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# Fire Ecology of the Recent Anthropocene

Keynote Lecture by

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## Preamble

Fire has the capacity to make or break sustainable environments. Today some places suffer from too much fire, some from too little or the wrong kind, but everywhere fire disasters appear to be increasing in terms of both severity and damages, with serious threats to public health, economic well being, and ecological values (Pyne 2001). Thus, fire ecology in the recent Anthropocene has evolved to a science of the biosphere with strong multi-disciplinary interconnectedness between natural sciences – notably ecology, biogeochemistry, atmospheric chemistry, meteorology and climatology – and the humanities – anthropology, cultural history, sociology, and political sciences.

## Abstract

The increasing incidence, extent and severity of uncontrolled burning globally, together with its many adverse consequences, has brought fire into the international environmental policy arena, with growing calls for international action leading to greater control of burning, especially in tropical countries. Despite this concern, there is a paucity of accurate and timely information on the numbers of fires, area burned and phytomass consumed annually at national, regional and global scales, and on the social, economic and environmental costs. Given that fire is also an important natural process in many ecosystems, and that people have traditionally used fire for millennia as a land-management tool, the challenge is to develop informed policy that recognizes both the beneficial and traditional roles of fire, while reducing the incidence and extent of uncontrolled burning and its adverse impacts.

This paper aims to highlight the recent changes of fire regimes at global level. Supported by members of the Working Group on Wildland Fire of the United Nations International Strategy for Disaster Reduction (UN-ISDR), Inter-Agency Task Force for Disaster Reduction, this paper intends to create awareness among the fire science community and those who need to apply the fundamental knowledge of fire science, the fire managers and policy makers.

## 1 Introduction

Fire is a prominent disturbance factor in most vegetation zones across the world. In many ecosystems it is an essential and ecologically significant force - organizing physical and biological attributes, shaping landscape patterns and diversity, and influencing energy flows and biogeochemical cycles, particularly the global carbon cycle. In some ecosystems,

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however, fire is an uncommon or even unnatural process that severely damages the vegetation and can lead to long-term degradation. Such ecosystems, particularly in the tropics, are becoming increasingly vulnerable to fire due to growing population, economic and land-use pressures. Moreover, the use of fire as a land-management tool is deeply embedded in the culture and traditions of many societies, particularly in the developing world. Given the rapidly changing social, economic and environmental conditions occurring in developing countries, marked changes in fire regimes can be expected, with uncertain local, regional, and global consequences. Even in regions where fire is natural (e.g., the boreal zone), more frequent severe fire weather conditions have created recurrent major fire problems in recent years. The incidence of extreme wildfire events is also increasing elsewhere the world, with adverse impacts on economies, livelihoods, and human health and safety that are comparable to those associated with other natural disasters such as earthquakes, floods, droughts and volcanic eruptions. Despite the prominence of these events, current estimates of the extent and impact of vegetation fires globally are far from complete. Several hundred million hectares of forest and other vegetation types burn annually throughout the world, but most of these fires are not monitored or documented. Informed policy and decision-making clearly requires timely quantification of fire activity and its impacts nationally, regionally and globally. Such information is currently largely unavailable.

The primary concerns of policy makers focus on questions regarding the regional and global impacts of excessive and uncontrolled burning, broad-scale trends over time, and the options for instituting protocols that will lead to greater control. Other key questions involve determining under what circumstances fires poses a sufficiently serious problem to require action; what factors govern the incidence and impacts of fires in such cases; and what might be the relative costs and benefits of different options for reducing adverse impacts? The elaborations in this paper reflect the rationale and the scope of work of the Working Group on Wildland Fire of the United Nations International Strategy for Disaster Reduction (ISDR) (Working Group on Wildland Fire 2002a), in association with international wildland fire research programmes of the International Geosphere-Biosphere Programme (IGBP) and other research organizations.

## 2 Extent, Impacts and Significance of Wildland Fire at the Global Scale

### 2.1 Global Wildland Fire Assessments

The Forest Resources Assessment 2000 conducted by the Food and Agriculture Organization of the United Nations (FAO) provided an opportunity to review the global effects of fires on forests as a part of the forest assessment that is undertaken every ten years. The Global Forest Fire Assessment 1990-2000 (FAO 2001), prepared in cooperation with the Global Fire Monitoring Center (GFMC), revealed strengths and weaknesses associated with adequate data collection and compilation, and with sustaining the health and productivity of the world's forests when threatened by drought, wildfires and an increasing demand for natural resources.

Much of the materials for the Global Forest Fire Assessment had been taken from the Global Fire Monitoring Center (GFMC) database or recruited through the GFMC global fire network. Beginning in the late 1980s the GFMC began to systematically collect worldwide fire information (statistical data, narratives), and published these materials in FAO-ECE International Forest Fire News (IFFN) and on the GFMC website (GFMC 2002). Together with the ECE fire database the GFMC fire statistical information represents a unique source that includes also information on fires occurring in other non-forest vegetation types (e.g., savanna fires and agricultural burning).

However, the format and completeness of wildland fire statistics collected are not consistent. Statistical datasets providing number of fires and area burned do not begin to meet the level of information required to assess the environmental and economic consequences of wildland fires. For example, currently formats for fire statistics collection do not include parameters that would permit conclusions on economic damages or impacts of emissions on the atmosphere or human health. Considering the complexity of pathways of regeneration of vegetation after fire, including the cumulative impacts of anthropogenic and environmental stresses, it is not possible at this time to conclude from existing statistical data whether long-term changes can be expected in terms of site degradation and reduction of carrying capacity of fire-affected sites. Thus, a new system for fire data collection that would meet the requirements of a growing number of different users is urgently needed.

The recently published Global Burned Area Product 2000 derived from a spaceborne sensing system (SPOT Vegetation) is the first important step towards obtaining prototype baseline data on the extent of global wildland fires for the year 2000 (JRC 2002). The dataset indicates that approximately 351 million hectares globally were affected by fire in the year 2000. Looking at individual countries the datasets differ considerably from the numbers provided by responsible national agencies. This fact that can be explained easily because statistical datasets of national agencies in many countries primarily include fire incidences in managed forests; with only a few countries providing fire statistics that cover non-forest ecosystems. Furthermore most countries do not have in place appropriate means to survey wildland fire occurrence impacts. On the other hand the area burned, as derived from the spaceborne instrument, also does not provide information on the environmental, economic or humanitarian impacts of fire. An appropriate interpretation of satellite-generated fire information requires additional information layers, particularly on ecosystem vulnerability and recovery potential; that are not yet available at a global level.

