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Vegetation Fires and Global Change
Challenges for Concerted International Action
A White Paper directed to the United Nations and International Organizations

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Abstract – 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 57 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 endeavor 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.

Keywords – *fire ecology, fire management, fire and climate change, global change, integrated wildfire disaster risk management, fire management policies, international cooperation if fire management.*

1. Introduction

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 (Crutzen and Goldamme r, 1993). In the subsequent years wildland fire science and related disciplines experienced rapid acceleration in sectoral and interdisciplinary research projects and programs. 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, 1992; Lindesay et al., 1996).[1]

During the 1980s and 1990s wildfire episodes with severe environmental and humanitarian consequences were increasingly experienced across the world, e.g. in temperate-boreal Central and East Asia (China, Soviet Union) in 1987 (Goldammer, 1993; 2006b), or in South East Asia (Indonesia) between 1983 and 1998 (Goldammer, 2006a) . 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 to-

[1] See also the Special Issue of Journal of Geophysical Research "Southern Tropical Atlantic Regional Experiment (STARE): Transport and Atmospheric Chemistry near the Equator-Atlantic (TRACE-A) and Southern African Fire-Atmosphere Research Initiative (SAFARI) (JGR, 1996) and the BIBEX website: `www.fire.uni-freiburg.de/bibex/Welcome.html`

[2] `www.fire.uni-freiburg.de/intro/team.html` and `www.unece.org/forests/fcp/methodsandprocesses/forestfire.html`

ward 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 International 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, edited by Goldammer (2013), published by the GFMC and summarized within the UK Government's Foresight Project "Migration and Global Environmental Change" (Goldammer and Stocks, 2011) is to support the endeavor 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 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. The aim of this paper is to provide a summary of the main findings and conclusions of the White Paper, allowing scientists and policy makers to access and understand the complex inter-relationships between fire, humans and the Earth system, and to interpret the findings in the context of cross-disciplinary approaches in disaster risk reduction. Ultimately the essence of the White Paper, which had been presented at the 5th International Disaster and Risk Conference IDRC Davos 2014, shall be conveyed to the Third UN World Conference on Disaster Risk Reduction as part of the collective messages of IDRC 2014.

2. 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.

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 'paleo fire' 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. Some estimates have fires affecting between 3 and 4 million square kilometers (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).

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 con-

[3] http://www.fire.uni-freiburg.de

[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

tinents, 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).

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 galvanized during numerous catastrophic wildland-urban interface fire events in the western USA 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.

3. Regional Fire Summaries

3.1. 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. 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 the Nordic Countries. 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. 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 CO2 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).

The development of large and sophisticated fire management programs 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.

3.2. 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 and the most disastrous fire season of 2012.

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).

3.3. Fires in the Mediterranean Region

On average 50000 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 (Silva et al., 2010), fire policies in this region still advocate total fire exclusion, with fires being attacked and suppressed as quickly as possible. Firefighting capacity is extensive and costly, with expenditures in prevention and suppression amounting to more than €2.5 billion annually. Despite these capabilities, fire impacts in this region are among the most severe in the world.

Human use of fire in this region dates back 400000 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). 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 firefighting capacity.

3.4. Fires in Australia

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 firefighting 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 2500 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 2000 homes and burned over 430000 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 indicate that public scrutiny of, and involvement in, fire management policy is increasing (ICLR, 2009; Royal Bushfire Commission, 2010).

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).

3.5. Fires in the United States

Organized fire protection in the USA 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 USA 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 USA (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 (>20000 ha) across the western USA. Fire costs are also continuing to rise dramatically (with federal agency costs averaging $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, 3500 homes destroyed and property losses of $3.5 billion in 2003) (González-Cabán, 2008). During the 1997-2008 period federal suppression costs totaled more than $13.1 billion (González-Cabán, 2008) with the number of fire exceeding $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 USA, 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).

The fire historian Pyne (2010) 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.

3.6. 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 re-burn 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 30-40000 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 Niño 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.

3.7. 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). 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 behavior 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 localized 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.'

