Global Fire Challenges in a Warming World

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38 authors, including:

François-Nicolas Robinne
University of Alberta

Promode Kant
Institute of Green Economy

Michael Kleine
IUFRO

Mike Flannigan
University of Alberta

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Summary Note of a Global Expert Workshop on Fire and Climate Change

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IUFRO, Vienna
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Contributing authors and reviewers:
Israr Albar, Lucy Amissah, David Bowman, Val Charlton, Mark Cochrane, Bill De Groot, David Ellison, Robert Field, Mike Flannigan, Johann Goldammer, Promode Kant, Muhammad Najeeb Khan, Werner L. Kornexl, Andrey Krasovskii, Sarah McCaffrey, Andrew M. Mitchell, A.K. Mohanty, Peter Moore, Daniel Murdiyarso, Alfredo Nolasco-Morales, Ainuddin Nuruddin, Stavros Papageorgiou, Natasha Ribeiro, François-Nicolas Robinne, Patricio Sanhueza, Jesús San-Miguel-Ayanz, Dmitry Schepaschenko, Alberto Setzer, Ross Smith, Britaldo Soares Filho, William Sommers, John Stanturf, Lara Steil, Guido Van der Werf, Cristina Vega-Garcia, E. Vikram.

Photography:
Matt Howard, USA; Prevfogo/Ibama‘s collection, Brazil; Xinli Cai, Canada.

For further information and feedback please contact:
IUFRO Headquarters - Secretariat
Marxergasse 2, 1030 Vienna, Austria
Tel.: +43-1-877-0151-0 / Fax: +43-1-877-0151-50
Website: www.iufro.org

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FOREWORD

Wildfires have played a critical role in shaping our environment. Iconic tree species, such as the giant sequoia, even depend on fire for their regeneration.

However, the role of fire is changing rapidly. Globally, wildfires have become a major factor causing deforestation and forest degradation. A potentially vicious cycle of climate change and fire is emerging. Available data shows a trend of increasing frequency and intensity of uncontrolled fires adversely affecting biodiversity, ecological services, human well-being and livelihoods and national economies. Recent fire seasons have been catastrophic with fatalities and dramatic consequences on people's health from smoke and haze as exemplified by the damage caused by wildfire incidences in Brazil, Canada, Chile, Greece, India, Indonesia, Portugal, Russia, South Africa, Sweden and the United States in 2017 and 2018. These modern-day fires are now largely anthropogenic, with lightning-caused fires becoming almost outliers in comparison. Although land use policies and management practices have focused on decreasing the global land area burnt every year, success has been mixed at best.

Against this background, the Program on Forests (PROFOR) housed at the World Bank and the International Union of Forest Research Organizations (IUFRO) jointly convened a Global Expert Workshop on Fire and Climate Change in Vienna, Austria, on 2-4 July 2018, with the aim of improving the understanding of the complex interrelations between wildfire, climate and land management and identifying urgently required response strategies and actions. The initiative will inform a forthcoming World Bank policy paper on forest fire management strategies.

The three-day expert workshop organized under the thematic lead of IUFRO's Working Party on "Forest Fires" brought together 32 scientists and governmental experts from around the globe and World Bank representatives who jointly discussed the complex fire-climate change-landscape restoration nexus. The work presented here brings together state-of-the-art scientific information on wildfire as discussed by the experts in the workshop, providing guidance for decision makers on policy and investments to better cope with, and adapt to, an increasingly fire-prone landscape.

We would like to thank all participating experts for their excellent contributions to the workshop in Vienna. Our special thanks go to the members of the IUFRO Working Party "Forest Fires" and especially to Mike D. Flannigan, Bill de Groot, François-Nicolas Robinne, Promode Kant, D. Mike Wotton, and Janice Burns who took on the task of synthesizing the wealth of information generated at the expert workshop into this concise and focused occasional paper. We would like to acknowledge also the outstanding quality and effectiveness with which the team of IUFRO's Special Programme for Development of Capacities led by Michael Kleine has organized the expert workshop. It is our sincere hope that those with a responsibility for dealing with wildfires will find this work a useful resource of information and inspiration.

Alexander Buck
IUFRO Executive Director

Benoit Blarel
(Practice Manager, Environment and Natural Resources Global Practice, the World Bank)

EXECUTIVE SUMMARY

Today, catastrophic wildfires are increasingly common across the globe. Recent disasters have attracted media attention and strengthened the perception of wildfires as "bad" events, a plague worsened by climate change that has yet to be eradicated. Although it is true that fire has a destructive potential, the reality of global fire activity depicts a much more complex picture in which fire can be a useful, if not necessary, tool for food security and the preservation of cultural landscapes, as well as a an integral element of many ecosystems and their biodiversity.

Global fire activity is shaped by diverse social, economic, and natural drivers influencing the fire environment. The culminating complexity of these factors defines in turn the likelihood of a landscape to burn and the potential positive or negative outcomes for communities and ecosystems that can result from a blaze. Although many regions remain understudied, the effects of ongoing climate change associated to other planetary changes are already visible, transforming fire activity in ways that are not well understood but that will likely be dramatic, with potential dire consequences to nature and society in case of adaptation failure.

Based on the limited available statistics, there is a growing trend in the costs of wildfires. On top of human lives that are lost to the flames or smoke and the billions of dollars imputable to firefighting and insurance coverage, the growing interest in costs linked to healthcare, business stability, or the provision of ecosystem services such as drinking-water indicates negative economic consequences impacting countries' GDP and social stability. Attempts to evaluate the future costs of wildfire disasters point at a worsening situation, yet the list of possible social and economic effects is likely incomplete and the magnitude of envisaged impacts is likely conservative.

Notwithstanding the difficulties inherent to global climate modeling, there is a scientific consensus on the future increase in the frequency of fire-conducive weather associated with drier ecosystems, a mix that will eventually result in more frequent and intense fire activity. When combined with an ever-growing world population and unsustainable land uses, the conditions leading to fire disaster will only be intensified. Although fire governance has historically advocated for fire suppression, a ‚No Fire' motto is not an option anymore in the new fire reality. Current policies aiming at total fire suppression have been shown to be detrimental and are therefore outdated. The key to wildfire disaster risk reduction in a changing world now lies in learning to live with fire.

Investments in international cooperation, integrated management, local community involvement, cutting-edge technologies, and long-term data collection are critically needed to ensure the future of fire disaster risk mitigation. Moreover, future land development policies must prioritize the protection and the restoration of natural and cultural landscapes that have been degraded by the inappropriate use of fire or, conversely, by historical fire exclusion; keeping a place for fire in forest resource management and landscape restoration has been shown to be a cost-effective and efficient solution to reduce fire hazard.

Overall, synthesis of globally available scientific evidence revealed the following key issues for landscape management and governance:

- Climate change, with longer, hotter, and drier fire seasons, in combination with other environmental changes linked to population growth and unsustainable land-use practices, is contributing to extreme wildfire events that exceed existing fire management capacities. The world is entering a 'new reality' that demands new approaches to fire governance.
- Fire is an inherent feature of the Earth system and many ecosystems, including their fauna, are dependent on it for their long-term survival; nevertheless, ongoing changes in global fire activity in terms of location, intensity, severity, and frequency will likely have immense costs to biodiversity, ecosystem services, human well-being and livelihoods, and national economies — to extents that have yet to be evaluated. Investment in social, economic, and environmental monitoring is therefore urgent, especially in under-studied regions.

- Integrated fire risk reduction is key to adapting to ongoing changes in global fire risk. Future sustainable fire risk mitigation demands integrated region-specific approaches based on a clear understanding of fires in context, population awareness and preparedness, fire surveillance and early-warning systems, adaptive suppression strategies, fire-regime restoration, landscape-scale fuel management, changes of many land use practices, and active restoration of landscapes.
- Engagement with local communities, land-owners, businesses and public stakeholders — via multiple tiers of governance — is crucial to restore and maintain landscapes that are biodiverse and functional, respectful of local cultures and identities, economically productive, and above all, fire-resilient.
- People have historically achieved sustainable co-existence with flammable ecosystems and have often used fire as a land-management tool, thereby shaping many modern and long-standing landscapes around the world. Traditional fire knowledge is thus key to adapting to local changes in fire activity, using known techniques for the reduction of dangerous fuel loads, prescribed burning and sustainable landscape management practices.
- Building adaptive capacity to confront fires must be based on knowledge of the natural and cultural roles of fire, how they have shaped our modern landscapes, and their importance in the long-term functioning of socio-ecological systems. Further developments in land-system science, geospatial technologies, and computer modeling will enhance our understanding of the long-term ecological and socio-economic drivers of fire through the widespread collection and distribution of harmonized fire data at the global level. However, creating and sharing such knowledge requires national and international investments in scientific and operational fire science programs.
- Catastrophic fires are undeniably part of our future. Current scientific estimates are likely conservative, meaning that changes in fire activity might likely be worse than anticipated. We have to act now to mitigate catastrophic fires and limit the occurrence of disastrous situations. Given disparities but also similarities in the levels of fire risk around the world, and the capacities to manage it, knowledge and technology transfers through international cooperation will be a paramount factor in learning to live with fire.

This Occasional Paper is the result of a large collaborative effort by fire scientists and practitioners who believe that learning to co-exist with changing fire activity is not only possible but necessary if we, as a global society, are to adapt to climate change and keep our natural and cultural landscapes healthy, resilient, and safe for the next generations. The work presented hereafter was developed during, and as follow-up to, the Global Expert Workshop on Fire and Climate Change hosted in Vienna, Austria, in July 2018. It stresses the diversity and the complexity of the global fire situation, a situation that is evolving, positively or negatively, in unknown proportions due to global environmental changes — with climate change being the most acknowledged manifestation.

LIST OF FIGURES

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1. INTRODUCTION

Fires burning through landscapes, governed by biomass availability, meteorological conditions, and human pressure, are a critical terrestrial and atmospheric process shaping the Earth system. Associated with other global environmental changes, such as urban expansion, unsustainable land uses, and water resource depletion, the warming climate is causing an ongoing increase in the frequency and intensity of fires, thereby degrading ecosystems and impairing their capacity to contribute critical services that form the backbone of the UN Sustainable Development Goals. Substantial and rapid shifts in future fire activity are projected within all biomes, thereby increasing population exposure and disaster risks, including in areas where fire has seldom been seen before in modern human history.

Yet the underlying problems have received insufficient ongoing recognition, and even less continuity of action, by responsible governing entities, except when human lives or economic growth is at stake. This lack of sustained attention hinders the development of appropriate international and national fire governance, especially in developing countries. Mitigating disaster risks and increasing the resilience of socio-ecological systems to fire must be acted upon, using holistic approaches to landscape management as a base for action. Considering fire risk reduction as an essential part of future landscape management, conservation and restoration investments will be a key to learning to live with fires in many parts of the world.

In view of this, the International Union of Forest Research Organizations (IUFRO) and the World Bank's Program on Forests jointly convened a Global Expert Workshop on Fire and Climate Change with the aim of improving the understanding of the complex interrelations between wildfire, climate, and land management, and of identifying urgently required response strategies and actions. A detailed agenda of the workshop, which was hosted July 2nd-4th, 2018 in Vienna, Austria, is presented in Annex 1.

The three-day workshop — organized under the thematic lead of IUFRO's Working Party on "Forest Fires" — brought together World Bank representatives and 32 scientists and governmental experts from around the globe to synthesize available knowledge on the complex fire-climate change-landscape restoration nexus. Besides the classical fields of expertise in fire management, the invited scientists represented a diverse array of specializations including meteorology and climate change science, land use planning, global fire monitoring, remote sensing, vegetation modeling, hydrology, sociology, and policy sciences. A list of workshop participants including distance contributors is presented in Annex 2.

1.1. Objectives

The objective of this Occasional Paper is to synthesize the current state of science on the understanding of the various causes, ramifications, and consequences of fires in natural and cultural landscapes across the globe, as identified by participants of the Global Expert Workshop on Fire and Climate Change and associated distance contributors. The paper also examines the manner and extent to which fire activity might be amplified by the changing climate and the challenges it will pose to current practices in fire risk mitigation. This document will ultimately help to identify key steps to be undertaken at local, regional, and global levels to adapt and enhance fire risk governance.

1.2. Defining "Fire"

The many terms used for fire on the landscape carry a range of meanings that depend on the socio-cultural setting, the nature of land and vegetation affected, and the legal framework used. It is variously described as landscape fire, wildfire, wildland fire, bushfire, veldfire, rural fire, or vegetation fire, among other designations used by different agencies around the world.

In Europe, where many countries suffer the impacts of fires in different land cover types, the terminology presently in use in the European Forest Fire Information System (EFFIS) is "forest fire"; however, due to the expansion of fires into non-forested areas of Europe, the wider term wildfire is also considered. The term "wildfire" is also used in the Global Wildfire Information System (GWIS) which aims at providing harmonized information on fire activity and impacts at the global level. The California Government Code defines fire as “any fire burning uncontrolled on any lands partially or wholly covered by timber, brush, grass, grain, or other inflammable vegetation”.

For the sake of coherence with existing international efforts this Occasional Paper uses “fire” or “wildfire” as a general term encompassing a diversity of controlled and uncontrolled vegetation fires with landscape-scale impacts, including agricultural land, grassland, shrubland, peatland, and forest fires.

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2. FIRES AT GLOBAL AND REGIONAL LEVELS

2.1 Global Distribution of Fire Activity

Fires, both natural and human-caused, have played a critical, and persistent, role in shaping our environment. Almost a third of the global landmass experiences recurrent fire activity, averaging ~4.5 $M.Km^2$ area burned yearly, which is larger in size than India. Although the global annual area burned has been decreasing for several years, the occurrence of extreme wildfire events with catastrophic consequences has been increasing.