Summarizing this state-of-the-knowledge review for the last decade of the 20th century the Global Forest Fire Assessment came to the following conclusions:

? Wildfires during drought years continue to cause serious impacts to natural resources, public health, transportation, navigation and air quality over large areas. Tropical rain forests and cloud forests that typically do not burn on a large scale were devastated by wildfires during the 1990s.

? Many countries, and regions, have a well-developed system for documenting, reporting and evaluating wildfire statistics in a systematic manner. However, many fire statistics do not provide sufficient information on the damaging and beneficial effects of wildland fires.

? Satellite systems have been used effectively to map active fires and burned areas, especially in remote areas where other damage assessment capabilities are not available.

? Some countries still do not have a system in place to annually report number of fires and area burned in a well-maintained database, often because other issues like food security and poverty are more pressing.

? Even those countries supporting highly financed fire management organizations are not exempt from the ravages of wildfires in drought years. When wildland fuels have accumulated to high levels, no amount of firefighting resources can make much of a difference until the weather moderates (as observed in the United States in the 2000 fire season).

- ? Uncontrolled use of fire for forest conversion, agricultural and pastoral purposes continues to cause a serious loss of forest resources, especially in tropical areas.
- ? Some countries are beginning to realize that inter-sectoral coordination of land use policies and practices is an essential element in reducing wildfire losses.
- ? Examples exist where sustainable land use practices and the participation of local communities in integrated forest fire management systems are being employed to reduce resource losses from wildfires.
- ? In some countries, volunteer rural fire brigades are successful in responding quickly and efficiently to wildfires within their home range; and residents are taking more responsibility to ensure that homes will survive wildfires.
- ? Although prescribed burning is being used in many countries to reduce wildfire hazards and achieve resource benefits, other countries have prohibitions against the use of prescribed fire.
- ? Fire ecology principles and fire regime classification systems are being used effectively as an integral part of resource management and fire management planning.
- ? Fire research scientists have been conducting cooperative research projects on a global scale to improve understanding of fire behaviour, fire effects, fire emissions, climate change and public health.
- ? Numerous examples were present in the 1990s of unprecedented levels of inter-sectoral and international cooperation in helping to lessen the impact of wildfires on people, property and natural resources.
- ? Institutions like the Global Fire Monitoring Center have been instrumental in bringing the world's fire situation to the attention of a global audience via the Internet.

In reviewing the global fire situation, it is apparent that a continued emphasis on the emergency response side of the wildfire problem will not address current needs and will only result in a continuation of the current trend towards large and damaging fires in the future.. The way out of the emergency response dilemma is to couple emergency preparedness and response programmes with more sustainable land use policies and practices. Only when sustainable land use practices and emergency preparedness measures complement each other will long-term natural resource benefits for society be realized..

In the following sections an updated review is provided on the changing fires regimes in the most important vegetation zones, the northern boreal forest, temperate forests, tropical rainforest and tropical / subtropical savanna regions.

### 2.1.1 The Fire Situation in Boreal Forests

The global boreal forest zone, covering approximately 12 million square kilometres, stretches in two broad transcontinental bands across Eurasia and North America, with two-thirds in Russia and Scandinavia and the remainder in Canada and Alaska. With extensive tracts of coniferous forest that have adapted to, and become dependent upon, periodic fire for their physiognomy and sustainable existence, and that provide a vital natural and economic resource for northern circumpolar countries, boreal forests are estimated to contain ~37% of the world's terrestrial carbon. These forests have become increasingly accessible to human activities, including natural resource exploitation and recreation, over the past century, with the export value of forest products from global boreal forests accounting for 47% of the world total.

The largest boreal forest fires are extremely high-intensity events, with very fast spread rates and high levels of fuel consumption, particularly in the deep organic forest floor layer. High intensity levels are often sustained over long burning periods, creating towering convection columns that can reach the upper troposphere and lower stratosphere, making long range smoke transport common. In addition, the area burned annually by boreal fires is highly episodic, often varying by an order of magnitude between years.

For many reasons boreal forests and boreal fires have increased in significance in a wide range of global change science issues in recent years. Climate change is foremost among these issues, and the impacts of climate change are expected to be most significant at northern latitudes. Forest fires can be expected to increase sharply in both incidence and severity if climate change projections for the boreal zone prove accurate, acting as a catalyst to a wide range of processes controlling boreal forest carbon storage, causing shifting vegetation, altering the age class structure towards younger stands, and resulting in a direct loss of terrestrial carbon to the atmosphere.

Over the past two decades forest fires in boreal North America (Canada and Alaska) have burned an average of 3 million hectares annually. While sophisticated and well-funded fire management programs in North America suppress the vast majority of fires while small, the 3% of the fires that grow larger than 200 hectares in size account for 97% of the total area burned. There is little likelihood of improving suppression effectiveness since the law of diminishing returns applies here – the 3% of fires that grow larger do so because they occur under extreme fire danger conditions and/or in such numbers that suppression resources are overwhelmed, and applying more funding would have no effect. In addition, Canada and Alaska have vast northern areas which are largely unpopulated and with no merchantable timber, and where fires are monitored but suppression is unwarranted and not practiced, allowing natural fire where possible. Combining the current high levels of fire activity across the North American boreal zone, with restricted suppression effectiveness and a recognition of the need for natural fire, it is all but certain that climate change will greatly exacerbate the situation, and the only option will be adaptation to increasing fire regimes.

The fire problem in Eurasia's boreal forests – mainly in the Russian Federation –is similar in some ways to the North American situation, but there are significant differences (Goldammer and Furyaev 1996, Goldammer and Stocks 2000, Shvidenko and Goldammer 2001). The Eurasian boreal zone is close to twice as large as its North American counterpart, stretching across eleven time zones, with a wide diversity of forest types, growing conditions, structure and productivity, and anthropogenic impacts that define different types of fires and their impacts. For example, surface fires are much more common in the Eurasian boreal zone than in North America where stand-replacing crown fires dominate the area burned, and many Russian tree species have adapted to low-intensity fires. While Canada has a strong continental climate in the boreal region of west-central Canada, where most large fire activity occurs, Eurasia has much stronger continentality over a much larger land base. The climate of the major land area of the Russian Federation is characterized by low annual precipitation and/or frequent droughts during the fire season, and more extreme fire danger conditions over a much larger area. In addition, large areas of the Eurasian boreal zone are not protected or monitored, so fire activity is not recorded for these regions.