3.8. *Fires in Sub-Saharan Africa*

In sub-Saharan Africa 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 numbers 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, but offer an opportunity to use prescribed fire for fuel and wildfire hazard reduction (Goldammer and de Ronde, 2004).

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 the abandonment of traditional, sustainable land-use practices and the loss of rural labor force as a consequence of 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 programs have begun to focus on fire prevention and preparedness, rather than direct fire suppression capacity. Community-based fire management programs, 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.

4. Wildland Fire Science and Policy

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 programs 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, 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 globalization, and climate variability. Thus, integrated strategies and programs 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.

What are the implications of these conclusions on fire science? The above-mentioned first major interdisciplinary and international research programs conducted in the early 1990s, including the inter-continental fire-atmosphere research campaigns such as the Southern Tropical Atlantic Regional Experiment (STARE) with the Southern Africa Fire-Atmosphere Research Initiative (SAFARI) (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 hydrometeorological 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 are 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 of the White Paper 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 democratized, 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 kinds 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 has 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 interdisciplinary 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, people, and ecology. Continued research prioritizing fire fundamentals, fascinating as it is, cannot address these matters.

5. Conclusions

The contribution of global wildland fire science and management community 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 Ramsar Convention on Wetlands or the *Hyogo Framework for Action [HFA] 2005-2015: Building the Resilience of Nations and Communities to Disasters.*

In 2013 the *UNECE/FAO Forum on Crossboundary Fire Management* provided rationale and recommendations to enhancing informal processes of cooperation in fire management toward the development of an international regime of coordinated wildfire preparedness and response.[8] The International Wildfire Preparedness Mechanism (IWPM), hosted by the Global Fire Monitoring Center (GFMC) since 2014, is a non-financial instrument serving as a broker / facilitator between national and international agencies, programmes and projects to exchange expertise and build capacities in wildland fire management and particularly in enhancing preparedness to large wildfire emergency situations.[9]

The Post-2015 HFA offers a suitable opportunity to address global fire at a cross-sectoral approach.

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[8] http://www.fire.uni-freiburg.de/intro/team.html
[9] http://www.fire.uni-freiburg.de/IWPM/

References

Note: The main reference for this paper, including the 25 chapters authored by the 57 contributing authors, is Goldammer (2013).

Abram, N.J., Gagan, M.K., Liu, Z., Hantoro, W.S., McCulloch, M.T., Suwargadi, B.W. (2007): Seasonal characteristics of the Indian Ocean Dipole during the Holocene epoch, Nature, 445: 299-302.

Achard, F., Eva, H.D., Stibig, H.J., Mayaux, P., Gallego, J., Richards, T., Malingreau, J.P. (2002): Determination of deforestation rates of the world's humid tropical forests, Science, 297: 999-1002.

Alencar, A., Nepstad, D.C., Diaz, M.C.V. (2006): Forest understory fire in the Brazilian Amazon in ENSO and non-ENSO years: area burned and Committed carbon emissions, Earth Interactions, 10: 1-17.

Andreae, M.O. (ed.) (1992): Biomass Burning Experiment: Impact of Fire on the Atmosphere and Biosphere (BIBEX). Activity 2.3 of Focus 2 "Natural Variability and Anthropogenic Perturbations of the Tropical Atmospheric Chemistry. IGAC Core Project Office, Massachusetts Institute for Technology, Cambridge, MA, 19 p. + App. Accessible online: http://www.fire.uni-freiburg.de/bibex/BIBEX-Brochure-1992.pdf.

Andreae, M.O., Merlet, P. (2001): Emission of trace gases and aerosols from biomass burning, Global Biogeochemical Cycles, 15: 955-966.

Andreae, M.O., Rosenfeld, D., Artaxo, P., Costa, A.A., Frank, G.P., Longo, K.M., Silva-Dias, M.A.F. (2004): Smoking rain clouds over the Amazon, Science, 303: 1337-1342.

Bachelet, D., Lenihan, J., Neilson, R., Drapek, R., Kittel, T. (2005): Simulating the response of natural ecosystems and their fire regimes to climatic variability in Alaska, Canadian Journal of Forest Research, 35: 2244-2257.