Global fire activity mostly affects savannas and woodlands in the tropical belts, temperate steppes, Mediterranean shrublands, equatorial peatlands and boreal forests (Fig.1). Due to variable combinations of natural and anthropogenic factors, there is always a fire burning somewhere on the planet.

At a global scale, fires are largely anthropogenic, lightning-caused fires being outliers in comparison. Scientific evidence suggests that more than 90% of all ignitions are linked, directly or indirectly, to human activities. Many customary rural practices, such as small-scale pasture maintenance, rely on broadcast burning and can be considered rather safe and sustainable, despite possible localized ecological changes. Conversely, many human-caused wildfires originate from large-scale and often illegal land clearing, arson, and outdoor accidents that cause an ignition to escape, though accurate records of causes are globally unavailable. There are however strong regional disparities.

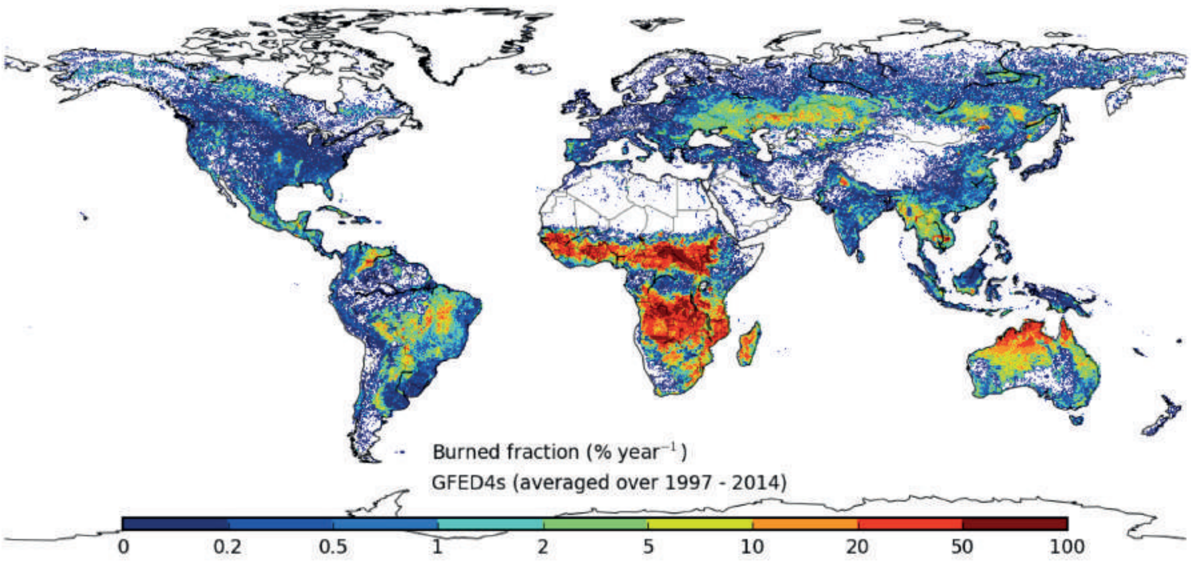

Figure 1: Global distribution of annual area burned, averaged over 1997-2014. White areas show no fire activity. Source: Global Fire Emission Database version 4, Giglio et al. 2013

2.2 Regional Fire Situations

We present hereafter a general description of fire regimes[1] for selected terrestrial biomes experiencing a large percentage of global fire activity. Based on ecological factors, biome classifications (Fig.2) are well known and accepted by the international community. Alternative and more complex fire geographies including human factors can be used for more advanced analysis.

Fires in Rainforests and Peatlands

Rainforests cover less than 10% of the global land surface. They are naturally fireproof given their location in regions of high and frequent rainfall and the absence or quasi-absence of a dry season. Fires in tropical and subtropical rainforests are thus mainly anthropogenic, with fire activity in the Amazon, Central America, and South-east Asia being almost exclusively related to deforestation and shifting cultivation.

In the Amazon, initial deforestation fires are usually set during dry spells in proximity to dense, intact forests that are normally too moist to burn. Rain forest trees are not fire-adapted and are extremely sensitive to even low intensity fires, potentially killing as many as one third of standing trees.

This mortality increases the fuel load and opens the forest canopy to desiccating sunlight and winds. As the forest "bleeds moisture", it becomes vulnerable to burn in even as short as a fortnight without rain. This positive feedback of increasing fire frequency, forest desiccation, and increased fire severity continues leading to complete deforestation.

In Indonesia, no natural fires have been observed and all fires are considered human-induced. Initial forest clearing that is followed by drainage in peatlands causes land desiccation and leads to the initial increase in fuel load. Deforestation fires burn intensely in felled trees or dry peat for several days, or even weeks, and escape to adjacent intact vegetation when winds push flames into forest edges. In areas where forest degradation takes place and secondary growth is observed fires can be more recurrent and severe. Those human-caused fires are amplified during prolonged hydrologic droughts related to inter-decadal El Niño events. During drought years, the maximum area burned can be ten-fold larger relative to non-drought years. The detrimental impact of peatland fires on greenhouse gas emissions is serious due to the fact that smoldering peat combustion is large-spread and that land conversion prevents carbon absorption by post-fire vegetation.

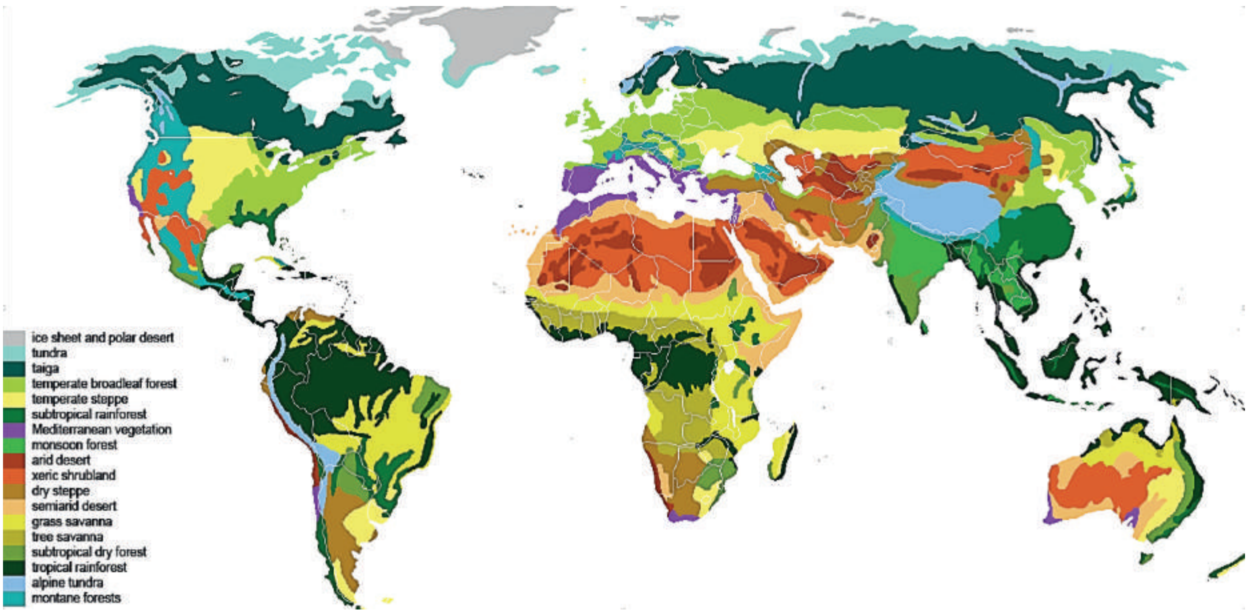

Figure 2: Terrestrial biomes of the world. Source: Wikimedia Commons, adapted from Olson, D. M. et al. Terrestrial ecoregions of the world: a new map of life on Earth: a new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity (2001).

1 The fire regime concept refers to the characteristics of fire activity at a given location: fire season, ignition sources, fire type (i.e., ground, surface, and crown), fire severity, fire intensity, fire frequency, and area burned.

Whereas landscape fragmentation likely leads to a decrease in fire activity in many regions of the world, it is landscape fragmentation and deforestation that drives fire activity in rainforests by drying up forest systems that are fully moisture-driven. Locating and extinguishing fires in those dense forests can also be very difficult, making operational fire management difficult.

Fires in Savannas and Dry Woodlands

Savannas and open dry woodlands cover one fifth of the land surface (~33M.Km^2). They host one fifth of the human population and contribute almost one third of terrestrial net primary production, most of which goes to sustain large wild herbivore and livestock populations. Unobstructed winds and plentiful grassy biomass that dries annually causes savannas to be the world's most frequently burned landscape, making fire an important driving force of this ecosystem's composition, structure and distribution.

Fires in the African savannas and woodlands have existed for millions of years and many species have adapted to dry-season fires by developing key traits, such as a thicker bark and leaves that allow them to survive. The rich taxonomic diversity of fire-adapted plants points to an ancient evolutionary association with landscape fires ignited by lightning. These ecosystems also show structural characteristics (e.g. lower tree density and higher grass biomass) that are intrinsically linked to fires, creating suitable habitat for wildlife such as grazers that are attracted to the fresh shoots from recently burned areas.

For the past millennia, fire activity in savannas has mostly been driven by humans to manage wildlife and livestock. Humans are able to change the seasonality of fires and the spatial pattern and frequency compared to lightning ignitions that are typically concentrated in the transitions from the dry and wet seasons. Loss of fire maintained fine-grained habitat mosaics created by indigenous fire management practices is one cause of biodiversity declines and landscape changes, particularly in northern Australian savannas, as well as in the Miombo woodlands of southern Africa, where the interaction between elephants felling trees and cultural anthropogenic fires seems to help maintaining the tree-to-grass balance.

Fires in Temperate Grasslands

Temperate grasslands cover ~25% of the global landmass. Like in tropical savannas, fire plays an important role in maintaining grassland biodiversity. The removal of fire in these systems is often associated with tree invasion, and population declines of herbaceous species with life cycles that require fire disturbance that provides temporary respite from grass competition and benefit from nutrient pulses from ash, and in some cases release chemicals that stimulate seed germination. The rapid resprouting of grass following surface fires increases forage quality and quantity for grazers, and the coupling of grazing and browsing can create fine grained habitat mosaics that increase the diversity of invertebrates, which in turn, provide a food resource for vertebrate predators thereby increasing biodiversity.

Temperate grasslands in North America and Eurasia provide important habitat requirements of flora and fauna that are dependent on open-land ecosystems without tree and brush cover. The North American prairies are an example where natural fires and fires set by the indigenous populations created suitable conditions for the occurrence and expansion of bison populations — an important source for tribal hunters and their livelihood. Other temperate grasslands, such as the Central Asian steppes, provide pasture resources for domestic livestock. In Mongolia, fires occurring at the steppe-forest transition have shaped the boundary between open grasslands and sub-boreal forests. With accelerating progress of regional climate change the fires entering the steppe-forest fringes are resulting in increasing loss of forest cover, notably when affecting not sustainably logged-over forests that sometimes occur due to illegal harvesting. Forest regeneration is increasingly impeded due to the combined effects of drought and wildfires.

Fires in Mediterranean Forests and Shrublands

Mediterranean areas cover less than 5% of emerged lands, but account for 20% of the Earth plant species. Their high levels of plant richness and endemism are increasingly threatened by urban growth and population density, agriculture, invasive species and wildfires. For instance, the Fynbos in South Africa is composed of fire-prone and fire–dependent shrubland vegetation that requires regular fire to ensure the persistence of the extremely high species diversity. Although fire ignition and intensity are often driven by prevalent high temperatures and drought conditions in hazardous fuel built-up Mediterranean landscapes, an essential driver of fires in these regions is the human component, both as a trigger of fire ignition and as a factor of vulnerability to fires.

In Europe, about 96% of the fires in the Mediterranean are caused by human activities, often by negligence, but also by arson, due to conflicts related to land ownership and land use change. The enlargement of areas in which human infrastructures and houses interact with wildland areas is one of the reasons for an increase on the socio-economic impacts in the Mediterranean regions. The Fynbos has been identified as the most vulnerable region in South Africa with respect to disaster risks from wildfire due to patterns of urbanization, agriculture and potential impacts upon water catchment areas. The devastating fires of 2017 and 2018 in the Mediterranean regions of the world, like those in Australia, California, Chile, Europe and South Africa showed that they are a function of a complex mix of climate and socio-economic factors.

Fires in Montane Biomes

Montane biomes cover approximately 15% of the global land surface. Mountains are the largest sources of freshwater in the world, and in spite of extensive snow coverage and high moisture, montane ecosystems also face fires. Those regions are characterized by high relief and steep terrain that makes fuels on the upper side of fires come in contact with flames more rapidly. Limited access to rugged terrain also makes it difficult to dispatch resources for combating fires. Slope and aspect characteristics of complex topography directly affect fuel moisture and fire behavior, such as occurs with enhanced drying and fire activity on south west-facing slopes in the northern hemisphere.

In the Himalayas, while monsoon plays the key role for fire seasonality, human factors also have an influence. The primary, almost exclusive, cause of fire in the region is anthropogenic, though for different underlying motives. In the western part, presence of Chir Pine, a high resin content species, is the primary reason for fire as people clear the pine needles to encourage grass growth, while in the eastern part fire activity is more related to shifting cultivation, which is increasingly applied at higher altitudes and in steeper terrain. Soil enrichment, clearance of pasture, collection of forest products, mining, and urbanization are other causes of fires.

In the Andes, more than 95% of the fires are human-caused, with an increase in arson around large urban areas seemingly linked to conflicts over land tenure between local governments and indigenous communities. The region has also endured a severe and long-lasting drought over the past few years leading to many incidences of extremely intense, fast-spreading and severe wildfires.