Official Russian fire statistics for the past five decades typically report annual areas burned between 0.5 and 1.5 million hectares, with very little inter-annual variability. In fact, as Russian fire managers agree, these numbers are a gross underestimation of the actual extent of boreal fire in Russia. There are two reasons for this: a lack of monitoring and documentation of fires occurring in vast unprotected regions of Siberia, and the fact that the Russian reporting structure emphasized under-reporting of actual area burned to reward the fire suppression organization. In recent years, with the advent of international satellite coverage of Russian fires in collaboration with Russian fire scientists, more realistic area burned estimates are being generated. For example, during the 2002 fire season satellite imagery revealed that about 12 million hectares of forest and non-forest land had been affected by fire in Russia, while official sources report 1.2 million hectares forest land and 0.5 million ha non-forest land burned in the protected area of 690 million hectares (Goldammer 2003a, Davidenko and Eritsov 2003, Sukhinin et al. 2003). During the early summer of 2003 remote sensing data indicate a total vegetated area affected by fire in Russia exceeding 22 million hectares (GFMC 2003). Based on recent remote sensing data, it appears that the annual area burned in Russia can vary between 2 and 15 million hectares/year.

In recent years there has been an increase in the occurrence of wildfires under extreme drought conditions (e.g. the Trans-Baikal Region in 1987 and the Far East in 1998, Yakutia in 2002, Chita and Buryatia in 2003), and the severity of these fires will greatly disturb natural recovery cycles. There is growing concern that fires on permafrost sites will lead to the degradation or disappearance of eastern Siberian larch forests. Russia has close to 65% of the global boreal forest, an economically and ecologically important area that represents the largest undeveloped forested area of the globe. With the vast quantities of carbon stored in these forests, Russian forests play a critical role in the global climate system and global carbon cycling. Projected increases in the severity of the continental climate in Russia suggest longer fire seasons and much higher levels of fire danger. The inevitable result will be an increase in the number, size, and severity of boreal fires, with huge impacts on the global carbon cycle and the Russian economy.

At the same time, recent political and economic changes in Russia have led to an extreme reduction in their fire suppression capability, with the State Forest Service showing a huge debt, and the outlook for future funding increases bleak. As a result, *Avialesookhrana*, the aerial fire protection division of the Forest Service, has been forced to reduce aerial fire detection and suppression levels, with operational aircraft flying hours and firefighter numbers now less than 50% of 1980s levels. Consequently, the occurrence of larger fires is increasing, and the areas being burned annually are unprecedented in recent memory.

Increasing fire risks in the boreal forests of Russia are a major threat to the global carbon budget, and this requires significant national and international attention (Kajii et al. 2003). Management and protection of these vital resources should not be given solely to the private sector or delegated to regional levels. The establishment and strengthening of a central institution to protect forests must be a priority supported by Russia and the international community.

### 2.1.2 The Fire Situation in Temperate Forests

In recent years fires have been increasing in number and severity across the temperate zone, with significant fire events becoming more common in the United States, the Mediterranean Basin, and Mongolia for example.

#### Temperate North America: The United States

Over most of the past century the United States has made a huge investment in wildland fire management, developing a sophisticated fire suppression capability. As the 1900s progressed, the United States became increasingly effective in excluding fire from much of the landscape. Despite numerous human-caused and lightning fires the area burned was greatly reduced from the early 1900s. However, the price for successful fire exclusion has proven to be twofold. The most obvious price was the huge cost of developing and maintaining fire management organizations that were increasingly requiring higher budgets to keep fire losses at an acceptable level. The second cost, hidden for decades, is now apparent, as the policy emphasis on fire exclusion has led to the build-up of unnatural accumulations of fuels within fire-dependent ecosystems, with the result that recent fires burn with greater intensity and have proven much more difficult to control. Despite extensive cooperation from other countries, and huge budget expenditures, intense droughts in 2000 and 2002 contributed to widespread wildfires in the western United States that burned between 2.5 and 3 million hectares in each year. Losses from these fires now include substantial destruction of homes, as the trend towards living in fire-prone environments grows, and the wildland urban interface is expanding.

#### The Mediterranean Basin and the Balkans

Within the Mediterranean Basin fire is the most important natural threat to forests and wooded areas. Mediterranean countries have a relatively long dry season, lasting between one and three months on the French and Italian coasts in the north of the Mediterranean, and more than seven months on the Libyan and Egyptian coasts to the south. Currently, approximately 50,000 fires burn throughout the Mediterranean Basin, and burn over an annual average of 600,000 hectares; both statistics are at a level twice that of the 1970s. In countries where data is continuous since the 1950s, fire occurrence and area burned levels have shown large increases since the 1970s in Spain, Italy, and Greece. Human-caused fires dominate in the Mediterranean Basin, with only 1-5% of fires caused by lightning. Arson fires are also quite prevalent.

Paradoxically, the fundamental cause of an increasing vulnerability of the vegetation of the Southern European countries bordering the Mediterranean Basin is linked to increased standards of living among the local populations (Alexandrian et al. 2000). Far-reaching social and economic changes in Western Europe have led to a transfer of population from the countryside to the cities, a considerable deceleration of the demographic growth, an abandonment of arable lands and a disinterest in the forest resource as a source of energy. This has resulted in the expansion of wooded areas, erosion of the financial value of the wooded lands, a loss of inhabitants with a sense of responsibility for the forest with a resultant increase in the amount of available fuel.

The demographic, socio-economic and political changes in many countries of

Southeast Europe and the neighbouring nations on the Balkan have resulted in an increase of wildfire occurrence, destabilization of fire management capabilities and increased vulnerability of ecosystems and human populations. The main reasons for this development include the transition from centrally planned to market economies, national to regional conflicts, creation of new nations involving political tensions and war, land-use changes, and regional climate change towards an increase in the frequency of extreme droughts. New solutions are required to address the increasing fire threat on the Balkans. Regional cooperation in the Mediterranean Region and the Balkans must address the underlying causes of changing fire regimes and a more economic trans-national use of fire management resources (Goldammer 2003b).

**Transition from Temperate Steppes to Boreal Forests: Mongolia**

With an area of 1.5 million square kilometres and a population of 2.3 million, Mongolia is one of the least populated countries in the world, yet significant fire problems exist there. With an extremely continental climate, poor soil fertility and a lack of surface water, wildfires in Mongolia have become a major factor in determining the spatial and temporal dynamics of forest ecosystems. Of a total of 17 million hectares of forests, 4 million hectares are estimated to be disturbed, primarily by fire (95%) and logging (5%). Forests are declining in Mongolia as continual degradation by wildfire turns former forests into steppe vegetation. The highest fire hazard occurs in the submontane coniferous forests of eastern Mongolia, where highly flammable fuels, long droughts, and economic activity are most common. In recent years fire activity in Mongolia has increased significantly, due to economic activity on lands once highly controlled or restricted. In Mongolia, only 50-60 forest fires and 80-100 steppe fires occur annually on average. The underlying causes of the majority of wildfires are due to the fact that urban people are seeking a livelihood in the forests because of the collapse of the industrial sector. During the 1996 to 1998 period, when winter and spring seasons were particularly dry, Mongolia experienced large-scale forest and steppe fires that burned over 26.3 million hectares of forest and steppe vegetation, including pasture lands, causing significant losses of life, property and infrastructure. The loss of forest land in Mongolia is increasing, with severe economic consequences, and a growing realization that a precious ecological resource which contains virtually all rivers, protects soils and rangelands, and provides essential wildlife habitat is at risk.