Balch, J.K., Nepstad, D.C., Brando, P.M., Curran, L.M., Portela, O., de Carvalho, O., Lefebvre, P. (2008): Negative fire feedback in a transitional forest of southeastern Amazonia, Global Change Biology, 14: 2276-2287.

Barbosa, P.M., Stroppiana, D., Gregoire, J.M., Pereira, J.M.C. (1999): An assessment of vegetation fire in Africa (1981–1991): burned areas, burned biomass, and atmospheric emissions, Global Biogeochemical Cycles, 13: 933-950.

BBC (2011): Brazil: Amazon rainforest deforestation rises sharply. deforestation of the Brazilian Amazon rainforest has increased almost sixfold, new data suggests. British Broadcasting Corporation News Latin America and Caribbean, http://www.bbc.co.uk/news/world-latin-america-13449792.

Bowman, D.M.J.S., Balch, J.K., Artaxo, P., et al. (2009): Fire in the earth system, Science, 324: 481-484.

Broadbent, E.N., Asner, G.P., Keller, G.P., Knapp, D.E., Oliveira, P., Silva, J.N. (2008): Forest fragmentation and edge effects from deforestation and selective logging in the Brazilian Amazon, Biological Conservation, 141: 1745-1757.

Campbell, B.M. (2009) Beyond Copenhagen: REDD+, agriculture, adaptation strategies and poverty, Global Environmental Change, 19, 397-399.

Cardoso, M.F., Hurtt, G.C., Moore, B., Nobre, C.A., Prins, E.M. (2003): Projecting future fire activity in Amazonia, Global Change Biology 9: 656-669.

CCFM (2005): Canadian wildland fire strategy: a vision for an innovative and integrated approach to managing the risks. Canadian Council of Forest Ministers, Catalogue No. Fo134-1/2005E. ISBN 0-662-42194-9.

Chuvieco, E., Giglio, L., Justice, C. (2008): Global characterization of fire activity toward defining fire regimes from Earth observation data, Global Change Biology, 14: 1488-1502.

Cochrane, M.A., Alencar, A., Schulze, M.D., Souza, Jr. C.M., Nepstad, D.C., Lefebvre, P., Davidson, E. (1999): Positive feedbacks in the fire dynamic of closed canopy tropical forests, Science, 284: 1832-1835.

Cochrane, M.A. (2001): Synergistic interactions between habitat fragmentation and fire in evergreen tropical forests, Conservation Biology 15: 1515-1521.

Cochrane, M.A. (2003): Fire science for rainforests, Nature, 421: 913-919.

Cochrane, M.A., Laurance, W.F. (2008): Synergisms among fire, land use, and climate change in the Amazon, Ambio 37: 522-527.

Crutzen, P.J., Andreae, M.O. (1990): Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles, Science, 250: 1669-1678.

Crutzen, P.J., and J.G. Goldammer (eds.) (1993): Fire in the environment: The ecological, atmospheric, and climatic importance of vegetation fires. Dahlem Workshop Reports. Environmental Sciences Research Report 13. John Wiley & Sons, Chichester.

Dai, A. (2011): Drought under global warming: a review, Climate Change, 2: 45-65.

European Commission (2010): Forest Fires in Europe 2009. JRC Scientific and Technical Report No. 10. EC Joint Research Centre, Institute for Environment and Sustainability.

Flannigan, M.D., Amiro, B.D., Logan K.A., Stocks, B.J., Wotton, B. (2005): Forest fires and climate change in the 21st Century, Mitigation and Adaptation Strategies for Climate Change, 11: 847-859.

Flannigan, M.D., Stocks, B.J., Turetsky, M.R., Wotton, B.M. (2009a): Impact of climate change on fire activity and fire management in the circumboreal forest, Global Change Biology, 15: 549-560.

Flannigan, M.D., Krawchuk, M.A., de Groot, W.J., Wotton, B.M., Gowman, L.M. (2009b): Implications of changing climate for global wildland fire, International Journal of Wildland Fire, 18: 483-507.

