia is from the civil war from the last decade of 20th century. It is estimated that about 300,000 ha are contaminated by land mines and UXO (mostly along to the line of conflict during the civil war). According to a report from Bosnia and Herzegovina about 127,000 ha of forests, or 10% of the total forest lands, are contaminated by UXO and land mines (Pešković, 2008). Croatia reports 95,000 ha of mined forests and other lands with a total of ca. 100,000 land mines left (Jungwirth, 2009). This is a significant problem and challenge for forest fire management since wildfires burning on mined lands cannot be fought on the ground using conventional equipment. Wildfires triggering explosions of land mines have caused casualties in several cases and resulted also in reluctance to attack wildfires, or in orders for firefighters to stay out of the "red zones". In Vietnam UXO stemming from the war in the 1960s and

28 „An Nabi Saleh demonstrates against violence in the midst of extensive brushfires", published on 16 May 2010 by www.palsolidarity.org and http://www.fire.uni-freiburg.de/media/2010/05/news_20100516_ps.htm

29 „Settler arson attack in the village of Burin", published on 30 June 2011 by http://palsolidarity.org/2011/06/19146/

30 At the time of finalizing this chapter the debate on false quotations and accusations are ongoing, see GFMC Media repository of December 2011 (http://www.fire.uni-freiburg.de/media/2011/12/news_december11.htm), notably see: http://www.fire.uni-freiburg.de/media/2011/12/news_20111228_gr.htm.

1970s continue to trigger wildfires and posing threats to firefighters more than 35 years after the termination of the armed conflict.[31]

Similar reports from the Line of Contact (LoC) between India-Pakistan in Jammu and Kashmir reveal that landmines are the main hindrance in controlling forest fires. There are reports of incidences in July and December 2009 and May 2011 of land mines laid along the LoC exploding during wildfire.[32] In Israel, wildfires in minefields on the Golan Heights threatened a UN peacekeeping battalion in August 2009.[33] In Turkey about one million land mines have been laid between the 1950s and the early 1990s. In the border region between Syria and the Turkish province Sanliurfa about 14,000 ha of productive agricultural land have been mined as a strip along the border. These areas with land mines pose a great danger in fire suppression (Bilgili, 2009).

Ironically land mines may also protect forests from destruction by non-sustainable or illegal use. The Global Fire Monitoring Center (GFMC) assessed the wildfire threats inside and around Quadisha Valley, Lebanon, which has been UNESCO World Heritage listed since 1998. The Joubbeh-Bcharri community forest at the edge of Quadisha Valley contributes to the few large forest tracts in Lebanon which have not yet been subjected to illegal cutting, occupation by constructions or other degradation. The reason for this lies in the contamination of the forest by land mines, which had been laid by Syrian and Lebanese troops during the civil war (1975-1990). These mine fields have not yet been cleared, thus people are not entering the forest. Grazing by goats is common around the edge of the forest complex and contributes to reduced fuel loads and thus decreased risk of wildfire spreading into the forest. The technical report to UNESCO concludes that land mines and goats so far have protected the forest from degradation (Global Fire Monitoring Center, 2010).

Unexploded Ordnance (UXO) is found on several hundred thousand hectares of forests and other lands throughout Western, Eastern and Southeastern Europe. Remnants of World War I battles along the frontlines of 1917 in the South of today's Former Yugoslav Republic of Macedonia have repeatedly created problems, e.g. during the fire season of 2007 when more than 70 incidents of explosions of ammunition triggered by forest fires

31 „Danang: Nearly 100ha of pine forest burnt down", published on 3 May 2012 by http://english.vietnamnet.vn/en/society/21890/danang--nearly-100ha-of-pine-forest-burnt-down.html and http://www.fire.uni-freiburg.de/media/2012/05/news_20120503_vn2.htm

32 „Landmines explode, hamper efforts to put out spreading LoC forest fires", published on 9 July 2009 by www.kashmirlive.com and http://www.fire.uni-freiburg.de/media/2009/07/news_20090710_in.htm; "Bushfire sets off 6 landmines in Poonch", published on 13 December 2009 by Rising Kashmir: http://www.risingkashmir.com/index.php?option=com_content&task=view&id=19095&Itemid=1; „Forest fire damages LoC minefield, explosions trigger panic", published on 17 May 2011 by http://in.news.yahoo.com/forest-fire-damages-loc-minefield-explosions-trigger-panic-152300779.html and http://www.fire.uni-freiburg.de/media/2011/05/news_20110517_in.htm

33 „Feueralarm: Grasbrände in der Zone", published on 3 August 2009 by the Austrian Army http://www.bundesheer.at/ausle/undof/artikel.php?id=2893

were noted (Goldammer and Nikolov, 2007). In Germany, the battlegrounds of the final phase of World War II in Brandenburg State around Berlin are still highly contaminated by approximately one hundred thousand tons of unexploded artillery, grenades and bombs. In addition, former and active military exercise areas and shooting ranges dating from the early 1900s to post-World War II, pose a high risk to civilian populations, especially firefighters (Goldammer, 2010; Goldammer et al., 2009). A recent estimate reveals that ca. 250,000 ha of former and active military training and shooting ranges in Germany are contaminated by UXO.[34]

Besides the above-mentioned land mine contamination in the Balkans and the South Caucasus the combat grounds in and around the Nagorno-Karabakh territory represent one of the major UXO-polluted terrains worldwide. In the Near East the aftermath of the Israel-Lebanon War of 2006 revealed numerous problems associated with unexploded cluster bombs. The National Demining Office of Lebanon reported 22 fatalities and 166 injuries due to post-conflict explosions of cluster bombs; two incidents occurred during wildfire suppression.

Similar risks are found in other continents. For example in Australia, where large tracts of lands are contaminated by World War II explosives, nearly 40,000 blocks of land across Brisbane and Ipswich on which UXO had reportedly exploded during bushfires.[35]

Threats arising from Wildfires Affecting Military Assets

Wildfires have the potential to affect other military assets, including ammunition depots, nuclear and conventional research and storage facilities, and active military shooting and exercise ranges. Forest fires have entered ammunition storage facilities in the territories of the former Soviet Union in recent years. In 2008 artillery shells and other ammunition at a storage facility in Ukraine exploded when a forest fire swept into the depot.[36] Details of the causes of other reported incidents remain unclear; a fire and subsequent explosions at a munitions depot in southern Ukraine in 2004 killed five people; a fire at a Soviet-era military base in Kagan, Uzbekistan spread to an ammunitions depot in July 2008, also igniting a series of explosions that killed three people and injured 21 others; and a fire that burnt an arsenal near Ulyanovsk (720 kilometers east of Moscow) in November 2009.[37] The latest

34 This assessment of January 2011 has been extracted from the databank „Nature Conservation and Military“, David Foundation, Germany (unpublished data on file at GFMC). See also Goldammer et al. (2012).

35 „Buried bomb risk worsened by bushfires: councilor“, published on 1 October 2009 by www.brisbanetimes.com.au and http://www.fire.uni-freiburg.de/media/2009/10/news_20090910_au3.htm

36 „Blaze sweeps Ukraine military base”, published on 29 August 2008 by http://english.aljazeera.net and http://www.fire.uni-freiburg.de/media/2008/08/news_20080830_ukn.htm

37 „Blasts rock Russian ammunition depot, 2 killed“, published on 15 November 2009 by Associated Press and http://www.google.com/hostednews/ap/article/ALeqM5hw4_DV-6Y-iKHHHg-sUKdvh92XIRAD9BUSIVG0

incident of this kind resulted in a large ammunition depot fire in Russia, which was attributed by some to be caused by a wildfire and which burned in May 2011 nearby the village of Urman (Bashkortostan).[38]

During the fire and smoke pollution episode in Western Russia in July/August 2010 several military depots and nuclear facilities were threatened by fire. In the first week of August wildfires overran a weapons storage facility near Moscow (the Central Air and Technical Naval Base 2512), with an estimated loss of 200 airplanes and half of the buildings destroyed. At the same time the Russian military garrison Naro-Fominsk near Moscow moved all its artillery ammunition and rockets to a safer location as wildfires advanced in the region. In the same week wildfires threatened a factory in Kolomna that produces guided missiles, the Novovoronez nuclear power station near Voronez and the Tryokhgorny nuclear closed city in the Urals (Soviet code name: Zlatoust-36) where nuclear warheads are assembled and dismantled.[39] A critical situation developed in the closed „nuclear city" of Sarov (Arzamas-16) as wildfires advanced towards nuclear arms-producing facilities.[40]

Similar incidences have affected other continents – for example in the U.S.A, where the Los Alamos nuclear weapons laboratory – located 70 miles north of Albuquerque (New Mexico) and employing 7,000 people – was threatened by wildfires in May 2000. The fires burned within 300 yards of a plutonium storage facility and forced the evacuation of more than 20,000 people from the main and an adjoining the facility.[41] A similar situation arose during the *Las Conchas Fire* in June / July 2011. This fire once again threatened the Los Alamos nuclear facility and spread fears of radioactive contamination (O'Brien and Goldammer, 2011).

In South Europe the most recent severe accident on a military site was caused by a wildfire in Cyprus, which occurred on an ammunition storage site and became the most disastrous recorded event in that region. On 11 July 2011 a brush fire triggered the explosion of the Iranian explosives that had been confiscated in 2009 and stored at the munitions dump of Evangelos Florakis naval base in Zygi. Two containers caught fire and a series of explosions followed. The blast killed six base personnel and six fire fighters who were battling the bush fire that preceded the explosion. More than 60 people were injured. Severe damage to the island's biggest power station – Vasiliko, which supplied about 60% of the island's electricity – resulted in severe power supply shortages (O'Brien and Goldammer, 2011).

38 „Unknown cause for Russian arms depot fire", published on 27 May 2011 by Euronews, see http://www.euronews.net/2011/05/27/unknown-cause-for-russian-arms-depot-fire

39 http://www.fire.uni-freiburg.de/GFMCnew/2010/08/06/20100806_ru.htm

40 For a detailed situation description and a map of Sarov and surroundings, with active fires, depicted by WorldView-2 satellite sensor (2-m resolution), on 6 August 2010, see: http://www.fire.uni-freiburg.de/GFMCnew/2010/08/07/20100807_ru.htm.

41 http://www.fire.uni-freiburg.de/media/2003/news_05122000_1.htm

Military Training and Wildfires

Military activities on training and shooting ranges are common in Europe. In 2009 and 2010 extensive fires burned near the suburbs of Marseille (France) as a consequence of exercise shelling by the Foreign Legion. In July 2009 more than 300 people were evacuated from their homes when fires caused by shelling became uncontrolled.[42] Similar experiences have been shared by countries in other continents. In the U.S.A. the "Machine Gun Fire" of September 2010 burned through the training range of Camp Williams, Utah. It was caused by automatic weapons training and affected the artillery impact area with UXO contamination, consuming 4,326 acres and three houses and forcing the evacuation of 1,652 houses and nearly 5,000 people.[43] In the extremely dry spring months of 2011 extensive fires caused by military shooting exercises in the training grounds of Fort Lee, White Sands Missile Range, Fort Bliss and Camp Pendleton were recorded.

The presence of UXO constitutes a considerable threat to land management authorities, ground firefighters and aerial fire suppression. Within this broad category of UXO, the threat of residual exercise ammunition is less than the risk of residual combat ammunition. In Germany fire services are not allowed to fight wildfires on demarcated terrain contaminated by UXO ("red zones"). Thus, as wildfires cannot be attacked swiftly and with conventional means there is high threat of fires becoming out of control and spreading to adjacent terrain.

Opportunities and Challenges of maintaining Military Training Ranges of high Conservation Value

In Europe active and former military training areas and shooting ranges have been shaped by wildfires in such a way that open land ecosystems of high biodiversity value have been created or maintained by recurrent fires. The Atlantic and continental *Calluna vulgaris* heathlands of Germany are a classic example of sub-climax ecosystems that historically had been maintained by intensive cultivation (grazing, mowing, biomass export) and intentionally or accidentally lit fires on military training grounds. In the wake of demilitarization at the end of the Cold War and the unification of Germany the 1990s and into the first decade of the 21st Century, the use of former military ranges was largely abandoned, and subsidized maintenance of open land habitats has reached critical limitations due to lack of appropriate policies and funding prioritization (Goldammer et al., 2009). The recent introduction of prescribed fire in Germany to maintain open heathland habitats is based on traditional

42 „'Imbeciles': Hundreds evacuated from their homes as bushfire caused by French military threatens Marseille", published on 23 July 2009 by www.dailymail.co.uk and http://www.fire.uni-freiburg.de/media/2009/07/news_20090723_fr.htm

43 „Utah National Guard admits fault in Machine Gun, Camp Williams Fire", published on 20 September 2010: http://www.fire.uni-freiburg.de/media/2010/09/news_20100920_us5.htm and http://www.fire.uni-freiburg.de/media/2010/09/news_20100920_us6.htm and http://www.fire.uni-freiburg.de/media/2010/09/news_20100921_us.htm

burning practices and coincides with new ecological insights of applied fire research that are receiving increased acceptance from nature conservation groups and the public. The above mentioned *White Paper on Use of Prescribed Fire in Land Management, Nature Conservation and Forestry in Temperate-Boreal Eurasia* (Goldammer, 2010a) is indeed calling for a widespread application of prescribed fire to maintain the conservation value of former military training sites.

The presence of UXO, however, is a limiting factor for the application of prescribed fire on approximately 250,000 ha of high conservation value terrain (Fig. 1). A pilot project is currently underway in the Heidehof-Golmberg Nature Reserve in the State of Brandenburg, Germany, to test safe application methods of using armored vehicles (demilitarized tanks) for prescribed fire ignition and control. Monitoring and control of the fire operations by an unmanned aerial system (helicopter drone with real-time video downlink to the control center) allows navigation and safe and efficient ignition and control of the armored vehicles (Goldammer et al., 2012).

Overall Global Wildland Fire Fatalities

Reliable global statistics on wildland fire fatalities (deaths and injuries) are not available. A major share of wildfire fatalities are occurring in developing countries and are not entering the electronic media or insurance statistics, and thus are not available for international evaluation. Injuries caused by indirect effects of fire are common but not systematically evaluated, e.g. short- to long-term effects of fire smoke pollution on human health, including premature mortality. Fire and smoke episodes in Southeast Asia and the Amazon lowlands caused by conversion burnings since the 1980s have sparked numerous media reports on such massive near-ground smoke pollution and the resulting threats and observations of people adversely affected by smoke inhalation, but only very few scientific investigations have been conducted (for details cf. chapter 18 of this volume).

Since 2008 annual global wildland fire fatalities reports are published by GFMC.[44] The reports reveal that 345, 374, 279 and 130 people were killed directly by wildfires in 2008, 2009, 2010 and 2011 respectively. The 2010 report does not include fatalities that could be possibly attributed to the consequences of the extreme heat wave and extended fire smoke pollution in Western Russia (cf. final remarks in chapter 18 of this volume).

44 http://www.fire.uni-freiburg.de/media/bulletin_news.htm. Starting with the 2011 report data will be provided on structures and other economic assets burned and damaged, as well as numbers of evacuations and evacuees.

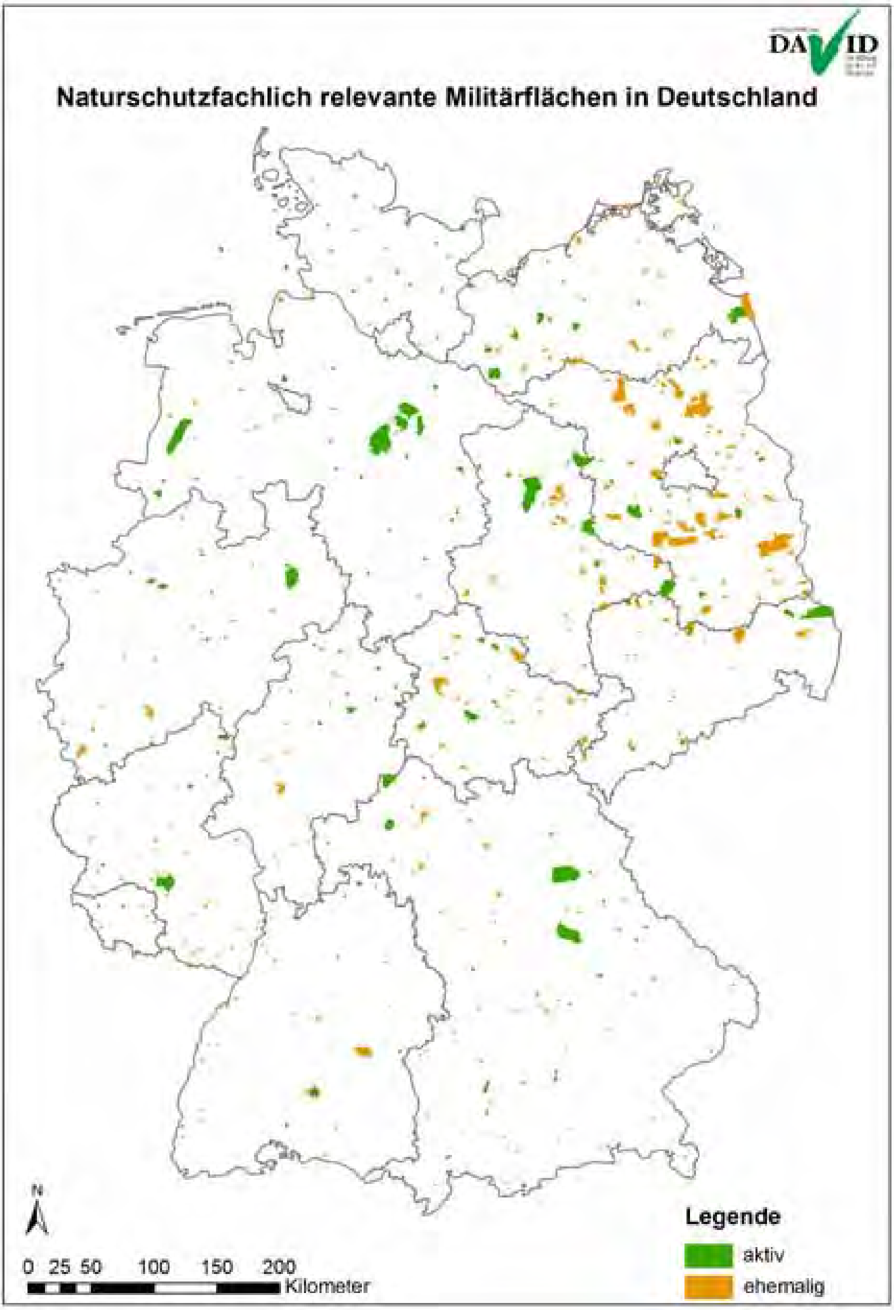

Figure 22.1. Germany has about 700,000 ha active or former military exercise and shooting ranges with high conservation value. About 250,000 ha of these lands are contaminated with Unexploded Ordnance (UXO). Source of map and contamination assessment: Naturstiftung David, Germany (Goldammer et al., 2012). Legend: green – active military areas; ochre – abandoned military areas.

The reports also include persons injured and – starting in 2011 – the extent of structural damages caused by wildfires and evacuations due to wildfire threat.[45] As stated by GFMC, the numbers of fatalities and damages include only those reported in the media and GFMC correspondents. Thus, due to the lack of a comprehensive national / international reporting system the statistical dataset is likely to be incomplete, especially considering the numerous unreported fatalities in remote regions of the developing world.

Addressing Politics and Policies

The chapters of this volume – the White Paper – have reflected on the natural and human-influenced history of vegetation fires globally. The individual chapters address a complexity of situations in which fire regimes are changing. Thus, conclusions point various directions, depending on the specific nature of local and regional environmental and socio-economic changes. In the final chapter some considerations about options of how to cope with changing fire regimes and fire management in future will be given. In the context of the questions addressed in this chapter two examples are selected to highlight the need for action: Wildfires as means or consequences of armed conflicts or strained political relations, and the prevention of dangerous wildfires on contaminated terrain.

Opportunities: Confidence Building for Human Security and Peace

Since wildfires and vegetation fire smoke can easily spread over boundaries, thus making fire management become an additional source of contention to already strained relations between neighbouring countries. Hence, because of the transboundary nature of wildfires and their potential impact, co-operating on fire management across borders is in the interest of all sides involved. Thus, like water management, fire-management has great potential to be a source of co-operation and an avenue for confidence-building.

The most recent events during a state of high tension between countries, or state of war, were the above-mentioned situations around the Nagorno-Karabakh conflict in 2006 and the armed conflict in Georgia in August 2008. Mandated by the UN Security Council in 2006 and by the Organization for Security and Cooperation in Europe (OSCE) the Global Fire Monitoring Center (GFMC) was entrusted with the technical lead to develop confidence building measures between countries directly and indirectly affected. The proposed measures of building national and transboundary fire management capacity are aimed at

45 According to the 2011 report a total of 125 evacuations in 15 countries involved the temporary displacement of 85,723 persons. The loss of private homes destroyed by wildfires in 2011 in 15 countries amounted a total of 7193. The number of homes damaged by wildfires in three countries amounted 269. Farmers lost more than 9800 livestock in six countries, more than 700,000 ha of valuable agricultural lands were affected by wildfires and were considered destroyed. Estimated agricultural loss in South Africa was $US 7.16. Only in Texas, U.S.A., wildfires during April have caused an estimated $20.4 million in agricultural losses, destroying fences, buildings, grazing pastures and resulting in livestock deaths.

managing and preserving natural assets and protecting populations from adverse impacts of fires. They were implemented starting in 2007 (ongoing) within the framework of the OSCE Mission and the Project "Enhancing National Capacity on Fire Management and Wildfire Disaster Risk Reduction in the South Caucasus", which comes under the umbrella of the ENVSEC Initiative.[46] Following the OSCE report to the UN General Assembly on the Nagorno-Karabakh mission in 2006, in which was stated "The Mission's hope is that, further to its recommendations, fires might be transformed from an additional source of conflict into an opportunity for regional co-operation, confidence building and ultimately reconciliation" (UN General Assembly, 2007) the OSCE considers the ongoing project as one of the successful non-military confidence building measures in the region.[47]

In December 2010 a wildfire affected the Mount Carmel massive near Haifa, Israel, resulting in a relatively short, but intense and dangerous inferno of planted, partially exotic tree stands and natural vegetation on the slopes of the mountain. Given the scarcity of forests in Israel, the high emotional value of the fire, and the tragic loss of 42 human lives entrapped by the fire, the country received a widespread response of assistance to combat the fire, including the provision of aerial firefighting resources from as far as the U.S.A. and Russia.[48] Most significant, however, was the assistance of Palestinian authorities by sending fire trucks and crews for support of fire suppression, despite fierce political tensions between the parties. On 7 December 2010 the President and the Prime Minister of Israel signed a letter of recognition, in which "The State of Israel expresses its gratitude and deep appreciation to the Special Delegation of the Palestinian Authority for the invaluable contribution and exemplary courage in battling the blaze of Mt. Carmel".[49]

During the Mt. Carmel fires in December 2010 Turkey assisted with massive firefighting support, despite the tensions between the countries that had earlier arisen from the incident on a Turkish ship bound for Gaza and seized by Israeli military, which resulted in the deaths of nine Turkish citizens in May 2010.[50]

In July 2011 a wildfire threatening the Yad Vashem holocaust memorial in Jerusalem was controlled with the assistance of Arab staff from East Jerusalem, who significantly contributed to save the archives.[51]

46 See section "Pressing Issues" above.

47 OSCE Guide on Non-Military Confidence Building Measures (2012): http://www.fire.uni-freiburg.de/GlobalNetworks/SEEurope/OSCE-Guide-CBM-Measures-2012-Extract-Fire.pdf

48 For a real-time log on the Mt. Carmel fires see GFMC daily updates archives at: http://www.fire.uni-freiburg.de/current/archive/archive.htm#ISRAEL.

49 Copy of letter available at GFMC repository.

50 http://en.wikipedia.org/wiki/Gaza_flotilla_raid

51 „Yad Vashem praises Arab staff for fighting Jerusalem Forest fire", published on 20 July 2011 by http://www.haaretz.com/print-edition/news/yad-vashem-praises-arab-staff-for-fighting-jerusalem-forest-fire-1.375644 and http://www.fire.uni-freiburg.de/media/2011/07/news_20110728_il.htm

In October 2011 rabbis from the United States of America thanked envoys from countries that helped Israel douse forest fires, "including some that now have difficult relations with the Jewish state", including a Palestine Liberation Organization envoy. [52]

Starting an international dialogue on Dangerous Fires on Contaminated Terrain

In 2009 an international seminar made history by addressing the problem of "Wildfires and Human Security: Fire Management on Terrain Contaminated by Radioactivity, Unexploded Ordnance (UXO) and Land Mines". The seminar was held in Kyiv and Chernobyl, Ukraine, and provided new insights into phenomena and problems arising from fires burning in radioactively contaminated terrain in the Eurasia biota. Most severe problems are in the territories of Ukraine, Russia, and Belarus, which were highly contaminated by the failure of Reactor 4 of the Chernobyl Nuclear Power Plant back in 1986. Traces of radioactivity are found in emissions from wildfires burning in Central Asia and are transported long-range and intercontinental. Wildfire incidents in the U.S.A. have threatened nuclear test facilities but so far have not resulted in severe contamination.