**The Fire Continent Australia: New Vulnerabilities**

Australia's fire problems are currently a growing focus of fire managers and policy makers in the Australasian region. The continent is facing a dilemma: On the one hand Australia's wildlands have evolved with fire and thus are extremely well adapted to fire. In the late 1990s more than 345,000 wildfires burned an average of ca. 50 million hectares of different vegetation types every year. In many of Australia's wildlands frequent fires of moderate intensity and severity are important to maintain properties and functioning of ecosystems and to reduce the accumulation of highly flammable fuels. Thus, it is generally accepted that fire protection (fire exclusion) in Australia's wildlands will lead to fuel accumulation and, inevitably, to uncontrollable wildfires of extreme behaviour, intensity and severity. These ecosystems need to be burned by natural sources or by prescribed fire.

On the other hand there is a trend towards the building of homes and infrastructure in the wildlands around Australian cities.

This exurban settlement trend has created new vulnerabilities and conflicts concerning the use of fire as a management tool. The extended wildfires occurring in the Southeast of Australia (New South Wales, A.C.T., Victoria) in 2002 and 2003 did not harm the vegetation but had a significant impact on values at risk at the wildland-residential interface.

### 2.1.3 Tropical Rainforests

Fires in tropical evergreen forests, until recently, were considered either impossible or inconsequential. In recent decades, due to population growth and economic necessity, rainforest conversion to non-sustainable rangeland and agricultural systems has proliferated throughout the tropics (Mueller-Dombois and Goldammer 1990, UNEP 2002). The slash-and-burn practices involve cutting rainforests to harvest valuable timber, and burning the remaining biomass repeatedly to permanently convert landscapes into grasslands that flourish for a while due to ash fertilization, but eventually are abandoned as non-sustainable, or to convert rainforest to valuable plantations. Beyond this intentional deforestation there is a further, more recent problem, as wildfires are growing in frequency and severity across the tropics. Fires now continually erode fragmented rainforest edges and have become an ecological disturbance leading to degradation of vast regions of standing forest, with huge ecological, environmental, and economic consequences. It is clear that, in tropical rainforest environments, selective logging leads to an increased susceptibility of forests to fire, and that the problem is most severe in recently logged forests. Small clearings associated with selective logging permit rapid desiccation of vegetation and soils increase this susceptibility to fire. Droughts triggered by the El Niño-Southern Oscillation (ENSO) have exacerbated this problem, and were largely responsible for significant wildfire disasters in tropical rainforests during the 1980s and 1990s.

Tropical rainforests cover ~45% of Latin America and the Caribbean. Between 1980 and 1990, when the first reliable estimates were made, the region lost close to 61 million hectares of forest, 6% of the total forested area. During the 1990-1995 period a further 30 million hectares were lost. The highest rates of deforestation occurred in Central America (2.1% per year) but Bolivia, Ecuador, Paraguay and Venezuela also had deforestation rates above 1% per year, while Brazil lost 15 million hectares of forest between 1988 and 1997.

Landscape fragmentation and land cover change associated with this massive deforestation combine to expose more forest to the risk of wildfire, and fires are increasing in severity and frequency, resulting in widespread forest degradation. This change in tropical fire regimes will likely result in the replacement of rainforests with less diverse and more fire-tolerant vegetation types. Although quantitative area burned estimates are sporadic at best, it is estimated that the 1997-1998 El Niño-driven wildfires burned more than 20 million hectares in Latin America and Southeast Asia. The widespread tropical rainforest wildfires of 1998 have changed the landscape of Latin America’s tropical evergreen forests by damaging vast forested areas adjacent to fire-maintained ecosystems, such that fires will likely become more severe in the near future, a fact not yet appreciated by resident populations, fire managers, and policy makers. The Latin American and Indonesian problems have much in common, and indicate the problems in tropical rainforests worldwide.

Smoke pollution from tropical rainforest fires, as is the case in many other fire regions of the world, greatly affects the health of humans regionally, with countless short- and long-term respiratory and cardiovascular problems resulting from the lingering smoke and smog episodes associated with massive wildfires.

The environmental impacts from tropical forest fires range from local to global. Local/regional impacts include soil degradation, with increased risks of flooding and drought, along with a reduced abundance of wildlife and plants, and an increased risk of recurrent fires. Global impacts include the release of large amounts of greenhouse gases, a net loss of carbon to the atmosphere, and meteorological effects including reduced precipitation and increased lightning. A loss of biodiversity and extinction of species is also a major concern.

The economic costs of tropical forest fires are unknown, largely due to a lack of data, but also attributable to the complications of cause and effect: negative political implications definitely discourage full disclosure. These can include medical costs, transportation disruption***s***, and timber and erosion losses. They can also, in the post-Kyoto era, include lost carbon costs which, in the case of the 1998 fires in Latin America, can be crudely estimated at 10-15 billion US dollars.

The driving force behind the devastating Indonesian fires of 1982-1983 and 1997-1998 was droughts associated with ENSO, in combination with the exposure of rainforest areas to drought as a result of selective logging. It has been estimated that the overall land area affected by the 1982-1983 fires, in Borneo alone, was in excess of 5 million hectares. In non-ENSO years fires cover 15,000-25,000 hectares. The 1997-1998 fire episode exceeded the size and impact of the 1982-1983 fires. During 1997 large fires occurred in Sumatra, West and Central Kalimantan, and Irian Jaya / Papua New Guinea. In 1998 the greatest fire activity occurred in East Kalimantan. In total, the 1997-1998 fires covered an estimated area in excess of 9.5 million hectares, with 6.5 million hectares burning in Kalimantan alone. These widespread fires, all caused by humans involved in land speculation and large-scale forest conversion, caused dense haze across Southeast Asia for an extended period. Severe respiratory health problems resulted, along with widespread transport disruption, and overall costs were estimated at 9.3 billion US dollars. Carbon losses were particularly severe due to high levels of fuel consumption, particularly in peatlands.