FAO (2006): Global Forest Resources Assessment 2005. Progress towards sustainable forest management. Food and Agriculture Organization of the United Nations Forestry Paper 147. Rome: FAO.

Geist, H.J., Lambin, E.F. (2002): Proximate causes and underlying driving forces of tropical deforestation, BioScience, 52: 143-150.

Goldammer, J.G. (1993): Feuer in Waldökosystemen der Tropen und Subtropen, Basel: Birkhäuser-Verlag.

Goldammer, J.G. (1999): Forests on fire, Science, 284: 1782-1783.

Goldammer, J.G. (2006a): History of equatorial vegetation fires and fire research in Southeast Asia before the 1997-98 episode. A Reconstruction of creeping environmental changes, Mitigation and Adaptation Strategies for Global Change, 12: 13-32.

Goldammer, J.G. (2006b): Global Forest Resources Assessment 2005 – Report on Fires in the Central Asian Region and Adjacent Countries. Fire Management Working Papers, Working Paper FM/16/E, Rome: Food and Agriculture Organization of the United Nations, Forestry Department.

Goldammer, J.G. (2010): Preliminary assessment of the fire situation in Western Russia. Analysis of 15 August 2010, presented at the State Duma, Moscow, 23 September 2010, International Forest Fire News, No. 40: 20-42.

Goldammer, J.G. (2011): Wildland fires and human security: challenges for fire management in the 21st century, in: Proceedings of the International Forest Fire Symposium Commemorating the International Year of Forests 2011, Sol Beachm Gangwon-do, Republic of Korea, 7-8 June 2011, Seoul: Korea Forest Research Institute.

Goldammer, J.G. (ed.) (2013): Vegetation Fires and Global Change. Challenges for Concerted International Action. A White Paper directed to the United Nations and International Organizations, Remagen-Oberwinter: Kessel Publishing House. Online version: `http://www.fire.uni-freiburg.de/latestnews/Vegetation-Fires-Global-Change-UN-White-Paper-GFMC-2013.pdf`.

Goldammer, J.G., Frost, P.G.H., Jurvélius, M., Kamminga, E.M., Kruger, T., Ing Moody, S., Pogeyed, M. (2002): Community participation in integrated forest fire management: experiences from Africa, Asia and Europe. In: Communities in Flames; Proceedings of an International Conference on Community Involvement in Fire Management, Balikpapan, Indonesia (25-28 July 2001). Bangkok: FAO Regional Office for Asia and the Pacific. RAP Publication 2002/25: 33-52.

Goldammer, J.G., de Ronde, C. (eds.) (2004): Wildland fire management handbook for Sub-Saharan Africa, Freiburg-Cape Town: Global Fire Monitoring Center and Oneworldbooks.

Goldammer, J.G., and Stocks, B.J. (2011): Migration and global environmental change. Special Report 10 (SR10): Specification for a state of science review – wildland fires. Review commissioned as part of the UK Government's Foresight Project, Migration and Global Environmental Change (Evidence Base to the Final Project Report). Compiled on behalf of the Team of Authors of the "White Paper on Vegetation Fires and Global Change". London: The Government Office for Science, `http://www.bis.gov.uk/foresight/our-work/projects/published-projects/global-migration`, and `http://www.bis.gov.uk/assets/foresight/docs/migration/science-reviews/11-1128-sr10-specification-for-review-wildland-fires.pdf`.

González-Cabán, A. (2008): Proceedings of the Second International Symposium on Fire Economics, Planning, and Policy: A Global View. Gen. Tech. Rep. PSW-GTR-208, Albany: US Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Heil, A., Goldammer, J.G. (2001): Smoke-haze pollution: a review of the 1997 episode in Southeast Asia, Regional Environmental Change, 2: 24-37.

Hinzman, L., Fukuda, M., Sandberg, D.V., Chapin, F.S. III, Dash, D. (2003): FROSTFIRE: An experimental approach to predicting the climate feedbacks from the changing boreal fire regime, Journal of Geophysical Research, 108(D1), 8153, doi: 10.1029/2001JD000415.

Houghton, R.A., Skole, D.L., Nobre, C.A., Hackler, J.L., Lawrence, K.T., Chomentowski, W.H. (2000): Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon, Nature, 403: 301-304.

