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SR10: Specification for a state of science review – wildland fires

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on behalf of the Team of Authors of the 'White Paper on Vegetation Fires and Global Change[1]'

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1. United Nations International Strategy for Disaster Reduction. 2011. White Paper on Vegetation Fires and Global Change (in prep.). Johann Georg Goldammer (ed.). Co-authored by Stephen J. Pyne, Thomas W. Swetnam, Cathy Whitlock, Brian J. Stocks, Mike D. Flannigan, Johann Georg Goldammer, Anatoly I. Sukhinin, Larry Hinzman, F. Stuart Chapin, 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, Allan Spessa, Guido van der Werf, Kirsten Thonicke, Jose Gomez Dans, Veiko Lehsten, Rosie Fisher, Lynn Gowman, Mike Wotton, Meg Krawchuk, 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 and Johann Georg Goldammer.

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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 impossible 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 for many eons. 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 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 kilometres annually (United Nations ISDR, 2011, in prep.), while others have estimated the total annual global area burned at more than 6 million square kilometres (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 USA (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 modelling 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 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.

This overview paper is intended to give a summary of global fire as seen by the group of contributors to the ‘White Paper on Vegetation Fires and Global Change’ (United Nations ISDR, 2011, in prep.), identifying the root causes of the major problems, and focusing on some of the major regions of concern. It is intended to inform policy makers, not to advocate or suggest policy.

Fires in boreal North America

The boreal zone stretches in two broad transcontinental bands across Eurasia and North America, covering approximately 12 million square kilometres, 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 organises 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 million hectares 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 300,000 hectares to more than 7,500,000 hectares in Canada. Over the past four decades, annual area burned has averaged 2.2 million hectares for Canada (Martinez *et al.*, 2006) and 400,000 hectares 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 million hectares 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 heatwave 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 500,000 hectares 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 hectares 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 heatwave 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 organised 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 emphasises 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 centralised 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

Organised 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 galvanised 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 million hectares in the early 1930s to 1–2 million hectares 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 million hectares) and the number of large fires (>20,000 hectares) across the western USA. 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. 300,000 hectares, 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 totalled more than US$13.1 billion (González-Cabán, 2008) with the number of fire exceeding USD $0 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).

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 USA 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 behaviour (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 million hectares being burned annually (UNEP, 2002). Amazon forest fires can burn ~40,000 km^2 in drought years (Alencar *et al*., 2006) and emit 20 Mg C/hectare 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 kilometres 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 million hectares 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 million hectares in Indonesia alone, of which 2.4 million hectares 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 million hectares burned in Africa in 2000 (JRC–EU, 2005).

Over the past million years most ecosystems of Subsahara 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 Subsaharan 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, and fires in 2007–08 resulted in losses of billions of US dollars (United Nations ISDR, 2011, in prep.).

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 centres, 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 centralised fire protection organisations. 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 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 WUI 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.

Summary

While not an exhaustive report on global wildland 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 AD, 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.

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 WUI 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 WUI 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 fires where they are desirable, and controlling them where they are not, will be an evolving and increasingly difficult task in the years ahead.

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