### 2.1.4 Southern African Savannas and Grasslands

Fire is a widespread seasonal phenomena in Africa (van Wilgen et al. 1997). South of the equator, approximately 168 million hectares burn annually, nearly 17% of a total land base of 1014 million hectares, accounting for 37% of the dry matter burned globally. Savanna burning accounts for 50% of this total, with the remainder caused by the burning of fuelwood, agricultural residues, and slash from land clearing. Fires are started both by lightning and humans, but the relative share of fires caused by human intervention is rapidly increasing. Pastoralists use fire to stimulate grass growth for livestock, while subsistence agriculturalists use fire to remove unwanted biomass while clearing agricultural lands, and to eliminate unused agricultural residues after harvest. In addition, fires fuel by wood, charcoal or agricultural residues are the main source of domestic energy for cooking and heating.

In most African ecosystems fire is a natural disturbance factor to maintain a dynamic equilibrium of vegetation structure and composition, and to nutrient recycling and distribution. Nevertheless, substantial unwarranted and uncontrolled burning does occur across Africa, and effective actions to limit this are necessary to protect life, property, and fire-sensitive natural resources, and to reduce the current burden of emissions on the atmosphere with subsequent adverse effects on the global climate system and human health. Major problems arise at the interface between fire savannas, residential areas, agricultural systems, and those forests which are not adapted to fire. Although estimates of the total economic damage of African fires are not available, ecologically and economically important resources are being increasingly destroyed by fires crossing borders from a fire-adapted to a fire-sensitive environment. Fire is also contributing to widespread deforestation in many southern African countries.

Most southern African countries have regulations governing the use and control of fire, although these are seldom enforced because of difficulties in punishing those responsible. Some forestry and wildlife management agencies within the region have the basic infrastructure to detect, prevent and suppress fires, but this capability is rapidly breaking down and becoming obsolete. Traditional controls on burning in customary lands are now largely ineffective. Fire control is also greatly complicated by the fact that fires in Africa occur as hundreds of thousands of widely dispersed small events. With continuing population growth and a lack of economic development and alternative employment opportunities to subsistence agriculture, human pressure on the land is increasing, and widespread land transformation is occurring. Outside densely settled farming areas, the clearance of woodlands for timber, fuelwood and charcoal production is resulting in increased grass production, which in turn encourages intense dry season fires that suppress tree regeneration and increase tree mortality. In short, the trend is toward more fires.

Budgetary constraints on governments have basically eliminated their capacity to regulate from the centre, so there is a trend towards decentralization. However, the shortage of resources forcing decentralization means there is little capacity for governments to support local resource management initiatives. The result is little or no effective management and this problem is compounded by excessive sectoralism in many governments, leading to uncoordinated policy development, conflicting policies, and a duplication of effort and resources. As a result of these failures, community-based natural resource management is now being increasingly widely implemented in Africa, with the recognition that local management is the appropriate scale at which to address the widespread fire problems in Africa. The major challenge is to create an enabling rather than a regulatory framework for effective fire management in Africa, but this is not currently in place. Community-based natural resource management programs, with provisions for fire management through proper infrastructure development, must be encouraged. More effective planning could also be achieved through the use of currently available remotely sensed satellite products.

These needs must also be considered within the context of a myriad of problems facing governments and communities in Africa, including exploding populations and health (e.g. the AIDS epidemic). While unwarranted and uncontrolled burning may greatly affect at the local scale, it may not yet be sufficiently important to warrant the concern of policy makers, and that perception must be challenged as a first step towards more deliberate, controlled and responsible use of fire in Africa.

### 2.1.5 Global Peatlands

The world's peatlands play a significant role in biodiversity patterns, socio-economic development and livelihood, water storage and supply, flood control, and climate regulation. Peatlands are fragile ecosystems vulnerable to fire, and impacted heavily by uncontrolled drainage (Parish et al. 2002). The increased conversion of forests on tropical peat lands to agricultural cultivations and the presence of large areas of drained peatlands in the boreal zone of is a growing concern for fire managers. Peat soils can reach a depth of 10 metres or more and thus contain burnable volumes in excess of 100,000 cubic metres of biomass per hectare.

Recent fire episodes in the tropical and boreal peat-swamp biomes have revealed that the combination of extreme droughts, especially in conjunction with the El Niño phenomenon or extended summer droughts in boreal Eurasia, lead to severe and often irreversible damages of wetland ecosystems, transfer of terrestrial carbon to the atmosphere and to severe smoke pollution affecting human health and security.

Projected regional climate changes, coupled with continuing trends of land-use changes, indicate that the vulnerability of peatlands will increase and the loss of peatlands by excessive, uncontrolled fire will accelerate.

However, there are options to proactively protect and maintain peatlands. To avoid major fire disasters in peatlands, there is a need to educate land managers in these areas about best fire management practices on peat soils.

Peat is a renewable natural resource, which will regenerate if the burned area is rehabilitated and properly protected, even if the re-accumulation of peat is a fairly slow process.

## 3 Fire-Atmosphere Interactions

Research efforts under the Biomass Burning Experiment (BIBEX) of the International Geosphere-Biosphere Programme (IGBP), International Global Atmospheric Chemistry (IGAC) Project, and a large number of other projects in the 1990s were successful in the sampling and quantification of fire emissions, and the determination of emission factors for various fuel types. However, global and regional emission estimates are still problematic, mostly because of uncertainties regarding amounts burned. Most recent estimates indicate that the amount of vegetative biomass burned annually is in the magnitude of 9200 Teragram (dry weight), i.e., 9.2 billion tons (Andreae and Merlet 2001, Andreae 2002).

Vegetation fires produce a range of emissions that influence the composition and functioning of the atmosphere. The fate of carbon contained in fire-emitted carbon dioxide ($CO_2$) and other radiatively active trace gases is climatically relevant only when there is no regrowth of vegetation - e.g., deforestation or degradation of sites. Alternatively, $NO_x$, CO, $CH_4$, and other hydrocarbons are ingredients of smog chemistry, contribute to tropospheric ozone formation and act as "greenhouse gases", while halogenated hydrocarbons (e.g. $CH_3Br$) have considerable impact on stratospheric ozone chemistry and contribute to ozone depletion.

Fire-emitted aerosols influence climate directly and indirectly. Direct effects include (a) backscattering of sunlight into space, resulting in increased albedo and a cooling effect, and (b) absorption of sunlight which leads to cooling of the Earth's surface and atmospheric warming. As a consequence convection and cloudiness are reduced as well as evaporation from ocean and downwind rainfall. The key parameter in these effects is the black carbon content of the aerosol and its mixing state.