Hulme, M., Doherty, R.M., Ngara, T., New, M.G., Lister, D. (2001): African climate change: 1900-2100, Climate Research, 17: 145-168.

ICLR (2009): The changing face of wildland fire: Key findings of a February 2008 Expert Meeting on Wildland Fire. Toronto: Institute for Catastrophic Loss Reduction.

IPCC (2007): Climate Change2007: the physical science basis, in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: IPCC.

Jotzo, F. (2011): Reaching for the sky? Indonesia has set ambitious emissions targets, but meeting them will require hard work. In: Inside Indonesia 105, Climate change and Indonesia, `http://www.insideindonesia.org/`.

JGR (Journal of Geophysical Research) (1996): Southern Tropical Atlantic Regional Experiment (STARE): TRACE-A and SAFARI, Special Issue J. Geophys. Res., 101, No. D19: 23,519-24,330.

JRC (Joint Research Center, European Commission) (2005): SAFARI 2000 Global Burned Area Map, 1-km, Southern Africa 2000, Ispra, Italy: Joint Research Centre/European Union.

Kasischke, E.S., Stocks, B.J. (eds.) (2000): Fire, Climate Change, and Carbon Cycling in the Boreal Forest, Ecological Studies 138, New York: Springer.

Kasischke, E.S., Turetsky, M.R. (2006): Recent changes in the fire regime across the North American boreal region- spatial and temporal patterns of burning across Canada and Alaska, Geophysical Research Letters, 33. doi: 10.1029/2006GL025677.

Krawchuk, M.A., Moritz, M.A., Parisien, M.-A., Van Dorn, J., Hayhoe, K. (2009): Global pyrogeography: Macro-scaled statistical models for understanding the current and future distribution of fire, PLoS One 4, e5102. doi: 10.1371/journal.pone.0005102

Kurz, W.A., Apps, M.J., Stocks, B.J., Volney, W.J.A. (1995): Global climate change: disturbance regimes and biospheric feedbacks of temperate and boreal forests, in: G. M. Woodwell and F. Mackenzie (eds.), Biotic feedbacks in the global climate system: will the warming speed the warming, Oxford University Press.

Kurz, W.A., Stinson, G., Rampley, G., Dymond, C., Neilson, E. (2008): Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain, Proceedings of the National Academy of Sciences of the United States of America, 105: 1551-1555.

Langner, A., Miettinen, J., Siegert, F. (2007): Land cover change 2002-2005 in Borneo and the role of fire derived from MODIS imagery, Global Change Biology, 13: 2329-2340.

Langner, A., Siegert, F. (2009): Spatiotemporal fire occurrence in Borneo over a period of 10 years. Global Change Biology, 15: 48-62.

Lavorel, S., Flannigan, M., Lambin, E., Scholes, M. (2007): Vulnerability of land systems to fire: Interactions among humans, climate, the atmosphere, and ecosystems, Mitigation and Adaptation Strategies for Global Change, 12: 33-53.

Lenihan, J.M., Bachelet, D., Neilson, R.P., Drapek, R. (2008): Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California, Climatic Change, 87: 215-230.

Lindesay, J.A., M.O. Andreae, J.G. Goldammer, G. Harris, H.J. Annegarn, M. Garstang, R.J. Scholes, and B.W. van Wilgen (1996): International Geosphere-Biosphere Programme/International Global Atmospheric Chemistry SAFARI-92 field experiment: Background and overview. J. Geophys. Res, 101, No. D19: 23,521-23,530.

Littell, J.S., McKenzie, D., Peterson, D.L., Westerling, A.L. (2009): Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003, Ecological Applications, 19: 1003-1021.

Liu, Y.Q., Stanturf, J., Goodrick, S. (2010): Trends in global wildfire potential in a changing climate, Forest Ecology and Management, 259: 685-697.

Lucas, C., Hennessy, K.J., Mills, G.A., Bathols, J.M. (2007): Bushfire weather in Southeast Australia: Recent trends and projected climate change impacts. Consultancy report prepared for the Climate Institute of Australia. Canberra: Bushfire Cooperative Research Centre, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research.