Reports from Germany, the Southern Caucasus countries Armenia and Azerbaijan, the Near East countries Lebanon and Israel and the Balkan countries Bosnia and Herzegovina, Croatia and FYROM Macedonia reveal the magnitude of unexploded ammunition and land mine contamination in forested and other lands and the problems associated with remnants from armed conflicts dating back as far as World War I. Reports on fires burning in former military exercise and shooting ranges reveal that unexploded ordnance are potentially very dangerous and have repeatedly resulted in firefighter casualties.

The seminar called on its host – the government of Ukraine – and the auspices of the seminar, the Global Fire Monitoring Center (GFMC), the Council of Europe (CoE), OSCE / ENVSEC, the UNISDR Regional Southeast Europe / Caucasus and Central Asia Wildland Fire Networks, and the UNECE / FAO Team of Specialists on Forest Fire to address the problems. The "Chernobyl Resolution on Wildfires and Human Security: Challenges and Priorities for Action to address Problems of Wildfires burning on Terrain Contaminated by Radioactivity, Unexploded Ordnance (UXO) and Land Mines" recommends to develop policies and practices related to fire management on contaminated terrain. [53]

Conclusions

Without intending to repeat the historic role of fire use in the evolution and maintenance of the cultural landscapes and land-use systems of temperate-boreal Eurasia (e.g., Goudsblom, 1993; Pyne, 1997; Goldammer et al., 1997), and the subsequent changes due to the

52 „Rabbis thank countries that helped with forest fires" published on 25 October 2011 by http://www.jta.org/news/article/2011/10/25/3089956/rabbis-thank-countries-that-helped-with-forest-fires and http://www.fire.uni-freiburg.de/media/2011/10/news_20111025_il.htm

53 See summary of seminar contributions and the Chernobyl Resolution published in UNECE / FAO International Forest Fire News (IFFN) No. 40 (2010), pp. 76-113.

takeover of using fossil-fuel driven technologies replacing traditional cultivation systems including fire use, it seems that the cultural landscapes of the region are on the brink of an era of transition.

While the rural exodus may offer opportunities for natural revegetation – a process welcomed by those supporting the transformation of former cultivated or otherwise intensively used lands to natural vegetation or "wilderness" areas – large tracts of cultivated landscapes are transitioning to a state of high wildfire hazard and wildfire risk as a consequence of vegetation succession and buildup of combustible materials readily susceptible to ignition and spread of wildfires.

This coincides with an obviously increasing vulnerability of society to fire and fire effects – a trend that is observed in other cultural landscapes around the world. New approaches in integrated land management are needed, ranging from small-scale approaches aimed at preserving or managing habitats of endangered species to landscape-scale approaches that take into account the overarching aspects of landscape functioning, environmental protection and climatic changes.

With increasing knowledge on the adverse effects of fire smoke emissions on human health, biogeochemical cycles and direct and indirect effects on climate, it may be expected that conflicts between the need for natural and cultural fires and the need to protect an increasingly vulnerable human society will become apparent.

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Note: Media reports quoted in footnotes and mirrored in the GFMC global wildland fire data repository can be accessed using a User ID and a Password, which will be made available on request by GFMC. Enquiries to be address to: fire@fire.uni-freiburg.de

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23 International Protocols and Agreements on Cooperation in Wildland Fire Management and Wildfire Disaster Response: Needs, Current Status, and the Way Ahead

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Abstract

The contributions of the White Paper „Vegetation Fire and Global Change“ 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 trans-boundary 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. Several international (global) and regional conventions are examples of international legal agreements that provide rationale and a catalogue of environmental protection obligations for signatory countries. However, none of these legally binding conventions or any informal or voluntary international instruments explicitly address wildland fires as either a driver of environmental degradation, or 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. Currently there are also no 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 co-operating parties. The Global Wildland Fire Network (GWFN) is a voluntary network which evolved in the late 1990s as an initiative of the Global Fire Monitoring Center (GFMC) and the UNECE/FAO Team of Specialists on Forest Fire. The GWFN operates through the GFMC as a "Thematic Platform" under the United Nations International Strategy for Disaster Reduction (UNISDR), and promotes international cooperation in wildland fire management – notably through capacity building in wildfire prevention, preparedness and suppression, and the development of standardized procedures for use in international wildfire incident response.

Keywords: Fire management, international cooperation, transboundary fire effects, international legal agreements, voluntary agreements

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Introduction

The contributions of this White Paper „Vegetation Fire and Global Change“ 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 trans-boundary 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.

Several international (global) conventions, such as the three "Rio Conventions" (CBD, CCD and 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 no 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.

In preparation for and following the International Wildland Fire Summit of 2003[2] the international wildland fire community has taken steps to develop preliminary concepts, templates and guidelines with widely agreed-upon principles and best practices in fire management and incident command. Detailed operational standards are now needed to facilitate the exchange of fire fighting resources, including aviation, management personnel, and equipment. The UN Disaster Assessment and Coordination (UNDAC) and the International Search and Rescue Advisory Group (INSARAG) Guidelines[3] and the principles laid down in the "Rosersberg Initiative – Improving the international environmental emergency response system" may serve as examples for developing interoperable standards, protocols, Standard Operating Procedures (SOPs) and rules of engagement.

At the level of multilateral bodies, such as the Association of South East Asian Nations (ASEAN), the UN Economic Commission for Europe (UNECE), the Asia-Pacific Economic Cooperation (APEC), the Council of Europe (European Open Partial Agreement on the Prevention, Protection Against and Organization of Relief in Major Natural

2 http://www.fire.uni-freiburg.de/summit-2003/introduction.htm

3 http://www.reliefweb.int/undac/documents/insarag/guidelines/topics.html and http://www.usar.nl/upload/docs/insarag_guidelines_july_2006.pdf

and Technological Disasters – EUR-OPA), the European Union (EU), or the Southern African Development Community (SADC), recent developments have revealed an interest of countries to enhance the capabilities of regional, transboundary cooperation in fire management. Experience gained in bilateral (reciprocal) agreements include common usage of the Incident Command System (ICS) – as practiced under agreements between North American countries (U.S.A., Canada and Mexico) and between the U.S.A. and Canada on the one side, and Australia and New Zealand on the other side. These experiences may serve as examples for developing other regional agreements or protocols.[4]

The Global Wildland Fire Network (GWFN)[5] is a voluntary network which evolved in the late 1990s as an initiative of the Global Fire Monitoring Center (GFMC)[6] and the UNECE/FAO Team of Specialists on Forest Fire[7]. The GWFN operates through the GFMC as a "Thematic Platform" under the United Nations International Strategy for Disaster Reduction (UNISDR), and promotes international cooperation in wildland fire management – notably through capacity building in wildfire prevention, preparedness and suppression, and the development of standardized procedures for use in international wildfire incident response. Lead institutions serve as coordinators of Regional Wildland Fire Networks and work with representatives of international organizations mandated or otherwise active in the wildland fire arena. These lead institutions are represented by the UNISDR Wildland Fire Advisory Group (WFAG), which provides advisory services to the UN system.

The application of fire management guidelines developed under the auspices of international organizations such as the International Tropical Timber Organization (ITTO) and the Food and Agriculture Organization (FAO) of the United Nations, and with major inputs of the members of the regional networks, provide a voluntary basis of common understanding of best practices and solutions in fire management.

In the long-term the GWFN is also aiming at developing an International Wildland Fire Accord (voluntary or binding under international law), which would be based on the rationale that there is a common international interest in protection of global vegetation cover against degradation or destruction and that common endeavors in fire management will contribute to disaster risk reduction. For example, reduction of the risks associated with direct fire damages to human assets and ecosystems, fire-generated smoke pollution affecting human health and security, release of greenhouse gases, secondary disasters such as landslides, erosion, floods and threats to biodiversity.

4 See special issue of UNECE/FAO International Forest Fire News (IFFN) No. 29, with examples of agreements and Annual Operating Plans: http://www.fire.uni-freiburg.de/iffn/iffn_29/content29.htm

5 http://www.fire.uni-freiburg.de/GlobalNetworks/globalNet.html

6 http://www.fire.uni-freiburg.de/

7 http://www.fire.uni-freiburg.de/intro/team.html, see section 2.6 of this chapter

In the following sections examples are given of achievements and ongoing activities which reflect some progress in the dialogue to enhance international cooperation in wildland fire management.[8]

Progress in Regional Cooperation in Fire Management

Association of South East Asian Nations (ASEAN)

As a consequence of extended fire and smoke episodes since the early 1980s and especially in the 1990s ten member states of the Association of Southeast Asian Nations (ASEAN) commenced negotiations for a ASEAN agreement addressing regional air pollution resulting from land-use fires and wildfires. In June 2002 the Agreement on Transboundary Haze Pollution was adopted and came into force on 25 November 2003, with nine states currently participating (Brunei Darussalam, Cambodia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Viet Nam).

This Agreement marks a world-first, as the first regional arrangement binding a group of contiguous states aimed at tackling transboundary haze pollution resulting from land and forest fires.[9] The Agreement requires the Parties to:

- cooperate in the development and implementation of measures to prevent, monitor, and mitigate transboundary haze pollution by controlling sources of land and/or forest fires, developing monitoring, assessment and early warning systems, exchanging information and technology, and allowing the provision of mutual assistance;
- respond promptly to a request for relevant information sought by a State or States that are or may be affected by such transboundary haze pollution, with a view to minimizing the consequence of the transboundary haze pollution; and
- take legal, administrative and/or other measures to implement their obligations under the Agreement.

The Agreement establishes an ASEAN Coordination Centre for Transboundary Haze Pollution Control to facilitate cooperation and coordination in managing the impact of land and forest fires – in particular haze pollution arising from such fires. Pending the establishment of the Coordination Centre, ASEAN Secretariat and ASEAN Specialized Meteorological Centre (ASMC) are co-performing its interim functions. Despite the fact that Indonesia is by far the largest source of the fires and haze the ratification of the ASEAN Agreements is still outstanding (Khee-Jin Tan, 2005; Nguitragool, 2011). In 2012 Indonesia indicated its willingness to move toward ratification.[10]

8 *Note:* Materials of this paper have been presented at the 5th International Wildland Fire Conference, South Africa, 9-13 May 2011 (http://www.fire.uni-freiburg.de/southafrica-2011.html).

9 See ASEAN website „Haze Online": http://haze.asean.org/hazeagreement/, and the full text of the agreement at: http://haze.asean.org/docs/1128506236/ASEANAgreementonTransboundaryHazePollution.pdf/view

10 http://www.fire.uni-freiburg.de/media/2011/01/news_20110122_id.htm

European Union (EU)

In the 1980s and 1990s there was some exchange of firefighting expertise within the EU but little formal cooperation. The European Union Civil Protection Mechanism was established in 2001 and further strengthened in 2007. It provided a new capacity for coordination for Europe and now plays a central role in the EU forest fire risk prevention and forest firefighting coordination at EU level. There are currently 32 countries participating in the Mechanism („Participating States"): The 27 Member States of the European Union (EU) together with Iceland, Liechtenstein, Norway, Croatia and the Former Yugoslav Republic of Macedonia. The Mechanism, which is managed by the European Commission, has tools to cope with wildfires in three phases of the disaster management cycle. The main responsibilities and the tools allocated to the European Commission are outlined as follows.[11]

Monitoring and prevention

The core operating body of the European Union Civil Protection Mechanism is the Monitoring and Information Centre (MIC). The MIC's three major roles are:

- to provide a coordination platform for exchanging requests for assistance and offers of resources among Participating States;
- to be an agent for information exchange and dissemination regarding natural and man-made disasters worldwide and the regarding Mechanism interventions;
- to act as a coordinator in identifying gaps and developing solutions on the basis of the information it receives, facilitating the pooling of common resources where possible and supplying expert teams to the disaster location to tackle the problems more effectively.

The Common Emergency Communication and Information System (CECIS) facilitates coordination between the MIC and national authorities. The main tasks of CECIS include hosting a secure and reliable database on potentially available assets for assistance; handling requests for assistance on the basis of this data; facilitating the exchange of information and documenting all action and message traffic.

The MIC receives fire risk assessment information from the European Forest Fire Information System (EFFIS). This web-based platform, which consists of a scientific and technical infrastructure, was developed jointly by the European Commission Joint Research Centre and Directorate General Environment (European Commission).

11 *Note:* Parts of this general description of the EU Mechanisms has been taken from the introduction to the report „Study on wild fire fighting resources sharing models", prepared by GHK Consultants to DG ECHO, European Commission (October 2010), in which the author participated. See executive summary at:
http://ec.europa.eu/echo/civil_protection/civil/prote/pdfdocs/future/Wildfire_Exec_Summary.pdf

Preparedness

The EU Civil Protection Mechanism intermediates information dissemination activities and exchange of best practice knowledge between Participating States. It also provides training programmes and exercises to intervention teams and organizes informative activities, seminars, conferences and pilot projects on the main aspects of interventions.

During a test phase this Mechanism provided access to the assets in the European Union Forest Fire Tactical Reserve (EUFFTR) – a pilot project designed to enhance cooperation between Member States for combating forest fires during high risk seasons. The project, to which two Canadair CL-215 aircraft were allocated during the summers of 2009 and 2010, was activated in the cases where Member States were not in a position to provide assistance to a requesting country due to their aerial resources being needed in their own territory or because they could not reach the fire site quickly enough.

The Mechanism develops implementing rules for module development and administers the CECIS module database.

Response

Through the EU Civil Protection Mechanism, the European Commission is able to:

- Mobilize small teams of experts to the site of an emergency;
- Provide and distribute information during an emergency/intervention;
- Play a facilitating role in the coordination of assistance requests and offers from Participating States;
- Coordinate with other actors at the international level and with other EU services; and
- Provide co-financing for the transport of assistance to the affected areas, on the request of the offering Participating States.

The EU Civil Protection Mechanism is well-accepted and is being increasingly used by Participating States. Twenty-eight requests for assistance were received by the MIC in 2009-2010 from within the EU and 18 requests from non-EU states. For comparison: In 2002 only three requests had been received. The Mechanism coordinates and facilitates voluntary efforts, with each Participating State free to decide its contribution on case-by-case basis.

Asia-Pacific Economic Cooperation (APEC)

In October 2010 the first "International Conference on Forest Fires: Management and International Cooperation in Preventing Forest Fires in APEC Region" was convened at the initiative of the Russian Federation. The aim of this conference was to strengthen cooperation between the emergency services of the APEC member economies in order to emphasize the readiness of the region to reduce the risks of disasters.[12] Following a deep and comprehensive analysis of the problem of forest fires in the APEC region and other regions, the

12 http://lesscentr.ru/en/en/index0.htm and GFMC repository: http://www.fire.uni-freiburg.de/GlobalNetworks/CentralAsia/APEC-Fire-Conference-2010-Recommendations-ENG.pdf

conference identified the urgent necessity for joint efforts, mutual help and cross-border cooperation in forest fire risk reduction. The conference released the "Khabarovsk Recommendations on Management and International Cooperation in Preventing Forest Fires in the APEC Region". The following priority directions of international cooperation under APEC were among those proposed:

- Development of an international mechanism to monitor and enhance responsibility of APEC member economies to ensure forest fire protection on their territories and coordinate action under APEC using existing institutions of international cooperation, such as UNISDR Global Wildland Fire Network, ASEAN, UNECE and others.
- Promotion of economic cooperation in projects that aim to reduce the degree of fire risk and restoration of forests on lands degraded by fire and non-sustainable forest management;
- Development of bilateral agreements on cooperation in fire management, particularly between APEC economies sharing common borders, and a voluntary regional agreement on cooperation in fire management, aiming at harmonizing cooperation with neighboring regional entities such as the UNECE and ASEAN, particularly in the light of overlapping membership of some economies.
- Development of long-term fire management strategies in each economy that allow for mitigation of the consequences of climate change.
- Improvement of strategic and operational early warning mechanisms in the APEC region as a regional activity to be coordinated with the Global Wildland Fire Early Warning system.
- Conduct regular consultations to exchange knowledge and best practice.
- Reconvene and contribute to the 5th International Wildland Fire Conference scheduled for 2011 (South Africa), and the following conference scheduled for 2015 (South Korea).

A priority follow-up activity has already included a joint fire management study course offered to APEC countries in 2011, hosted by the Russian Federation.[13]

Southern African Development Community (SADC)

In the last two decades, vegetation fires have become a major concern in the region of the Southern African Development Community (SADC) with regard to the negative impacts they have on the welfare of the environment and humans.[14] Uncontrolled wildfires cause

13 http://www.fire.uni-freiburg.de/intro/APEC-EMERCOM-Wildfire-Management-Study-Course-2011-Agenda.pdf

14 The information provided in the chapter are taken from the SADC Regional Fire Management Programme Document, draft proposal (June 2010). Web source: http://www.fire.uni-freiburg.de/GlobalNetworks/Africa/SADC%20Regional%20Fire%20Management%20Programme%20Document-Final-6.pdf

forest and vegetation degradation as well as biodiversity loss. This can result in immediate and long-term impacts on the livelihoods of local communities and upstream impacts on national and regional economies. Fires in the tropical environment are a major contributor to tropical forest degradation and over time frequent fires lead to savannization in these areas. However, fires are also needed to maintain healthy ecosystems and biodiversity of natural savannah and grassland vegetation types – many being adapted to regular fire occurrence. Prescribed or controlled burning is used to meet objectives often essential to sustaining livelihoods. Fire is also used for conservation reasons, removal of old growth, suppression of bush encroachment and stimulation of the growth of grazing grass as well as the removal of fuel with the aim of pre-empting dangerous wildfires at the peak of the fire season.

The SADC region of 14 Member States is home to 238 million people, of which approximately 75% are rurally based. The perceived rise in the number of wildfires negatively affects these rural communities which are often situated near the forests that provide them with their basic needs. The on-going process of climate change has the potential to exacerbate this situation by altering the frequency, intensity, severity and seasonality of fires in the SADC region.

A SADC regional fire management programme was proposed in 2010. It provides a framework for cooperation on fire management issues across national boundaries. Fire management is a technical, socio-cultural and political challenge that requires an effective network of willing partners that include governments, the private sector, local communities and international partners to find the appropriate balance between developing and conserving natural resources and managing unwanted fires while at the same time promoting the safe and beneficial use of fire. The programme intends to foster cooperation and collaboration in fire management on a regional basis to move towards integrated environmental policies and fire management practices. The programme pursues a multiple stakeholder approach working closely with regional and international organizations to support five areas of fire management. These are; legal and regulatory aspects of fires; community based fire management; institutional strengthening and establishment of a fire management coordination centre; generation and dissemination of relevant fire information for detection and early warning and; associated capacity building in the respective areas.

The envisaged programme is based on the SADC Protocol on Forestry of 2002, which forms the policy framework for sustainable forest management in the SADC member states. Its objectives include the goal to achieve effective protection of the environment and to safeguard the interests of both the present and future generations.

The SADC Forestry Strategy of 2010 is based on the vision to develop and maintain a forest sector that contributes to rural development, poverty reduction and industrial progress, meanwhile continuing to retain vital ecosystem services such as water supply, climate change mitigation and biodiversity protection. The Strategy thereby provides motivation for countries to cooperate for the protection, management, and sustainable use of their forests. The primary purpose of the strategy is to provide a framework for both regional cooperation and international engagement on forest issues by paying special attention to issues that transcend national boundaries The Strategy's mission is to facilitate cooperation among member states to 'promote the active protection, management and sustainable use of forest resources through sound policy guidance and the application of requisite skills and the best available technology, in order to enjoy the multiple benefits of forests in perpetuity'.

There is increased willingness by SADC member states to cooperate on fire management on a regional and international basis. There is also recognition that a regional framework based on cross border cooperation is required to address issues of national, regional and transboundary fire management. Member states have expressed the need for a regional agency or centre to foster and coordinate such cooperation and information exchange in fire management. Establishing an agency responsible for collecting and analyzing fire related data and formulating standardized rules, guidelines and procedures will ensure coordinated dissemination of relevant information and guide policy development. Furthermore it would spearhead the promotion of integration of Community-Based Fire Management (CBFiM) into national policies and fire management strategies.

The expected activities and outcomes of the SADC Regional Fire Management Programme include the establishment of a Regional Fire Management Coordination Center. This center will also facilitate and coordinate international and regional cooperation in fire management by providing a mechanism through which one country may request and receive wildfire suppression resources from another country. This mechanism should also encourage cooperation and exchange on other fire management activities such as training and lessons learnt. A SADC fire management programme will allow the development of a SADC Memorandum of Understanding (MoU) which will prescribe the conditions of cross border cooperation to combat transboundary fires and include operational guidelines for the regional coordination centre.

The programme intends to foster regional level interaction by developing guiding policy frameworks and procedures for several aspects of fire management. During the Consultative Workshop on the Development of a SADC Regional Fire Management Programme (January 2010, Maputo) participants from all SADC member states compiled capacity development measures that must be carried out by all SADC member states to ensure success of a regional fire management program. The project includes the following components:

- Establishment of a Regional Fire Management Coordination Center. Objective: To promote the establishment of a regional fire management coordination centre for improved stakeholder cooperation and collaboration
- Reform and Harmonize Policies and Procedures. Objective: To secure essential policy harmonization at national and regional level to provide the basis for controlling harmful fires and promoting the safe use of beneficial fires within SADC
- Community-based fire management. Objective: To promote integration of CBFiM into Member States' fire and natural resources management systems/programmes
- Fire information. Objective: To improve production, access, dissemination and application of fire information within the region

- Capacity development. Objective: To increase awareness of and proficiency in balanced and integrated fire management and its elements

Between 2010 and 2013 the Trilateral Cooperation Fund (TRI-CO Fund) project between South Africa, Tanzania and Germany (Trilateral Cooperation Fund – TRI-CO Fund) "Tanzania – South Africa Fire Management Coordination Project" was implemented to demonstrate the utility of coordination and exchange of techniques, resources, science and capacity building in fire management amongst contributing parties and SADC member states. The GIZ project "Transfrontier Conservation and Use of Natural Resources in the SADC Region" (2013-2015) is also addressing the cooperation of border-crossing processes in conservation, including transboundary fire management.

Latin America

Mesoamerica

Several developments during the last decade indicate the political willingness of nations in Mesoamerica to share information and resources in fire management. An important regional initiative has been launched by the First Central Mesoamerican Meeting on Forest Fire Protection (*Primera Reunión Mesoamericana de Cooperación en Materia de Protección contra Incendios Forestales*) held in Guatemala City in 2002. This regional meeting was organized within the framework of the project "Prevención y Combate de Incendios Forestales en Mesoamerica" of the "Programa Mesoamericano de Cooperación 2001-2002", launched at the 4th Tuxtla regional dialogue. Delegates of Belize, Costa Rica, El Salvador, Guatemala, Honduras, México, Nicaragua and Panamá formally agreed to launch a programme of co-operation which includes the sharing of information and resources in fire management as well as in capacity building. [15]

A number of follow-up conferences and workshops have consolidated these dialogues and strategic visions for cooperation in fire management. The Mesoamerica Meeting was followed by a meeting in Honduras (*Taller para el Desarrollo de un Plan Estratégico Regional para el Manejo del Gorgojo del Pino y los Incendios Forestales en Centroamérica*, 26-30 August 2002) in which the representatives from Central America developed a strategic plan for fire and bark beetle management in Central America. The momentum created by the Meso-

15 In June 2003 consultations were held with the Government of Guatemala concerning cooperation between the *Mesoamerican Cooperation Regarding Protection against Forest Fires* and the GFMC. A Memorandum of Understanding was signed by the Mesoamerican Permanent Technical Group on Forest Fires (*Grupo Técnico Mesoamericano Permanente sobre Incendios Forestales*), represented by the President of the Coordinating Council of the *Sistema Nacional de Prevención y Control de Incendios Forestales* (SIPECIF), Guatemala, and Executive Coordinator of the Presidency of Guatemala, and the Global Fire Monitoring Center (GFMC), operating under the auspices of the UN International Strategy for Disaster Reduction (ISDR), concerning Cooperation in the Global Wildland Fire Network through active participation of the Regional Mesoamerica Wildland Fire Network.

american Meeting and the Honduras Strategy is currently maintained and coordinated by the *Comisión Centroamericana de Ambiente y Desarollo* (CCAD). A Technical Commission on Forest Fires and Pests has been established under the CCAB/AP. In 2004 the Technical Commission requested the Consejo Centroamericano de Bosques y Áreas Protegidas (CCAB/AP) to officially create the Regional Central America and Mexico Forest Fire and Pest Network (*Red Regional de Centro América y México de Incendios y Plagas Forestales)* operating under the CCAD. The recommendations of the network were presented at the Pan-American Wildland Fire Conference on 23 October 2004, San José, Costa Rica.[16] The Central American Strategy on Fire Management 2005-2015 (*Estrategia Centroamericana para el Manejo del Fuego*) was published in 2005[17] and implemented in a number of regional activities in the following years.[18]

South America

In 2004 the Regional South America Wildland Fire Network was founded in Curitiba, Brazil.[19] In 2005 the South America Subregional Technical Workshop, sponsored by the FAO Latin American and Caribbean Forestry Commission (COFLAC) developed the first draft of the South American Strategy on Fire Management 2006-2010 (*Estrategia de Cooperación de América del Sur para el Manejo del Fuego*). In the frame of this Strategy it was decided to establish the Fire Management Working Group of South America. The network is co-chaired by PREVFOGO / IBAMA (Brasilia, Brazil), the Federal University of Paraná (Curitiba, Brazil) and the National Forestry Corporation (CONAF), Chile.