Indirect effects of pyrogenic aerosols are associated with cloud formation. Fire-emitted aerosols lead to an increase of Cloud Condensation Nuclei (CCN) that are functioning as seed for droplet formation. Given a limited amount of cloud water content this results in an increase of the number of small droplets. As a first consequence clouds become whiter, reflect more sunlight, thus leading to a cooling effect. As a second indirect effect of "overseeding" the overabundance of CCN coupled with limited amount of cloud water will reduce the formation of droplets that are big enough (radius ~14 µm) to produce rain; consequently rainfall is suppressed. In conclusion it can be stated that

- ? The fire and atmospheric science community has made considerable progress in determining emission factors from vegetation fires
- ? Global and regional emission estimates are still problematic, mostly because of uncertainties regarding amounts of area and vegetative matter burned
- ? Fire is a significant driver of climate change (as well as a human health risk)
- ? Fire, climate, and human actions are highly interactive
- ? Some of these interactions may be very costly both economically and ecologically

## 4 Forest Fires, Climate Change and Carbon: The Boreal Forest Example

Growing exploitation of the global boreal zone cannot be accomplished without a reconciliation, and compromise, with the fact that the boreal forest is dependent on periodic natural disturbance (fire, insects, disease) in order to exist (Stocks 2001). Forest fire is the dominant disturbance regime in boreal forests, and is the primary process which organizes the physical and biological attributes of the boreal biome over most of its range, shaping landscape diversity and influencing energy flows and biogeochemical cycles, particularly the global carbon cycle since the last Ice Age. Human settlement and exploitation of the resource-rich boreal zone has been accomplished in conjunction with the development of highly efficient forest fire management systems designed to detect and suppress unwanted fires quickly and efficiently. Over the past century people throughout northern forest ecosystems have, at times somewhat uneasily, coexisted with this important natural force, as fire management agencies attempted to balance public safety concerns and the industrial and recreational use of these forests, with costs and the need for natural forest cycling through forest fires. Canadian, Russian, and American fire managers have always designated parts of the boreal zone, usually in northern regions, as "lower priority" zones that receive little or no fire protection, since fires occurring there generally have little or no significant detrimental impact on public safety and forest values.

While humans have had some influence on the extent and impact of boreal fires, fire still dominates as a disturbance regime in the boreal biome, with an estimated 5-20 million hectares burning annually in this region. Canada and Alaska, despite progressive fire management programs, still regularly experience significant, resource-stretching fire problems, with 2-8 million hectares, on average, burning annually. In contrast, Scandinavian countries do not seem to have major large fire problems, probably due to the easy access resulting from intensive forest management over virtually all of the forested area of these countries. Russian fire statistics are available over the past four decades but, until recent years, these statistics are considered very unreliable. However, based on recent remote sensing data, it appears that the annual area burned in Russia can vary between 2 and 15 million hectares/year.

Boreal forest fires are, most often, crown fires - high-intensity events that combine high spread rates with significant levels of fuel consumption to generate significant fire intensity and energy release rates. When sustained over an extended afternoon burning period each day, this results in the development of towering convection columns reaching the upper troposphere/lower stratosphere, with significant long-range transport potential.

Recent Intergovernmental Panel on Climate Change (IPCC) reports have emphasized the fact that climate change is a current reality, and that significant impacts can be expected, particularly at northern latitudes, for many decades ahead. Model projections of future climate, at both broad and regional scales, are consistent in this regard. An increase in boreal forest fire numbers and severity, as a result of a warming climate with increased convective activity, is expected to be an early and significant consequence of climate change. Increased lightning and lightning fire occurrence is expected under a warming climate. Fire seasons are expected to be longer, with an increase in the severity and extent of the extreme fire danger conditions that drive major forest fire events. Increased forest fire activity and severity will result in shorter fire return intervals, a shift in forest age class distribution towards younger stands, and a resultant decrease in terrestrial carbon storage in the boreal zone. Increased fire activity will also likely produce a positive feedback to climate change, and will drive vegetation shifting at northern latitudes. The boreal zone is estimated to contain 35-40% of global terrestrial carbon, and any increase in the frequency and severity of boreal fires will release carbon to the atmosphere at a faster rate than it can be re-sequestered. This would have global implications, and must be considered in post-Kyoto climate change negotiations.

Increased protection of boreal forests from fire is not a valid option at this time. Fire management agencies are currently operating a maximum efficiency, controlling unwanted fires quite effectively. There is a law of diminishing effects at work here though, as increasing efficiency would require huge increases in infrastructure and resources. While it is physically and economically impossible to further reduce the area burned by boreal fires, it is also not ecologically desirable, as fire plays a major and vital role in boreal ecosystem structure and maintenance. Given these facts, it would appear that, if the climate changes as expected over the next century, northern forest managers will have to constantly adapt to increasing fire activity. The likely result would be a change in protection policies to protect more valuable resources, while permitting more natural fire at a landscape scale.

## 5 Fire Emissions and Human Health

Smoke from burning of vegetative matter contains a large and diverse number of chemicals, many of which have been associated with adverse health impacts (Goh et al. 1999). Nearly 200 distinct organic compounds have been identified in wood smoke aerosol, including volatile organic compounds and polycyclic aromatic hydrocarbons. Available data indicate high concentrations of inhalable particulate matter in the smoke of vegetation fires. Since particulate matter produced by incomplete combustion of biomass are mainly less than 1 micrometers in aerodynamic diameter, both $PM_{10}$ and $PM_{2.5}$ (particles smaller than 2.5 micrometers in aerodynamic diameter) concentrations increase during air pollution episodes caused by vegetation fires. Carbon monoxide and free radicals may well play a decisive role in health effects of people who live and/or work close to the fires.

Inhalable and thoracic-suspended particles move further down into the lower respiratory airways, can remain there for a longer period of time, leaving deposits. The potential for health impacts in an exposed population depends on individual factors such as age and the pre-existence of respiratory and cardiovascular diseases and infections, and on particle size. Gaseous compounds adsorbed or absorbed by particles can play a role in long-term health effects (cancer) but short-term health effects are essentially determined through particle size. Quantitative assessment of health impacts of air pollution associated with vegetation fires in developing countries is often limited by the availability of baseline morbidity and mortality information. Air pollutant data are of relatively higher availability and quality but sometimes even these data are not available or reliable.