In the Euro-alpine region both natural lightning-caused and human-set fires, which have been recorded historically, had relatively limited impacts on forests and ecosystem stability. However, during recent years changes in fire occurrence have been noted due to more common drought conditions. Even small-scale fires often penetrate litter and humus layers, exposing the soil and leading to rock falls, landslides and mudslides on steep slopes. The urban-industrial development and traffic corridors of the Euro-alpine countries, which is concentrating on often narrow valleys, are threatened by such secondary disturbances, even if small scale.

Fires in the Boreal Forest

Boreal forests cover 1.3M.Km^2 of northern circumpolar lands, containing 90% of global peatlands and storing about 30% of the global terrestrial phytomass. The Boreal biome covers a large part of Canada, USA (Alaska), Scandinavia, Russia, and northern China. In total, the annual area burned across the circumboreal region is estimated at 9-20M.Ha, and fire is an integral part of the life cycle of boreal forest landscapes with natural fire cycles ranging from 50 to 300 years. As long, cold, and often dry winters limit species diversity and natural decay, fires constitute a natural mechanism that assists forest regeneration, maintains forest type diversity and mosaic pattern on the landscape, controls forest pest populations, reduces waterlogging, and supports post-fire forest productivity by releasing nutrients in warmer soils. However, the high release of nutrients and the changes in soil moisture after fires can strongly alter the water budget and the health of rivers and lakes, which are key aspects of boreal ecosystem functioning and of critical importance to manage water supplies of local populations.

The North American boreal forest is characterized by relatively infrequent, high intensity crown fires, in contrast with the northern Asian boreal region which experiences moderately frequent fires that are predominantly low to moderate intensity. This dichotomy in boreal fire regimes appears to be related to continental differences in tree species morphology and fire ecology. The infrequent but high intensity crown fires of boreal North America result in large, periodic stand-replacing fires; a characteristic that can be locally worsened by the use of fire-sensitive timber yielding species instead of native broadleaved tree species. In the northern Asia boreal region, relatively frequent low intensity surface fires result in repeated stand underburning with low tree mortality due to presence of thick-barked tree species.

Lightning-caused fires occurring in remote locations account for more than 90% of the area burned. However, up to 95% of fires in the Boreal forest are human-caused, and many large and extreme fire incidents in recent years, such as Fort McMurray in Canada, have been attributed to human activities. Demographic trends are resulting in more people living in proximity to wildland fuels, particularly in North America, where industrial development, urban sprawl, and outdoor leisure help to carry fire deep into homogeneous fire-prone landscapes.

2.3. The Costs of Fires

Social Impacts

Fires can have significant adverse impacts on societies, with dramatic consequences on local populations — affecting living conditions, mental health, and trust in governmental authorities. Perhaps most recognized are the direct impacts on human lives and health. In 2018 and 2017, wildfires in Europe resulted in the death of hundreds of people, more than 100 of them in Portugal alone. The death toll in Greece reached 80 and hundreds of injured individuals, and the 2017-2018 fires claimed more than 50 people in California. Southern India was struck with the death of 23 people in March 2018. Eleven people were killed in Chile during fires in early 2017. And in 2009, 173 lives were lost in the Black Saturday fires in Australia. Dozens of firefighters also die every year on the fireline. These are only the direct deaths due to burns. Post-fire hazards can also take a toll; in January 2018, post-fire rainstorms caused a mudslide that killed 13 people in California.

Further, the health impacts due to respiratory illnesses brought about by heavy smoke can be several orders of magnitude higher. Global estimates suggest an average of ~340,000 annual premature deaths from fire-related particulate matter <2.5μm. Model-based estimates of premature mortality due to smoke exposure vary widely, but range from 11,880 to 100,300 excess depending on different model assumptions and whether the effects on neighboring countries are included. Large and intense fires often inject smoke high into the atmosphere where it can be transported globally impacting distant populations. The inclusion of other toxic pollutants (e.g. mercury) released by fires and firefighting and then inhaled or ingested would likely lead to even higher numbers, though no estimates are available at the moment.

There are also indications of post-traumatic stress disorders (PTSD) linked to stressful emergency situations such as firefighting, evacuation, the loss of lives or property, and community instability. However, social and medical research in this domain is limited and the socio-economic burden of post-fire PTSD has never been estimated on a global scale. Overall limited data poses challenges for assessing the full health cost of fires. Moreover, the figures given by the World Health Organization in the international disaster database, EM-DAT, are critically underestimated — reporting capacities indeed differ substantially from one country to another, and indirect human losses due to smoke or post-fire hazards are rarely taken into account.

Economic Cost

Fires result in significant adverse impacts on an array of economic values from house loss to business disruption. The economic burden of wildfires is the sum of wildfire management costs and wildfire-related losses. Estimates of the economic burden of wildfires vary greatly depending on the type of fire involved, values at risk and ability to assign valuations to non-commodity values. Health costs and losses are poorly accounted for, particularly in regard to smoke impacts. Many argue that the encroachment of human activities and structures into natural lands changes fire management priorities and increases the financial cost of firefighting, as well as the burden on national economies and insurance companies.

This encroachment problem, commonly referred to as the wildland-urban interface (WUI), is widespread in the United States and in many other parts of the world including Argentina, Australia, France, Greece and South Africa. Within the perimeter of recent wildfires (1990–2015) in the US, there were 286,000 houses in 2010, compared with 177,000 in 1990. In Chile, more than 1600 homes were lost to fires in 2017. More than 2500 homes were destroyed during the Fort McMurray fire in Canada in 2016 and the estimates of direct and indirect costs reached over $7.5B USD. Over the last decade, annual wildfire suppression costs on US federal lands exceeded $1.7B USD and $1B USD in Canada with coincident impacts on people, resources, and budgets. In many countries, the loss of timber also represents an economic impact of dozens of millions. In Knysna, South Africa, 1200 structures were destroyed or damaged during the June 2017 fire, with approximately 30% of property owners not having the benefit of insurance to draw upon. Estimated losses due to catastrophic fires in the European Union during the period 2000-2017 accounted for 63.3B EUR, approximately $94B USD. Damages in 2017 alone were estimated at $11.8B USD in the European Union. In the summer of 2015, large parts of Indonesia burned an estimated $16.1B USD in losses and damages, roughly equivalent to 1.9% of the country's GDP.

The transnational effect of the smoke and haze can also be very severe. In 2015, Indonesia and neighboring countries were forced to close schools for up to 34 days resulting in $34M USD in costs. In parallel, high levels of haze cost the transportation sector $372M USD mainly through delays. Immediate health costs totaled $151M USD. In Europe, future projections may increase to over 5B EUR a year of losses (~$7.5B USD), from 3B EUR on average for 2000-2017. Out-of-control conflagrations near country borders could also trigger population movements that could be considered climate-change refugees and represent a new economic burden for receiving countries and NGOs.

It is important to emphasize that adverse impacts can range far beyond human health and costs during the fire: impacts on society can continue for many years after the fire is extinguished. Damage to surrounding commercial plantations, hotels and homes, coupled with the closure of small businesses can result in significant job losses and loss of income from tourism. Studies in the USA show that tourists are less likely to go to places that recently burned. Post-fire rehabilitation to avoid soil slippage and mudslides above homes immediately created a second, costly disaster mitigation intervention that still continues. Mass germination of woody invasive species that favor such fires can create a third

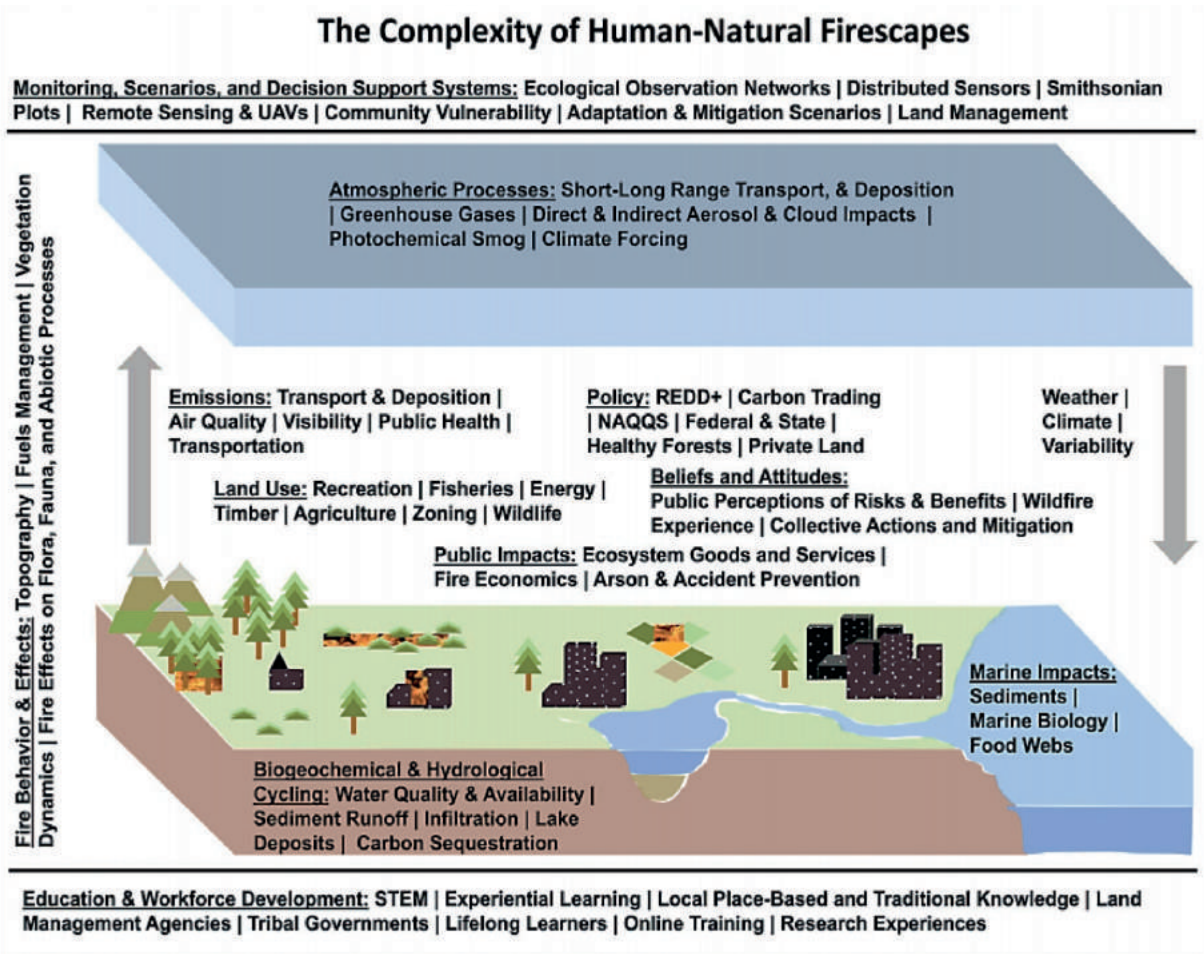

Figure 3: Complex cascading consequences of fire in coupled human-natural systems. Source: Smith et al. 2016

emergency, requiring rehabilitation investments by government and civil society over many years. Re-investment by residents of the town is curtailed, as the fear of re-occurrence is valid.
To date, there is no global data or estimations on national health expenditures, national fire management budgets, firefighting expenditures, or economic losses due to wildfires; a significant gap that precludes appropriate global fire disaster governance. Insights regarding the impact of fires on structure disaster relief response or social relationships are in their infancy and geographically limited.

Enviromental Cost

A key conundrum of fires is that they can have both negative and positive ecological impacts: in many ecosystems fires can be beneficial, sometimes even necessary, to certain flora and fauna, but high intensity fires can be detrimental to even highly fire adapted ecosystems. In some ecosystems, burned areas have been shown to have higher biodiversity levels compared to surrounding unburned sites. The alternation of burned and unburned areas also creates a landscape mosaic that can be beneficial for species using different biotopes. However, in other ecosystems, fires can adversely affect a range of ecosystem functions and services (Fig.3). Indonesia hosts 47% of the global area of tropical peatland, which are massive carbon sinks and thus critical ecosystems to mitigate climate change. Deforestation fires in those peatlands result in negative impacts on animal populations, such as the emblematic orang-outan.