Together with the representatives from Central America and the Caribbean the "Regional Strategy on Cooperation in Wildland Fire Management in Latin America and the Caribbean" was finalized in a regional meeting in Santiago de Chile in 2005 and presented and at the 24th COFLAC Session in 2006. In 2007 IBAMA and COFLAC signed an MoU on technical cooperation and development of the South American Strategy on Fire Management (Memorando De Entendimiento Para la Cooperacion Tecnica y el Desarrollo de la Estrategia de Cooperación de América del Sur Para el Manejo del Fuego) and agreed on an operational bi-annual plan for the Secretariat of the network (Plan Operativo Bianual de la Secretaria Ejecutiva del Grupo de Trabajo de América del Sur de Manejo del Fuego). Effective inter-governmental cooperation in fire management has been proven during mutual assistance in wildfire emergencies in 2012 by the cooperation between the authorities of Argentina, Brazil and Chile. Progress can also be noted in development and use of common

16 http://www.fire.uni-freiburg.de/GlobalNetworks/Panamerica/Panamerican-Conference.htm

17 http://www.fire.uni-freiburg.de/GlobalNetworks/MesoAmerica/CCAD-FINAL-Estrategia-Manejo-Fuego-con-logos.pdf

18 http://www.fire.uni-freiburg.de/GlobalNetworks/MesoAmerica/MesoAmerica.html

19 http://www.fire.uni-freiburg.de/course/meeting/meet2003_14.htm

regional assets in wildland fire early warning and satellite monitoring, led by Brasil[20] and *Red Latinoamericana de Teledetección e Incendios Forestales* (RedLaTIF).[21]

UN Economic Commission for Europe (UNECE)

Within the last decade the region of the United Nations Economic Commission for Europe (UNECE) has experienced a number of wildfire episodes that have resulted in severe environmental damages, high economic losses and considerable humanitarian problems.[22] Reasons and underlying causes of changing fire regimes have been elaborated in detail in Chapter 22 of this White Paper. There is a high interest of governments, national agencies, international organizations and civil society in the UNECE region to address the increasing threats and imminent problems by fire management solutions that could be developed collectively, thus economically, allowing inter-operability in fire management between nations and regions.

At the time of publishing this White Paper the preparation of the "UNECE / FAO Forum on Cross-boundary Fire Management" in November 2013 at the United Nations in Geneva is underway. The Forum will be organized by the Global Fire Monitoring Center (GFMC) and the Secretariat of the UNECE/FAO Forestry and Timber Section, and co-sponsored by the Secretariat of the Euro-Mediterranean Major Hazards Agreement (EUR-OPA), Council of Europe.

The conference will elaborate on recommendations to UNECE and CoE member states to take advantage of recent insights and solutions of contemporary and expected future wildfire problems. The central focus of the conference will be to address the situation in countries in which progress of enhancing fire management capabilities is limited, for example as a consequence of political and administrative transition, difficult economic conditions, or countries experiencing extraordinary fire situations, and hence would benefit from the experience of their neighbor countries.

The outcome of the conference will build on existing and already proposed initiatives, such as

- New approaches in integrated vegetation management regarding renewable energy concepts and carbon storage. Some of these initiatives fall within the context of the UNFCCC endeavor to reduce deforestation and forest degradation by identifying opportunities to incorporate wildfire hazard reduction and fire management;

20 http://www.fire.uni-freiburg.de/current/archive/br/2001/10/br_10082001.htm

21 http://www.redlatif.org/

22 This section refers to the planning document for the UNECE/FAO Regional Forum on Cross-boundary Fire Management, to be organized by the UNECE/FAO Teams of Specialists on Forest Fire through its Coordinator – the Global Fire Monitoring Center (GFMC), Germany, and supported by the Council of Europe. For details and updates: see website of the UNECE/FAO Teams of Specialists on Forest Fire: http://www.fire.uni-freiburg.de/intro/team.html

- Wider application of prescribed fire in nature conservation, forestry and landscape management, with encouraging progress of countries cooperating under the "Eurasian Fire in Nature Conservation Network"[23] and similar initiatives;
- Exploitation of the results of successful international fire research projects with the aim to develop adequate public policies affecting fire management, e.g. the most recently accomplished multinational "Fire Paradox"[24] project, or the ongoing development of the multinational Alpine Forest Fire Warning System (ALPF FIRS)[25];
- Introduction and further development of competency-based fire management training standards offering qualifications to fire fighters, foresters and land managers, e.g. the "EuroFire Competency Standards";"[26]
- Strengthening dedicated networks of wildland fire specialists, agencies and other representatives from civil society, e.g. the six Regional Wildland Fire Networks of the Global Wildland Fire Network that are covering the UNECE region;
- Application and further strengthening of existing as well as development of new bilateral agreements on reciprocal transboundary assistance in wildfire emergencies across the ECE region;
- Endeavor to enhance governance of UNECE member states in order to provide and receive assistance in wildfire (and other environmental) emergency situations by setting up standards, protocols and agreements. This should happen in cooperation with procedures evolving under the lead of the UNEP/OCHA Joint Environment Unit and the UN Advisory Group on Environmental Emergencies, e.g., the proposed creation of an Environmental Emergencies Center (EEC);
- Follow up of the recommendations of regional groups, projects, programmes and earlier regional conferences aimed at enhancing international cooperation in fire management in the UNECE region and adjoining regions. Examples of such recommendations include
  - the development of a "Regional Strategy for Cooperation in Fire Management in Southeast Europe" proposed in 2006;[27]
  - the outcomes of expert meetings such as the workshop "Assessment of Forest Fire Risks and Innovative Strategies for Fire Prevention" – an activity of the Ministerial Conference for the Protection of Forests in Europe (MCPFE) of 2010;[28]

23 http://www.fire.uni-freiburg.de/programmes/natcon/natcon.htm
24 http://www.fire.uni-freiburg.de/programmes/other/intr.html
25 http://www.alpffirs.eu/
26 http://www.euro-fire.eu/
27 http://www.fire.uni-freiburg.de/GlobalNetworks/SEEurope/Strategy-WFM-RSEEW-FN-2-02-05-2006.pdf
28 http://www.foresteurope.org/documentos/FOREST_EUROPE_Forest_Fires_Report.pdf

- the European Commission study entitled “Study on wild firefighting resources sharing models”;[29]
- the recommendations from projects supported by the Environment and Security (ENVSEC) Initiative addressing wildland fire, human security and peace in the EECCA region;[30] and
- the outcomes of the International Conference on Cross-Boundary Fire Management (Irkutsk, Russia, 2010)[31] and the APEC Conference on Forest Fire Management and International Cooperation in Fire Emergencies of the Asia Pacific (Khabarovsk, Russia, 2010).[32]

The outcomes of the Forum shall be regarded as complementary to existing agreements and mechanisms. The conference will further the objectives of the international forest and climate regimes and shall contribute to the evolving of an “international wildland fire regime” as envisaged by the UNISDR Global Wildland Fire Network.

A large number of countries of the UNECE region are members of the Council of Europe, member states of the European Union and signatory states of the MCPFE, and are all concerned about the impact of climate change on forests and forest destruction by fire. There is also a collective demand for robust forest policies. However, wildland fires are not only impacting on the protection and function of forest ecosystems. Fire use and wildfire occurrence in the cultural landscapes of the region are shaped by agriculture, pastoralism and forestry and have considerable impacts, both positive and negative, on landscape patterns, land productivity, biodiversity and the atmosphere – with considerable implications for air quality, human health and security, and climate change.

The UNECE Convention on Long-Range Transboundary Air Pollution[33], the European Landscape Convention[34] and the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention)[35] are examples of conventions that address the pressing regional issues and relevant to – although not yet explicitly referring to – a potential regional “wildland fire regime”.

Thus, the overall aim of the Forum will be a first step towards the development of an agreement on international cooperation to enhance fire management dialogue and capacity in the UNECE region. The political consultation and technical planning process in preparation of the Forum refers to the outcomes and the follow-up of the 4th and 5th International Wildland Fire Conferences (see section 3.4. and Annexes I and II).

29 http://ec.europa.eu/echo/civil_protection/civil/prote/perspectives_en.htm
30 http://www.fire.uni-freiburg.de/GlobalNetworks/SEEurope/SEEurope_1.html
31 http://www.fire.uni-freiburg.de/GlobalNetworks/CentralAsia/CentralAsia_6.html
32 http://lesscentr.ru/en/en/index0.htm
33 http://www.unece.org/env/lrtap/
34 http://www.coe.int/t/dg4/cultureheritage/heritage/Landscape/default_en.asp
35 http://www.plantaeuropa.org/pe-wider_context-Bern.htm

Bilateral reciprocal agreements with multilateral character: Examples

Looking back a decade, the United States wildland fire season of 2000 at that time was the worst fire season in more than 50 years. Almost 100,000 fires burned more than 2.8 million hectares of forest and range lands. This was approximately twice the U.S. ten-year average. The season was long and difficult and firefighters faced dangerous burning conditions throughout the western U.S.A.

Faced with this unprecedented situation, and with a forecast for continuing hot and dry weather patterns, fire managers realized they would need to reach beyond U.S. borders for assistance. During the remainder of the 2000 fire season, the U.S. received assistance from more than 1200 Canadian firefighters, 96 fire specialists from Australia and New Zealand and 20 Mexican firefighters. These additional resources performed important roles in the U.S. fire fighting efforts. Some international fire fighters provided much needed support to fire crews on the fireline while others performed as middle managers on incident management teams. International agreements with Canada and Mexico were in place prior to the 2000 fire season but none existed with Australia and New Zealand.

Throughout 2001 and up to August of 2002 fire managers, risk managers and solicitors from the U.S., Australia and New Zealand proposed and reviewed options to solve the liability concerns raised after the 2000 fire season. One alternative that was explored was the purchase of sufficient liability insurance to meet risk managers requirements. However, the cost was prohibitive and the policies would have become unwieldy and complex. The best possible solution was to change U.S. law that would give any international firefighter brought to the U.S. under the "Wildfire Suppression Assistance Act," tort liability coverage equivalent to that provided to U.S. Government fire fighters. In early August the bill was passed and signed by the President of the U.S. The language in the bill provided the assurance required by Australian and New Zealand with the result that U.S. fire managers were once again allowed to request assistance from these countries. Signatures of the Secretaries of Agriculture and the Interior were quickly inked on the official Arrangement papers and posted overnight to Australia and New Zealand. The Australian States of Victoria, New South Wales, Tasmania, Western Australia, and South Australia and New Zealand signed these documents and within a week of the passage of legislation, 50 Australian and New Zealand fires specialists were again on U.S. fire lines filling critical mid-level management fire positions in operations and aviation.

Through mobilizations of firefighters and numerous exchange activities, these arrangements have repeatedly proven the value of having effective, flexible, cooperative and formal relationships. These Arrangements are not static but must be periodically reviewed, adjusted, and re-approved by the signatories. The U.S. will continue to work with its partners in Australia and New Zealand to improve and expand on these valuable relationships in order to cooperatively address the common global challenges of wildland fire management.[36]

36 For details see USDA Forest Service (2003).

Progress in Developing Gidelines, Protocols and Standards for Increasing Efficiency and Effectiveness of Transnational Cooperation

In addition to bi- and multilateral agreements the international community has, in recent years, developed a number of proposals, templates and models for improving governance, efficiency and effectiveness of international cooperation in wildfire disaster risk reduction, management and response. The "tools" include common international wildland fire terminology, methods for wildland fire risk identification at national, regional, and global levels and non-binding guidelines for fire management and smoke management – including dedicated eco-zonal fire management guidelines. The use of a standardized, commonly accepted wildland fire incident management system for international cooperation in a disaster situation has been proposed. The Global Wildland Fire Network has also developed a template for international cooperative agreements for countries interested in entering formal relationships on reciprocal assistance with others facing similar issues. Training in fire disaster management through development of internationally compatible standards and competency, as well as certification of international fire responders, are important elements of improving international cooperation in wildland fire management. In the following some key activities are described.

International Wildland Fire Terminology

The fundamental prerequisite for international cooperation in fire management is a commonly agreed upon terminology – a language that is understood by all partners intending to develop cooperation in fire management. In a number of countries very useful terminologies have been developed. This includes English-speaking countries in which fire terminologies are becoming increasingly compatible at an international level. However, terminologies show some differences in the use and meaning of terms. In some countries specific terms have been developed that are unknown elsewhere. As the English language is becoming the major language used for international cooperation in fire management it has proven useful to develop a basic English glossary with English explanations of the terms, which would then be translated directly. The "Global Wildland Fire Management Terminology", first published by FAO (1986) was updated by the Global Fire Monitoring Center (GFMC) on behalf of FAO in 1999. The glossary has not been printed as it is considered a dynamic document, open for ongoing changes considered necessary. The glossary is available as an interactive search engine on the web.[37] In the 1999 version, the only non-English language updated was German. The FAO also added French and Spanish in the FAO web-based terminology.[38] In 2010 the GFMC published the Russian and Mongolian version (together with English and German).[39] In 2013-2014 Chinese and Korean will be added.

37 http://www.fire.uni-freiburg.de/literature/glossary.htm
38 http://www.fao.org/forestry/firemanagement/13530/en/
39 http://www.fire.uni-freiburg.de/literature/glossary.htm

International Statistical Wildland Fire Data Collection

Internationally agreed methodologies and procedures for establishing fire databases and formatting national fire reports are not in place. Such databases and national fire reports (assessments) are important decision support tools at national, regional and international levels and for targeted cooperation in fire management.

The FAO "Global Forest Fire Assessment 1990-2000" (a special report of the Global Forest Resources Assessment 2000 [FRA-2000])[40] and reports from 12 Regional Wildland Fire Networks were summarized and evaluated in the "Fire Management Global Assessment 2006"[41]. This exercise revealed the lack of compatible and up-to-date statistical data sets at the global scale. The concept proposed in the "Global Wildland Fire Assessment 2004" – an initiative of the GFMC – was used for a number of national reports submitted to the Regional Wildland Fire Networks.[42] However, the assessment covered only a small number of countries.

The effective flow of information from national and regional levels to a central repository for receiving, processing and disseminating fire data must be ensured. This central organization should also feed fire information back to countries and other users that are connected through a network of national fire management agencies. The validity of an earlier recommendation by the UNECE/FAO/ILO in 1996 advising the establishment of a Task Force to produce a proposal for harmonized and coordinated data collection and reporting systems that will meet the demands of various user communities is therefore underscored and considered priority.[43]

The next step to overcoming uncertainties and inconsistencies of fire inventories is the development of a global satellite-based vegetation fire inventory. The Global Observations of Forest and Land Cover Dynamics (GOFC/GOLD) project, an element of the Global Terrestrial Observing System (GTOS), sponsored by the Integrated Global Observing Strategy (IGOS), provides a forum for international information exchange, observation and data coordination (including calibration and validation of sensors and algorithms) and a framework for establishing the necessary long-term monitoring systems. The GOFC/GOLD Fire Mapping and Monitoring Theme aims to refine and articulate common observation requirements and make the best possible use of fire products from the available satellite observation systems – for fire management, policy decision-making and global change research.[44]

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40 Global Forest Fire Assessment 1990-2000: http://www.fao.org/docrep/006/ad653e/ad653e00.htm

41 Fire Management Global Assessment 2006: http://www.fao.org/docrep/009/a0969e/a0969e00.htm

42 Global Wildland Fire Assessment 2004: http://www.fire.uni-freiburg.de/inventory/assessment.htm

43 Initial proposal for a global fire dataset by the ECE/FAO International Conference "Forest, Fire, and Global Change": http://www.fire.uni-freiburg.de/iffn/org/ecefao/ece_3.htm#Appendix%20I

44 GOFC/GOLD Fire Implementation Team: http://gofc-fire.umd.edu/; see also section 6 of this paper.

Template for International Wildland Fire Management Cooperation

The International Wildland Fire Summit of 8 October 2003[45] provided an important forum for discussions of how to manage the future of international wildland fire management and share solutions to global problems. One of the outcomes of the Summit was a paper that offered a template and other information on cooperation in wildland fire management to countries interested in entering formal relationships and agreements with others facing similar issues.[46] The paper is intended to enhance current international coordination and cooperation by providing information on the following:

- A template outlining areas to consider when developing international cooperative agreements;
- Listing of the types of cooperation and assistance that may occur between countries;
- The responsibilities of countries sending assistance and of those receiving assistance;
- Websites containing information and examples of existing cooperative agreements and arrangements.

The role of the International Wildland Fire Conferences

With the first International Wildland Fire Conference, hosted by the North American Fire Management Working Group (FMWG) in the United States (Boston, Massachusetts) in 1989, a forum was initiated which aimed to share knowledge and expertise in wildland fire management, research and operational techniques in North America. The second conference was held in Canada (Vancouver) in 1996 and saw already increased international interest and participation. The third conference, held in Australia (Sydney) in 2003, became the first truly global conference of its type, as it included the inaugural "International Wildland Fire Summit" . Since the time planning the Sydney conference and summit the "International Liaison Committee" (ILC) of the conference series has consciously involved international experts and leading organizations. This is in large part thanks to the support offered by the U.S. Forest Service and the fact that they operate under the FMWG. The outcomes of the 2003 International Wildland Fire Summit and the following conferences in Spain (Sevilla) in 2007 and South Africa (Sun City / Pilanesberg National Park) in 2011 reveal that the IWFC have become the premier international forum on wildland fire policy, management, and transfer of science and technology applications.

45 See section 3.4 of this chapter

46 Published in International Forest Fire News (IFFN) No. 29, p. 10-14: http://www.fire.uni-freiburg.de/iffn/iffn_29/content29.htm

The outcomes of the International Wildland Fire Summit included a Summit Communiqué and five strategic papers released by the Summit participants:[47]

- Guiding Principles for Wildland Fire Management: Guiding principles are suggested for consideration by international collaboration on fire management projects.
- International Wildland Fire Management Agreements Template: The paper identified issues and provided a template to encourage countries to cooperate in dealing with wildland fire.
- Incident Command System (ICS): A globally implemented ICS will improve firefighter safety, efficiency and effectiveness in management response.
- A Strategy for Future Development of International Cooperation in Wildland Fire Management: The Summit participants recommended a series of strategies that will build on the work of many groups, conferences and regional summits and produce a series of actions building towards enhanced international cooperation in wildland fire management.
- Community-Based Fire Management: The paper addressed the role of local communities to become involved in fire management, and examples of and suggestions for implementation.

The conclusions of the 4th and the 5th International Wildland Fire Conferences identified priority issues concerning wildland fires globally and recommended to systematically strengthen fire management at national, regional (multinational) and global levels. The calls for enhancing international cooperation in fire management are reflected by the outcomes of the regional sessions and the conference statements. [48] The 6th International Wildland Fire Conference will be held in the Republic of Korea in 2015 and evaluate the achievements of the previous conferences.[49]

Internationally Compatible Training, Standards and Competency; Certification of International Fire Responders

Capacity building of human resources is a key prerequisite for efficient planning and implementation of sustainable fire management. Many countries that are in need of developing or reviewing fire policies or upgrading existing fire management methods and / or technologies do not have the necessary resources or expertise in capacity building in fire management. International cooperation in fire management is critical to do so. Priority for internation-

47 The outcomes of the International Wildland Fire Summit are published in the special issue of UNECE/FAO International Forest Fire News No. 29 (2003): http://www.fire.uni-freiburg.de/iffn/iffn_29/content29.htm. The Summit website at http://www.fire.uni-freiburg.de/summit-2003/introduction.htm provides a full set of documentation of the Summit, its precursor events and the follow up.

48 See documentations of the conferences on http://www.fire.uni-freiburg.de/sevilla-2007.html and http://www.fire.uni-freiburg.de/southafrica-2011.html

49 http://www.wildfire2015.kr/

al cooperation should focus on capacity building targeted at those groups responsible for developing fire policies, fire management planning and the subsequent implementation. Multi-stakeholder, inter-sectoral and inter-agency approaches will be a key consideration. It is also important to look beyond the responsible government agency to non-government organizations and the private sector to develop these capacities. Capacity building of instructors (training for trainers) is also a key prerequisite for the success of building capacities at local to national levels. Several fire management handbooks are available that are tailored for use in countries that need to build fire management capacity. They strive to guide the application of advanced knowledge in fire ecology and fire management, including participatory approaches to fire management (Community-Based Fire Management).[50]

Advanced international training courses for fire management specialists working in high-level positions in their country's public or private sector will support the development of a culture of trans-national cooperation. Experience has been gained by several UN inter-agency training courses conducted by the United Nation University (UNU) and GFMC in Africa and in the South Caucasus countries. Progress has also been made in developing unified approaches for capacity building in fire management in Latin America through the joint efforts of the U.S. Forest Service, U.S. AID and its Office of U.S. Foreign Disaster Assistance (OFDA). The most recent example is the joint firefighter mobilization exercise in 2010 in Ecuador, which for the first time has been held at pan-Latin American level (*Quarto Ejercicio Nacional y Primer Latinoamericano de Movilisación para Brigadas de Control de Incendios Forestales*).[51]

All of this progress has been made while keeping the vision in mind to establish a decentralized worldwide network of training institutions in which donor organizations can collaborate. The development of training materials for international use is desirable.

The "Partnership for Environment and Disaster Risk Reduction" (PEDRR) is currently developing training materials on "Ecosystem-based Disaster Risk Reduction for Sustainable Development", in which a module "Integrated Fire Management" has been included.[52]

In the case of fire suppression, the first steps have been taken to develop competency standards that will ensure the smooth cooperation between firefighting units of different nations, i.e. their inter-operability in international missions. The EuroFire project is an initiative that has been financed by the EU Leonardo da Vinci programme and implemented jointly by the Global Fire Monitoring Center (GFMC) and partners between 2006 and 2008. [53] EuroFire reviewed competency-based wildfire training systems to identify best practice examples from Europe and around the world. This research was the basis for the production of competency-based basic training materials specifically for use in European countries. The key target end-user groups for the EuroFire project included: firefighters; the rural and

50 http://www.fire.uni-freiburg.de/Manag/CBFiM.htm and FAO (2011)

51 http://www.fire.uni-freiburg.de/GlobalNetworks/MesoAmerica/MesoAmerica_6.html

52 www.pedrr.net

53 EuroFire partners included the International Association of Fire and Rescue Services (CTIF) and Rural Development Initiatives Ltd.

land-based sector; sectoral organizations and; education and training institutions.[54] Meanwhile, EuroFire competency standards and training materials have been translated to Armenian, Azerbaijanian, French, Georgian, German and Russian, and tested in Europe and neighboring countries in East Europe / Caucasus in the frame of the Environment and Security (ENVSEC) Initiative.

In future competency-based standards could serve for certification of firefighters to be deployed on international fire response missions. In 2011 The "International Fire Aviation Working Group" (IFAWG) started to draft a set of voluntary guidelines for improving the safety, efficiency and effectiveness of international aerial firefighting missions (cf. section 7 of this paper).

Fire Management Guidelines

Fire Management Guidelines are needed for the various user levels – ranging from practical guidelines for local fire managers to guidelines for land-use planning and policy development. Guidelines must consider the specific natural (ecological) conditions of vegetation fire, as well as the social, cultural, economic and political environment. Valuable examples of such guidelines already exist for local to global use. However, in many countries these guidelines are not known or not applied, are in need of adaptation for the specific conditions or simply need to be translated. Fire management guidelines for international use that have been developed by international organizations since the 1990s and are available on the Internet:[55]

- International Tropical Timber Organization (ITTO) Guidelines on Fire Management in Tropical Forests (1997)
- The WHO/UNEP/WMO Health Guidelines for Vegetation Fire Events (1999)
- The FAO Guidelines on Fire Management in Temperate and Boreal Forests (2002)
- The UN Fire Management Voluntary Guidelines (2006)[56], with its implementation group, the Fire Management Actions Alliance (2007)[57]
- FAO Legislative Study "Forest fires and the law. A guide for national drafters based on the Fire Management Voluntary Guidelines" (Morgera and Cirelli, 2009).