Marlon, J.R., Bartlein, P.J., Carcaillet, C., et al. (2008): Climate and human influences on global biomass burning over the past two millennia, Nature Geosciences, 1: 697-702.

Martinez, R., Stocks, B.J., Truesdale, D. (2006): Global Forest Resources Assessment 2005 – Report on Fires in the North American Region, Fire Management Working Papers, Working Paper FM/15/E, Rome: Forestry Department, FAO.

Moreno, J.M., Vázquez, A., Vélez, R. (1998): Recent history of forest fires in Spain, in: J.M. Moreno (ed.), Large Forest Fires, Leiden: Backhuys Publishers.

Moritz, M.A., Stephens, S.L. (2008): Fire and sustainability: considerations for California's altered future climate, Climatic Change, 87: 265-271.

Moritz, M.A., Keeley, J.E., Johnson, E.A., Shaffner, A.A. (2004): Testing a basic assumption of shrubland fire management: how important is fuel age? Frontiers in Ecology and the Environment, 2: 67-72.

Mouillot, F., Field, C.B. (2005): Fire history and the global carbon budget: a 1°×1° fire history reconstruction for the 20th century, Global Change Biology, 11: 398-420.

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.-D.V., Adi, J., Limin, S. (2002): The amount of carbon released from peat and forest fires in Indonesia during 1997, Nature, 420: 61-65.

Pechony, O., Shindell, D.T. (2010): Driving forces of global wildfires over the past millennium and the forthcoming century, Proceedings of the National Academy of Sciences of the United States of America, 107: 19167-19170.

Pitman, A.J., Narisma, G.T., McAneney, J. (2007): The impact of climate change on the risk of forest and grassland fires in Australia, Climatic Change, 84: 383-401.

Power, M.J., Marlon, J., Ortiz, N., et al. (2008): Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data, Climate Dynamics, 30: 887-907.

Price, C., Rind, D. (1994): The impact of a 2×CO2 Climate on lightning-caused fires, Journal of Climate, 7: 1484-1494.

Pyne, S.J. (1995): World Fire: the Culture of Fire on Earth. New York: Henry Holt and Company.

Pyne, S. (2001): Challenges for Policy Makers. In: ISDR Working Group on Wildland Fire 2002. UN International Strategy for Disaster Reduction (ISDR) Inter-Agency Task Force for Disaster Reduction, Working Group 4 on Wildland Fire, Report of the Second Meeting. Geneva, 3-4 December 2001, http://www.unisdr.org/unisdr/WGroup4.htm.

Pyne, S.J. (2010): America's Fires: A historical context for policy and practice. Forest History Society, Durham, North Carolina.

Pyne, S.J., Andrews, P.L., Laven, R.D. (1996): Introduction to wildland fire. New York: Wiley. Randerson, J.T., Liu, H., Flanner, M.G., et al. (2006): The impact of boreal forest fire on climate warming, Science, 314: 1130-1132.

Rees, J.R. (2009): Statement of Russell James Rees to the 2009 Victorian Bushfires Royal Commission. Available from: http://www.royalcommission.vic.gov.au.

Rego, F. (1992): Land use changes and wildfires, in: A. Teller, P. Mathy, J.N.R. Jeffers, (eds.), Response of Forest Ecosystems to Environmental Changes, Elsevier: London.

Royal Bushfire Commission (2010) Final report. Parliament of Victoria 2009, Victorian Bushfires Royal Commission, Victoria, Australia.

Silva, J.S., Rego, F., Fernandes, P., Rigolot, E. (eds.) (2010): Towards integrated fire management – Outcomes of the European project Fire Paradox, European Forest Institute Research Report 23, Joensuu, Finland.

Schoennagel, T., Vebien, T.T., Romme, W.H. (2004): The interaction of fire, fuels, and climate across Rocky Mountain forests, Bioscience, 54: 661-676.

Scholze, M., Knorr, W., Arnell, N.W., Prentice, I.C. (2006): A climate-change risk analysis for world ecosystems, Proceedings of the National Academy of Sciences of the United States of America, 103: 13116-13120.