Pyrogenic carbon (PyC) emissions from fires are a major environmental concern. Fire combustion degrades organic material that was sequestered via photosynthesis. Most of the fire emissions of CO_2 are, therefore, not a net source of emission like the burning of fossil fuels except when the burned forests are not allowed to regrow, or when old carbon in peatlands is combusted. In addition, fires are a source of methane (CH_4) and nitrous oxide (N_2O) that further increases the greenhouse effect, and aerosols that amplify albedo and land-atmosphere interactions. The net climate impact of fires and changes therein is complicated and under certain conditions increased fire activity may lead to cooling, although this effect is restricted to snow-covered regions. In the Russian Boreal, the direct carbon emissions from fire were estimated as 92±18 Tg C yr-1 for

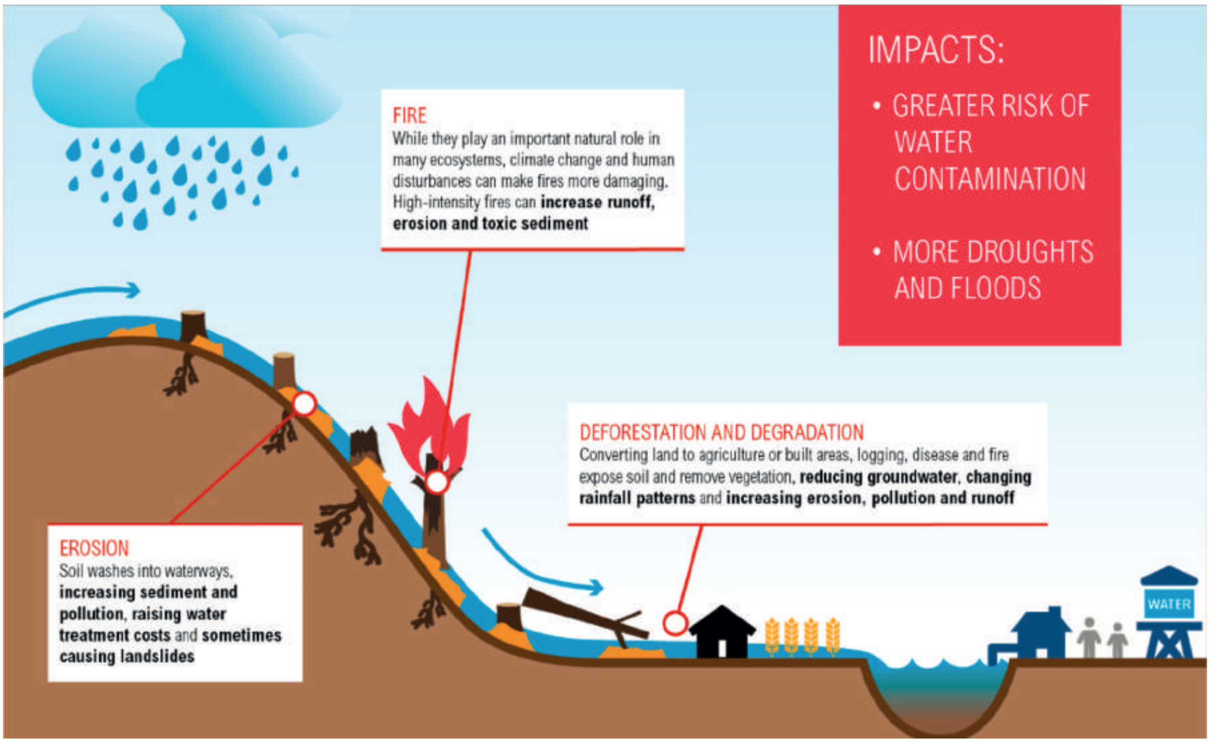

Figure 4: A degraded landscape threatens the water supply. Source: World Resources Institute, 2016

the years 2000-2013. Smoke can also deposit on surface freshwater and impact drinking-water quality, as well as impact plant photosynthetic capacities.

Forests and forested soils are providers of freshwater resources but sufficiently intense fires leave behind burned soils that are bare and highly susceptible to erosion. Severe surface fires can change soil porosity; waxes and oils from litter volatize part of which may condense on soil particles and create or enhance water repellent conditions in soils that act to reduce infiltration and increase overland flow. Reduced microbial activity immediately after fires also acts to reduce soil porosity and pH value. This combined with changes in soil texture and aggregation can lead to increased surface runoff and erosion, with serious consequences on water quantity and quality, among which flash floods and acute water pollution can pose serious threats to water security (Fig.4). More generally, the opening up of the canopy caused by fires may lead to the landscape drying out, in particular through the loss of soil moisture storage. This then could affect the future loss of evapotranspiration outputs to downwind locations and reduce precipitation.

2.4. The Governance of Fires

Research done in Australia identified three categories of actors and stakeholders to consider in wildfire risk reduction:

1. Those that create the risk — the formal planning and land development systems and the informal attitudes and actions of people at risk.
2. Those dealing with the results of the activities that create the risk — the key groups are the fire and emergency services, insurers and groups that work with them such as forest and land managers. In an informal way the media, volunteerism and individual and group behavior are all part of dealing with the risk.
3. Those that create the future risk — these are factors such as urban expansion, governance, changes in lifestyle or values, possibly emergency management trends and climate change. These influences arise both from institutions and from individual choices and behavior.

In general, in most circumstances these three groups of actors and stakeholders are basically operating separately from each other and this may well be a characteristic that is experienced more widely and not restricted to the jurisdictions in Australia. The governance of fires therefore involves the land use and management, as well as the laws, rule, procedures and processes that surround preparing for and fighting wildfires.

Existing Policies

Although fire policies and suppression practices have focused on decreasing the global land area burned every year, there is, despite sky rocketing suppression expenditures, an overall global trend of increasing frequency and intensity of wildfires in inhabited areas, often with extensive social, ecological and economic costs. In countries where fire policies exist, aggressive fire suppression remains the norm combined with few prescribed burns. In places where fires are suddenly becoming a new phenomenon (e.g. in parts of boreal Europe), the introduction of aggressive fire management is the immediate gut-level reaction. However, as far as the authors know, no current national or regional fire policy specifically factors in fire regime alteration due to global change and the consequent changes in risks, although several countries have undertaken projects aiming at reducing future fire hazards linked to climate change.

Policies relating to prescribed burning often pose dilemma to forest managers. On top of reducing fire probability, prescribed burns assist in maintaining soil organic carbon (SOC) stocks by reducing the risk of intense fires and even building up carbon stocks through the incorporation of unburned or partially unburned fragments into the soil. But air quality concerns, implementation capacity, limited burn windows, and liability concerns are often presented as empirical reasons to limit the use of prescribed fire in many places. Ecological consequences of prescribed fires are also largely unknown, although they seem to generally have limited negative impacts.

In many countries, the primary strategy has been to implement a "zero fire policy" for all situations. Fire suppression is at the core of the strategic approach, with little or no recognition of any potential negative effects of eliminating fires from the ecosystem. However, as recognition of the ecological role of fire in certain ecosystems has grown, as well as ways in which suppression may increase long-term fire risk, many countries have begun to pay greater attention to integrating the use of fire into their strategic management approach. For instance, Brazil has begun to take into account the fire ecology of savanna ecosystems of the Brazilian Cerrado, which has evolved under long-term influence of natural and cultural fire regimes. As a result, more attention is being paid to enhancing the capacity of local communities, individual farmers, other land owners and state institutions in the traditional, safe, and ecologically sound application of fire where required or needed and to reduce unnecessary or detrimental burnings. A similar mindset in parts of Canada supports leaving remote fires to burn to enhance the boreal forest mosaic for ecological benefits. This approach is emerging more strongly and has been recently documented, but it is so far the exception rather than the rule and more efforts are needed to acknowledge "positive fire policies" as valid and sustainable options.

Perverse Incentives

In many areas, fires can be a result of other land use demands. Wildfires in tropical forests have increased sharply since about the 1980s when fire started being increasingly used in large-scale deforestation generally in a desire for more industrial uses; globalization of commercial trade for wood, oil palm, meat, and crops is often pointed at as a major driver for this type of deforestation. For example, in the Amazon and Indonesia the use of fire, often illegally, is a leading means of clearing land for oil palm and wood fiber plantations. In Brazil, the Amazon and the Cerrado are the ecosystems with higher occurrence of fires due in part to drought but also to purely economic factors like the price of commodities on the international market.

In many locations, such as European Mediterranean nations, and in north-eastern states of India where shifting cultivation is still practiced, it is the cessation of community fire management practices linked to rural land abandonment that is a major cause of increased fire events. This migration also reduces the collection of fuelwood from adjacent forest floors by the rural people thereby contributing to the accumulation of fuels in forests. There are examples of this in the Indian hill state of Uttarakhand where the incidences of fires have increased in recent years because of accumulating fuel on the floor of pine forests in middle elevation areas. The area at risk of wildfires is continuously expanding as a result of land abandonment and the increase of the wildland-urban interface in many countries.

National forestry and land use policies can substantially affect fire regimes, for instance by establishing highly flammable Pinus and Eucalyptus plantations, although fire hazards are more of a land planning issue than a species issue. Forestry incentives presumably for fuel management could favor large scale plantations, as well as post-fire salvage logging that have negative consequences on biodiversity and soil erosion. In Europe, the lack of forest management in low productivity forests has led to fuel accumulation, fuel connectivity, and increased fire hazard within coarser-grain landscapes. There are examples of singular policy formulations, or a lack of policy formulation, with little or no integration within sector, across sectors or with checks and balances to identify unintended risks and consequences. In developing countries, land use policies giving access to land for cultivation to smallholders favor the extensive but detrimental use of fire creating landscape mosaics of trees and pasture characteristic of silvopastoral/agrosilvicultural traditions to provide green pick for game and stock.

Institutional Responsibilities

As fire does not recognize property boundaries, effectively managing fire risks requires involvement of a wide range of stakeholders (e.g. NGOs, companies, governments). While institutional responsibility for fire risk reduction can be variable across countries, governmental authorities, from local to national, tend to play a critical role for the design and enforcement of national fire strategies. The success of risk reduction strategies is dependent on a deep understanding of how different social dynamics pre- and post-fire can influence fire management. A key challenge here is that governments often tend to follow "Conventional Wisdoms" or "Narratives" about public response to fire management that scientific findings do not support. This can lead to an 'imagined public' and thus strategies less likely to be effective in reducing fire risk and public vulnerability. This is amplified by mass media that have an enormous influence, and therefore responsibility on how fire is perceived by society. Additionally, the methodologies to assess fire risk vary across countries and regions in the world and proper information on global wildfire risk is still missing, although this exercise is envisaged in the Global Risk Assessment Framework (GRAF) of the United Nations International Strategy for Disaster Reduction (UNISDR), supported by data collection in the Global Wildfire Information System.

Policies and practices that fail to take into account needs and concerns of local communities, as well as their traditional knowledge, are unlikely to lead to desirable outcomes. Research has shown that four key social processes are associated with more proactive community response to wildfire issues: 1) the degree that the reason for and process behind a practice are understood by all stakeholders, 2) the level of trust in key institutional actors, 3) the level of interactive communication, and 4) the decision-making role and capacity of the community regarding mitigation, control, and use of fire. In this respect, an overemphasis on command-and-control solutions often found in emergency response approaches to fire management are unlikely to lead to communities and regions more able to absorb increasing fire impacts without significant negative social impacts. Awareness and community engagement thus need to focus not solely on information provision but on interactive and cooperative efforts that can more effectively identify mutual concerns and creative solutions more likely to lead to risk reduction. Awareness is also needed for the institutions of emergency management to ensure they cooperate effectively, flexibly, consistently and continuously with stakeholders, including the local community, all levels of government, other arms of government, the private sector and civil society organizations.

3

3. CLIMATE CHANGE AND FUTURE FIRE REGIMES

3.1. The Fire and Weather Linkage

At a local scale, the prerequisites for a fire to ignite are dry fuels, oxygen, and a source of ignition (i.e., the fire triangle). Fuel desiccation is accelerated when humidity and atmospheric pressure are low and the temperature and wind are high. The latter also favors higher oxygen input and therefore better combustion and spread potential. At a regional scale, fire activity is influenced by vegetation type and pattern, terrain, climate and weather, and people. Fuel amount, type, continuity, structure, and moisture content are critical elements for fire occurrence and spread. Fuel moisture, which may be the most important aspect of fuel flammability, is a function of the weather, and weather and climate also in part determine the type and amount of vegetation (i.e., fuel) at any given location. Temperature, precipitation, wind, and atmospheric moisture are the other weather-driven elements of regional fire activity. A growing body of evidence also points at the global importance of the forest cover for the conservation of vegetation moisture, which would make the historical loss of forest cover and ongoing deforestation another driving feature of fuel flammability.

Additionally, the occurrence of lightning-caused fires is determined by meteorological conditions. Weather arguably is the best predictor of regional fire activity for time periods of a month or longer. Research shows that weather and climate best explained modelled area burned estimated from landscape fire models compared with variation in terrain and fuel pattern. Although wind speed may be the primary meteorological factor affecting the growth of an individual fire, numerous studies suggest that temperature is the most important variable affecting overall annual wildfire activity, with warmer temperatures leading to increased fire activity.

3.2. Scientific Consensus on Climate Change Impacts on Fires

The adaptation of ecosystems to specific fire regimes means they are vulnerable to local extinction should fire regimes abruptly change. There are several ways this can happen, the most common being a change in anthropogenic ignitions, the presence of a novel fuel or a novel herbivore that consumes specific types of fuel, and climate change. Longer and more severe fire seasons can indeed cause drastic changes in plant species composition because populations of some species are unable to recover even when others do. For instance, increased frequency of fires can disadvantage obligate seeder species because they are unable to mature fast enough to provide a seed crop before the next fire, and the few seedlings that establish have reduced survival because of unfavorable climatic conditions, which also reduces seed production by mature individuals and can eventually lead to extinction.

Global projections depict more extreme droughts and a general increase in global aridity. All else being equal, this means more evapotranspiration and drier vegetation. Many locations on Earth might thus experience an increase in fire activity (i.e., the tropics) for a time, until vegetation recovery becomes limited and ecosystems reach tipping points leading to complete change in vegetation assemblage, or potentially desertification. Montane Mediterranean pine woodlands are an example of fire-sensitive ecosystems replaced by shrublands under reduced higher fire frequency and emerging crown-fires in the past few decades in Spain.

The reason for the positive relationship between temperature and regional fire pattern is three-fold. First, warmer temperatures will increase evapotranspiration, as the ability for the atmosphere to hold moisture increases rapidly with higher temperatures, thereby lowering water table position and decreasing forest floor and dead fuel moisture content unless there are significant increases in precipitation. Second, warmer temperatures translate into more lightning activity that generally leads to increased ignitions. Lastly, warmer temperatures may lead to a lengthening of the fire season. From a purely meteorological perspective, the bottom line is that we expect more wildfires in a warmer world (Fig.5).

In short, we will experience more extreme fire weather. Based solely on meteorological aspects we expect more fire occurrence, a longer fire season, more high intensity fires, increased fuel consumption (i.e., more emissions) and more area burned. This can be a problem for fire management as high intensity fires will occur outside the traditional/historical fire season.