While guidelines have been developed primarily to assist countries in developing sound, sustainable fire management capacities – including fire management policies and implementation strategies – they also provide guidance on standard approaches or standards in fire management that have been proven internationally and which will facilitate international cooperation in fire management.

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54 EuroFire project website with competency standards and training materials for download: http://www.euro-fire.eu/

55 Overview / portal: http://www.fire.uni-freiburg.de/literature/Fire-Management.htm

56 http://www.fao.org/docrep/009/j9255e/j9255e00.htm

57 http://www.fao.org/forestry/firealliance/en/

International Systems to be Shared: Global Wildland Fire Monitoring and Early Warning

There are a number of fire management support tools that are based on international Earth Observation Systems (EOS). These systems include spaceborne sensors for fire detection and monitoring, and terrestrial networks of hydrometeorological services for recording and forecasting of fire weather (cf. Chapters 20 and 21 of this White Paper; Ahern et al., 2001).

The Fire Mapping and Monitoring Theme of the Global Observations of Forest and Land Cover Dynamics (GOFC/GOLD) project (cf. section 3.2.) and GFMC are closely interacting with the United Nations Office for Outer Space Affairs (UNOOSA), UNOSAT (Operational Satellite Applications Programme of the United Nations Institute for Training and Research – UNITAR), the International Charter "Space and Major Disasters", and the Group on Earth Observations (GEO) with its Global Earth Observing System of Systems (GEOSS).

A number of public providers of near-real time satellite-based observations of active fires and burned area allow free access to public domain data and free open source software (Alexandris, 2011), such as the Rapid Response system – part of NASA's Land Atmosphere Near Real-time Capability for EOS (LANCE). Rapid Response provides daily MODIS images in near real time.[58] Monthly MODIS Burned Area images have been available in the Web Fire Mapper since 2010.[59] The Fire Information for Resource Management System (FIRMS) – a part of LANCE since 2011 – integrates remote sensing and GIS technologies to deliver global MODIS fire locations and burned area information to natural resource managers and other stakeholders around the World.[60] The operational transition of the FIRMS system to FAO in 2011 is now complete. Operational users are advised to use the services of the Global Fire Information Management System (GFIMS) hosted by the FAO.[61]

Monitoring and modeling global emissions from vegetation fires is a component of Monitoring Atmospheric Composition and Climate (MACC), which is the current pre-operational atmospheric service of the European Global Monitoring for Environment and Security (GMES) programme. Its D-FIRE sub-project provides estimations of global emissions from biomass burning to the other MACC services and to the general public. The emissions are calculated in real time and retrospectively from satellite-based observations of open fires (Kaiser et al., 2011).[62]

In 2005 a global multi-hazard early warning system was proposed in the Hyogo Framework for Action. Subsequently a concept for the development for a Global Early Warning System for Wildland Fires was endorsed by the United Nations and presented at the Third

58 http://lance.nasa.gov/imagery/rapid-response/
59 http://firefly.geog.umd.edu/firemap/ and http://maps.geog.umd.edu/firms/burnedarea.htm
60 http://maps.geog.umd.edu/firms/
61 http://www.fao.org/nr/gfims/en/
62 http://www.gmes-atmosphere.eu/about/project_structure/input_data/d_fire/

International Conference on Early Warning (EWC-III) in March 2006.[63] The Global Early Warning System for Wildland Fires is an activity of GOFC-GOLD implemented by the Canadian Forest Service (CFS) and the Global Fire Monitoring Center (GFMC)[64]and is linked to the Group on Earth Observations (GEO)[65]. Its central aims are to develop:

- Early warning of fire danger on a global basis that will provide international agencies, governments and local communities with an opportunity to mitigate fire damage by assessing threat, likelihood and possibility of extreme behavior. This should enable implementation of appropriate fire prevention, detection, preparedness, and response plans before wildfires arise.
- A robust global operational early warning framework with an applied system that will provide the foundation upon which to build resource-sharing agreements between nations during times of extreme fire danger.
- Local expertise and capacity building in fire management for system sustainability through technology transfer and training.

International Wildfire Incident Management System: A Proposal

As a result of severe fires over a number of years, national leaders have demanded a more coordinated approach to the management of wildfires, including receiving or sending firefighting assistance to other countries. However, the ability to effectively cooperate is still limited by organizational and communication barriers. In the U.S.A., State and Federal legislators that are concerned at the lack of uniform emergency management protocols have directed federal, state, and local government to develop common incident management systems. The purpose is to provide a framework that enables wildland fire protection agencies to effectively facilitate clear response authority, acquire and mobilize resources, coordinate interagency actions and provide effective management during incident response. A fundamental element of incident management was the creation of the "Incident Command System" (ICS), which provides consistent terminology and established organizational structures to enable effective, efficient incident management. Australia and New Zealand, faced with similar emergency response issues, have evaluated incident management systems around the world and elected to adopt the ICS and modify it to meet their specific needs.

The complexity of incident management, coupled with the growing need for multi-agency and multi-functional involvement at incidents has increased the need for standard inter-agency incident management systems within countries and states as well as internationally. Many countries have chosen to adopt similar or common systems of addressing emergencies. In addition a number have developed firefighting agreements based on a com-

63 Website of the Global Early Warning System for Wildland Fires: http://www.fire.uni-freiburg.de/fwf/EWS.htm

64 See chapter 21 of this White Paper

65 GEO Task DI-09-03B "Implementation of a Fire Warning System at Global Level" http://www.earthobservations.org/geoss_imp.php

mon system designed to enable interoperability when lending support to other countries. In the past this has usually been to support adjoining States or Countries within the same geographical region. Since 2000 we have seen examples of this being broadened by the provision of support occurring from different hemispheres. In 2000 and 2002, Australia and New Zealand sent critically needed incident managers to the U.S.A. Similarly, early in 2003 the U.S.A. reciprocated by sending fire specialists to Australia. Canada and the U.S.A. frequently exchange firefighting forces, especially along their borders and New Zealand sent firefighting forces to Australia in 2002 and 2003.[66] ICS was also used commonly by all firefighting forces during the wildland fire emergency in Ethiopia in 2000.[67]

The Incident Command System may need to be adapted to suit a particular country's existing political, administrative or cultural systems, customs and values. Where the primary purpose is to enhance emergency management within a country, such adaptations are not only beneficial, but may be essential to have the ICS system adopted. If the purpose of adopting ICS is to enhance cooperation between countries, through the sharing of resources such as fire management teams, it is highly recommended that the sending country and the receiving country both use the same emergency management system.

One of the strategic papers produced by the International Wildland Fire Summit in 2003 suggests that the ICS is the most suitable tool available to fill this role on the international scene (see section 3.4 of this chapter). Given that ICS is a proven model in many countries and given that training materials for ICS are freely available, there is considerable benefit to be gained by a country adopting this system over any other.

It is hereby proposed that there be broad-scale introduction of a single International Wildfire Incident Management System (IWFMS) based on the incident management components discussed previously, including the principles of the ICS. This system would not necessarily require that specific components, such as ICS, be used as the incident management system of the country receiving or providing firefighting assistance. However, IWFMS components would need to be previously agreed upon, ideally in a formal arrangement, and utilized by all countries at the time of cooperation in wildfire emergencies.

IWFMS should also be considered as a candidate to be introduced in the UN-driven process to strengthen the international potential to respond to environmental emergencies. The UNEP and OCHA have established the Advisory Group on Environmental Emergencies (AGEE) as their most important cooperation and support mechanism for the response to environmental disasters. The AGEE is an international forum that brings together environmental experts from around the world to share information, expertise and lessons learned in order to improve response to environmental emergencies worldwide – particularly in developing countries. In 2007 AGEE founded the "Rosersberg Initiative", which

66 See: International Arrangements on the Sharing of Wildland Fire Suppression Resources between the United States of America and Australia and New Zealand: http://www.fire.uni-freiburg.de/iffn/iffn_29/U.S.A.-Australia-NZ-Int-Arrangements.pdf

67 See: The Ethiopia Fire Emergency between February and April 2000: http://www.fire.uni-freiburg.de/iffn/country/et/et_1.htm

aims at strengthening the global regime that governs environmental emergency response and preparedness[68] and initiated the establishment of the online Environmental Emergencies Center (EEC) in 2012.[69]

In this context the application of the principles of developing High Reliability Organizations (HRO) may be of interest (Weick et al., 1999). A cooperation project between the U.S.A. and France reveals the utility of mutual exchanges of expertise and "lessons learned" by HRO may contribute improving incident management (Vidal et al., 2011).

The international firefighting assistance offered during the wildfire emergencies in Greece (2007), the Russian Federation (2010) and Israel (2010) reveal the need for introducing a unified incident management system – especially for the international deployment of aerial firefighting assets. Following the International Wildland Fire Summit (2003) an interest group was formed at the 4th International Wildland Fire Conference and returned recommendations for concerted international action.[70] In a series of International Aerial Firefighting Conferences (2008-2010) this idea became further consolidated.[71] In 2010 the International Fire Aviation Working Group (IFAWG) was founded and officially launched at the meeting of the UNISDR Global Wildland Fire Network / Wildland Fire Advisory Group at GFMC.[72] [73] The terms of reference have been laid down in the IFAWG Charter:

The "International Fire Aviation Working Group" (IFAWG) is working under the framework of the UNISDR Wildland Fire Advisory Group (WFAG) / UNISDR Global Wildland Fire Network (GWFN) as an advisory committee with the following principal objectives:

- Sharing of relevant information, especially information that will support the promotion and improvement of safety in the sector;
- Providing a conduit or facilitation mechanism for the sharing of resources between jurisdictions;
- Identification of opportunities for international harmonization of operating practices and establishment of consistent standards; and recommend or initiate suitable harmonization action, including the development of voluntary guidelines;
- Providing advice and guidance to individual states and the United Nations regarding fire aviation through the UNISDR Wildland Fire Advisory Group / Global Wildland Fire Network.

68 http://ochaonline.un.org/ToolsServices/EmergencyRelief/EnvironmentalEmergenciesandthe-JEU/RosersbergInitiative/tabid/2647/language/en-US/Default.aspx

69 http://www.eecentre.org/

70 http://www.fire.uni-freiburg.de/sevilla-2007/groups/Session-Aviation-Communique.pdf

71 See website of the last AFF Conference in Spain (December 2010), which includes the reports of all AFF conferences between 2008 and 2010: http://www.fire.uni-freiburg.de/course/meeting/2010/meet2010_19.htm

72 http://www.fire.uni-freiburg.de/GlobalNetworks/Joint-WFAG-FAWG-ILC-FMAA-Meeting-June-2010-Agenda-final.pdf

73 IFAWG website: http://www.ifawg.org/

Sharing of resources in fire emergency situations that exceed the capacities of the fire-affected country are addressed by the study "Wildfire fighting resources sharing models" commissioned by the European Commission.[74]

Conclusions

The United Nations International Strategy for Disaster Reduction (UNISDR) and its Wildland Fire Advisory Group are working to strengthen the efforts of United Nations agencies, other international organizations, non-governmental organizations, and a large number of national agencies responsible for fire managements with the aim to reduce the negative impacts of wildland fires and to promote a safe and ecologically benign model of fire use in ecosystem management. Similarly, the Global Wildland Fire Network (GWFN), the Global Fire Monitoring Center (GFMC) and the FAO are working systematically to increase the intra- and inter- regional cooperation in wildland fire management around the world. The outcomes of the International Wildland Fire Summit of 2003 and the 4th and 5th International Wildland Fire Conferences in 2007 and 2011 reveal that the majority of countries worldwide are ready to establish and strengthen regional and international dialogues on co-operation and exchange of information, research and wildland fire management, including through formalized agreements.[75] [76]

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Note: Numerous references have been provided as footnotes or embedded in the text of this paper in order to facilitate online reading. Further search for documents on international cooperation in wildland fire management is facilitated by the search engine on the GFMC homepage (http://www.fire.uni-freiburg.de/). For searching documents only a relevant term (without adding "fire" etc.) needs to be entered.

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74 http://ec.europa.eu/echo/civil_protection/civil/prote/pdfdocs/future/Wildfire_Exec_Summary.pdf

75 See Annexes I and II

76 The 6th International Wildland Fire Conference "Fire of the Past, Fire in Future" will be hosted by the Republic of Korea in 2015 (http://www.wildfire2015.kr/)

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Annex I

At the 4th International Wildland Fire Conference (Sevilla, Spain, May 2007) the representatives of the Regional Wildland Fire Networks and the participants of the joint regional sessions agreed on the need to develop synergies through coordinated and collective action to address the most pressing problems related to fire management globally.[77] Furthermore, the conference participants recommended that:

- The international wildland fire community pursue the development of a global-scale international resource sharing strategy to assist countries with fire management planning activities (including prescribed fire for ecological purposes and fuels management), and active support during periods of wildland fire;
- The FAO promote the global adoption of Incident Command System (ICS) including the publishing of an annual list of countries which have implemented ICS;
- Regional strategies for fire management be developed and designed to the specific needs of regions;
- An international framework for fire management standards be developed and regional wildland fire training be supported, especially to meet the needs for capacity building in developing countries;
- Scientific research programmes addressing the consequences of changes of climate, land use and land cover, and socio-economic changes on fire regimes, environment and society must be supported at all levels;
- The Strategy to Enhance International Cooperation in Wildland Fire Management and the implementation of the Fire Management Voluntary Guidelines be encouraged and endorsed;
- Agencies and groups be encouraged to participate in the Fire Management Actions Alliance in support of their adoption of the Voluntary Guidelines;
- The UNISDR Global Wildland Fire Network, the Regional Wildland Fire Networks and the Secretariat of the global network, the Global Fire Monitoring Center (GFMC), be supported by national agencies and international donors aimed at fostering international cooperation in fire management, including collecting and disseminating fire information, arranging and enhancing international policy dialogue, and supporting projects;
- A series of Regional Consultations tentatively addressing "Global Change and Wildland Fire: Regional Solutions for Fire Management" – be held globally, within the next 1-2 years, to progress the global issues that are impacting people, resources and livelihoods;
- The 2nd International Wildland Fire Summit – tentatively addressing "Global Change and Wildland Fire: Fire Management Solutions for Mitigation and Adaptation" – be held within the next 2 to 4 years under the auspices of the United Nations and partners.

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77 The results of the 4th International Wildland Fire Conference are documented at: http://www.fire.uni-freiburg.de/sevilla-2007.html

Annex II

Four years after the Sevilla Conference the 5th International Wildland Fire was held in 2011, hosted by South Africa. The conference was held under the auspices of the United Nations International Strategy for Disaster Reduction (UNISDR) and the Food and Agriculture Organization of the United Nations (FAO) in conjunction with the Third Session of the Global Platform for Disaster Risk Reduction in Geneva. The Secretary General of the United Nations, Mr. Ban Ki-moon, conveyed an opening statement to the 500 delegates from 61 countries. He welcomed the efforts of fire specialists from around the world to develop a spirit of global cooperation in addressing the role of fire in the global environment and its impacts on society. The conference participants elaborated on both the need for the wise use of fire in sustainable management of natural and cultural ecosystems, and on the adverse effects of wildfires at local to global scales. They expressed strong concern at the escalation of wildfires across the globe – many unprecedented in the modern era regarding their severe impact on communities, the environment and the world economy. The conference participants acknowledged the benefits derived through collaboration in sharing information and researching new ways to tackle emerging issues. The conference participants, including the representatives of Regional Wildland Fire Networks and international thematic networks concluded that efforts be strengthened in capacity building in wildland fire science and management, and that this can be fostered by international cooperation and sharing of expertise and resources. The post-conference website includes all regional session reports as well as the global conference report.[78]

78 The results of the 5th International Wildland Fire Conference are documented at: http://www.fire.uni-freiburg.de/southafrica-2011.html

24 Summary[1]

Global Fire History and Context

With the arrival of the Pleistocene, humans gained the ability to ignite and manipulate fire, and have maintained a monopoly over fire since that time, carrying and spreading it everywhere on planet Earth (Pyne, 1995). 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 substitution of fossil fuels for biomass 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 global environmental concerns in terms of catastrophe, 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 humans as affected by global environmental changes, notably changes of climate and land. This is an increasingly challenging undertaking given expanding social and economic pressures globally.

Documentary-based fire histories and paleo-ecological reconstructions from tree rings and charcoal in sediments confirm that fires have been a natural disturbance in nearly all terrestrial ecosystems since prehistoric times. Fire history information is necessary to understand the suite of natural and human drivers that have shaped vegetation fires 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). Through recent advances in 'paleofire' research, reconstruction of past fire occurrence at regional, continental and global scales is now possible (e.g. Power et al., 2008; Swetnam and Anderson, 2008).

Currently, fire is a very important disturbance in global vegetation cover worldwide, affecting ecosystems that are adapted to, tolerant of, dependent on or susceptible to either natural or human-caused fires. Chuvieco et al. (2008) found that more than 30% of the global land surface has a significant fire frequency. An accurate assessment of the total global area affected by different fire regimes is difficult to determine, and not available at this time.

1 This summary is a synthesis by Johann Georg Goldammer and Brian J. Stocks, published also in a modified version as a peer-reviewed paper, which was commissioned as part of the UK Government's Foresight Project, Migration and Global Environmental Change, on behalf of the Team of Authors of this White Paper (Goldammer and Stocks, 2011).

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A White Paper directed to the United Nations and International Organizations (Johann Georg Goldammer, ed.)
A publication of the Global Fire Monitoring Center (GFMC)

Some estimates have fires affecting between 3 and 4 million square kilometres (300-400 x 10^6 ha) annually (cf. various sources quoted in this volume), while others have estimated the total annual global area burned at more than 6 x 10^6 ha (Mouillot and Field, 2005). Trends in vegetation fires in recent decades have shown the largest increases in fire activity in tropical forests, directly related to deforestation and land-use change in Southeast Asia and South America (Cochrane, 2003; Carmona-Moreno et al., 2005). Fire activity has also increased in Mediterranean Europe as a result of changing socioeconomics, which led to rural abandonment and forest/shrub encroachment on abandoned land in the second half of the last century (Mouillot and Field, 2005).

In many ecosystems across the world fire is a natural and essential force in maintaining ecosystem structure and productivity. In other regions fire is an important land management tool embedded in the culture of many societies in the developing world (e.g. Africa). Fire is also uncommon and unnatural in many ecosystems (e.g. tropical rain forests), where its current application is causing widespread vegetation damage and site degradation. Many societal and economic issues are driving the increasing impacts of wildland fire globally, and an awareness of these relationships is essential in order to fully understand future adaptation and management options.

Vegetation fires are a significant source of atmospheric pollutants, affecting air quality and human health at local to regional scales, especially over the tropical continents, but also over temperate and boreal zones (Andreae and Merlet, 2001). Smoke aerosols perturb regional and global radiation budgets through their light-scattering effects and influences on cloud microphysical processes (e.g. Andreae et al., 2004). For some atmospheric pollutants, vegetation fires rival fossil fuel use as a source of atmospheric pollution (Crutzen and Andreae, 1990). At the global scale, fire frequency, fire intensity and emissions from biomass burning are strongly sensitive to climate and to land use (Mouillot and Field, 2005; Schultz et al., 2008; van der Werf et al., 2010). Over the last century, global trends in burned area have been shown to be driven by changes in land use, principally through (i) fire suppression policies in mid-latitude temperate regions, which reduce fire activity in the short term but may lead to a greater incidence of catastrophic fire in the long term (Littell et al., 2009) and (ii) increased use of fire to clear forest in tropical regions (Cochrane, 2003; Spessa et al., 2010). There is also evidence that drought frequency (coincident with major weather system anomalies such as El Niño or the North Atlantic Oscillation) is strongly linked to increased fire frequency in western U.S.A. (Littell et al., 2009), Canada (Gillett et al., 2004), the Mediterranean (Pausas, 2004), Central Asia (Goldammer, 2006a), Amazonia (Cochrane, 2003), Borneo (Spessa et al., 2010) and northern Australia (Spessa et al., 2005).

Several climate model-based studies indicate that future fire activity is likely to increase markedly across much, but not all, of the globe, including most tropical biomes, Mediterranean climate areas, temperate biomes and the boreal zone (Cardoso et al., 2003; Flannigan et al., 2005, 2009a; Scholze et al., 2006; Marlon et al., 2008: Liu et al., 2010; Pechony and Shindell, 2010). The principal driver of this increase generally appears to be a combination of reduced rainfall and/or higher temperatures (which lead to drier fuels through increased evaporation). This is supported by a recent review of the future extent and severity of droughts as predicted by IPCC 4th Assessment report climate models (Dai, 2011). Nonetheless, considerable uncertainty exists in exactly where and how much fire activity will change in future due to the wide range of possible future climates predicted by climate models (Flannigan et al., 2009b; Krawchuk et al., 2009). Furthermore, the role of future vegetation changes, and future land-use practices in influencing future fire remain comparatively unexplored. This is important because while climate model-based studies of future fire can help us quantify future fire risk, future prediction of burnt area, fire intensity and emissions from wild fires requires a process-based understanding of and modeling approach that seeks to capture the three main precursors to fire, viz. an ignition source, ample fuel and suitably dry fuel (Pyne et al., 1996).

Severe fire incidents have been increasing in recent years in many parts of the world, raising both public and political awareness of a growing and dangerous trend. This awareness was galvanised during numerous catastrophic wildland-urban interface fire events in the western U.S.A. over the past decade. Most recently, the 2007 fires in Greece, the 2009 Black Saturday fires in Australia and the 2010 fires in Western Russia, which resulted in the significant loss of lives, infrastructure and property, have brought home the message that societies globally are becoming more vulnerable to fire and fire events more severe, damaging and deadly.

Fires in Boreal North America

The boreal zone stretches in two broad transcontinental bands across Eurasia and North America, covering approximately 20 x 10^6 ha, two-thirds in Russia and Scandinavia and the remainder in Canada and Alaska. Forest fire is the dominant disturbance regime in boreal forests, and is the primary process which organizes the physical and biological attributes of the boreal biome over most of its range, shaping landscape diversity and influencing energy flows and biogeochemical cycles, particularly the global carbon cycle since the last Ice Age (Weber and Flannigan, 1997). The physiognomy of the boreal forest is therefore largely dependent, at any given time, on the frequency, size and severity of forest fires. The result is a classic example of a fire-dependent ecosystem, capable, during periods of extreme fire weather, of sustaining the very large, high-intensity wildfires which are responsible for its existence.

On average, boreal forest fires burn over between 5 and 20 x 10^6 ha annually, almost exclusively in Canada, Alaska and Russia, as fire is not a dominant disturbance regime in Scandinavia. The annual area burned in these regions is highly episodic, with inter-annual variability often exceeding an order of magnitude, e.g. from less than 0.3 x 10^6 ha to more than 7.5 x 10^6 ha in Canada. Over the past four decades, annual area burned has averaged 2.2 x 10^6 ha for Canada (Martinez et al., 2006) and 0.4 x 10^6 ha for Alaska (Kasischke and Stocks, 2000). In addition, large areas in northern Canada and Alaska receive a modified level of fire protection, as values at-risk do not warrant intensive suppression efforts. In these regions fires are most often allowed to burn freely, fulfilling a natural role in maintaining boreal ecosystem integrity. Close to 50% of the average area burned in Canada is the result of fires receiving a modified suppression response (Stocks et al., 2003).

Rising fire management costs in the boreal zone in recent years are the result of more extreme fire weather, more expensive equipment and expanding use of the forest. Annual expenditures in Canada are currently averaging close to CAD700 million, approaching CAD1 billion in extreme years, and Alaskan costs are rising at a similar rate. Reliable suppression expenditure data are not available for Russia.

The rate of both ongoing and future climate change is expected to be most significant at northern latitudes, and numerous studies project an increase in fire danger conditions and impacts (fire frequency, area burned, fire severity) across the boreal zone (e.g. Stocks et al., 1998; Flannigan et al., 2005, 2009a; Soja et al., 2007). Fire is also a major driver of the forest carbon budget in boreal countries (e.g. Kurz et al., 1995, 2008), making future climate change-driven fire regimes a major concern.