Vegetation fire smoke sometimes overlies urban air pollution, and exposure levels are intermediate between ambient air pollution and indoor air pollution from domestic cooking and heating. Because the effects of fire events are nation- and region-wide, a “natural” disaster can evolve into a more complex emergency, both through population movement and through its effects on the economy and security of the affected countries. The fire and smog episodes in South East Asia during the El Niño of 1997-98, in the Far East of the Russian Federation in 1998, and again in Moscow Region in 2002**,** are striking examples.

The World Health Organization (WHO), in collaboration with the United Nations Environmental Programme (UNEP) and the World Meteorological Organization (WMO), has issued comprehensive guidelines for Governments and responsible authorities on actions to be taken when their population is exposed to smoke from fires (Schwela et al. 1999). The Guidelines give insights into acute and chronic health effects of air pollution due to biomass burning, advice on effective public communications and mitigation measures, and guidance for assessing the health impacts of vegetation fires. They also provide measures on how to reduce the burden of mortality and preventable disability suffered particularly by the poor, and on the development and implementation of an early air pollution warning system.

## 6 Global Observation and Monitoring of Wildland Fires

From the changing role of fire in the different vegetation zones described above it can be concluded that fire management is becoming increasingly important with respect to global issues of resource management, disaster reduction and global change. With this increasing importance comes the need for a concerted effort to put in place the international global observation and monitoring systems needed to give early warning and identify disastrous fire events, inform policy making and to support sustainable resource management and global change research (Justice 2001). The observation systems will need to include both ground based and space based monitoring components. Advances in information technology now make it easier to collect and share data necessary for emergency response and environmental management. Current satellite assets are under-utilized for operational monitoring and fire monitoring falls largely in the research domain. Increasing attention needs to be given to data availability, data continuity, data access and how the data are being used to provide useful information.

There is no standard *in-situ* measurement/reporting system and national reporting is too variable and inadequate to provide a regional or global assessment. It is also often hard to relate the satellite and *in-situ* data reporting. Reliable information is needed to inform policy and decision making, and management policies should be developed based in part on a scientific understanding of their likely impacts. Fora are needed for exchange of information on monitoring methods, use of appropriate technology, policy and management options and solutions. A continued and informed evaluation of existing monitoring systems, and a clear articulation of monitoring requirements and operational prototyping of improved methods, is also required.

The Global Observation of Forest Cover / Global Observation of Land Dynamics (GOFC/GOLD) program, a part of the Global Terrestrial Observing System (GTOS), is designed to provide such a forum. The GTOS, which is sponsored by the International Global Observing System Partners, has its Secretariat at the FAO in Rome. GOFC/GOLD has its Secretariat in the Canadian Forest Service. The GOFC/GOLD Program is an international coordination mechanism to enhance the use of earth-observation information for policy, natural resource management and research. It is intended to link data producers to data users, to identify gaps and overlaps in observational programs, and recommend solutions. The program will provide validated information products, promote common standards and methods for data generation and product validation and stimulate advances in the management and distribution of large volume datasets. Overall it is intended to advance our ability to obtain and use environmental information on fires and secure the long-term observation and monitoring systems.

GOFC/GOLD has three implementation teams: fire, land cover and biophysical characterization. The principal role of GOFC/GOLD is to act as a coordinating mechanism for national and regional activities (Justice et al. 2003). To achieve its goals GOFC/GOLD has developed a number of regional networks of fire data providers, data brokers and data users. These networks of resource managers and scientists provide the key to sustained capability for improving the observing systems and ensuring that the data are being used effectively. GOFC/GOLD regional networks are being implemented through a series of regional workshops. These regional network workshops are used to engage the user community to address regional concerns and issues, provide a strong voice for regional needs and foster lateral transfer of technology and methods within and between regions. Networks are currently being developed in Central and Southern Africa, Southeast Asia, Russia and the Far East and Central and South America.

The GOLD-Fire program has a number of stated goals:

? To increase user awareness by providing an improved understanding of the utility of satellite fire products for resource management and policy within the United Nations and at regional national and local levels.

? To encourage the development and testing of standard methods for fire danger rating suited to different ecosystems and to enhance current fire early warning systems.

? To establish an operational network of fire validation sites and protocols, providing accuracy assessment for operational products and a test bed for new or enhanced products, leading to standard products of known accuracy.

? To enhance fire product use and access for example by developing operational multi-source fire and GIS data and making these available over the Internet.

? To develop an operational global geostationary fire network providing observations of active fires in near real time.

? To establish operational polar orbiters with fire monitoring capability. Providing a) operational moderate resolution long-term global fire products to meet user requirements and distributed ground stations providing enhanced regional products. These products should include fire danger, fuel moisture content, active fire, burned area and fire emissions. b) operational high resolution data acquisition allowing fire monitoring and post-fire assessments.

? To create emissions product suites, developed and implemented providing annual and near real-time emissions estimates with available input data.

It is particularly important to improve the quality, scope, and utility of GOFC-Fire inputs to the various user communities through:

? gaining a better understanding of the range of users of fire data, their needs for information, how they might use such information if it was available, and with what other data sets such information might be linked;
? increasing the awareness of users with respect to the potential utility of satellite products for global change research, fire policy, planning and management; and

based on ongoing interaction with representatives of the various user communities developing enhanced products.

## 7 Early Warning of Wildfire and Sustainable Development

Sustainable development in rural societies in many countries with different natural vegetation types and land-use systems are often jeopardized by wildfires that devastate valuable vegetation resources (forests, farmlands, pastures, plantations, etc.), in both the short-term (economic losses and humanitarian problems due to destruction of crops and other values at risk) and the long-term (degradation of stability and productivity of ecosystems and land-use systems).

These fires often occur as consequence of extreme weather situations, e.g. inter-annual climate variability such as droughts caused by El Niño, coupled with application of fire in land-use systems that escape control. The underlying causes of damaging wildfires are deeply rooted in the problems of rural societies that are undergoing rapid demographic changes, experiencing the loss of traditional knowledge and skills due to the trend of globalisation, and confrontation with external pressure on limited vegetation resources.

Secondary effects of destructive wildfires include the loss of vegetation that protects the soil. As a consequence the fire-affected sites are often degraded due to wind and water erosion. Increased water runoff also leads to disastrous floods and landslides, affecting drinking water availability and quality, or leading to siltation of reservoirs.

### Community Involvement in Fire Management

Wildland fire risk, hazard and danger are determined by humans (as ignition sources), ecosystem properties (through the presence of fuels that determine fire intensity and severity) and weather (by desiccation of dead and living vegetation). Fire prevention at the community level traditionally involves instruments such as awareness raising, public information and incentive elements (e.g. participation in advantages gained by successful prevention of destructive fires).