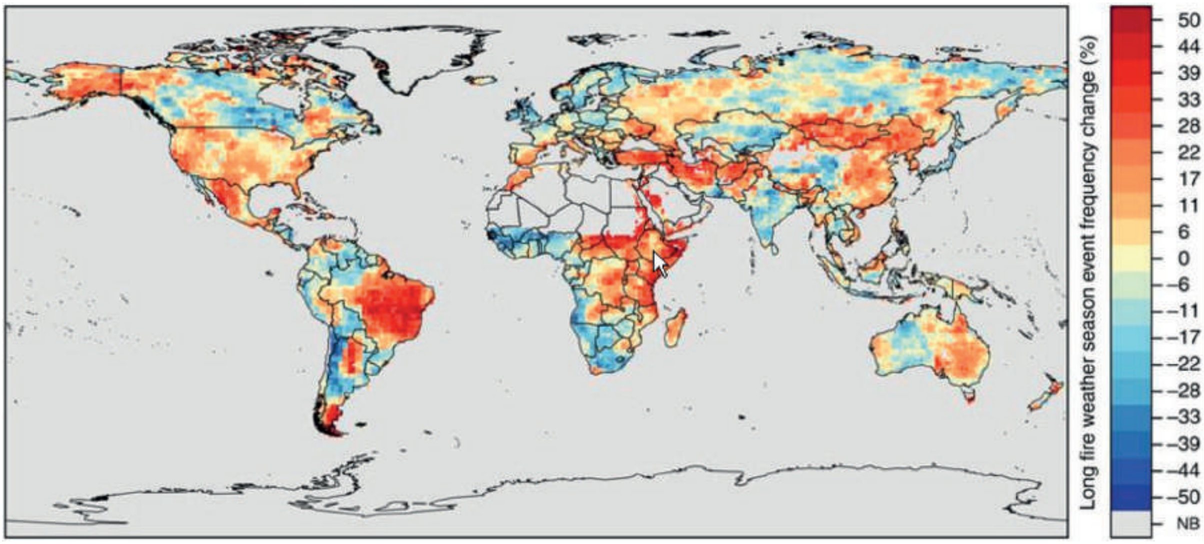

Figure 5: Global changes in the frequency of long fire weather seasons over 1979–2013 due to climate. Reds indicate areas where fire weather seasons have lengthened or long fire weather seasons have become more frequent. Blues indicate areas where fire weather seasons have shortened or long fire weather seasons have become less frequent. Source: Jolly et al. 2015

3.3. Global Climate Modelling and Future Burning Conditions

Climate change leading to more extreme weather events means more fires since extreme weather drives fire activity. Intensely burning fires that occur under dry and warm conditions in flammable fuels release more carbon than fires that occur under cool, moist conditions. Many climate models have projected an overall increase in temperature worldwide and a drying trend in many subtropical and mid-latitude areas thus the frequency of fires is expected to increase in many areas and cause a marked loss of soil organic carbon that might not be compensated by vegetation regrowth.

Ensemble projections from the Fifth Climate Model Intercomparison Project (CMIP5) for different emissions scenarios are summarized in the IPCC Fifth Assessment Report (AR5). Ensemble mean surface temperature increases in the zonal mean under the RCP4.5 scenario range from 1.5-2°C over the tropics and subtropics to greater than 3-4°C over northern North America and Eurasia by 2081-2099. Mean surface temperature under the RCP 8.5 scenario projects high-latitude warming increases to greater than 7°C. Projected precipitation changes are less homogeneous and less certain, but robustly show increased winter, spring and fall precipitation at high northern latitudes of up to 40%. Projected summer increases are weaker and less certain. Over the tropics, there is less agreement across the models, showing a mix of increasing and decreasing precipitation depending on the season. Fire-prone areas showing consistently reduced precipitation are located in southern Africa and the Mediterranean over summers.

More realistic than considering temperature or precipitation changes in isolation is to consider changes in aridity, which account more explicitly for the balance between increases or decreases in precipitation and increases in temperature via its control on potential evapotranspiration. An early assessment showed a southward increasing in drying over North America, drying over northern South America and Chile, very strong drying over Southern Europe and Southern Africa, and along the coasts of Australia. Follow-up studies have shown similar regional drying. Other studies have examined seasonal differences in projected aridity, which are more relevant to understanding changes in fire climate, and projected an increase in the frequency of exceptional drought over much of Canada and Eurasia.

More specific are projections of fire weather using indices used operationally by fire management agencies, which are conceptually similar to offline aridity metrics. Using the Canadian Fire Weather Index (FWI) System — measuring the combined influence of surface temperature, relative humidity, wind speed and precipitation — researchers project uniform increase in the length of the fire season at high latitudes and show regional increases in FWI values during the fire seasons of Central America, southern Brazil, southern Africa and the Mediterranean. Other global studies corroborated these regional findings.

3.4. Fire Projections: A Few Regional Cases

Future Fires in Europe

Climate change predictions for Mediterranean regions foresee an increase in the length of the dry periods, with less precipitation overall, and increased temperatures. These factors will definitely lead to longer fire seasons, which are already noticeable as in the events of 2017 and 2018, and more intense fires in the coming years. While plants in these biomes show fire-adapted traits that enable them to cope with fire, changes in the frequency, intensity and season of fires will cause major plant biodiversity loss and trigger desertification processes. Highly technical fire suppression has shown effects on European burned area in the last decades but management faces multifaceted challenges related to large high severity fires out of suppression capacity, ecological consequences and social acceptance of prescribed fire, increasing trends in human-caused ignitions, and increasing budgetary constraints.

The European Fire Information System has been monitoring fires in Europe over the past two decades, although its database contains longer time series up to 30 years for European Mediterranean countries. Increasingly it is seen that many of these fires take place outside the standard critical fire months of July-September, with the most damaging episodes concentrated in June, October, and even November in the Italian Alps.

Modeling work in Europe has projected a 140% increase in burned areas in the Mediterranean region for the time period 2070–2100 relative to 1985–2004. The estimated potential increase of average annual area burned in Europe under "no adaptation" scenario in the long term is within the range of 120-270% by 2090s relative to 2000s. However, the projected impacts of climate change on burned areas in the EU depend on a multitude of factors. Most work in Europe has been developed assuming that spatiotemporal patterns of ignitions would remain stable. However, recent work done on the inter-annual variability of ignition patterns suggests that human driving factors change with time. For instance, a need for incorporating new explanatory variables related to climate change and to drop others, like interfaces and protected areas, has been pointed out for Spain. Relevance of human-related factors on occurrence also changes within a year.

Future Fires in the Boreal Region

Global climate models and climate change scenarios suggest future fire regimes across the circumboreal region will have more severe fire-conducive weather, increased fire season length (by up to 30 days), and greater fire frequency and area burned, all resulting in increased fire. In North-America, large and intense wildfires result from blocking weather patterns, yielding anomalously hot dry surface conditions. If increased blocking patterns become a long-term feature of climate change, the frequency of large, long-lasting, intense fires in North America will continue to increase. Burned areas in Alaska and western Canada are projected to increase by 250%-450% by the last decade of the 21st century as compared to 1991-2000. Fire is also an important driver of permafrost thaw, releasing both methane and carbon dioxide, so changes in future fire regimes due to climate change could have a substantial impact on global greenhouse gas build-up.

Species with no direct fire survival traits ('fire avoiders') will decline under shorter fire cycles. Seed storing species ('fire evaders') will benefit at the expense of fire avoiders but could face local extinction when fire cycles are shorter than at 25-30 years, the time required to reach full reproductive maturity. Deeper burning fires of greater fire severity support enhanced establishment of deciduous species by seed, suggesting that increased fire severity in the future may promote a shift towards deciduous dominated boreal forests in North America. Studies also show that more active and severe fire regimes combined with a drier climate could promote northward grassland expansion. There are also growing concerns that a worsening fire situation could facilitate the spread of invasive fire-adapted species.

Future Fires in the Miombo Woodlands

Global climate changes and human population growth are a reality in southern Africa. The IPCC predicts a 10% reduction in already erratic rainfall and an increase in temperature of about 1.6°C by 2050 over the region. On parallel, recent estimations indicate that human population in southern Africa is growing at a rate of about 1.28% a year. The implication of both climate change and human growth is still uncertain but there will likely be an increase in fire frequency and intensity with immediate consequences on Miombo ecology. Despite the uncertainties, several scientists have predicted significant reductions in vegetation cover and productivity, as well as changes in the timing and distribution of fires in southern Africa, irrespective of the fire management system. The recent increase in particularly dry years can likely be attributed to climate change.

It is important to highlight that the variable effects of the current fire regime in the Miombo are not completely understood. Fires started by humans as a means of providing additional green stems for cattle seem to reduce fuel loads and promote the establishment of undesired woody species. Early dry-season fires promote landscape heterogeneity by creating islands of burned and non-burned vegetation, preventing the spatial diffusion of damaging fires later in the season. However, this landscape fragmentation has been related to a decrease in plant species diversity and increasing fire frequencies over time in East Africa. These different outcomes suggest scale-specific effects of fires and thus addressing the effects of climate change on the woodlands needs to be scale-related. Regional estimates are important to understand large-scale variations in fire regime but need to be tied up with local-scale studies in order to manage fire risks in a way that integrates the realities of climate change and human growth in the Miombo region.

3.5. Compound Impacts of Climate Change and Future Fire Regimes

Impacts on GHG Emissions

Savanna fires contribute 65% of total GHG emissions annually followed by tropical forests (15%), Boreal (8%) and tropical peatlands (4%). However, savannas also regrow annually and thus take back almost all of CO_2 they emit within a year. The emissions from the boreal and tropical peats, however, are for the most part lost forever and get added to the atmospheric load of GHG and are thus of greatest concern. Over the past decades, emissions from savanna fires at a global scale have declined mostly because of land conversion but fires in tropical forests have increased sharply since the 1980s because of land clearing and farmland maintenance. To date, tropical fire emissions have been mostly fueled by the deforestation process and future emissions are largely a function of socio-economic decisions, with further warming and longer dry seasons being additional factors. Experiments in Amazon forests indicate that increased droughts and continued anthropogenic ignitions associated with frontier land uses may promote high-frequency fire regimes that may substantially alter regeneration and therefore successional processes that balance out emissions by absorbing CO_2 for plant growth.

This situation is different in boreal regions and possibly temperate regions where there is a clear link between anomalously high temperatures and fire occurrence and ongoing climate change. Given the large amount of carbon stored in soils in boreal regions, including tundras where fires have now been observed, this is the most important region for increased fire emissions related to climate change because of the strong warming trend, large amounts of fuel, and relatively minor human interference. With the expected increase in the rate of permafrost thaw with climate warming, a serious concern is the potential for a globally substantial climate feedback due to the resulting increase in soil greenhouse gas emissions and black carbon from fires.

Impacts of Pests and Invasive Plant Species on Fires

While insect attacks are a natural process in any forest, recent years have seen them in epidemic proportions, which have been attributed to both the consequences of fire suppression and climate change. Fire suppression has led to more homogenous (i.e., same tree species and age class) and overly dense forests that have less ability to resist insect attacks. A vicious circle between fire and pests then takes place, with fire damaged trees being more likely to be infected, the insects spread and attack healthy trees which in turn create dead dying and dry trees creating a more acute fire hazard. This problem is most severe in both higher latitudes and altitudes where the effects of climate change have been felt more intensely, putting additional stress on ecosystems. In North America, a larger portion of mountain pine beetles are surviving the warmer winters enabling their population to explode and extend their habitat further north, causing the death of dozen of millions of trees. In Russia, Siberia alone has 1.7M.Ha infected by the Siberian Pine moth, and large areas are affected by an invasive bark beetle. Conversely, the intensely managed European forests have been less affected due to regular thinning, harvesting and other hygienic measures which have increased forest health and tree's ability to effectively resist the insect attacks.

Introduction of a number of invasive species (e.g. acacia, cheatgrass) can also present a significant threat to native ecosystems not merely by affecting biodiversity but also by increasing the system's vulnerability to fires. Positive feedbacks can allow the invasive plant to increase its presence by increasing fuel availability resulting in increased fire intensity that could in turn allow the more fire resistant invasive species to dominate more components of the native ecosystem, further influencing the fire regime in favor of the invasive plant. In savannas, invasion by woody species may increase fuel loads several fold and cause a shift from low-intensity surface fires to higher-intensity canopy fires. Similarly, invasion of grasses and woody species encroaching into arid shrublands in southern Africa and the Mediterranean could radically alter the seasonality, severity and frequency of fires in these ecosystems.

Fire category	CO_2	CH_4	N_2O	All	Contribution (%)
Savanna	4.85	0.19	0.17	5.21	65
Boreal forest	0.51	0.07	0.04	0.62	8
Temperate forest	0.17	0.01	0.00	0.19	2
Tropical forest	1.07	0.11	0.04	1.22	15
Tropical peatland	0.23	0.10	0.01	0.33	4
Agricultural waste burning	0.44	0.06	0.01	0.50	6
Total	**7.27**	**0.53**	**0.27**	**8.08**	**100**

Table 1: Fire greenhouse gas emissions (in CO_2 equivalents) for various fire categories based on the Global Fire Emissions Database (GFED4s). Source: van Der Werf 2018

4

4. IMPACTS OF FUTURE FIRE REGIMES ON SOCIETIES

4.1. On the Wildland-Society Interface

Historically, development has taken place in fire-prone and fire-adapted landscapes with little consideration for the potential natural hazards, whether these are the need for fire to occur as part of the natural fire regime, fire exclusion policies relating to land use such as commercial plantations, changes in land use such as land abandonment, or absence of land use planning that takes hazards into account. All can substantially increase the fire hazard for societies living nearby, but very seldom are communities engaged meaningfully in planning, mitigating and reducing the hazards on their doorstep, so that the fire risk is lowered. The likelihood of catastrophic fires impacting upon communities already exists, with or without alteration to fire regimes due to climate change. Unless civil society is fully engaged in a call to action, adaptation to future conditions is unlikely. Adaptation requires a change of social mindset from feeling helpless to one of living with fire and being personally prepared.