Boreal fires have an immediate effect on the surface energy and water budget by drastically altering the surface albedo, roughness, infiltration rates and moisture absorption capacity in organic soils, and in permafrost areas these effects become part of a process of long-term cumulative impacts and slow recovery. With the removal of the insulating organic layer, permafrost thaws, creating instability in soils. Repeated severe fires, coupled with permafrost degradation will lead to large-scale ecosystem changes. The boreal permafrost biome is warming very rapidly (ACIA, 2005), and annual area burned in this region increasing (Kasischke and Turetsky, 2006). This is leading to further permafrost degradation, and a growing concern over positive feedbacks to climate resulting from increased CO_2 and methane emissions from permafrost thawing and the microbial decomposition of previously frozen organic carbon (Hinzman et al., 2003). It has also been suggested that the net effect of fires may not result in a positive feedback to climate when the effects of greenhouse gases, aerosols, black carbon deposition and changes in albedo are taken into account over a longer time period (Randerson et al., 2006). Clearly, further research is required to properly address the complexity of interactions between human-driven alterations of ecosystems by fire and the global environment.

The development of large and sophisticated fire management programmes aimed at protecting human and forest values from unwanted fire has been largely successful in the North American boreal zone over the past century. However, frequent periods of extreme fire danger, coupled with multiple ignition sources, often overwhelm suppression efforts and large areas burn. In addition, recent evaluations (CCFM, 2005) reveal a growing awareness that the current levels of fire management success will not be sustainable under projected future fire regimes influenced by climate change, forest health and productivity issues, an expanding wildland–urban interface, and aging fire management personnel and infrastructure.

Fires in Temperate-Boreal Eurasia

In temperate-boreal Eurasia the Russian Federation is responsible for the largest share of forest land – about 20% of the global total forested area (FAO, 2006). Russia's fire statistics were largely unreliable before the mid-1990s, but since that time area burned statistics have averaged 6-7 x 10^6 ha of forested land annually (Stocks et al., 2001; Goldammer, 2006b). Within the framework of the former Union of Soviet Socialist Republics (USSR), Russia maintained a very large and effective forest fire suppression capability, but this has largely disappeared due to economic difficulties following the collapse of the Soviet Union. While Russia has enormous natural resource-based wealth, very little of this is being used to promote or encourage sustainability. As a result, wildland fires annually burn over extremely large areas, particularly in Siberia, where illegal logging and an underfunded fire management program fuel largely uncontrolled fires. These systemic problems, as much as the extreme heat wave and drought, contributed greatly to the inability of Russia to cope with the disastrous fires of 2010. These problems must be addressed before effective forest and fire management can be achieved in Russia.

The majority of wildfires occurring in the Central Asian and Far East regions of the Russian Federation burn in remote natural forests and other vegetated lands. The Western Eurasian region, however, has largely been transformed by cultural and industrial activities. Thus, risk and hazards of wildfires and their environmental and humanitarian impacts are influenced by current land use and inherited residuals of anthropogenic activities, e.g. drained peat bogs and wetlands, soils and vegetation contaminated by urban and industrial waste, chemical deposits, radioactivity and remnants of armed conflicts. At the same time the vulnerability of urban and rural societies is increasing at the interface between urban fringes, both by direct impacts, such as destruction of infrastructure and private property, and by indirect effects such as smoke pollution impacting human health and mortality (Goldammer, 2011).

Fires in the Mediterranean Region

On average 50,000 fires annually burn nearly 0.5 x 10^6 ha of vegetated lands in the countries of southern Europe bordering the Mediterranean Sea. Approximately 95% of fires are human caused, the result of both accidents and arson, with a small percentage of fires growing large and accounting for most of the area burned (European Commission, 2010). Despite the scientific progress in exploring and promoting integrated fire management, including the use of prescribed fire in wildfire hazard reduction (Sande Silva et al., 2010), fire policies in this region still advocate total fire exclusion, with fires being attacked and suppressed as quickly as possible. Fire fighting capacity is extensive and costly, with expenditures in prevention and suppression amounting to more than 2.5 billion euros annually. Despite these capabilities, fire impacts in this region are among the most severe in the world. Fire incidence in non-European Mediterranean countries is generally much lower.

Human use of fire in this region dates back 400,000 years, and fire history studies have shown that fire return intervals were 300-400 years during the Late Quaternary, decreasing to 150 years during the warmer and drier Holocene (Carrion et al., 2003). As populations grew and land management (grazing, ploughing and coppicing) expanded, fire frequencies increased accordingly, and until the mid-twentieth century land occupancy and cultivation remained high, with vegetation composition reflecting the legacy of extensive land use over centuries.

The last half of the twentieth century, however, saw changing lifestyles across all southern European countries, with traditional land use largely abandoned, primarily through a rural exodus to urban areas along with mechanization of agriculture and afforestation. This resulted in increased wooded areas, with tree and shrub encroachment on abandoned lands. Landscapes became more homogeneous, facilitating fire spread (Viedma et al., 2009). The number of fires and area burned increased significantly until the end of the 1980s, reflecting increases in fuel accumulation (Rego, 1992) more than a climate effect (Moreno et al., 1998). Countries on the south coast of the Mediterranean have not experienced increasing fire activity despite similar climate conditions, reinforcing the belief that socioeconomic and land-use changes were the main driver of changes in fire in southern Europe. While fire trends among countries are very variable, more recently, overall fire number and area burned have been decreasing. Mean fire size has also been decreasing, which probably reflects increased fire-fighting capacity and awareness (European Commission, 2010). Nevertheless, the variability in area burned among years is very high, and, for some countries, some of the most catastrophic years have occurred during the last decade. This reflects the importance of meteorological and climate conditions on fire activity in this part of the world, despite increased fire fighting capacity.

Climate change projections for the Mediterranean region indicate increasing temperatures, particularly during summer, with precipitation generally decreasing, although with some spatial variability (Christensen et al., 2007). Drought risks and dry spells are also projected to increase (Lehner et al., 2006), along with plant water stress and plant mortality (Gracia et al., 2005). Fire danger conditions are projected to increase in general, with a concurrent increase in the frequency and persistence of periods of extreme fire danger (Moriondo et al., 2006), conditions that would exacerbate the already dangerous fire situation in this region. Further land-use changes induced by climate change and socioeconomic change, particularly in the south coast of the Mediterranean, are likely to add fire risk in the region.

The expanding wildland-urban interface (WUI) in southern Europe, along with expanding and popular tourist attractions, are placing more people and high-value properties in close proximity to highly flammable wildland areas. This creates a growing source of ignitions (Badia-Perpinyà and Pallares-Barbera, 2006) within already dangerous wildlands that are expected to become even more flammable in the years ahead. The devastating 2007 fires in Greece, in which 78 people were killed, more than 270,000 ha and 3000 homes burned, and 110 villages directly affected (Xanthopoulos, 2009), are just the most recent example of the risks facing these areas. Nevertheless, not all severe weather conditions have to result in catastrophic fires. The heat wave of 2003 was catastrophic for Portugal, but not for Spain, despite similar weather in much of the country. This suggests that there might be ways of improving our capacity to cope with adverse future conditions.

Fires in Australia

Australia is often referred to as a 'fire continent', given that Australian bushfires have been a force of nature for millennia. All of Australia's dominant landscapes – the temperate sclerophyllous forests, woodlands and shrublands of the south-west and eastern seaboards, the tropical savanna grassy forests and woodlands of the north, and the semi-arid and arid woodlands, shrublands and grasslands of the vast interior (Groves, 1994) – are subject to recurrent fire. Native aboriginal peoples used and managed fire extensively to suit their purposes. Early settlers suppressed fire or used it to convert lands to agriculture, and communities organized volunteer fire brigades for protection.

The vast majority of the area burned by fire occurs in the tropical savannas of northern Australia, where fire is natural and largely unsuppressed. Area burned is therefore not a reliable indicator of the severity of a fire season in Australia. Much more relevant are the number and severity of fires that burn in and near the heavily populated Australia coastline from Queensland south and west to Perth in West Australia.

With Australian wildlands well adapted to fire, land management agencies have, for many decades, used prescribed burning extensively to reduce understory and surface fuels accumulation and promote patchiness, in order to prevent catastrophic high-intensity uncontrollable wildfires. While this practice is still in use, particularly in West Australia, there has been a strong trend towards a fire management approach that emphasizes early detection and aggressive suppression of fires. This has required large investments in aerial and ground fire fighting equipment, and the creation of agencies with a mandate of emergency response rather than land management (ICLR, 2009).

The fire suppression model has been growing in popularity, both publicly and politically. Most current Australian residents, including many in the expanding WUI areas of Australia, do not understand the value of fire-maintained land and increasingly believe in centralized fire prevention and control. This, in a sense, transfers an urban philosophy to the wildlands and the WUI, as people increasingly move from cities to the rural landscape, and increases demands for government protection. Litigation is also on the rise.

In recent decades, major fires in southern Australia have caused enormous loss of lives and property. Most recent examples are the 1983 Ash Wednesday fires in south-eastern Australia (75 lives and 2,500 homes lost), the 2003 Canberra fires (four lives and 500 homes lost) and the 2009 Black Saturday Fires in Victoria, which claimed 173 lives, destroyed over 2,000 homes and burned over 430,000 hectares (Rees, 2009). These devastating fires have exposed the dangers of building homes in landscapes dominated by extremely flammable fuels in a region with arguably the most extreme fire weather and fire danger conditions on Earth. They have also reignited the debate over fire management approaches in Australia.

Major coronial inquiries and Royal Commissions after these fires (there have been 13 such reviews in Australia since 1939) indicate that public scrutiny of, and involvement in, fire management policy is increasing (ICLR, 2009; Royal Bushfire Commission, 2010).

With respect to the rising cost of current fire management practices in Australia, a recent paper by Ashe et al. (2009) estimates the cost of bushfires to Australia taxpayers at US$6.625 billion, and questions the effectiveness and efficiency of this level of investment. In reaching this conclusion, the authors also determined that Australia is investing approximately US$5.612 billion (or 85% of the total cost of fire) to manage a loss of approximately US$1.013 billion (or 15% of the total cost of fire).

Climate change projections for Australia generally show increases in fire danger conditions over most of the country, largely driven by increases in temperature and decreases in relative humidity (Williams et al., 2001; Pitman et al., 2007), with more frequent periods of extreme fire weather (Lucas et al., 2007). The impact of climate change on fuels is more complicated, with drier conditions generally decreasing fuel moisture in forested areas, while inhibiting growth in grasslands that rely on biomass accumulation to promote higher-intensity fires (Williams et al., 2009). Climate change-driven shorter fire return intervals and higher fire intensities are also anticipated to have effects on biodiversity, particularly in temperate biomes dominated by sclerophyllous vegetation (Williams et al., 2009).

Fires in the United States

Organized fire protection in the U.S.A. began in the early 1900s, largely driven by two factors: a legacy from European forestry that fires had no part in forest management and should be eliminated, and a growing number of large conflagrations in the western U.S.A. that galvanized public and political concerns. The result was a fire suppression policy aimed at fire exclusion.

This policy of general fire exclusion was very successful, although very costly, as annual area burned declined from an average of 15-20 x 10^6 ha in the early 1930s to 1-2 x 10^6 ha by the 1970s, largely as previously unprotected areas were brought under protection. However, by the mid-1970s concerns were being raised over constantly growing fire expenditures and the legacy of excluding fires in forests where they were normally a natural ecological force. At this time federal agencies relaxed the fire exclusion policy to allow more natural and prescribed fire. However, several decades of widespread fire exclusion had created extensive landscapes of over-mature and decadent forests with significant fuel accumulation issues, particularly in the western U.S.A. (Schoennagel et al., 2004). Large, uncontrollable fires returned to this region, beginning in the late 1980s and continuing to the present time, fuelled by widespread drought in combination with heavy fuel accumulations. The lesson learned was that a fire exclusion policy may delay large fires for a period of time, but it would not eliminate them.

The last decade has seen a dramatic rise in area burned (annual average 7–8 x 10^6 ha) and the number of large fires (>20,000 ha) across the western U.S.A. Fire costs are also continuing to rise dramatically (with federal agency costs averaging US$1.5 billion annually since 2000), driven by an increasing number of high-cost WUI fires, particularly in the highly populated areas of southern California (e.g. 0.3 x 10^6 ha, 22 fatalities, 3,500 homes destroyed and property losses of US$3.5 billion in 2003) (González-Cabán, 2008). During the 1997-2008 period federal suppression costs totaled more than US$13.1 billion (González-Cabán, 2008) with the number of fire exceeding USD $10 million increasing from 6 in FY 2004-2005 to 32 in FY 2008 (QFR, 2009).

Growth of the WUI is a significant driver of the US fire programme (31% of US homes are now reported to be in the WUI) and programme emphasis has shifted from resource management to fuels management in the WUI. In 1991 13% of the US Forest Service budget was associated with fire management, and this had increased to 48% by 2008 (ICLR, 2009). Many of the shrubland ecosystems in southern California are exposed to extreme fire weather events in which fire suppression activities are largely ineffective (Moritz et al., 2004). This raises the issue of whether further WUI expansion in these areas is prudent, but this is unlikely to stop the process. With future fire danger conditions likely to be more severe, citizens in the WUI will face an increasing need to adopt community-based proactive measures to reduce fire impacts (Moritz and Stephens, 2008).

Climate change projections indicate increasing lightning-caused fire occurrence in the western US (Price and Rind, 1994), along with increases in area burned (e.g. Bachelet et al., 2005; Lenihan et al., 2008). Fire season length was found to have increased substantially during the 1980s in the western U.S.A., due to earlier snowmelt and higher spring/summer temperatures (Westerling, et al., 2006). Along with climate change impacts, future changes in fire-related policy, including WUI development, wilderness fire management options, and a growing public awareness of fire risk will also influence future fire regimes (Moritz and Stephens, 2008).

A Quadrennial Fire Review (QFR) strategic assessment process is conducted every four years to evaluate current fire management strategies and capabilities against best estimates of the future fire management. The 2009 QFR identifies five major forces driving future trends:

- Climate change effects resulting in more severe fire seasons in more regions, with an increase in large wildfires;
- Cumulative drought effects, exacerbated by competition for water, that will further stress fuel accumulation and promote widespread insect infestations;
- Continued and expanding wildfire risk in the WUI, driven by population shifts and development of former timberlands;
- Escalating emergency response demands as fire management programme plays a larger role in other climate change-driven natural disasters;
- Strained fire management budgets at federal, state and local levels, as costs exceed budgets.

The latest attempt to prepare for anticipated future fire problems in the U.S.A. is the passage of the FLAME (Federal Land Assistance, Management and Enhancement) Act in 2009, which promotes a 'Cohesive Wildfire Management Strategy' involving federal, state, local and tribal governments working collectively in emphasizing suppression, fire restoration and fire-adapted communities.

In his most recent book, fire historian Steve Pyne argues that America does not have a fire problem: it has many fire problems, each requiring particular, distinctive responses. He suggests mixing and matching four approaches: letting fire burn naturally as much as possible, excluding fire through aggressive prevention and suppression, practicing widespread prescribed fire, and redesigning landscapes to control fire behavior (Pyne, 2010).

Fires in Tropical South America – the Amazon Region

The land cover of tropical South America is dominated by the Amazon, the world's largest formation of tropical forests, which play a vital role in maintenance of biodiversity, water and carbon cycles, as well as regional and global climate (e.g. Houghton et al., 2000). In recent decades these forests have become a global focus, as fire has been used to clear forests and maintain pastures and farmlands, with approximately 20 x 10^6 ha being burned annually (UNEP, 2002). Amazon forest fires can burn 4 x 10^6 ha in drought years (Alencar et al., 2006) and emit 20 Mg C/ha from initial fuel emissions (Balch et al., 2008). Three types of fire occur in these landscapes: deforestation fires where slashed vegetation is initially burned, maintenance fires that reburn charred vegetation remnants and accidental forest fires that escape into surrounding forests (Cochrane, 2003). These accidental forest fires can be quite intense, particularly when burning in previously degraded forests (Cochrane and Laurance, 2008).

In this region, fire is used in shifting cultivation (slash and burn agriculture), ranching (creating pastures), industrial agriculture and logging. Selectively logged forests are opened to sunlight and can become flammable in a matter of days (Uhl and Kauffman, 1990). New forest edge is being created at a rate of 30-40,000 kilometers annually by a combination of deforestation processes and logging (Cochrane and Laurance, 2008; Broadbent et al., 2008). An obvious synergism between fire and edges takes place, as fires occur along drier, exposed edges, and spread into remaining forest patches, especially during periodic El Nino Southern Oscillation (ENSO) events (Cochrane et al., 1999). Natural fire-return intervals of 500-1000 years are being shortened to 5-10 years (Cochrane, 2001), preventing natural regeneration and replacing rainforests with degraded, fire-resistant vegetation.

Climate change projections for tropical South America indicate the region will continue to warm over the next century, while precipitation will be spatially and temporally variable (IPCC, 2007). The Amazon region is expected to experience longer periods between rainfall events (Tebaldi et al., 2006), which is a critical factor as fire susceptibility is more closely related to time since rain than total rainfall amounts (Uhl and Kauffman, 1990).

Climate will affect fire impacts in tropical South America, through changes in temperature and precipitation, but also through climate-forced changes in vegetation, fuel composition and structure (World Bank, 2010). However, given the overwhelming influence of human activity on fires, future fire regimes will be a product of both climate changes and human land management practices.

Given the societal and economic importance of converting Amazonian rain forest to agricultural lands, it seems unlikely that extensive fire-related land management practices can or will be curtailed. Despite the regional and global scale importance of these forests in terms of biodiversity, climate and carbon/water cycles, it seems certain that they will exist on a smaller land base in the near future.

Fires in Tropical Southeast Asia

In recent decades the Southeast Asia region has experienced extreme rates of deforestation and forest degradation (Achard et al., 2002; Langner et al., 2007). During the 5 decades between 1950 and 2000, 40% of Indonesian forests were cleared, with recent deforestation rates of 2 x 10^6 ha annually since 1996 (Global Forest Watch, 2002). Agricultural expansion and wood extraction are the main drivers of this rapid deforestation (Geist and Lambin, 2002), which has also increased the risk of fire, resulting in further forest loss and fragmentation (Siegert et al., 2001).

ENSO events have been shown to strongly exacerbate fire occurrence and severity (Langner and Siegert, 2009). The 1997-98 fires were the largest of many ENSO-driven events in tropical Southeast Asia in recent decades, affecting an area of 11.7 x 10^6 ha in Indonesia alone, of which 2.4 x 10^6 ha was carbon-dense peat swamp forest (Page et al., 2002). ENSO-related peatland fires contribute substantially to the loss of biodiversity (Goldammer, 2006a), global burden of greenhouse gases (Bowman et al., 2009) and, through the production of fine particulate matter and aerosols, cause a wide range of human health problems (Heil and Goldammer, 2001). These health issues are often widespread across the region, as near-ground smoke circulates for extended period, resulting in lengthy exposure to toxic smoke byproducts in one of the most densely populated regions of the world.

Millions of hectares of peatland in Southeast Asia, particularly Indonesia and Malaysia, have been deforested, drained and burned, and converted to oil palm and pulpwood estates. Peatland drainage and increased human access has resulted in extensive fires, particularly along edges of previously disturbed forests (Spessa et al., 2010). Losses in tree cover lead to more fire activity as tree-dominated ecosystems are transformed to more fire-prone grassy ecosystems, creating a positive feedback loop (Goldammer, 1993, 1999). This process is very similar to that occurring in the tropical ecosystems of Amazonia.

Future land use and climate changes will likely increase the frequency and severity of fires in the Southeast Asian region. Climate change predictions are for a median warming of 2.5°C by the end of the twenty-first century accompanied by a predicted mean precipitation increase of about 7% (IPCC, 2007), although with potentially enhanced seasonality, i.e. wet-season precipitation increase and dry season decrease. The future behaviour of ENSO is uncertain, but a recent study indicates that Indonesia as a whole could expect more frequent and longer droughts in the future (Abram et al., 2007). Deforestation itself, i.e. large-scale alterations in land cover, may also lead to more localised reductions in rainfall. These changes will be critical for peatland areas which are increasingly fragmented and degraded by over-logging, drainage and agricultural conversion; fires in these areas are likely to provide a persistent source of greenhouse gas and particulate emissions over the decades to come. Incentives to reduce the excessive use of fire in land use and land-use change resulting in ecosystem degradation or destruction through tools such as the Reduced Emissions from Deforestation and Degradation (REDD) are encouraging (Campbell, 2009; UNFCCC, 2010). While Indonesia in 2010-11 pledged a deforestation moratorium and Brazil for some time has successfully reduced deforestation, the reality reveals a different picture of continuing burning activities and even a recent acceleration of deforestation in Brazil (BBC, 2011). With reference to the ambitious goals of Indonesia to halt deforestation Jotzo (2011) states: 'As with many other areas of policy, the difficulty is not coming up with a vision, but implementing it.'

Fires in Sub-Saharan Africa

Africa, along with Australia, is often referred to as a 'Fire Continent', as more routine fires occur here than on any other landmass on earth (Pyne, 2005). In sub-Saharan Africa (that region south of the Sahara desert), more vegetation fires burn, and at higher frequencies, than anywhere on the planet. Given the lack of infrastructure surrounding much of the fire activity in this region, no reliable ground data on fire statistics are available. However, satellite-based analysis of active fires and recent burn scars has been used in recent years to gain a perspective on the extent of fire in this region. While estimates vary, there is general agreement that in excess of 230 x 10^6 ha burned in Africa in 2000 (JRC, 2005).

Over the past million years most ecosystems of Sub-Saharan Africa evolved primarily through the human use of fire, and require fire to maintain ecosystem health and biodiversity. After some attempts at fire control during colonial times, fire continued to be used indiscriminately by local populations, in a largely unsupervised manner. Today large parts of Sub-Saharan forests and woodlands are fully or partially burned every year as populations rapidly increased (Barbosa et al., 1999).

Although lightning is a significant cause of fires in this region, the majority of fires are human-caused. The highest number of fires, intentional or otherwise, occur in the savanna biome, followed by slash-and-burn agriculture, and burning of agricultural residues. In addition to savanna fires, agricultural burns are often left unattended and spread to neighbouring lands and forests. Economically important resources are increasingly destroyed by fires burning into fire-sensitive environments, including communities (Goldammer and de Ronde, 2004).

In addition to areas that burn too frequently, resulting in site degradation, there are also a large number of areas that do not burn frequently enough. This results in bush encroachment in extensive savanna areas, significantly altering biome characteristics. High-value conifer plantations in southern Africa also pose a major wildfire threat.

Traditional African societies used fire wisely as a land management tool, but that cultural understanding of use of fire has been largely lost in recent generations, due to migration, rural exodus to urban centers, civil unrest and conflicts, and the ongoing HIV/AIDS epidemic.

The lack of infrastructure in Sub-Saharan African countries, along with other competition for scarce financial support, has thwarted the establishment of centralized fire protection organizations. Recently international assistance programmes have begun to focus on fire prevention and preparedness, rather than direct fire suppression capacity. Community-based fire management programmes, aimed at empowering communities to apply local knowledge in assuming responsibility for fire management, are growing across southern Africa, with international assistance (Goldammer et al., 2002).

Vegetation fire issues in Sub-Saharan Africa are symptomatic of much larger economic and societal issues in this region. Although some progress is being achieved in terms of public education and involvement, it is unlikely that the level of unwanted fire problems will be reduced in the near future.

Future trends of continental warming by 0.2-0.5°C per decade as projected by Hulme et al. (2001), particularly over the interior semi-arid tropical margins of the Sahara and central Southern Africa, may indicate that the associated changes of precipitation and drought regimes may influence fire regimes and vulnerability of human populations to adverse climate and fire events.

Wildland Fires, Sciety and Migration

The consequences of human migration on wildland fire activity and impacts are a growing concern that requires further analysis. Migration of populations seeking living space and livelihood in forests and other lands will continue to involve land clearing by fire, with consequences on land degradation, carbon sequestration and emissions. In contrast, abandonment of land cultivation due to urbanisation will lead to a greater wildfire risk and to reduced rural fire management capacity in some regions, e.g. in Europe. In other regions rural exodus may result in the recovery of native vegetation, its biodiversity and potentially reduced fire wildfire hazard, e.g. in the tropics. Consequences of wildfires on migratory processes have been noted in temporarily and spatially limited dimensions, e.g. evacuations of populations from fire-threatened or fire-affected areas. Recent mass evacuations of more than 3,500 First Nation's people in Ontario, Canada, in July 2011, or the evacuation and destruction of Slave Lake by a wildfire, a town of a population of 7,000 in Alberta, Canada, in May 2011, may serve as an indication that human health and lives in remote high-fire-risk regions are threatened during the fire season (O'Brien and Goldammer, 2011). With continuing severe forecast for the future, protection of remote settlements will be an increasing concern. The impacts of wildfire smoke pollution, coupled with extreme heat waves, on megacities, urban agglomerations and other wildland-urban interface locations, such as those recurring in South East Asia, western Russia and the Siberian Far East, have forced numerous temporary evacuations (Goldammer, 2010, 2011). Permanent dislocations of populations due to changing fire regimes, however, so far have not been noted.