Schultz, M.G., Heil, A., Hoelzemann, J.J., et al. (2008): Global wildland fire emissions from 1960 to 2000. Global Biogeochemical Cycles, 22: 10.1029/2007GB003031.

Siegert, F., Ruecker G., Hinrichs, A., Hoffmann, A.A. (2001): Increased damage from fires in logged forests during droughts caused by El Niño, Nature, 414: 437-440.

Soja, A.J., Tchebakova, N.M., French, N.H.F. et al. (2007): Climate-induced boreal forest change: predictions versus current observations. Global and Planetary Change, 56: 274-296.

Spessa, A., Weber, U., Langner, A., Siegert, F., Heil, A. (2010): Fire in the vegetation and peatlands of Borneo: Patterns, Drivers and Emissions. Paper presented at European Geosciences Union General Assembly 2010, Vienna, Austria.

Stocks, B.J., Fosberg, M.A., Lynham, T.J., et al. (1998): Climate change and forest fire potential in Russian and Canadian boreal forests, Climatic Change, 38: 1-13.

Stocks, B.J., Wotton, B.M., Flannigan, M.D., Fosberg, M.A., Cahoon, D.R.. Goldammer, J.G. (2001): Boreal forest fire regimes and climate change, in: M. Beniston and M.M. Verstraete (eds.), Remote Sensing and Climate Modeling: Synergies and Limitations. Advances in Global Change Research, Dordrecht and Boston: Kluwer Academic Publishers.

Stocks, B.J., Mason, J.A., Todd, J.B., et al. (2003): Large forest fires in Canada, 1959-1997, Journal of Geophysical Research, 10: 1029/2001JD000484.

Swetnam, T.W., Anderson, R.S. (2008): Fire climatology in the western United States: introduction to special issue, International Journal of Wildland Fire, 17: 1-7.

Tebaldi, C., Hayhoe, K., Arblaster, J.M., Meehl, G.E. (2006): Going to the extremes: an intercomparison of model-simulated historical and future changes in extreme events, Climate Change 79: 185-211.

Uhl, C., Kauffman, J.B. (1990): Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon, Ecology, 71: 437-449.

UNEP (2002): Spreading Like Wildfire – Tropical Forest Fires in Latin America and the Caribbean: Prevention, Assessment and Early Warning (authored by M.A. Cochrane). United Nations Environment Program, Regional Office for Latin America and the Caribbean.

UNFCCC (2010): Decision 1/CP.16. The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention, Bonn, Germany: United Nations Framework Convention on Climate Change (UNFCCC) Secretariat.

Van der Werf, G.R., Randerson, J.T., Giglio, L., et al. (2010): Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009), Atmospheric Chemistry and Physics, 10: 16153-16230.

Viedma, O., Angeler, D., Moreno, J.M. (2009): Landscape structural features control fire size in Mediterranean forest areas of Central Spain, International Journal of Wildland Fire, 18: 575-583.

Weber, M.G., Flannigan, M.D. (1997): Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes, Environmental Reviews, 5: 145-166.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W. (2006): Warming and earlier spring increase western US forest wildfire activity, Science, 313: 940-943.

Williams, A.A.J., Karoly, D.J., Tapper, N. (2001): The sensitivity of Australian fire danger to climate change, Climatic Change, 49: 171-191.

Williams, R.J., Bradstock, R.A., Cary, G.J., et al. (2009): Interactions between Climate Change, Fire Regimes & Biodiversity in Australia – A Preliminary Assessment. Report to the Department of Climate Change and Department of Environment, Water, Heritage and the Arts, Canberra.

World Bank (2010): Assessment of the risk of Amazon dieback. Environmentally and Socially Sustainable Development Department, Latin America and Caribbean Region. The World Bank, Washington, DC.

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White Paper Science Team (2015): Vegetation Fires and Global Change. Challenges for Concerted International Action. A White Paper directed to the United Nations and International Organizations. In: Planet@Risk, 3(1): 45-57, Davos: Global Risk Forum GRF Davos.