Increased potential for very large fires is projected across most historically fire-prone ecosystems. As the intersection between fires and human activities and communities grows, governments and managers must expect an increase in the likelihood of extreme fire events leading to potential disaster situations. Continuing changes in climate, invasive species, and consequences of past fire management, added to the impacts of larger, more frequent fires, will drive further disruptions to fire regimes of fire-prone ecosystems of the world. Ignitions caused by human activities are a substantial driver of overall fire risk to ecosystems and economies. Given this, it will be important for people living in fire prone areas to plan for and be prepared to live with fire. While some specific locations may be so hazardous that building should be strongly discouraged, this likely will not be feasible in many places due to other population and economic demands.

In many other parts of the world rural communities live in homesteads made of wood and thatch in enclosures and there are no fire services to assist them. In fire-prone areas, these communities are exposed to runaway fires and can suffer damage to property, crops, livestock and even human lives. Similar situations also exist in a large number of small urban communities living close to forests in the western part of North America, Mediterranean regions of Europe and South Africa and in South America where the loss of lives in fires is not uncommon. Therefore, most important will be providing appropriate institutional support to encourage local capacity building to support activities that can effectively mitigate the local fire risk. In some areas this could mean a focus on building fire resistant infrastructure and structures and support of appropriate land management activities (e.g. removing flammable invasive vegetation, use of prescribed fire or thinning dense vegetation).

4.2. On Agricultural Land Uses

In tropical wet forests, in developing countries where shifting cultivation is still practiced, fire is a useful tool because it quickly and effectively reduces the biomass of newly cleared forests, transforming it to nutrient-rich ash that can fertilize crops. Most fires currently used in shifting cultivation lands are maintenance fires intended to consume the vegetation that grows in the interim fallow period. With limited fuel availability, these fires last a short time and only seldom cause ancillary damage.

In 1950, less than one third of the world's population was urban; in 2018, it is estimated to be 55%, and by 2050, 68 % of the world's population is projected to be urban. Such rapid urbanization invariably involves significant abandonment of rural lands by landowners because resource management from a distance is not feasible and also because policies and laws in many countries discourage owners from leasing out their lands. Many recently abandoned lands are overtaken by annual grasses and shrubs, along with a few pioneer species of light demanding trees. However, it is worth noting that rural land abandonment happens predominantly in developed countries where farming activities tend to decrease. In savannas, fires used for ongoing conversion to cropland especially in Africa where the population growth projections are highest will likely lead to a further decline in fire activity, despite climate change. Although it seems desirable, decreasing fire activity will negatively impact the resilience of those fire-prone ecosystems to new climate conditions and, on parallel, will favor fuel build-up, fire escape from surrounding rural lands, and consequently more intense and potentially dangerous fires.

To date, a significant part of human-caused fires have been linked to land use conversion and agricultural activities. Coping with future fires will thus be partly a function of socio-economic decisions, in addition to the effect of climate change. Future extreme fire behavior may turn traditional fire breaks such as agricultural areas into flammable landscapes, and the traditional use of fire for land clearing or maintenance may become unsafe with a higher frequency of extreme fire weather. Promoting agricultural techniques and crops that can substitute for the role played by fire in agricultural production coupled with strict land use management could minimize the risk of wildfires, although more research is needed on this topic. Failure to adapt to climate change in agricultural landscapes will lead to degradation from an unusual combination of droughts and frequent fires leading to post-fire soil degradation, and eventually desertification limiting agricultural or forestry capacities of the land.

5

5. ADDRESSING THE CHALLENGES OF FUTURE FIRE REGIMES

5.1. Towards Global Fire Governance

Integrated Governance Enviroment

Addressing wildfire disaster risks begins by acknowledging the diversity of fire uses in the world, and the fact that fire can be a necessary tool for community survival. However, translating global scale guidelines expressed in the SDGs or the NDCs into a locally-adapted set of fire management recommendations is complex. Knowing how society perceives prescribed burning, and restoration of the natural fire regime is critical to gain social support. Although top-down approaches to fire management are needed, there is a need to move away from paternalistic/controlling strategies to ones that enable all stakeholders to have more responsibility in fire risk management decisions. Current social science work has shown how local context can have an important influence on acceptable and beneficial fire management practices. It is therefore important to understand the social context of fire on parallel to the natural fire context at a given location (Fig.6).

A key need is the development of national action plans that lay down the principles for managing fires, beginning with a clear statement of goals and priorities. Such a plan should also address the respective roles and responsibilities of different levels of governments, the role of implementing agencies, the role of the civil society, and establish funding mechanisms. Formulating the plan should be an open, participatory, consultative, and time-bound process. This may be followed by the development of similar action plans at the next lower level of the political jurisdictions, after collaborative discussions with agencies and all stakeholders, including communities at risk, environmental associations, and industries. The directives of regional policies could then be incorporated in landscape management plans at the district or county levels. Although solutions to fire risks lie in holistic environmental management and governance, in the end, adaptation to fires can only be achieved with political willingness to address the problem.

Although recent catastrophic fire events can serve to reinforce current policies of total fire suppression that have found support in Western countries for decades, such a ‚No Fire' approach is not a realistic option. Besides the potential undesirable ecological effects, such a focus on short term fire risk reduction tends to increase the long-term fire risk. Learning to co-exist with fires means involving communities, building trust, understanding their concerns, and engaging in a transparent discourse to decide on the policy options, options that should be recognized in the national fire plan and that should consider local and traditional knowledge in fire management. Without adequate attention to the complexity of the social situations there are good chances that the efforts towards integrated fire management will fail and that national fire policies will default to mere fire suppression, which would impede adaptation to future fire threats.

Nationally Determined Contributions (NDC)

In the Nationally Determined Contributions notified under the Paris Climate Agreement all countries where fires are a significant source of greenhouse gas (GHG) emissions — Indonesia, Russia, Brazil, USA, Canada, China, Australia and India among others — have promised enhancement of forest carbon sinks as a significant climate-change mitigation measure. Indonesia has specifically mentioned reduction of emissions from fires as an objective. Russia has acknowledged that rational use, protection, and maintenance of the boreal forest are key elements of its policy to reduce GHG emissions. China and Brazil have indicated their intentions to strengthen and enforce forest resource protection at all management levels. Canada has included the protection and enhancement of carbon sinks in forests, wetlands and agricultural lands in its Framework on Clean Growth and Climate Change.

Australia has pledged to reduce its greenhouse gas emissions by 26-28% below 2005 levels by 2030, a significant part of which emanates from fires. India has made no mention of emissions from fires in its NDC but its huge forest sink target of an additional sink of 2.5 to 3 billion tons of CO_2 by 2030 is not achievable unless effective fire management is made an integral part of its strategy. Quantifying peat emissions will also be a key factor for successful climate change mitigation strategies, particularly in Indonesia, but also in the boreal forest where permafrost thaw makes more peat available for burning.

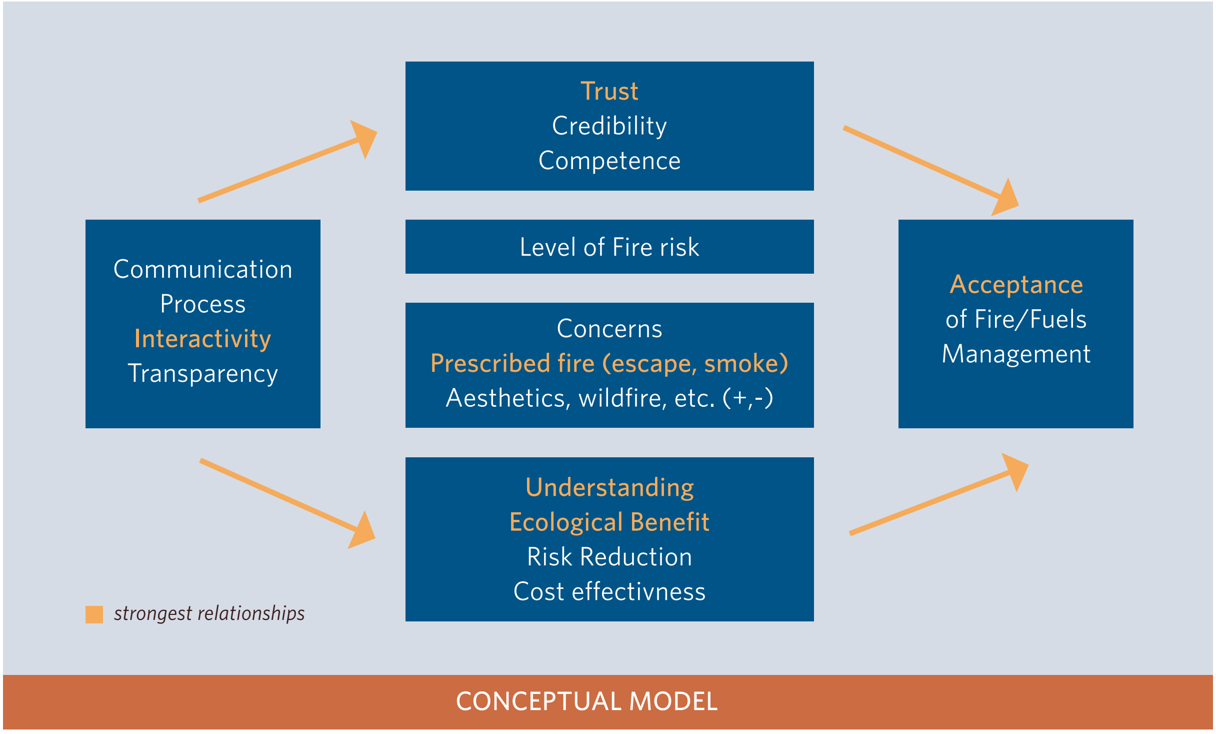

Figure 6: The fire/fuels management public acceptance model. Source: McCaffrey and Olsen 2012

5.2. Gathering Fire Information

Collecting and Sharing Fire Data

Understanding the role of fires in the functioning of societies and ecosystems is necessary for designing appropriate adaptation and risk reduction strategies. Fire risk reduction is facilitated by reliable data collection and analysis to report or estimate human and economic losses, fire mitigation expenditures, and firefighting expenditures. However, at a global scale, it is difficult to foresee that global information on fires could be obtained from the aggregation of national/regional datasets, because of the diversity of definitions of fire, differences in methodologies, political problems leading to discontinuity/gaps in data collection, lack of means/funds, etc. That being said, the evolution of fire services from remote sensing has advanced dramatically in pre-fire biomass estimation and carbon stocks, fuel classification, hotspots and burned area products, biomass consumption, fire severity and emissions. Those technological progresses must be built on to create standardized methods to be used in the assessment of socio-economic and natural consequences of fires.

The uncertainties surrounding the causes, factors, and consequences of current and future fire activity in many regions hinders efficient fire risk reduction and makes development of appropriate modeling techniques difficult. Collection of fire records and procedures vary between countries and jurisdictions, and recording of fire regime metrics such as ignitions, area burned, or fire severity is lacking in many countries and globally. The development of a global network of long-term social and ecological research sites is necessary to monitor the local effects of global environmental change and evaluate their impacts on fires. Already existing sites in North America and Europe could be used as references to locate and design future research locations. Such a network led by a consortium of universities and international organizations would provide an open access to the collected data so global change forecasting and planning capacities towards designing better options for fire risk reduction can be improved.

Where communities are at risk, it is necessary to intervene through appropriate mitigation measures, which could involve participatory appraisal and the selection of less vulnerable vegetation in wildland-community interfaces, for instance. However, there is to date no public repository where damage assessments or community-based management methodologies can be shared and discussed among stakeholders. This could be another area for international cooperation.

Global and Regional Fire Modeling Efforts

New approaches to global fire governance must be informed by projections of future fire activity, beginning with projections of future climate. Future projections of aridity are dependent on data available and modeling choices, and do not necessarily agree. However, drier conditions are projected consistently over Central America, Chile, the Mediterranean, Southern Africa, and coastal Australia, and more severe fire weather emerges at higher latitudes from season-specific studies compared to the annual mean. Although climate change will make some ecosystems more flammable, there is uncertainty as to the magnitude and geography of those changes and their interaction with changing land cover and patterns of human development. This uncertainty creates legitimate concerns regarding what future fire landscapes might look like, which in turn will influence how best to live with fires. It will be critical to understand long-term trends and changes in certain weather conditions (e.g. maximum temperature, annual rain-free days, maximum wind speeds) that are key determinants of severe fire weather.

In moving beyond aridity or fire weather indices, there is a nascent body of work to consider dynamic vegetation and human activity in making projections of future fire activity, but which show varying projections of fire. There is now a coordinated effort under the Fire Modeling Intercomparison Project (FireMIP) to systematically compare historical performance and projected changes in global fire activity, and to reconcile the wide spread in projections of future fire activity for more comprehensive models. Ultimately, this work is being done in the context of a greater focus in Earth System model development on coupling between human and climate systems.

There is a great heterogeneity on the information available for different topics in fire science. Research on human-caused fire occurrence studies has mainly focused on mixed temperate forests, and Mediterranean forests, woodlands and scrubs, while Africa and Latin America, which are among the most active fire areas in the world, have been understudied so far. Research on emissions, for instance, has produced several studies on emission factors in tropical forest and savannas in Brazil, Africa and Australia. On the contrary, emission studies in Europe and central Asia are scarce. For boreal forest, though 20% of the total fire emissions come from this region, only info from Canada and Alaska is available. Models coupling climate models and vegetation change are very much in their infancy, and the Fire Modeling Intercomparison (FireMIP) project now underway will work at a systematic evaluation of fire models with common climate drivers in order to decrease projection uncertainties.