Conclusions: Wildland Fire Science and Policy [2]

The challenge of developing informed policy that recognizes both the beneficial and traditional roles of fire, while reducing the incidence and extent of uncontrolled burning and its adverse impacts, clearly has major technical, social, economic and political elements. In many countries better forest and land management techniques are required to minimize the risk of uncontrolled fires, and appropriate management strategies for preventing and controlling fires must be implemented if measurable progress is to be achieved.

A better understanding by both policy-makers and the general population of the ecological, environmental, socio-cultural, land-use and public-health issues surrounding vegetation fires is essential. The potential for greater international and regional co-operation in sharing information and resources to promote more effective fire management also needs to be explored. The recent efforts of many UN programmes and organizations are a positive step in this direction, but much remains to be accomplished. In the spirit and fulfilment of the 1997 Kyoto Protocol to United Nations Framework Convention on Climate Change, the 2002 World Summit for Sustainable Development (WSSD) and the UN International Strategy for Disaster Reduction (UNISDR), there is an obvious need for more reliable data on fire occurrence and impacts. Remote sensing must and should play a major role in meeting this requirement. In addition to the obvious need for improved spaceborne fire-observation systems and more effective operational systems capable of using information from remote sensing and other spaceborne technologies, the remote sensing community needs to focus its efforts more on the production of useful and meaningful products.

It must be underscored that the traditional approach in dealing with wildland fires exclusively under the traditional forestry schemes must be replaced in future by an inter-sectoral and interdisciplinary approach at landscape levels. The devastating effects of many wildfires are an expression of demographic growth, land-use and land-use changes, the socio-cultural implications of globalisation, and climate variability. Thus, integrated strategies and programmes must be developed to address the fire problem at its roots, while at the same time creating an enabling environment and develop appropriate tools for policy and decision makers to proactively act and respond to fire.

2 These conclusions have been formulated by the Working Group on Wildland Fire of the United Nations International Strategy for Disaster Reduction (UNISDR) and the Global Fire Monitoring Center (GFMC), with main inputs by Meinrat O. Andreae, Peter Frost, Johann Georg Goldammer, Chris O. Justice, Stephen J. Pyne, Dieter Schwela, and Brian J. Stocks, published first as background paper for the International Wildland Fire Summit (Sydney, Australia, 2003) in UNECE/FAO international Forest Fire News No. 29, pp. 40-55: http://www.fire.uni-freiburg.de/iffn/iffn_29/IWFS-6-Background.pdf. These recommendations have been edited for inclusion in this White Paper.

What are the implications of these conclusions on fire science? Back in the early 1990s the first major inter-disciplinary and international research programmes, including inter-continental fire-atmosphere research campaigns such as the Southern Tropical Atlantic Regional Experiment (STARE) with the Southern Africa Fire-Atmosphere Research Initiative (SAFARI) in the early 1990s (JGR, 1996), clearly paved the way to develop visions and models for a comprehensive science of the biosphere. At the beginning of the Third Millennium it is recognized that progress has been achieved in clarifying the fundamental mechanisms of fire in the global environment, including the reconstruction of the prehistoric and historic role of fire in the genesis of planet Earth and in the co-evolution of the human race and nature.

However, at this stage we have to examine the utility of the knowledge that has been generated by a dedicated science community. We have to ask this at a time when it is becoming obvious that fire plays a major role in the degradation of the global environment. It follows from the statement of Pyne (2001) "*Fire has the capacity to make or break sustainable environments. Today some places suffer from too much fire, some from too little or the wrong kind, but everywhere fire disasters appear to be increasing in both severity and damages*" that we must ask whether wildland fire is becoming a major threat at the global level? Does wildland fire at a global scale contribute to an increase of exposure and vulnerability of ecosystems to secondary / associated degradation and even catastrophes?

The regional analyses provided in this White Paper reveal that environmental destabilization by fire is obviously accelerating. This trend goes along with an increasing vulnerability of human populations. Conversely, humans are not only affected by fire but are the main causal agent of destructive fires, through both accidental, unwanted wildfires, and the use of fire as a tool for conversion of vegetation and reshaping whole landscapes.

This trend, however, is not inevitable. There are opportunities to do something about global fire because – unlike the majority of the geological and hydro-meteorological hazards – wildland fires represent a natural hazard which is primarily human-made, can be predicted, controlled and, in many cases, prevented.

Here is the key for the way forward. Wildland fire science has to decide its future direction by answering a number of basic questions: What is the future role of fundamental fire science, and the added value of additional investments? What can be done to close the gap between the wealth of knowledge, methods and technologies for sustainable fire management and the inability of humans to exercise control?

From the perspective of the authors the added value of continuing fundamental fire science is marginal. Instead, instruments and agreed procedures need to be identified to bring existing technologies to application. Costs and impacts of fire have to be quantified systematically to illustrate the significance of wildland fire management for sustainable development.

Fire science must also assist to understand which institutional arrangement would work best for fire management in the many new nations that have been created over the past dozen years, e.g. the nations built after the collapse of the former Soviet Union or Yugoslavia, or countries that democratised, a few by simple independence or dramatic regime changes. The questions to be addressed include:

- What kind of fire policies and fire institutions should such nations adopt?
- What research programs are suitable?
- What kind of training yields the biggest results?
- What kind of fire management systems are appropriate for what contexts?
- What kind of international aid programs achieve the best outcomes?
- How should such countries reform in a way that advances the safety of their rural populations and the sustainability of their land and resources?

So far no such study – no such field of inquiry, the political ecology of fire – exists. Yet there are ample examples available from history, especially Europe's colonial era, and many experiments over the past 50 years. There is the record of policy and institutional reforms for the major fire nations such as the United States, Russia, Canada, and Australia. There were scores of projects sponsored by international organizations. What is needed is a systematic collection and analysis of these experiences and data. This is something that can be achieved with a modest investment of scholarship and money.

Similarly, a compelling need exists to understand better the impact of industrialization which involves the burning of fossil biomass. Both developed and undeveloped countries are struggling to understand the consequences of fossil fuel use for fire management, of this transformation. How, precisely, does burning fossil biomass change the patterns of fire on the land, for good or ill? We understand something about the relationships and cumulative effects between biomass burning and fossil-fuel burning in the atmosphere; we do not understand the mechanics of their competition on the Earth's vegetated surfaces. Modern transportation systems can open forests to markets, and lead to extreme fires. Equally, chemical fertilizers, pesticides, and mechanized ploughs can remove fire from agricultural fields. The replacement of biofuels for cooking and heating in some regions by fossil fuels have led to a vast accumulation of hazardous fuels in wildlands. In other regions the availability of fossil or solar energy has eased the pressure of vegetation depletion. Yet both fire's introduction and its removal have ecological consequences. These are linked problems for which there are no models or theory.

Most of the current fire research is sponsored by governments, and that because those governments have responsibility for large tracts of public land. These landscapes matter because their fires can (and do) threaten communities, because the mismanagement of fire can undermine the ecological health of the protected biota, and because they influence carbon cycling and global warming. But most of the world's fires reside in the developing world and are embedded within agricultural systems or systems subject to rapid logging for export or conversion to plantations. These are the scenes of many of the worst fires and most damaging fire and smoke episodes. Traditional research into fire fundamentals has scant value in such conditions, which are the result of social and political factors. Yet these are circumstances in which even a small amount of research could produce large and immediate dividends.

This implies that scientific focus has to be shifted. The fire domain for a long time has been governed by inter-disciplinary natural sciences research. Engineering research has contributed to a high level of development in the industrial countries. What is needed in future is a research focus at the interface between the human dimension of fire and the changing global environment. The new fire science in the third millennium must be application-oriented and understood by policy makers, a science that bridges institutions, politics, and ecology. Continued research prioritizing fire fundamentals, fascinating as it is, cannot address these matters.

The contribution of global wildland fire science to the way forward must lead towards the formulation of national and international public policies that will be harmonized with the objectives of international conventions, protocols and other agreements, e.g., the Convention on Biological Diversity (CBD), the Convention to Combat Desertification (UNCCD), United Nations Framework Convention on Climate Change (UNFCCC), the the Ramsar Convention on Wetlands or the *Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters*.

Summary

While a summary of a global analysis of history, contemporary state-of-science, and the assumed or modeled future of vegetation fires cannot be an exhaustive synthesis of the extremely facet-rich and complex global fire issues, this synopsis focuses on key regions around the world, from tropical to temperate to boreal ecosystems, and is intended to give the reader some insight into the key environmental, economic and societal issues associated with managing fire now and in the immediate future. Some common themes emerge when considering these issues.

Climate change impacts, which are already being observed in some countries, will be variable, but will generally promote more fire activity across all regions. More frequent, severe and larger fires are anticipated, as climate variability is likely to result in more extreme weather events in some regions, particularly heat-related events. However, policy makers and the public are already dealing with a myriad of social and economic issues, and it is difficult to gain their attention with respect to future fire problems.

Current climate change projections of future fire activity are hampered by the relatively coarse spatial and temporal resolution of the general climate models used. Most projections of fire activity are under $2xCO_2$ and $3xCO_2$ scenarios (roughly 2030 AD and 2090 AD), and it is impossible to increase the temporal resolution of these projections with any degree of confidence. However, one common theme is that fire activity and severity will increase substantially by 2020, and much more substantially by 2090 AD, in all regions covered by this report.

In temperate and boreal regions, future fires will impact communities and landscapes even more than at present, and there is a strong need to educate both the public and policy makers that a new accommodation with fire will be required. This in turn will mean reassessing fire suppression policies and encouraging public education on fire prevention, hazard mitigation, and safety. The rising costs of current fire suppression approaches are not sustainable, and are not leading to increased success.

In tropical regions it is difficult to imagine that deforestation practices will be curtailed in the near future, as these are crucial to economic development in countries with more critical problems. Population growth continues unabated in these regions, often making fire a symptom of much larger issues. Tropical and subtropical ecosystems affected by desertification will likely see fewer fires because of lack of vegetation to burn (Larsen, 2009).

In the Mediterranean region, fire risk is likely to increase due to additional land-use change due to less productive areas being abandoned as a result of climate change or further socioeconomic change, particularly in the countries of the southern coast. Changes in lifestyles that expand the wildland-urban interface are also expected to add more risk. Education and awareness can help reduce ignitions, but once these occur, future landscapes and conditions will have greater capacity to spread fire.

Clearly, wildland fire impacts are increasing in most regions around the world. There are many contributing factors, often acting in concert, that will continue to exacerbate this problem in future years. Climate change, constantly expanding wildland-urban interface areas as a consequence of urban exodus, land abandonment due to rural exodus, changing lifestyles and economic development are the most common factors mentioned in this report, but there are many others. Traditional fire management practices are being reassessed in developed countries, while the developing world continues to use widespread fire for social and economic development. However, all countries have one thing in common: with growing populations, industries, infrastructure and disturbance-sensitive technologies, society is becoming more vulnerable to the consequences of vegetation fires, particularly fire smoke pollution. Fire emissions are negatively impacting human health and security, regardless of whether they are resulting from ecologically benign natural fires and sustainable land-use fires, or from unwanted or destructive wildfires. A new accommodation with fire that recognizes and adapts to these rapid changes is required. Promoting wildland fire use where desirable, and controlling wildfires and / or reducing fire use where they are not, will be an evolving and increasingly difficult task in the years ahead. While fire regimes are undergoing changes throughout the continents and vegetation zones, and society becoming increasingly vulnerable to fire and secondary effects of fire, the exchange of knowledge, expertise and resources to address newly arising problems seems to become mandatory. So is also the need to develop national and international policies that envisage to pay respect to the nature and benign effects of fire, and to reduce the threats of destructive wildfires and fire use collectively and cooperatively.

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25 Executive Summary for Policy Makers

1 Introduction

Johann Georg Goldammer

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.

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

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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" (CBD, CCD and 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 no 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 trans-boundary 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 – Cultural Fire History of Planet Earth

Stephen J. Pyne

The Earth is a uniquely fire planet, and humanity a uniquely fire creature. *Homo sapiens* has exercised a species monopoly over fire for all of our existence. Our use of fire has evolved from control over ignition to include also control over fuels and in the last 150 years to the substitution of fossil fuels for surface ones. Each stage comes with powers and limitations, each creates different fire practices, and each inscribes new fire regimes on landscapes.

Humanity remains today the keystone species for Earthly fire. People add and remove fire, rearrange vegetation (its fuels), and determine which fires they want and which they don't. In particular, industrial combustion cannot be understood without the commanding presence of people as fire agents.

Today, fire interacts with global environmental concerns in terms of catastrophe, carbon, and climate. Proper fire management will meant putting fire into places where it belongs and keeping it out of places where it does not.

3 Paleofire and Climate History: Western America and Global Perspectives

Thomas W. Swetnam

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 (e.g., ENSO, PDO, AMO) exert significant control over past and current fire regimes in some regions. Better understanding of these relationships is useful for seasonal to decadal forecasting and is also needed to disentangle natural from anthropogenic causes of past and recent secular changes.

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. 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.

Additional fire history and fire climatology research is needed in many regions. Hemispheric and global-scale fire history perspectives are now developing from documentary, satellite-based, and charcoal records, but much more work is needed to compile, standardize and evaluate these records. Tree-ring based fire histories are mostly restricted to North and South America and parts of Europe, but substantial opportunities and need exist to expand these records in Eurasia and elsewhere. The most fruitful approach for improving our understanding of changing fire regimes and responses to climate, past and present, is likely to be the integrated use of paleofire and modern fire (i.e., documentary and satellite-based) data sets in combination with simulations of climate and ecosystems.

4 Current Fire Regimes, Impacts and the Likely Changes – I: Past, Current and Future Boreal Fire Activity in Canada

Brian J. Stocks

Forest fire has been natural and essential to forest ecosystem health and maintenance across much of Canada since the last Ice Age, and has been a particularly dominant disturbance regime throughout Canada's vast boreal region. Over the past century Canada has developed highly sophisticated forest fire management programs designed to protect the public and forest values from unwanted fire, while also permitting fire to burn naturally in vast regions of the country where values-at-risk do not warrant fire suppression. It is neither economically or physically possible, nor ecologically desirable to suppress fires in these remote regions. Appreciating this philosophical dichotomy is essential to understanding the role of fire and fire management in Canadian forests.

Responsibility for forest fire management rests with each of 13 autonomous provinces and territories, and technologically-advanced programs, along with extensive cooperation among fire management agencies, often through the assistance of the Canadian Interagency Forest Fire Centre (CIFFC), has reduced the extent and impact of unwanted wildland fires. Still, frequent extreme fire danger conditions, when combined with multiple ignitions, often result in large-scale fires that destroy forest resources, and increasingly threaten communities. While highly variable between years, fire occurrence numbers and area burned have averaged ~8600 fires and 2.2 million ha annually across Canada over the past four decades, with roughly 50% of this area burning in remote regions where fires are largely allowed to burn freely. Only 3% of Canadian fires grow larger than 200 ha in size, but these fires account for ~97% of the total area burned. Although variable between regions of the country, lightning is responsible for an average of 35% of Canadian fires, yet lightning fires account for 85% of the total area burned.

In recent decades fire management costs have been steadily rising in Canada due to more extreme fire weather, more costly equipment, expanding forest operations, and protection of a growing wildland-urban interface. Currently, annual costs average $500-600 million CAD, with costs in significant fire years (e.g. 2003) approaching $1 billion CAD. Rising concerns over increasing vulnerabilities to Canadian wildland fires led to the development of the Canadian Wildland Fire Strategy (CWFS) in 2005, in which all three levels of government (federal, provincial/territorial, and municipal) would be required to work closely together to mitigate and adapt to future fire impacts.

A number of important emerging issues that were major impetus in the development of the CWFS including:

- Climate change research that projects increases in the incidence and severity of forest fires, resulting in larger areas burned, shorter fire-return intervals, and a net loss of carbon to the atmosphere, and raising doubts over the economic sustainability and success of current fire management programs.
- Forest health and productivity has suffered as effective suppression programs have led to a shift to older, more disease-prone forests with significant accumulations of dead woody fuel.
- An expanding wildland-urban interface (WUI), driven by a strong public desire to live in flammable landscapes, that is resulting in escalating property losses and evacuations, and bringing wildfire closer to home.
- Increasing and competing demands on the forest land base, with market demands driving pressure for increasing wood supply at a time when accessible Canadian forests are fully committed, international competition is growing, and the public is demanding that more land be reserved to address environmental concerns.
- Aging fire management equipment and infrastructure, and the loss of experienced and qualified personnel through retirement.
- Increasing public awareness of, and involvement in, wildland fire issues across Canada.

The complexity of wildland fire management issues in Canada is growing, and these pressures will continue to escalate. As we move forward in the 21st century it is extremely unlikely that the rapidly increasing complexity of wildland fire management that has been experienced over the past two decades will subside. These pressures will continue to escalate, and innovative policies and practices that address both the root causes and the symptomatic problems of wildland fire must be developed and implemented. In spite of this level of adaptation, it seems certain that a new accommodation with wildland fire is on the horizon in Canada.

5 Current Fire Regimes, Impacts and the Likely Changes – II: Forest Fires in Russia – Past and Current Trends

Johann Georg Goldammer, Brian J. Stocks and Anatoly I. Sukhinin and Evgeni Ponomarev

The boreal and sub-boreal forests, grasslands and agricultural lands of the Russian Federation, notably in Siberia, have long been noted as a region where extensive fire activities are common. No reliable or comprehensive statistics were ever published by the former Union of the Soviet Socialist Republics (USSR), which would allow accurate quantification of the magnitude of the problem in that country. Evaluation of satellite-derived information of active fires and area burned reveals that much larger areas are affected by fire than had been previously reported. Preliminary analysis of area burned trends during the 1979-1995 period shows that, as anticipated, area burned exhibits great inter-annual variability. The area burned varies between ~1 million ha in low years to ~8-10 million ha in severe fire years. With growing international interest in the future of the global boreal zone, where climate change impacts are forecast to have regional to global implications, it is critically important to have forest fire statistics that are reliable, and can be used by the international modeling community with confidence. Reconstruction of area burned in Russia for the 1979-1995 period, when combined with post-1995 data, will provide a reliable 30-year database that can be used for future climate change projections, including carbon budget impacts.

The aerial forest protection system began using helicopters to transport firefighters and equipment (some mechanized) in the mid-1970s, and exerted a major influence on the area burned throughout Russia. At that time over 8 000 smokejumpers and rappellers were employed and able to suppress about 70% of the fires at initial attack. About 600 aircraft were rented from aviation enterprises. By the late 1980s the Soviet Union had amassed the largest firefighting system in the world. However, when the Soviet political system collapsed in 1991, budgets for fire control (prevention, detection, monitoring, and suppression) were greatly reduced. With these recent political and economic changes in Russia, the past gains in fire suppression have become difficult to sustain as the area receiving fire protection, the frequency of reconnaissance flights, and the numbers of fire fighters that can be hired and deployed have all decreased dramatically. Consequently the average size of fires at detection and initial attack has constantly increased in recent years resulting in an increase of the number of large fires. The Forest Code of Russia of 4 December 2006 regulates that starting 1 January 2007 forest fire management is under the responsibility of the regions of the Russian Federation. In the wake of the decentralization the number of fires and area burned increased almost by two times during the fire seasons of 2007 and 2008, even if these two years have been classified as moderate seasons as compared with the average seasonal fire occurrence. The main reasons of this negative development was attributed to a lack of resources in some regions. No single inter-regional assistance was implemented between 2007 and 2009 since every region had limitations in finances and availability of firefighter special forces and could not share them with the neighboring regions.

Agricultural fires within Russia now commonly burn beyond intended borders into neighbouring steppe and forest lands, creating significant local to regional smoke pollution issues with significant impacts on urban communities and human health. Peatland fires in areas drained for agriculture are also a growing problem. Long-distance inter-continental transport of smoke from fires burning in Russia and other countries in Central Asia has also been observed in recent years. The northern hemispheric smoke pollution generated by Russian fires has attracted international, interdisciplinary scientific interest. Emissions from boreal fires, and the likelihood that fire activity in this region will dramatically increase with climate change, resulted in boreal fires becoming a major component of recent International Polar Year studies.

The global boreal zone is expected to be affected early and substantially by climate change, although predicting the rate and extent of climate change impacts is fraught with uncertainty. Central Siberia has the most continental climate on earth, and forest fires can be expected to increase both in frequency and severity with climate change, as extreme events become more common. Indeed, forest fires will likely accelerate vegetation shifting, and provide a positive feedback to climate change. The climate-driven change of permafrost regimes, reinforced by increasing occurrence and severity of wildfires, will lead to a release of paleo-gases, notably methane that is currently trapped in permafrost and wetlands. A recent estimate of the global circumboreal terrestrial carbon pool reveals a magnitude of 1600 billion tons of organic carbon stored in the northern permafrost region and accounting for approximately 50% of the estimated global belowground organic carbon pool.

The size of Russia's forests and other vegetation types regularly exposed and affected by fire, the expected consequences of regional climate change on vegetation cover, wetlands, permafrost and fire regimes, coupled with the impacts of socio-economic changes on increasing wildfire hazard and risk, imply that the extent and severity of fires will affect ecosystems and the environment and most likely will result in a rapid transfer of terrestrial carbon to the atmosphere. With this scenario in mind the country is challenged with a mammoth task to develop and implement a rigid policy and technical capacity aimed at protecting vegetation resources with emphasis on managing the largest terrestrial carbon pool in the possession of a single country.

6 Current Fire Regimes, Impacts and the Likely Changes – III: Boreal Permafrost Biomes

Larry Hinzman, F. Stuart Chapin and Masami Fukuda

Forest fires in the boreal forest project an immediate effect upon the surface energy and water budget by drastically altering the surface albedo, roughness, infiltration rates, and moisture absorption capacity in organic soils. Although the forest fire creates a sudden and drastic change to the land cover, it is only the beginning of a long process of recovery and perhaps a shift to a different successional pathway. In permafrost regions, these effects become part of a process of long-term (20-50 years) cumulative impacts. Burn severity may largely determine immediate impacts and long-term disturbance trajectories. As transpiration decreases or ceases, soil moisture increases markedly, remaining quite wet throughout the year. Because the insulating quality of the organic layer is removed during fires, permafrost begins to thaw near the surface and warm to greater depths. Within a few years, the once permanently frozen soil may thaw to the point where it can no longer completely refreeze every winter, creating a thawed layer in the soil called a *talik*. After formation of a talik, soils can drain internally throughout the year. At this point, soils may become quite dry as the total precipitation received annually in interior Alaska is quite low.

The local ecological community must continuously adapt to the changing soil thermal and moisture regimes. The wet soils found over shallow permafrost favor black spruce forests. After a fire creates a deeper permafrost table (thicker active layer) the invading tree species tend to be birch or alder. The hydrologic and thermal regime of the soil is the primary factor controlling these vegetation trajectories and the subsequent changes in surface mass and energy fluxes. Permafrost provides the structural integrity to hillsides and stream channel banks. As permafrost thaws, thermal and fluvial erosion can cause drastic changes in surface morphology and may make restoration efforts useless.

The rapidly changing climate in the Arctic and Subarctic present greater complexities and imperatives in understanding the role of fire in ecosystem evolution. Although ecosystem response to climate change is often thought to be a relatively slow process, it is now apparent that increases in fire frequencies and intensities, coupled with permafrost degradation, will lead to large-scale ecosystem changes. Understanding these shifts in vegetative communities and quantifying the consequences of thawing permafrost are essential to developing reliable predictions of future climate and ecosystem trajectories.

7 Current Fire Regimes, Impacts and the Likely Changes – IV: Tropical Southeast Asia

Susan Page, Jack Rieley, Agata Hoscilo, Allan Spessa and Ulrich Weber

The Southeast Asian region is currently experiencing some of the world's highest rates of deforestation and forest degradation, the principle drivers of which are agricultural expansion and wood extraction in combination with an increased incidence of fire. During 1997-1998, for example, large-scale wildfires occurred throughout the region; these were linked to rapid land use changes, exacerbated by an extended ENSO-related drought. This fire episode led to an increased awareness of the wide-ranging impacts that uncontrolled fires in this region have on biodiversity, economy, human well-being and climate. Fires are not a new phenomenon in Southeast Asian forests but, prior to human-induced modifications of land cover, they were relatively rare events. Even when they did occur, the long interval between fires would have provided adequate time for recovery of forest structure and biodiversity. In recent years, however, fires have become more frequent and extensive. In Borneo, for example, ~21% of the land was subjected to fires over the period 1997-2006, with 6.1% (4.5 million ha) of the forest affected more than once; some of the most severe fires occurred on peatland, particularly in Kalimantan and Sumatra.

Recent changes in fire regimes in Southeast Asia are indicative of increased forest disturbance, but ENSO events also play a role in exacerbating fire occurrence and severity. During the 20th century, some of the worst fires were associated with strong ENSO-related droughts. In 1982-83, for example, fires were estimated to have burnt 3.2 million ha, of which 2.7 million ha were forest (including 0.55 million ha of peat swamp forest), whilst the 1997-1998 fires affected an estimated 11.7 million ha of forested land in Indonesia alone (of which 2.4 million ha were peat swamp forest). Fires are now occurring on a much more extensive scale – in part because forest margins are at greater risk of fire as a result of disturbance through logging activities, but also as a result of rapid, large-scale forest clearance for the establishment of plantations. Millions of hectares have been deforested and drained to make way for oil palm and pulpwood trees, and many plantation companies, particularly in Indonesia, have employed fire as a cheap land clearance tool; uncontrolled fires have entered adjacent forests or plantation estates, and burnt both the forest biomass and, in peatland areas, underlying peat.

Peatland drainage lowers the water table, exposing a greater volume of dry peat to combustion, and increasing greatly the risk of fire. This effect is demonstrated by the fire regime in the former Mega Rice Project (MRP) on peatland in Central Kalimantan where, prior to drainage, fires were of small extent, mostly in disturbed forest and close to human settlements. This situation changed markedly following construction of an extensive canal network in 1995-96, In 1997, fire affected extensive areas of forest as a consequence of both peatland drainage and human access; drainage increased the risk of peat combustion, whilst human activity provided the fire ignition source.

Forest fires cause changes to forest structure, biodiversity, soil and hydrology. There have been very few ecological studies of post-fire vegetation response in lowland forests in Southeast Asia and hardly any in peat swamp forest. The limited data show that fire causes increased mortality of trees, particularly in the forest understorey, thus limiting the regeneration potential, and converts forest stands with a high diversity of primary canopy species into stands dominated by a few fire-adapted or pioneer species. Repeated fires over successive or every few years lead to a progressive decline in the number of primary forest species. Secondary forest regrowth may act as a carbon sink over the long term but rapid accumulation of forest biomass following a fire can only occur once pioneer species are replaced by primary tree species, i.e. over a much longer time scale. In peat swamp forest, recovery of biomass production can be slow with sites subject to a single, low intensity fire achieving a woody biomass equivalent to about 10% of that of undisturbed forest within 9 years, whilst forests on mineral soils can reinstate 24% of the original forest biomass after 8 years. Multiple fires have a more profound effect: the seed bank and the numbers of tree species and of individual trees, saplings and seedlings within the secondary vegetation are greatly reduced, and, following multiple fires over a short time period, ferns and grasses invade and dominate burnt sites where there are very few or no trees. The high density of non-woody vegetation suppresses tree recolonisation leading to a sharp decline in seedlings and saplings. A further consequence of repeated fires on tropical peatland is land subsidence, the result of drainage (de-watering) and fire (combustion losses) of the peat surface, which lead to an increased risk of flooding during wet seasons. In peatland, uncontrolled fires are the result of increased fire susceptibility of both over-drained peatland and disturbed forest. This is consistent with studies conducted in other fire affected tropical ecosystems, e.g. in Amazonia, where recurrent fires transform tree-dominated ecosystems to grassy ecosystems, in which fires become part of a so-called 'vicious positive feedback loop'. A similar process is now occurring in Southeast Asia, where fern- and grass-dominated savannah-type communities dry out quickly during periods of low rainfall and thus burn more easily, creating a positive feedback through increased flammability.

Fire leads to reduction in both aboveground and below ground organic carbon stocks and also changes carbon cycling patterns. In non-peatland areas, losses of carbon from fire affected forest vegetation exceed greatly soil carbon losses, but on carbon-rich substrates, e.g. peat, combustion losses can be considerable. Peatland fires make a major contribution to atmospheric emissions of greenhouse gases, fine particular matter and aerosols and thus contribute to climate change as well as presenting a problem for human health. The devastating 1997-1998 Indonesian forest and peatland fires were one of the largest peak emissions events in the recorded history of fires in equatorial Southeast Asia, releasing more than 870 million tons of carbon to the atmosphere, which was equivalent to 14% of the average global annual fossil fuel emissions released during the 1990s. These emissions represent a serious perturbation in terms of forcing from trace gases and aerosols on regional and global climate. The scale of emissions is unlikely to reduce in coming decades, since climate modelling studies have predicted that parts of this region will experience lower rainfall in future and greater seasonality.

Forest and peatland fires in Southeast Asia, and the environmental changes that they bring about, have had significant impacts on the atmosphere, the carbon cycle and various ecosystem services, notably conservation of biodiversity. Protecting the rainforests of this region from further fire disasters should be at the top of the global environmental agenda, with highest priority given to peatland areas.

8 Current Fire Regimes, Impacts and the Likely Changes – V: Tropical South America

Mark A. Cochrane

There is consensus that tropical South America will warm substantially over the next century. The biodiversity-rich Amazon forest is a region of growing concern because several global-climate model (GCM) scenarios of climate change forecast reduced precipitation and much higher temperatures in some regions. To date, fires have generally been spatially co-located with road networks and associated human land use because almost all fires in this region are anthropogenic in origin. Climate change, if severe enough, could alter this situation, potentially changing the fire regime to one of increased fire frequency and severity for vast portions of the Amazon forest. High moisture contents and dense canopies have historically made Amazonian forests extremely resistant to fire spread. Climate change will affect the fire situation in the Amazon directly, through changes in temperature and precipitation, and indirectly, through climate-forced changes in vegetation composition and structure. The frequency of drought will be a prime determinant of both how often forest fires occur and how extensive they become. Fire risk management needs to take into account landscape configuration, land cover types, and forest disturbance history as well as climate and weather. Maintaining large blocks of unsettled forest is critical for managing landscape level fire in the Amazon. The Amazon has resisted previous climate changes and should adapt to future climates as well, if landscapes can be managed to maintain natural fire regimes in the majority of forest remnants.

9 Current Fire Regimes, Impacts and the Likely Changes – VI: Euro Mediterranean

José M. Moreno, V. Ramón Vallejo and Emilio Chuvieco

Every year, more than 0.5 million ha of vegetated lands are burned in the countries of Southern Europe, around the Mediterranean, threatening human and natural values: The Mediterranean region is second to the tropics in biodiversity in the world. Mediterranean plant species and ecosystems were selected in a world with fire. But fire regimes were characterized by a long fire cycle (>100 yr). This cycle was accelerated as humans occupied the land and fire became part of the management tools. However, during the second half of the 20th century, as people fled to the cities, unproductive land was abandoned and fuels accumulated, wild-fires became more frequent and widespread throughout the territory, and catastrophic. This process might have been favored in some countries by afforestation with flammable species.

Most fires are caused by people. Fires are extreme phenomena, which means that few, infrequent dangerous weather and climate situations can lead to major fire-disasters. That is so despite the huge efforts made to increase fire-fighting capacity. Multiple very large fire episodes, in which fire-fighting services are overwhelmed, have been occurring in the last years. With time, an additional cause of concern is the increment of ignitions in the proximity of human settlements. Encroachment by vegetation of rural areas and the growth of housing in the wildlands can have disastrous consequences, as attested by some of the most devastating multiple fire episodes, e.g. in Greece in 2007. High population density, even more in summer time, along the costal rim and makes the Mediterranean highly sensitive to fire impacts.

Although Mediterranean ecosystems can be considered to have evolved under fire, the current fire regime is different from what it might have been in the past. Changes in fire regime, such as increased frequency and severity of fires, threatens ecosystem stability and their provision of services through degradation loops that impedes the recovery of the vegetation towards more mature stages. In addition, long-term over-exploitation of Mediterranean ecosystems during millennia makes them more sensitive to fire impacts.

Future land-use and land-cover is very likely to continue as a result of climate change and additional socioeconomic changes, thus adding more land to that already existing in a state of abandonment, with the corresponding consequences of worsening fire hazard. Future climate scenarios project increases in temperature that are higher than the global mean, plus decreases in rainfall. Additionally, and increase in the frequency and intensity of droughts and heat waves is anticipated. This is very likely to increase fire risk in most areas, as well as the frequency of extreme situations, thus affecting the probability of fire, in particular of large fires. Regeneration under such conditions can be slower or impeded, hence contributing to the degradation of these lands.

Managing Mediterranean areas that are the result of human transformation for thousands of years is a challenge, much more so under the evolving conditions of climate and other global change drivers. Maintaining its natural values, including their cultural landscapes, is a daunting task. Preparedness to cope with increased fire risk is a major challenge for Mediterranean societies in the short-term.

10 Current Fire Regimes, Impacts and the Likely Changes – VII: Australian Fire Regimes under Climate Change: Impacts, Risks and Mitigation

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 and Christopher Lucas

Australia is the most fire prone of all continents. Climate change will affect fire regimes in Australia through the effects of changes to temperature, rainfall, humidity, wind – the fire weather components – and through the effects of increases in atmospheric CO_2, and changes in moisture, on vegetation, and therefore fuels.

Examination of weather data from south-eastern Australia over the period 1973-2007 has indicated that fire danger (as measured by the annual sum of the Forest Fire Danger Index, ΣFFDI) rose by 10-40% at many sites from 2001-2007 relative to 1980-2000. Increases in ΣFFDI have also been detected in some other parts of Australia. Climate change projections are for warming and drying over much of Australia, and hence an increased risk of severe fire weather, especially in south-eastern Australia. Modelling suggests an increase of 5 to 65 per cent in the incidence of extreme fire danger days by 2020 in this region. Climate change will have complex effects on fuels. On one hand, elevated CO_2 may enhance vegetation production and thereby increase fuel loads. On the other hand, drought may decrease long-term vegetation production (thereby decreasing fuel loads) and may decrease fuel moisture (thereby increasing potential rates of spread). The outcomes of these process on fuels, and hence fire regimes, are highly uncertain, and require further research.

Regional fire regimes differ across the country because of variation in key drivers such as fuel accumulation and drying, fire weather an ignitions. Climate change can be expected to affect fire regimes more in regions where the constraining factor(s) are fire weather related (e.g., temperate forests of the south-east), than in places where the fire regimes are determined more by fuel or ignition than fire weather (e.g. tropical savannas of the north). Future fire regimes will also be affected by other agents of change, such as invasions of exotic species. Simulation modeling of climate change impacts on the fire regimes for the Australian capital territory of Australia indicated that a 2°C increase in mean annual temperature increased the landscape measure of fire intensity by 25%, increased area burnt, and reduced intervals between fires caused by lightning.

Managing fire regimes to reduce risk to property, people and biodiversity under scenarios of global change will be increasingly challenging. In Australia, management has variously emphasized fire detection and suppression, fuel management, with a strong focus on community awareness and safety. There needs to be an enhanced research effort on the complex interactions between fire, biodiversity, people, fuel management and land-use change, to help meet these challenges.

11 Current Fire Regimes, Impacts and the Likely Changes – VIII: Temperate-Mediterranean North America

Max A. Moritz, Meg A. Krawchuk and Jon E. Keeley

One of the biggest challenges in addressing fire-related issues is an over-simplified understanding of fire's natural role in most terrestrial ecosystems. Our focus in this chapter is on recent and projected trends in temperate-Mediterranean (T-M) North American forest and shrubland ecosystems in the western portion of North America. A particular emphasis is placed on areas where humans may be most vulnerable to climate change effects on fire regimes, particularly in the more densely populated western U.S. coastal regions.

Management of fire-prone ecosystems requires the somewhat complex idea of a fire regime – the range of frequencies, sizes, intensities, and timing of wildfires – be considered with respect to the species or vegetation type in question. A one-size-fits-all conception of wildfire and how humans have altered this natural disturbance is inadequate. For example, suppression of fires has altered the vegetation composition in many T-M forests, leading to fuel accumulation and higher fire severities in recent decades; however, this is most relevant and ecologically damaging in those ecosystems where predictable, frequent, low-severity fires were prehistorically common. In contrast, in shrubland-dominated ecosystems of T-M North America, especially the vast expanses found in southwestern California, large and high-intensity shrubland fires have not shown an increasing trend since fire suppression became effective.

Although climate change is likely to alter future fire regimes in many T-M ecosystems of North America, it is not clear how much change to expect. Fire regimes are driven by different variables in different locations and in ecosystems with different fuel structures. More area may burn in western forests with warmer springs and earlier snowmelt, while larger shrubland fires are associated with drier springs and longer droughts. Modeling future wildfire scenarios is instructive, however models are not yet as ecologically meaningful as we need them to be. One of the limitations of these models is that they often do not adequately consider the impacts of changes in fire frequency on fuel structure and subsequent fire intensity. For example, southwestern California historically has experienced a greatly increased fire frequency due to human ignitions and this has had the net effect of type converting shrublands to grasslands with the resulting decrease in potential fire intensity.

Fire is often viewed in a negative light, despite being an integral ecosystem process in many T-M ecosystems of North America. However, wildfire and carbon fluxes in naturally fire-prone regions may be roughly in net steady state over longer timescales, as amounts of carbon fixed approximately equal the amounts released in fires, with the exception of a small percentage sequestered in each fire as black carbon. Well-intentioned, emissions reductions efforts involving wildfire are thus somewhat incomplete and disconnected with ecosystem management goals that affect many public goods and ecosystem services.

While there have been some novel ideas about how to manage western forests in the face of climate change, a different approach may be needed for shrubland-dominated wildland-urban interface (WUI) areas. Many of these shrubland T-M ecosystems are exposed to extreme fire weather events, during which most fire management activities are relatively ineffective. The safest strategy is to avoid building in vulnerable environments in the first place, but there are many existing communities where adapting will be complex and involve a variety of tradeoffs. Adaptation to future climates will require changes in how and where we live, as well as ways to accommodate fire-related effects on key resources and amenities.

12 Current Fire Regimes, Impacts and the Likely Changes – IX: Subsahara Africa

Winston S.W. Trollope and Cornelis de Ronde

Fire is recognized as a natural ecological factor of the environment in Africa that has been occurring since evolutionary time scales in the savanna and grassland areas of the continent. The continent of Africa is highly prone to lightning storms and has a fire climate comprising dry and wet periods causing the regular occurrence of fire on the continent. It also has the most extensive area of tropical savanna in the world which is characterized by abundant grass fuel that becomes extremely inflammable during the dry season. The use of fire in the management of vegetation for both domestic livestock systems and in wildlife management is widely recognized. A research program was initiated in South Africa and later extended to East Africa to characterize the behavior of fires burning in savanna and grassland vegetation and determine the effect of type and intensity of fire on the vegetation. This research program successfully developed a greater understanding into the effects of type and intensity of fire in African grasslands and savannas. This in turn has led to the development of more effective and practical guidelines for the fire regimes to be used in controlled burning for domestic livestock and wildlife management systems in the grassland and savanna areas of Africa.

The fynbos vegetation only covers a small portion of the Cape regions of South Africa and have a unique requirement of fire to maintain biodiversity. While prescribed burning has been applied during earlier decades, the vegetation is now generally allowed to grow too old, and is subsequently exposed to a growing number of extremely damaging high-intensity wildfires, which now not only threatens its biodiversity, but also surrounding agricultural lands and industrial timber plantations. Re-introduction of prescribed burning in fynbos is now seriously reconsidered, and in places re-applied.

Industrial plantations have been established in Southern Africa within (mainly) montane and savanna grassland biomes since the late 1800s. Exclusion of fire from these plantations has resulted in an exponential increase in plantations lost by wildfires, and to counteract this, prescribed burning has now been introduced inside even-aged pine stands in these regions at a significant scale.

13 Magnitude and Impacts of Vegetation Fire Emissions on the Atmosphere

Meinrat O. Andreae

From its beginnings, the human species has evolved in the presence of air pollution from biomass burning. Fires ignited by lightning were always present in the African savanna, the cradle of our species. Once we learned to tame fire, we were surrounded by its emissions both outside and inside our dwellings. Biomass smoke remains one of the globally most important air pollutants, rivaling or exceeding for many compounds the emissions from fossil fuel burning.

Biomass smoke affects air quality and climate. The emission of volatile organic compounds (VOC), carbon monoxide (CO), and nitrogen oxides (NO_X) constitutes the precursor mixture for the formation of photochemical smog, leading to production of ozone (O_3) and other oxidants and irritants, which together with the smoke particles adversely affect human health and plant productivity.

Vegetation fires including natural and human-caused wildfires, traditional land-use fires including slash-and-burn agriculture and agricultural maintenance and pasture burning, advanced, science-based prescribed fires, fire used as tool in land-use change, biofuel use, charcoal production, and charcoal combustion release about two-thirds as much CO_2 as fossil fuel combustion, some of which is taken up into the biosphere when plants re-grow. For two other greenhouse gases, methane and nitrous oxide, pyrogenic emissions are very significant as well. In the case of methane, vegetation fires emit much more than fossil fuel burning. The pyrogenic sources of N_2O far exceed those from fossil fuel combustion, and rival the sum of all industrial emissions. This makes biomass burning a globally important source of greenhouse gases.

Smoke particles have influence the Earth's climate and hydrological cycles in ways that are still inadequately understood. Smoke particles absorb sunlight, warm the atmosphere, and reduce the evaporation of water from oceans and land. They also scatter sunlight back into space, which results in a surface cooling. Biomass smoke can also change the properties of clouds, including their ability to produce rain. The enhanced aerosol concentration leads to increased numbers, but smaller size, of cloud droplets. This suppresses the early formation of rainfall from convective clouds, but can lead to an invigoration of convection and precipitation by enhanced formation of ice particles in later stages of cloud development. Given the uneven distribution of smoke aerosols in space and time, we must expect substantial regional and global impacts on climate and water availability. In particular, they are likely to change monsoon circulations in critical regions, such as the Amazon and South Asia.

To assess the atmospheric impact of biomass burning, and especially to represent it quantitatively in models of atmospheric transport and chemistry, accurate data on the emission of trace gases and aerosols from biomass fires are required. Considerable progress has been made over the last decade with regard to the determination of emission factors from biomass burning, but many open questions remain. An essential task will be the development of dynamic emission models that are able to forecast emissions based on fuel type and properties, meteorology, topography, etc. The agreement between the results from inverse models and the inventory-based emission estimates is encouraging, but more rigorous constraints of emission estimates could come from regional experiments designed to test the agreement between emission inventories and transport and chemistry models.

14 Modelling Vegetation Fires and Fire Emissions

Allan Spessa, Guido van der Werf, Kirsten Thonicke, Jose Gomez Dans, Veiko Lehsten, Rosie Fisher and Matthew Forres

Fire is the most important ecological and forest disturbance agent worldwide, is a major way by which carbon is transferred from the land to the atmosphere, and is globally a significant source of greenhouse gases and aerosols. Wildfires across all major biome types globally consume about 5% of net annual terrestrial primary production per annum, and release about 2-4 Pg C per annum, of which approximately 0.6 Pg C comes from tropical deforestation and below-ground peat fires. The global figure is equivalent to about 20-30% of global emissions from fossil fuels. Tropical savannas comprise the largest areas burned and greatest emissions sources from vegetation wildfires. Fires in Mediterranean forests and shrublands, tropical forests and boreal forests are also significant sources of emissions because they are generally characterized by much higher fuel loads per unit area compared with grasslands.

Improved satellite data and sophisticated biogeochemical modeling enables emissions assessments on a global scale with fine spatial and temporal resolution. Emissions estimates are still comparable to those based on older inventory-based techniques, but uncertainties remain large. Fires increase during El Niño periods because parts of the tropics where humans use fire as a tool for deforestation experience drought conditions. These spikes contribute to the inter-annual variability of CO_2 and CH_4 observed in the atmosphere.

Future prediction of burnt area and emissions from wildfires requires a process-based understanding of the three main pre-cursors to fire *viz*: an ignition source, ample fuel, and suitably dry fuel. Prognostic fire models, embedded in process-based vegetation models, can in principle simulate the effects of changes in climate and vegetation dynamics on fire activity and emissions. This capability is fundamental to quantifying and assessing how fire and fire-related emissions might change with changing climate conditions, vegetation and land use patterns in future. Similar work cannot be achieved by relying empirical fire danger indexes because they tell us only about the risk of fire.

Recently developed dynamic fire-vegetation models are capable of simulating the extent of wildfires as well as their emissions of CO_2 and other greenhouse gases for ambient as well as for projected climatic conditions. The performance of fire-vegetation models however needs to be strongly improved and validated by field studies investigating the processes leading to emissions as well as by remotely sensed approaches linking recent climate with vegetation, fires and burned areas as well as by socio-geographic studies.

Wildfires in their effect as well as in their origin can have a high socio-geographic component. Most wildfires are ignited by humans. Lightning-caused fires can be important in western U.S.A., Canada, northern boreal Eurasia, and in tropical savannas during the dry-wet season transition. Future improvements to fire-vegetation models should focus on a more explicit consideration of the following: human- and lightning-caused ignitions; fire spread through heterogeneous landscapes; fire-induced tree mortality; fire-induced ecological succession; stand-replacement fires vs. recurrent fires in fire-adapted or -dependant ecosystems; bio-climatically sensitive emission factors; and peat fires – a mounting problem in Indonesia and the boreal zone.

15 Modelling Future Wildland Fire in the Circumboreal

Mike Flannigan, Lynn Gowman, Mike Wotton, Meg Krawchuk, William de Groot and Brian Stocks

Wildland fire is a key process influencing the structure and function of the circumboreal forest which covers 1.2 billion ha in northern Eurasia and North America. Fire activity in the circumboreal responds dynamically to the weather/climate, fuels, and people. Recently, our climate has been warming as a result of increases of radiatively active gases (carbon dioxide, methane etc.) in the atmosphere from human activities. Such warming is likely to have a rapid and profound impact on fire activity, as will potential changes in precipitation, atmospheric moisture, wind, and cloudiness. Vegetation patterns, and thus fuels for fire, will change in the future due to both direct effects of climate change and indirectly as a result of changing fire regimes.

Overall, we expect that fire activity will continue to increase due to climate change. It appears that fire weather, area burned, and fire occurrence are generally increasing, but there will be regions with no change and regions with decreases in the circumboreal forest. Some of the increases in area burned are expected to be significant with increases of 6 times the observed area burned by the end of this century. The length of the fire season appears to be increasing already and should continue to lengthen in the future. Fire intensity and severity are more difficult to summarize and this is an area in need of further research. There could be surprises in the future, perhaps even the near future, with respect to fire activity and this is due to our limited understanding of the interactions between weather/climate, fuels, and people.

The role of people in global fire regimes needs much more work as policy, practices, and behavior vary across the circumboreal and with time. The more physical aspects of wildland fire have received greater attention by the research community but there are still areas that need further work including global studies that dynamically model weather, vegetation, people, fire, and other disturbances. Humans will continue to be a crucial element of fire activity in the future through fire management, human-caused fire ignitions, and land-use. In the future, changes in weather/climate, fuels, and people and the non-linear, complex and sometimes poorly understood interactions among these factors will determine fire activity. Lastly, we require accurate data sets of fire activity. The advent of satellite sensors appropriate to monitor wildland fire has been a significant advance in terms of area burned but even those data provide a wide range of estimates, and we still do not have an accurate estimate of circumboreal fire occurrence.

16 Social Dimensions of Fire

Stephen J. Pyne

People have used fire in every setting to improve their lives. They have adapted fire for homes, buildings, factories, fields, pastures, and public wildlands. Whatever they could enhance by fire they did. They have also used fire destructively as arson, warfare, and accident.

There are regular patterns to human fire practices, both geographically and historically. These remain understudied, however, for fire lacks an intellectual discipline of its own and exists as a subset of other fields. Still, there are typical patterns associated with aboriginal economies, agricultural (and pastoral) economies, and industrial economies. The latter is prime driver of fire dynamics on Earth today, as the planet divides into two grand combustion realms, one fed by surface fuels and the other by fossil fuels. The link between the various expressions of fire remains humanity.

17 The Economic Dimension of Wildland Fires

Armando González-Cabán

The economic relevance of wildland fire management and protection programs is ever growing, particularly considering mounting wildfire costs and losses globally, and the justifications required for budget allocations to management and protection of forest ecosystems. However, there are major difficulties in grappling with the problem of rapidly increasing wildland fire management costs. For example, in the U.S., the U.S. Department of Agriculture Forest Service from 1997-2008 has spent more than $US11.5 billion on fire suppression alone, on wildfires affecting more than 26 million ha of land. It is important to keep in mind that inclusion of the expenditures for the other four federal agencies with fire protection responsibilities and the expenditures of all other states with wildland fires could possibly put the figure in the realm of hundreds of billions.

Canada spends an average of between $US531 million annually on fire suppression, prevention, and prescribed burning alone. Mexico and the Central America region are also suffering tremendous losses to forest fires. For example, during 1998 more than 7.7 million ha of forest and agricultural were affected. Recent estimates of the area affected annually in the combined Caribbean and Central American regions were estimated at 1.1223 million ha. Unfortunately, fire suppression expenditures information is not readily available in many of the Central America and Caribbean region countries.