5.3. Tackling Climate Change and Future Fires on the Ground

Fire Suppression

Modeling work done in Europe estimated a potential increase of average annual burned areas under "no adaptation" scenario to be within the range of 120-270% by the 2090s relative to the 2000s. Improvements in fire suppression might reduce the impact of climate change. Boosting the probability of putting out undesirable fires within a day by 10% would result in about a 30% decrease in annual burned area. However, fire suppression while it can delay ultimately cannot mitigate fires over the long term as some wildfires will continue to exceed the capacity of suppression, especially given an increase in fire weather severity. Fire suppression may even have detrimental long-term consequences by increasing fuel loads leading to more extreme future fires, which will eventually make fire suppression more expensive.

Recent fire events around the world have shown how domestic response capacities can be overwhelmed during the occurrence of multiple extreme fire events straining fire suppression capacities, and international assistance must be requested. However, the existing international disparities in the preparedness level of firefighters can limit the efficacy of international assistance. There is therefore a need to encourage and expand international cooperation, and a need to develop an international firefighting protocol through the conduct of joint exercises, the development of standard operating procedures, safety rules, and increased familiarity with equipment used across the countries. The use of the same language between cooperating countries should be mandatory in order to avoid serious, and maybe fatal, errors.

Suppressing and avoiding fire might only fit best in the urban portion of the landscape. In forests and associated predominantly natural landscapes, fire is an inherent property of fire-adapted ecosystems and needs to be used judiciously to manage fuels to safe levels while protecting and enhancing biodiversity. This is best done through active land management and use of prescribed burning to keep fuels at manageable levels and to keep fires at low intensity. The goal is to make the landscape resilient. The intrusion of people into fire-adapted landscapes requires other strategies of hardening structures to resist fire and landscaping the vegetation around structures to keep fires on the ground and low intensity.

Fire Mitigation

Mitigation is a key, often missing, link in fire management and should receive unhindered policy support. It should be carried out by developing region-specific protocols for dealing with all aspects of fire risks and make communities 'FireSmart' or 'FireWise' (i.e., fire-resistant). The process is best begun with extensive stakeholder engagement and an awareness-creation process, fire risk zonation and mapping, effective communication, empowerment of communities, and improved law enforcement. In practice, communities have been, and in many places still are, an integral part of effective fire management. Three key social processes are associated with more proactive community response: 1) the degree that the reason for and process behind a practice are understood by all stakeholders, 2) the level of trust in key institutional actors, and 3) the level of interactive communication.

In most countries, mitigation activities include the creation and maintenance of fuel breaks and prescribed burning. In Europe for instance, the application of prescribed burning has the potential to reduce burned areas in the 2050s and keep the increase in the 2090s below 50% compared to the 2000s. The estimated impact of prescribed burning is also in accord with other studies on the effectiveness of prescribed burning for fire hazard reduction, suggesting threefold and twofold differences between the average size of fires in treated and untreated areas in US and Australia respectively. However, prescribed burning is primarily meant to create areas of lower intensity during a fire event and does not create a fireproof landscape. A fire mitigation approach fully based on prescribed burning will therefore not work. In developing countries with highly populated rural areas, timing of burning for agriculture and pasture management is the issue, in order to avoid escaped fires into the natural vegetation. The solution lies in awareness, better weather information to time burning, and community fire management to organize effective suppression when fires get out of control.

Although it may seem appealing to emphasize the risks of fire, it is important that communication strategies don't focus on fear which has been found to be an ineffective motivator for taking protective actions. The 'Smokey Bear' syndrome is an illustration of how turning fires into evil can have detrimental consequences in the long term. Terms like 'mega-fire' or 'unprecedented' may seem appealing from a media point of view of getting attention, although such phrasing is unlikely to lead to appropriate fire risk management practices. In fact it may serve more to reinforce the tendency to believe that the only appropriate response to wildfires is a warfare-type of approach. Those terms also suggest that the large and severe wildfires that occur nowadays have no analogs in the past, which is erroneous since a quick glance at historical records would clearly identify fires had occurred before.

Fire danger rating is the cornerstone of fire management. In contemporary fire management organizations, fire danger rating provides a metric that is used to support many daily operational decisions (suppression resource needs, alert levels, mobilization and positioning), and longer-term strategic planning (defining burn prescriptions, justifying financial requirements, assessing future fire risk, etc.). Fire danger rating is a mature science with almost a century of research, development and applications. As such, it forms the basis of many global and regional fire models. Due to the extensive history and experience in using fire danger rating systems, many new national systems have been successfully developed through technology transfer and local adaptation for countries without the necessary financial or institutional capacity. Global and regional early warning systems have also been developed by combining fire danger rating information with various remotely sensed landscapes, active fire and medium range forecast weather data. These early warning systems provide key information to support international suppression resource-sharing agreements, which is an important fire management strategy recognized by the global fire community for combatting the increasing severity of fire seasons under climate change.

Fire occurrence is not stationary; on the contrary, it is highly variable in time and space, displaying changing trends that can be modelled with different techniques. Enhanced fire risk mitigation requires better fire behavior models, an area of very active research in the US. Most fire models are based on the Rothermel fire spread model, a model that was performant for when it was developed but very simplified and it does not meet the modern demand for realistic fire behavior modeling. Physics-based models that are being developed capture the way fire moves over the landscape but also are better coupled with fire weather, including fire-weather created by extreme wildfires themselves. These are the fires that account for most of the area burned and that are likely to increase in occurrence under altered future climate.

Forest Landscape Restoration

Forest Landscape Restoration (FLR) is "the ongoing process of regaining ecological functionality and enhancing human well-being across deforested or degraded forest landscapes" (Fig.7). The success of FLR is based on the premise that healthy landscapes provide a diversity of long-term benefits that can only be sustainably managed by and for the local population. This approach is at the heart of the Bonn Challenge, which is a global effort to bring 150 million hectares of the world's deforested and degraded land into restoration by 2020, and 350 million hectares by 2030. Therefore, FLR recognizes the need for local and adaptive options and that the "one size fits all" model is to be avoided. Anthropogenic fire has been a major cause of forest and land degradation in many regions of the world, thereby threatening the achievement of SDG #15. Nevertheless, fire is inherent in many ecosystems and attempts to entirely exclude fire generally would lead to further degradation. To understand the role of fire in fire-adapted ecosystems is to recognize its significance in sustaining healthy forested landscapes.

FLR and fire can be viewed in two ways: restoring burned areas following severe wildfire and restoring fire into adapted ecosystems to correct long periods of fire suppression. These are not distinctly different scenarios since high severity fires can occur because of hazardous fuel loads due to suppression and re-introducing the historical fire regime can be an element of restoration. Similarly, restoring the historical fire regime may be the way to avoid high severity wildfire in the future. Besides re-introducing fire through prescribed burning or allowing wildfires to burn safely, other restoration treatments will help increase resilience of forest and landscapes in general to fires, through moisture conservation, fuel management, and control of invasive species. Acknowledging that many ecosystems are adapted to periodic burning and contain species that depend on fires to thrive means that restoration opportunities will have to include local fire management needs as an integral part of their strategy. In restoring burned landscapes, FLR can benefit local ecosystem services by mitigating post-fire impacts such as soil erosion, sedimentation, and watershed degradation. In some instances, restoring fire may benefit biodiversity, e.g. by enhancing habitat for rare or endangered species. Therefore, FLR will have to integrate the use of fire as a part of the solution to maintain ecological integrity.

It is more and more common to talk about the restoration of natural fire regimes. But what does natural mean in the context of human dominated landscapes and possibly changing fire regimes? Restoring a semblance of historic fire regimes in forests subjected to long-term fire suppression could stabilize carbon by trading-off multiple low-intensity prescribed fires versus infrequent high-intensity fires. But the historic fire regime may indeed be one of infrequent, high intensity fires. What about ecosystems that have evolved with human-caused fires, such as in the Mediterranean, which is a highly-modified and cultural landscape, as much as a pyrodiversity hotspot? The more ecosystems change the more difficult it will be to restore historic conditions; indeed attempts to "set back the clock" might not be desirable. The concept of the New Normal, or New Reality, essentially suggests that adaptation must always consider and adjust for new stages of environmental development, which means that action cannot be aimed at what is natural, but rather at adapting to new stages in Earth system and human evolution.

FLR does not involve covering the landscape with forests and examples of failed afforestation can be found. Originally, forest landscape restoration practices would not create new forest lands where forest did not exist before degradation. As biome distribution is expected to evolve, that expanding existing forest cover where possible and where suited and adapted to the local environment, is likely to further promote both resilience and permanence, in particular because of the positive climate promoting benefits of forest cover. There are of course places where additional forest cover is unsuited to the local environment. And in such cases, for the most part, expanding forest cover is only likely to exacerbate the potential for natural disturbances. But where the opposite it is true, forests can frequently and reasonably be expected to improve and enhance the local environment, temperatures and also the regional water cycle.

Although FLR favors historic fidelity, native species, and strongly advises against ecosystem conversion, the challenges imposed by climate change will require adaptation to novel conditions including novel fire regimes that may arise spontaneously or as a result of intentional adaptation. For example climate and fire influence the transition between forest and grassland; novel conditions may favor restoring forest where historically grassland

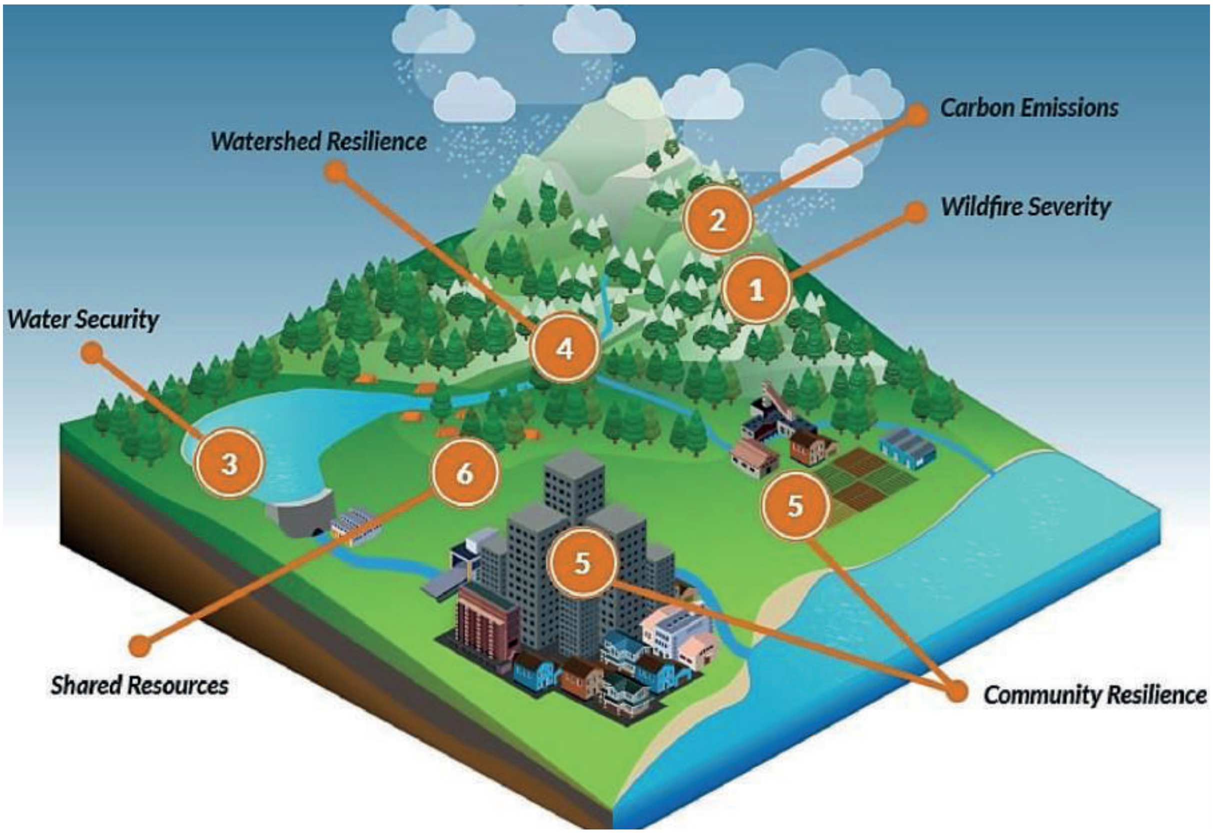

Figure 7: The benefits of forest restoration. Source: the Forest Resilience Bond, "Fighting fire with finance", 2017

persisted or vice versa. Considering "assisted migration", the process by which species are relocated by humans, might be an efficient way to integrate climate change adaptation into restoration strategies, thereby enhancing the resilience of newly restored landscapes. Altered climate may spontaneously give rise to novel vegetation assemblages with fire regimes outside our experience; this will require research and collaboration with affected communities to develop sustainable fire risk management strategies that maintain desired forest functions, in particular supply of quality water.

Sustainable Forest Management

Sustainable forest management (SFM) means the environmentally appropriate, socially beneficial, and economically viable management of forests for present and future generations. The application of this management strategy would assure the maintenance of ecosystem services (ES) provided by natural or restored lands. ES are the benefits people obtain from nature, from the provision of timber, water and medicine, a spiritual connection, the pollination of crops, buffering of natural disasters, and more. Healthy ecosystems maintained, restored, or protected through sustainable forest management therefore provide a multitude of services that can be capitalized on to reach the SDGs. However, the preservation of forests and their services requires financing. As it is illusionary to fund 100% of sustainable forest management needs, the recourse to forest-smart investments, product certification, and payment-for-ecosystem-services schemes are likely the path forward.