In the South American continent, during the 1990s Brazil, Argentina, and Bolivia had wildfires that burned annually an average of 1.03, 1.5 and 0.92 million hectares respectively of forest lands. These three countries alone account for about 88 percent of the total annual area burned in the decade. Suppression expenditures and financial losses due to wildfires in the South American region are difficult to obtain. However, some estimates of the financial losses of forest fires in South America go as high as $US1.6 billion annually in the 1990s. The most recent estimates place the number of fires and area affected annually in all South America at 278,460 and 21.276 million ha respectively.

Every year, on average, Europe experiences 45,000 forest fires, burning approximately half million hectares of forest and woodlands. Between 1989 and 1993 close to 2.6 million ha of land were burned. 2003 was a particularly significant year for Europe. More than 450,000 ha of forests and other lands were affected by wildfires in Portugal; France saw an increase in area burned of more than 30 percent from the previous decade; and the Russian Federation was affected by wildfires burning 23.7 million ha of forest and non-forest lands, an area about the size of the United Kingdom. Considering that the export value of forest products from global boreal forests is close to 47% of the world total the economic impact of fires in the boreal forests could be enormous, although not yet quantified.

During 2007 Greece experience significant forest fires that affected more than 270,000 ha of forests and other lands, burned more than 3000 homes and killed more than 78 people. Italy also experienced significant fires affecting almost 230,000 ha of forest lands.

The five most southern countries of the European Union during the period from 2000 to 2007 suffered on average 60,000 fires affecting 476,000 ha of forest lands. Unfortunately, there is not yet an estimate of the suppression expenditures or the economic impact of those fires in the individual countries and the Mediterranean basin region. In 2009 Australia experienced large wildfires affecting more than 430,000 ha, wiping out complete towns, killing 173 persons, destroying over 2000 homes, leaving more than 7,500 people homeless and creating havoc in the local economies. Recent estimates place the cost of bushfires to Australia at $US6,625 ($AUD8,500) million. No country is exempted from wildfires impact. For example, the economic impact of the Indonesian fires and haze of 1997 has been estimated conservatively at about $US4.5 billion to the economies of Indonesia, Malaysia, and Singapore.

Worldwide it is estimated that approximately 350 million hectares of land (forest and non forest) are burned annually. This is equivalent to burning the area of the Indian subcontinent every year! An individual country response approach is no longer the solution. Yet, we are still struggling with the problem of lack of good statistical data on suppression expenditures and economic impact of wildfires in the majority of the countries of the world. Not enough is being done to develop a better system of collecting economic data uniformly.

18 Vegetation Fire Smoke Emissions and Human Health

Milt Statheropoulos, Sofia Karma and Johann Georg Goldammer

Air pollution generated by vegetation fire smoke (VFS) is a phenomenon that has influenced the global environment in prehistoric and historic time scales. Although historic evidence of the impacts of VFS on societies is scarce, there are indications that VFS has been a factor that influenced society significantly since the Middle Ages. In recent decades, increasing application of fire as a tool for land-use change has resulted in more frequent occurrence of extended fire and smoke episodes with consequences on human health, and security. Some of these events have been associated with droughts that are attributed to inter-annual climate variability or possible consequences of regional climate change. In metropolitan or industrial areas, the impacts of VFS may be coupled with the emission burden from fossil fuel burning and other technogenic sources, resulting in increasing adverse affects on the human population.

Strategic considerations to cope with the vulnerability of humans to fire smoke emissions include the following:

- Quantification of resulting concentrations of ambient air pollutants in populated areas
- Evaluation of likely exposure scenarios for affected populations (both indoors and outdoors)
- Assessment of consequent health risks posed by such human exposures

- Special attention to fire-generated radioactive emissions
- Physical/chemical factors contributing to the changes that occur over time and space during VFS transport

Exposure and vulnerability of humans to fire emissions, however, is a subject that needs more information on options for limiting smoke impacts on human health and security. A number of recent vegetation fire smoke pollution episodes have caused public concerns and alerted policy makers. Some responses, such as calls or laws for eliminating the use of fire in land management, have resulted in conflicts, contradicting effects, or are difficult – if not impossible – to enforce. Besides the implications of fire bans on potentially uncontrolled fires and smoke production, it must be reminded that fire exclusion from fire-adapted or fire-dependent ecosystems, which require a regular influence of fire, can also result in dramatic changes of structure, biodiversity, stability, and productivity of such ecosystems. Therefore, a complete exclusion of fire from land-use systems would affect livelihoods of hundreds of millions of people worldwide.

The consequences of fire burning on radioactively contaminated lands and its consequences on redistribution of radioactive particles lifted by fire smoke is another serious issue that needs to be addressed. These examples reveal the transboundary and international nature of vegetation fire smoke emissions that can cause many problems, in an increasingly vulnerable global society. These problems have to be addressed cooperatively and collectively. Consequently, bilateral and multilateral agreements or protocols are necessary to address these issues.

19 Effects of Increasing Atmospheric CO_2 on Flammable Ecosystems

William J. Bond and Guy F. Midgley

Increasing CO_2 in the atmosphere can influence vegetation directly by increasing photosynthetic rates and by reducing plant water use because plants transpire less. These CO_2 fertilization effects are greatest where other plant growth requirements, especially light and nutrients, are well supplied. Where they are not, as in mature forests, plants will be less responsive to increasing CO_2 since shade inhibits photosynthesis. Burnt forest and shrublands in the early recovery stages may be most responsive because they are well lit and fertilized by ash. Rapid regrowth rates (under elevated CO_2) are likely to favour plants that have 'sinks', where they can use the extra carbon, such as swollen roots that store starch promoting resprouting after fire.

CO_2 fertilization should promote rapid post-burn recovery of burnt shrublands and forests. However faster fuel build-up in crown-fire regimes is unlikely to alter the frequency and intensity of fires as much as extreme weather conditions linked to global warming. The impacts are likely to be much larger in the surface (grass-fuelled) fire regimes of savannas. Savannas are mixtures of grassland and trees which occupy vast areas of the tropics and sub-tropics. They burn so frequently that savannas account for by far the largest global burnt area. Increasing CO_2 may change this in future by promoting woody plants with feedbacks to vegetation type and fire activity. Under elevated CO_2, tree seedlings and saplings can recharge root starch reserves more rapidly than ever before and saplings may grow fast enough to escape the flame zone and reach fire-proof tree sizes more frequently than ever before. Savannas often occur adjacent to tropical forests and fires sometimes spread into the forests under extreme weather conditions. If such conditions increase under global warming, then forests will shrink at the expense of the grasses. However increasing CO_2 may cause the reverse trend with forests expanding at the expense of savannas. Both trends have been observed, on a local scale, in diverse geographic regions. There is still much debate as to whether woody increase is due to increased CO_2 and other global drivers or to land use change or to their interactions.

A separate CO_2 related effect is likely to cause additional major disruption of grasses in tropical and sub-topical savannas (~20 % of the world's vegetated surface). Grasses that currently dominate these regions have a distinct type of photosynthesis that performs best under warm growing conditions and low atmospheric CO_2. But the climatic conditions under which these grasses outperform 'temperate' grasses, with a different photosynthetic pathway, are predicted to disappear at $2\times CO_2$. Whether the grasses will disappear too, and at the same rate, is unlikely but poorly known. The net effect, coupled with CO_2 fertilization of woody plants, is likely to be severe disruption of the vast grassy ecosystems in the warmer parts of the world.

The general tendency to more wooded vegetation under high CO_2 scenarios may, at first sight, seem beneficial. But a full accounting has yet to be made. Grasslands and savannas include wilderness areas hosting some of the last populations of free-roaming large herbivores and pastoral lands which support the livelihood of millions of people. Increase in trees will be accompanied by reduced grass and grass-fuelled fires, changed albedo, hydrology, aerosol content of the atmosphere, NO_X emissions and other disruptions along with increases in above-ground carbon. The net effect on climate change is uncertain and poorly understood.

20 Satellite Monitoring and Inventory of Global Vegetation Fire

Chris Justice, Ivan Csiszar, Luigi Boschetti, Stefania Korontzi, Wilfrid Schroeder, Louis Giglio, Krishna Prasad Vadrevu and David Roy

Fire is conceived as a two-edged sword that greatly influences the ecosystem structure and function. Depending upon the complex effects of fire, it can either have beneficial or harmful effects. Remote sensing technology with its multi-temporal, multispectral, synoptic and repetitive coverage capabilities can provide valuable information on the fire counts, radiative power, the amount of area burned and the type of ecosystem burned. We review the potential benefits of satellite remote sensing for monitoring vegetation fires at a global scale followed by the usefulness of fire products in climate change research. We also highlight some of the international efforts of Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) in fire research and outreach activities.

Remote sensing instruments on-board polar and geostationary satellites are capable of monitoring of vegetation fires at varied spatial scales. Observations from the coarse and medium resolution sensors are complemented by moderate to high spatial resolution narrow-swath sensors in detecting, monitoring as well as validating fire products. Currently, three different fire products are derived from the satellite sensors a). Active fires that can be detected through the elevated thermal radiance signal typical of flaming and smoldering conditions; b). Fire radiative power product based on the measured rate of radiant energy output of detected fires; c). Burned area product derived mostly through measuring changes in surface reflectance before and after the fire from red, near infrared and short-wave infrared channels. We argue that these satellite derived products can provide useful insight to both operational and policy formulation settings for climate change research. More specifically, for programs such as the implementation of Reducing Emissions from Deforestation and Degradation (REDD), satellite fire monitoring could contribute to emissions estimation, detection of fires in fire-exclusion areas, monitoring fire type, identifying illegal forest clearance, etc. Further, satellite data can be useful for generating long-term Essential Climate Variables (ECVs), including fire disturbance. We also stress on the need to validate satellite products at multiple scales and geographical settings. To address the validation issues, an international coordination effort is currently underway through the Land Product Validation (LPV) subgroup of the Committee on Earth Observation Satellites (CEOS), in cooperation with the GOFC-GOLD Fire Implementation Team. The first international protocol for the production of reference (validation dataset) for the coarse resolution continental and global burned area products is being developed by GOFC-Fire implementation team. In addition, GOFC-GOLD fire teams at the University of Maryland, U.S.A., as well as Global Fire Monitoring Center (GFMC), Germany, through their outreach activities have been providing several web-links on satellite derived fire products. Also, the GOFC-GOLD Fire Implementation Team in conjunction with the GFMC is currently planning on a Global Fire Assessment report based on the long term satellite data. Through coordinating with researchers from the regional fire networks and the United Nations International Strategy for Disaster Reduction (UNISDR) activities, the assessment aims to provide detailed information on the fire metrics useful for land managers as well as policy makers. For several years, GFMC as well as GOFC-GOLD have been quite active in serving the broader needs of the fire monitoring community. To provide more robust information to users, we call for an increased international coordination in terms of the satellite observations as well as consistent national reporting of in-situ observations. Such coordinated efforts can aid in understanding the role of fire on ecosystem functions in a much more effective way.

21 The Global Fire Danger and Early Warning System for Wildland Fire

William J. de Groot and Johann Georg Goldammer

Wildland fires burn several hundred million hectares of vegetation every year, and increased fire activity has been reported in many global regions. Many of these fires have had serious negative impacts on human safety, health, regional economies, global climate change, and ecosystems in non-fire-prone biomes. Worldwide fire suppression expenditures are rapidly increasing in an attempt to limit the impact of wildland fires. To mitigate fire-related problems and costs, forest and land management agencies, as well as land owners and communities, require an early warning system to identify critical periods of extreme fire danger in advance of their potential occurrence. Early warning of these conditions allows fire managers to implement fire prevention, detection, and pre-suppression plans before fire problems begin. Fire danger rating is commonly used to provide early warning of the potential for serious wildfires based on daily weather data. Fire danger information is often enhanced with satellite data, such as hot spots for early fire detection, and with spectral data on land cover and fuel conditions. Normally, these systems provide a 4- to 6-hour early warning of the highest fire danger for any particular day that the weather data is supplied. However, by using forecasted weather data, as much as two weeks of early warning can be provided. This short paper presents a proposed global early warning system for wildland fire to provide advanced early warning capabilities at local to global levels. This system will provide 1) new longer term predictions of fire danger based on advanced numerical weather models, 2) a common international metric for implementing international resource sharing agreements during times of fire disaster, and 3) a fire danger rating system for the many countries that do not have the financial or institutional capacity to develop their own system. Because the system can be used at the local level, it can support local capacity-building by providing a foundation for community-based fire management programs.

22 Beyond Climate Change: Wildfires and Human Security in Cultural Landscapes in Transition – Examples from Temperate-Boreal Eurasia

Johann Georg Goldammer

In many regions of Eurasia cultural landscapes that were formed by traditional agrarian societies over centuries are changing rapidly. The process of rural exodus and the rapidly accelerating trend of urbanization is associated with abandonment of land cultivation and thus directly or indirectly affecting cultural and wildland fire regimes. This chapter looked at the specific issues linked with wildland fire, land use and land-use change in Eurasia, and to wildfires and threats emerging from the heritages of civilization. While the temperate-boreal zone of Eurasia is in the focus of this chapter, some views to the cultural landscapes of North America reveal comparability and similarities between continents.

Several recent wildfire episodes in temperate-boreal Eurasia have resulted in severe environmental damages, high economic losses and considerable humanitarian problems. After the Mediterranean fire crisis in 2007, followed by the fire and smoke episode in Western Russia in 2010, several key issues affecting wildland fire in the cultural landscapes of temperate-boreal Eurasia have been identified:

- Increasing rural exodus and urbanization, resulting in abandonment of traditional land cultivation (agriculture, pastoralism, forestry) and thus an increasing wildfire hazard;
- Urbanization resulting in a reduced rural work force, including availability of rural firefighters;
- Re-privatization of formerly nationalized forests resulting in vacuums of forest and fire management in smallholder forest estates;
- Weakened governance over forestry and decreased fire management capabilities in many Eastern European and Central Asian countries as a consequence of the transition of national economies, often associated with the uncontrolled or illegal forest use and increase of related wildfires;
- Increasing occurrence of wildfires affecting the perimeters of metropolitan areas, settlements and developments dispersedly located in wildlands;
- Secondary problems associated with wildfires, e.g., those burning on territories contaminated by radioactivity and remnants from armed conflicts (e.g., unexploded ordnance, land mines, uranium-depleted ammunition); or wildfires affecting agricultural lands treated with pesticides; landfills, other industrial waste and structures containing hazardous materials, especially at the urban / residential perimeters;
- Consequences of climate change on cultural fire regimes and ecosystem vulnerability (e.g., transformation of former fire-excluded or -protected natural ecosystems or land-use systems such as peat bogs, or high-altitude mountain ecosystems, such as the European Alps).

The assessment of changing fire regimes, increasing vulnerability of society and subsequent public policy responses are influenced by new scientific insights in the composition of fire emissions and their impacts on the environment and human health and must address the following considerations:

- Effects of gaseous and particle emissions from fossil fuel, biofuel and other open burning that affect human health hence an increasing vulnerability of society to fire-generated air pollution;
- Impacts of radiatively active trace gases and particle emissions from vegetation fires affecting the functioning of the atmosphere and contributing to climate change;
- Impacts of fire emissions on ecosystems, e.g. the consequences of deposition of fire-emitted black carbon to the arctic environment;

- Resulting conflicts in fire management, e.g., controversial views on the acceptance of prescribed burning.

An increasing awareness of newly arising or newly perceived fire-related problems by the general public and by policy makers is apparent. However, development of fire management solutions such as the adjustments to public policies affecting land management and operational fire management to the changing land use conditions and society's vulnerability are lagging behind.

The recently published *White Paper on Use of Prescribed Fire in Land Management, Nature Conservation and Forestry in Temperate-Boreal Eurasia* is an example for changing perceptions of the role of fire in cultural landscapes. The white paper reveals that the use of fire – including disturbance related to swidden (shifting) agriculture and other land cultivation practices – have contributed to shaping landscape patterns of high ecological and cultural value and diversity across temperate-boreal Eurasia in areas such as heathlands, open grasslands and meadows. In the eastern Euro-Siberian biota, e.g. in the light taiga, natural fires have shaped open and stress-resilient forest ecosystems.

Changing paradigms in ecology and nature conservation have recently led to reconsidering fire-exclusion policies in certain sectors of land / landscape management, nature conservation and forestry. However, the use of prescribed fire in ecosystem management in Europe may not exclusively target those vegetation types that have been shaped by fire over historic time scales, but rather to introduce fire as a tool to substitute abandoned cultivation practices.

A sound understanding of the "pros and cons" of prescribed fire application is as necessary as consideration of side effects of fire use. Large areas threatened by land abandonment are embedded in industrialized regions in which society is becoming increasingly intolerant of fire emissions. The fire and smoke episode in Western Russia in 2010 is a striking example for both increased perception and vulnerability. Legal restrictions for open burning are included in clean-air rules and the obvious general necessity to reduce those gas and particle emissions that are threatening human health (cf. chapter 18 of this volume). Concerns of those parties that consider prescribed fire emissions a contribution to the increase of the anthropogenic *greenhouse effect* and thus global warming complicate the debate. Traditional use of fire in agriculture is being questioned where new insights into the side effects of burning are revealed by recent research. For example, there are indications that deposition of black carbon emitted from agricultural spring fires in Northern Eurasia are impacting the albedo of the Artic environment, leading to acceleration of warming and melting of snow and ice cover. As a symptom of these developments the terms "necessary" and "unnecessary" burning in the agricultural sector in temperate-boreal northern Eurasia are entering the wildland fire terminology.

On the other hand it is noted that nature conservation agencies, non-government actors and the general public have meanwhile developed a rather sound understanding and perception of the "nature of fire" as compared to the situation two to three decades ago. International (regional) dedicated networks and research projects such as the *Eurasian Fire in*

Nature Conservation Network (EFNCN), within which the *White Paper on Use of Prescribed Fire* was developed, and particularly the European Integrated Project *Fire Paradox*, have significantly contributed to the acceptance of fire use in wildfire hazard reduction and fire suppression.

23 International Protocols and Agreements on Cooperation in Wildland Fire Management and Wildfire Disaster Response: Needs, Current Status, and the Way Ahead

Johann Georg Goldammer

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 trans-boundary 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 trans-boundary cooperation, means that the transition from informal information exchange and networking to a more systematic and formalized cooperation is more necessary than ever.

Several international (global) conventions, such as the three "Rio Conventions" (CBD, CCD and 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 no 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.

In preparation for and following the International Wildland Fire Summit of 2003 the international wildland fire community has taken steps to develop preliminary concepts, templates and guidelines with widely agreed principles and best practice in fire management and incident command. Detailed operational standards are now needed to facilitate the exchange of fire fighting resources, including aviation, management personnel, and equipment.

At the level of multilateral bodies, such as the Association of South East Asian Nations (ASEAN), the UN Economic Commission for Europe (UNECE), the Asia-Pacific

Economic Cooperation (APEC), the Council of Europe (European Open Partial Agreement on the Prevention, Protection Against and Organization of Relief in Major Natural and Technological Disasters – EUR-OPA), the European Union (EU), or the Southern African Development Community (SADC), recent developments have revealed an interest of countries to enhance the capabilities of regional, transboundary cooperation in fire management. Experience gained in bilateral (reciprocal) agreements include common usage of the Incident Command System (ICS) – as practiced under agreements between North American countries (U.S.A., Canada and Mexico) and between the U.S.A. and Canada on the one side, and Australia and New Zealand on the other side. These experiences may serve as examples for developing other regional agreements or protocols.

The Global Wildland Fire Network (GWFN) is a voluntary network which evolved in the late 1990s as an initiative of the Global Fire Monitoring Center (GFMC) and the UNECE/FAO Team of Specialists on Forest Fire. The GWFN operates through the GFMC as a "Thematic Platform" under the United Nations International Strategy for Disaster Reduction (UNISDR), and promotes international cooperation in wildland fire management – notably through capacity building in wildfire prevention, preparedness and suppression, and the development of standardized procedures for use in international wildfire incident response. Lead institutions serve as coordinators of Regional Wildland Fire Networks and work with representatives of international organizations mandated or otherwise active in the wildland fire arena. These lead institutions are represented by the UNISDR Wildland Fire Advisory Group (WFAG), which provides advisory services to the UN system.

The application of fire management guidelines developed under the auspices international organizations such as the International Tropical Timber Organization (ITTO) and the Food and Agriculture Organization of the United Nations (FAO) and with major inputs of the members of the regional networks, provide a voluntary basis of common understanding of best practices and solutions in fire management.

In the long-term the GWFN is also aiming at developing an International Wildland Fire Accord (voluntary or binding under international law), which would be based on the rationale that there is a common international interest in protecting of global vegetation cover against degradation or destruction and that common endeavors in fire management will contribute to disaster risk reduction. For example, reduction of the risks associated with direct fire damages to human assets and ecosystems, fire-generated smoke pollution affecting human health and security, release of greenhouse gases, secondary disasters such as landslides, erosion, floods and threats to biodiversity.

24 Summary with Conclusions and Recommendations

While a summary of a global analysis of history, contemporary state-of-science, and the assumed or modeled future of vegetation fires cannot be an exhaustive synthesis of the extremely facet-rich and complex global fire issues, this synopsis focuses on key regions around the world, from tropical to temperate to boreal ecosystems, and is intended to give the reader some insight into the key environmental, economic and societal issues associated with managing fire now and in the immediate future. Some common themes emerge when considering these issues.

Climate change impacts, which are already being observed in some countries, will be variable, but will generally promote more fire activity across all regions. More frequent, severe and larger fires are anticipated, as climate variability is likely to result in more extreme weather events in some regions, particularly heat-related events. However, policy makers and the public are already dealing with a myriad of social and economic issues, and it is difficult to gain their attention with respect to future fire problems.

Current climate change projections of future fire activity are hampered by the relatively coarse spatial and temporal resolution of the general climate models used. Most projections of fire activity are under $2xCO_2$ and $3xCO_2$ scenarios (roughly 2030 AD and 2090 AD), and it is impossible to increase the temporal resolution of these projections with any degree of confidence. However, one common theme is that fire activity and severity will increase substantially by 2020, and much more substantially by 2090 AD, in all regions covered by this report.

In temperate and boreal regions, future fires will impact communities and landscapes even more than at present, and there is a strong need to educate both the public and policy makers that a new accommodation with fire will be required. This in turn will mean reassessing fire suppression policies and encouraging public education on fire prevention, hazard mitigation, and safety. The rising costs of current fire suppression approaches are not sustainable, and are not leading to increased success.

In tropical regions it is difficult to imagine that deforestation practices will be curtailed in the near future, as these are crucial to economic development in countries with more critical problems. Population growth continues unabated in these regions, often making fire a symptom of much larger issues. Tropical and subtropical ecosystems affected by desertification will likely see fewer fires because of lack of vegetation to burn.

In the Mediterranean region, fire risk is likely to increase due to additional land-use change due to less productive areas being abandoned as a result of climate change or further socioeconomic change, particularly in the countries of the southern coast. Changes in lifestyles that expand the wildland-urban interface are also expected to add more risk. Education and awareness can help reduce ignitions, but once these occur, future landscapes and conditions will have greater capacity to spread fire.

Clearly, wildland fire impacts are increasing in most regions around the world. There are many contributing factors, often acting in concert, that will continue to exacerbate this problem in future years. Climate change, constantly expanding wildland-urban interface areas as a consequence of urban exodus, land abandonment due to rural exodus, changing lifestyles and economic development are the most common factors mentioned in this report, but there are many others. Traditional fire management practices are being reassessed in developed countries, while the developing world continues to use widespread fire for social and economic development. However, all countries have one thing in common: with growing populations, industries, infrastructure and disturbance-sensitive technologies, society is becoming more vulnerable to the consequences of vegetation fires, particularly fire smoke pollution. Fire emissions are negatively impacting human health and security, regardless of whether they are resulting from ecologically benign natural fires and sustainable land-use fires, or from unwanted or destructive wildfires. A new accommodation with fire that recognizes and adapts to these rapid changes is required. Promoting wildland fire use where desirable, and controlling wildfires and / or reducing fire use where they are not, will be an evolving and increasingly difficult task in the years ahead. While fire regimes are undergoing changes throughout the continents and vegetation zones, and society becoming increasingly vulnerable to fire and secondary effects of fire, the exchange of knowledge, expertise and resources to address newly arising problems seems to become mandatory. So is also the need to develop national and international policies that envisage to pay respect to the nature and benign effects of fire, and to reduce the threats of destructive wildfires and fire use collectively and cooperatively.





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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 achievement of the world's most renowned scientists and research groups working in fire science, ecology, atmospheric chemistry, remote sensing and climate change modeling. 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. The White Paper provides insight into the complexity of global vegetation fire issues and rationale for coordinated, international action in crossboundary fire management at global scale.

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.

Global Fire Monitoring Center (GFMC)

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