Climate-change driven shifts in forest composition may lead to increased exposure to fires and may change the capacity of forests to offer ES, as well as further tax already overburdened emergency services. The health of forested watersheds around the world will likely be strongly impacted, leading to a decrease in evapotranspiration outputs. Iterated across up- and downwind space, this will have an increasingly powerful impact on rainfall in locations that are more dependent upon precipitation recycling. At the end of this chain, some downwind communities could suffer significantly by losing an important share of their water. As the hydrological cycle accelerates, terrestrial water balance faces greater disturbances, with an increase in extreme weather events and the alternation of droughts and floods. Droughts favor fires, and heavy rainstorms will favor rapid post-fire hydrological response. An increasing demand for water under climate change will put higher pressure on water distribution systems and the power grid fed by hydro-electricity, making this overall water-dependent system much more vulnerable to fire disturbances. In short, increasing fire activity might represent an additional challenge to preserving water security in many regions.

The future of SFM therefore lies in the protection of the existing forest cover and composition cover and where appropriate incorporating holistic and community-based fire management that includes periodic prescribed burning. Particularly, protecting and restoring "water towers" that are the high altitude, montane and cloud forest regions are of particular importance. Situated at the "receiving end" of forest-water hydrologic cycle, with the potential to directly extract moisture out of the atmosphere, many montane and cloud forests contribute disproportionately to downstream runoff. Not all places in the world are experiencing increasing temperatures and declining rainfall. Some, like the Boreal region, are experiencing rising rainfall due to an acceleration of the hydrologic cycle. Placing transboundary and transregional forest continuity at the core forest management strategies and natural reserve design would help maintaining atmospheric moisture circulation and thus limiting fire occurrence, as well as conserving water and other ecosystem services provided by primary, secondary, or restored forests. A study conducted in Myanmar indeed suggests that protected areas experience 11% fewer incidences of fires than those lying outside, which indicates that, where appropriate, a legal protection status can be an effective way for fire risk reduction.

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6. CONCLUSION: LEARNING TO LIVE WITH FIRE

We live on a flammable planet; although not everything is meant to burn, fire cannot be eliminated. Ongoing global climate change combined with other planetary changes is leading to more frequent and more extreme fires exposing vulnerable societies, economies, and ecosystems to disaster situations. The recognition of fire activity as a worsening hazard threatening human security is the necessary first step towards international cooperation for the mitigation of disaster risk situations in fire-prone areas.

However, we are not defenseless. Fire scientists in many regions of the world have been developing successful strategies and tools based on cutting-edge technologies for several years. Those are now mature enough to be up-scaled and adapted to other geographic contexts as part of national fire management frameworks. Additionally, integrating existing and future scientific knowledge on climate change and changing fire regimes, and systematically collecting long-term data on current and past fire uses will foster better informed decisions and models and enhanced efforts towards wildfire disaster risk reduction, as well as contribute to the development of sustainable Anthropocene fire regimes.

We hope this paper will be a catalyst for paradigm shift so fires are not seen as an enemy to fight but as natural and necessary phenomena, as well as a useful and necessary tool that can often help protect people and nature. It is paramount to revise, fund, and fulfill future management, research, and governance needs if we are, as world citizens, to trigger a societal change that will help us better live with fires.

The information and insights contained in this Occasional Paper connect together to promote the use of several existing solutions to the problem: defining national fire risk reduction frameworks, collecting and analyzing relevant traditional knowledge and biophysical fire data, investing in fire detection and prediction technologies, involving and preparing stakeholders, and improving fire use and landscape management in ways that help control the fuel load and the spread of fire, while limiting GHG emissions and protecting the communities and the landscapes they live in and often depend on.

Status Quo is no longer an option; it is time to make integrated fire management the rule rather than the exception.

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ANNEX 1

Forest Fires Global Expert Workshop

Vienna, Austria, 2-4 July 2018

DRAFT PROGRAMME

Sun-01-Jul	Mon-02-Jul	Tue-03-Jul	Wed-04-Jul	Thu-05-Jul
Arrival	Workshop	Workshop	Workshop	Departure

Venue: Gustav Hempel Haus at Knödelhüttenstraße 37, 1140 Vienna

ANNOTATED AGENDA

DAY 1	Time	Subject Responsible
02 JUL 2018	08:15	Travel to workshop venue
	09:00 – 09:30	**OPENING OF THE WORKSHOP** Opening remarks by IUFRO and PROFOR Moderator: Michael Kleine
	09:30 – 10:30	**SETTING THE STAGE** • Objectives and purpose of the issue paper • Workshop programme and methodology • Format, authorship and dissemination • Framework and scope Moderator: Michael Kleine *Audience Q&A and Discussions*
	10:30 – 11:00	Tea/Coffee Break
	11:00 – 12:30	**CONCEPTUAL BACKGROUND AND OVERVIEW OF THE TOPIC (Part 1)** Overview of Global Forest Fire and Climate Change (Mike Flannigan) State of knowledge on forest fires • Boreal Fires (Bill de Groot) • Forest Fire and Peat Swamps (Daniel Murdiyarso) • Forest Fires in Cerrado and Amazonia (Lara Steil) • Forest Fire in South America (Patricio Sanhueza) Moderator: Michael Kleine *Audience Q&A and Discussions*
	12:30 – 13:30	Lunch
	13:30 – 15:30	**CONCEPTUAL BACKGROUND AND OVERVIEW OF THE TOPIC (Part 2)** • Forest Fires in Southern Africa (Natasha Ribeiro) • Forest Fire in North America (William Sommers) • Forest Fire in Mexico and Central America (Alfredo Nolasco Morales) • Forest Fire in Russia (Dmitry Schepaschenko) • Forest Fire in Hindukush Himalayas (A.K. Mohanty) • Scientific consensus on impact of the changing climate on forest fires Moderator: Michael Kleine *Audience Q&A and Discussions*

02 JUL 2018	15:30 – 16:00	Tea/Coffee Break
	16:00 – 17:30	**FUTURE CLIMATE AND ALTERED FIRE WEATHER** The fire and weather linkage Global climate modelling Local climate modelling challenges Forecasting other environmental factors (e.g. river water flow) • Global Forest Fire Modelling (Robert Field) • Forest Fire Modelling (Britaldo Soares Filho) • Modelling Forest Fire in Indonesia (Andrey Krasovskii) Moderator: Michael Kleine *Audience Q&A and Discussions*
	17:30 – 18:00	Group Discussion and Summary *Audience Q&A and Discussions*
	18:10 – 18:30	Transport to hotel
	19:30	Dinner near hotel

DAY 2	Time	Subject Responsible
03 July 2018	08:00	Shuttle departs hotel for workshop venue
	08:30 – 10:30	**IMPACTS ON FUTURE FIRE REGIMES, FORESTS AND PEOPLE (Part 1)** Fire Regimes and Forests • Fire Adapted Forest Ecosystems (David Bowmann) • Wildfires and Water (David Ellison) • Forest Fire and Soil Hydrology (François Robinne) Moderator: François Robinne Audience Q&A and Discussions
	10:30 – 11:00	Tea/Coffee Break
	11:00 – 12:30	**IMPACTS ON FUTURE FIRE REGIMES, FORESTS AND PEOPLE (Part 2)** Fire and society • Social Aspects of Wildfire (Sarah McCaffrey) • Changing Trends in Forest Fires and Social Perceptions (Cristina Vega- Garcia) Moderator: François Robinne *Audience Q&A and Discussions*
	12:30 – 13:30	Lunch
	13:30 – 15:30	**ECONOMICS OF FOREST FIRES** Economic valuation of forest fire losses (Britaldo Soares Filho) • Economic benefits of burning forests to small communities • Economic costs of forest fires • Ecological costs of forest fires • Direct loss of human lives in forest fires Moderator: François Robinne *Audience Q&A and Discussions*
	15:30 – 16:00	Tea/Coffee Break
	16:00 – 18:00	**MITIGATION AND ADAPTATION OPPORTUNITIES** Greenhouse Gas Emissions on Forest Fires (Guido Van de Werf) Forest Fire and Nationally Determined Contributions (Janice Burns) • Mitigation • Adaptation • Forest Landscape Restoration (FLR) as forest-smart solution Moderator: François Robinne *Audience Q&A and Discussions*

	18:10	Transport to hotel
	19:00	Dinner in Vienna's historic city centre

DAY 3	Time	Subject Responsible
04 July 2018	08:00	Shuttle departs hotel for workshop venue
	08:30 – 10:00	**ENABLING ENVIRONMENT FOR EFFECTIVE FIRE RESPONSE OPTIONS AND RESTORATION (Part 1)** • Governance, legislative and policy frameworks (A.K. Mohanty) • Policy and law enforcement • Policy responses and cross-sector coordination/cooperation Moderator: Michael Kleine *Audience Q&A and Discussions*
	10:00 – 10:30	Tea/Coffee Break
	10:30 – 12:30	**ENABLING ENVIRONMENT FOR EFFECTIVE FIRE RESPONSE OPTIONS AND RESTORATION (Part 2)** Emergency responses (e.g. fire suppression) Capacity development at institutional and individual levels Climate financing for forest fires • Forest Fire Management Practices in Developing Tropics (Mark Cochrane) • Forest Fire Management in Indonesia (Israr Albar) • Fire Danger Rating System (Vikram E.) Moderator: Michael Kleine *Audience Q&A and Discussionss*
	12:30 – 13:30	Lunch
	13:30 – 15:30	**REVIEW OF ISSUE PAPER CONTENT** Reviewing the final issue paper outline (prepared by note takers and co-authors during the workshop), which would include key points and content from each of the sessions. This should help to ensure that the group's views are accurately reflected and make the work clear for the editors of the issue paper. Moderator: Michael Kleine
	15:30 – 16:00	Tea/Coffee Break
	16:00 – 17:30	**REVIEW OF ISSUE PAPER CONTENT** Moderator: Michael Kleine Rapporteurs, Q&A, Feedback
	17:30 – 18:00	**CLOSING OF EXPERT WORKSHOP** Closing remarks by PROFOR and IUFRO
	18:10	Transport directly to restaurant
	18:30	Dinner at Winery Cobenzl Vienna and afterwards return to hotel by shuttle

ANNEX 2

LIST OF WORKSHOP PARTICIPANTS

Surname	Name	Country	Organisation
Albar	Israr	Indonesia	Climate Change and Land & Forest Fire Office for Sumatra Region Ministry of Environment & Forestry
Bowmann	David	Australia	University of Tasmania
Charlton	Val	South Africa	Landworks
Cochrane	Mark	United States	Center for Environmental Science University of Maryland
De Groot	Bill	Canada	Canadian Forest Service
E.	Vikram	India	Forest Survey of India
Ellison	David	Switzerland	Consultant
Field	Robert	United States	NASA Goddard Institute for Space Studies, Columbia University
Flannigan	Mike	Canada	University of Alberta
Kant	Promode	India	Institute of Green Economy
Krasovskii	Andrey	Austria	International Institute for Applied Systems Analysis (IIASA)
McCaffrey	Sarah	United States	USDA Forest Service
Mohanty	A. K.	India	Ministry of Environment, Forests, and Climate Change
Murdiyarso	Daniel	Indonesia	Center for International Forestry Research (CIFOR)
Nolasco Morales	Alfredo	Mexico	National Forestry Commission (CONAFOR)
Nuruddin	Ainuddin	Malaysia	Institute of Tropical Forestry and Forest Products (INTROP), University Putra Malaysia
Ribeiro	Natasha	Mozambique	Miombo Network
Robinne	François-Nicolas	Canada	Canadian Partnership for Wildland Fire Science
Sanhueza	Patricio	Chile	Corporación Nacional Forestal (CONAF)
San-Miguel-Ayanz	Jesús	Italy	Joint Research Information Centre (JRC)-European Forest Fire Information System (EFFIS)
Schepaschenko	Dmitry	Austria	International Institute for Applied Systems Analysis (IIASA)
Setzer	Alberto	Brazil	National Institute for Space Research (INPE)
Soares Filho	Britaldo	Brazil	Federal University of Minas Gerais
Sommers	William	USA	George Mason University
Steil	Lara	Brazil	Prevfogo Programme / Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA)
Van der Werf	Guido	Netherlands	Vrije Universiteit Amsterdam
Vega-Garcia	Cristina	Spain	University of Lleida
Special Guest			
Levy	Joaquim	Brazil	World Bank

WORLD BANK/PROFOR AND IUFRO STAFF

Surname	Name	Country	Organization
Khan	Muhammad Najeeb	United States	WB/PROFOR
Kornexl	Werner L.	United States	WB/PROFOR
Mitchell	Andrew	United States	WB/PROFOR
Papageorgiou	Stavros	United States	WB/PROFOR
Burns	Janice	Austria	IUFRO
Kleine	Michael	Austria	IUFRO
Schimpf	Eva	Austria	IUFRO

LIST OF WORKSHOP DISTANCE CONTRIBUTORS

Surname	Name	Country	Organization
Amissah	Lucy	Ghana	Forestry Research Institute of Ghana (FORIG)
Goldammer	Johann	Germany	Global Fire Monitoring Centre
Kostantinov	Artem	Russia	Saint Petersburg Forestry Research Institute
Moore	Peter	Italy (Australia)	Food and Agriculture Organization of the United Nations (FAO)
Smith	Ross	Australia	Consultant
Shu	Lifu	China	Chinese Academy of Forestry (CAF)
Stanturf	John	United States	Estonian University of Life Sciences
Wotton	Mike	Canada	Natural Resources Canada / University of Toronto

IUFRO Headquarters - Secretariat
Marxergasse 2, 1030 Vienna, Austria
Tel.: +43-1-877-0151-0
Fax: +43-1-877-0151-50
www.iufro.org