Integrated fire management measures includes fuel management, thus enabling people to proactively work in fire prevention. On the other side, weather as the natural driver of fire danger is the only element that cannot be manipulated. However, it can be predicted. Early warning systems of fire danger have been developed for many climate and vegetation types. They are mainly designed or operational at national or regional levels and are of low resolution. Some pilot products have been designed for application at the community level. Widespread application or technology transfer, however, is still in its infancy stages.

### Challenges

The greatest challenges ahead are transfer of knowledge and adapted technologies to the grassroot levels of those population groups that are dependent on using the ecologically beneficial effects of fire in their land-use systems, while at the same time becoming increasingly vulnerable to the destructive effects of uncontrolled wildfires. These population groups cannot take advantage of sophisticated fire warning and information systems or the theories and practical approaches of Integrated Fire Management that are available, but outside their reach.

Global scale early-warning system for fire occurrence and fire risk already exist and can be accessed and used at that scale by organizations that have the training and technology. Thus, priority must be given to develop and establish operational early warning systems feasible for the use in economically disadvantaged countries, in sub-regional and local areas that require site specific data and local interpretation.

Local bodies -- e.g., “Fire Management Committees” -- entrusted to take responsibility for fire management must be responsible for early warning of wildland fire. They can range from a strong federal or national system down to a local, community-based group. The full range of systems exist and work well in various parts of the world. The particular organization needed is dependent on the local/regional social and political system. Experience for developing such community-based fire management approaches exist but they are not widely applied. What is needed are the resources to organize the transfer of the technical knowledge and provide training and support.

The establishment of fire management networks can be a very effective tool for providing support to local communities. As with the “Fire Management Committees”, the networks can be at various levels; regional, national, or local groups. The network’s purpose will also vary from assisting with the highly technical use of remote sensing data and products, to the application of local fire risk methods for communities.

UN and other international organizations and programmes, such as the FAO, WMO, WHO, NGOs, as well as national government and non-government institutions including academic ones, could be actively participating in the networks (Working Group on Wildland Fire 2002b).

## 8 The Way Forward

Periods of severe drought were common during the 1990s and in the first years of the Third Millennium, and devastating wildfires occurred in almost all regions of the world with wide-ranging and long-term impacts on ecosystem sustainability, regional economies and environments, and on human health. The resulting widespread public, media and political attention focused on these wildfires caused decision-makers and resource management agencies to concentrate on this growing problem, and to develop policies and practices to reduce the flammability and vulnerability of wild land ecosystems in the future.

The challenge is the development of informed policy that recognizes both the beneficial and traditional roles of fire, while reducing the incidence and extent of uncontrolled burning and its adverse impacts. Such a challenge clearly has major technical, social, economic and political elements. In developing countries, improved forest and land management techniques are essential to minimize the risk of uncontrolled fires, and appropriate fire prevention and control strategies must be developed and implemented quickly or ongoing wildfire problems will continue. Enhanced early warning systems for assessing fire hazard and risk are also essential, along with improvements in regional capacity and infrastructure to use satellite data quickly. This must be coupled with technologies and programs that permit rapid detection and response to fires.

Policy-makers are beginning to realize that continued emphasis only on emergency response will do nothing to prevent large and damaging wildfires in future years. Emergency preparedness and response programs must be coupled with better land use policies and practices. Actively working towards sustainable forestry practices with community-level involvement is a critical strategy for better conservation of natural resources and reduced wildfire impacts.

A better understanding by policy-makers and the general public of the ecological, environmental, socio-cultural, land-use, and public health issues surrounding vegetation fires is also critical. The potential for greater international and regional cooperation in sharing information and resources to promote more effective fire management must be explored and implemented. The traditional approach of dealing with wildland fires exclusively under the traditional fire-exclusion schemes must be replaced by an inter-sectoral and interdisciplinary approach. The devastating effects of increasing wildfires are an expression of demographic growth, land-use and land-use change, the socio-cultural implications of globalisation, and climate variability. Thus, integrated programs and strategies must be developed to address the wildfire problem at its roots, while at the same time creating an enabling environment where appropriate tools are developed so that policymakers can become proactive in dealing with wildfire.

## 8 Conclusions: Policy and Wildland Fire Science

The challenge of developing informed policy that recognizes both the beneficial and traditional roles of fire, while reducing the incidence and extent of uncontrolled burning and its adverse impacts, clearly has major technical, social, economic and political elements. In developing countries better forest and land management techniques are required to minimize the risk of uncontrolled fires, and appropriate management strategies for preventing and controlling fires must be implemented if measurable progress is to be achieved. In addition, enhanced early warning systems for assessing fire hazard and estimating risk are necessary, along with the improvements in regional capacity and infrastructure to use satellite data. This must be coupled with technologies and programs that permit rapid detection and response to fires.

A better understanding by both policy-makers and the general population of the ecological, environmental, socio-cultural, land-use and public-health issues surrounding vegetation fires is essential. The potential for greater international and regional co-operation in sharing information and resources to promote more effective fire management also needs to be explored. The recent efforts of many UN programmes and organizations are a positive step in this direction, but much remains to be accomplished.

In the spirit and fulfilment of the 1997 Kyoto Protocol to the United Nations Framework Convention on Climate Change, the Plan of Implementation of the World Summit for Sustainable Development (WSSD) and the UN International Strategy for Disaster Reduction (ISDR), there is an obvious need for more reliable data on fire occurrence and impacts. Remote sensing must and should play a major role in meeting this requirement. In addition to the obvious need for improved spaceborne fire-observation systems and more effective operational systems capable of using information from remote sensing and other spaceborne technologies, the remote sensing community needs to focus its efforts more on the production of useful and meaningful products.

Finally, it must be underscored that the traditional approach in dealing with wildland fires exclusively under the traditional forestry schemes must be replaced in future by an inter-sectoral and interdisciplinary approach. The devastating effects of many wildfires are an expression of demographic growth, land-use and land-use changes, the socio-cultural implications of globalisation, and climate variability. Thus, integrated strategies and programmes must be developed to address the fire problem at its roots, while at the same time creating an enabling environment and develop appropriate tools for policy and decision makers to proactively act and respond to fire.

What are the implications of these conclusions on fire science? Back in the early 1990s the first major inter-disciplinary and international research programmes, including inter-continental fire-atmosphere research campaigns such as the Southern Tropical Atlantic Regional Experiment (STARE) with the Southern Africa Fire-Atmosphere Research Initiative (SAFARI) in the early 1990s (JGR 1996), clearly paved the way to develop visions and models for a comprehensive science of the biosphere. At the beginning of the 3rd millennium it is recognized that progress has been achieved in clarifying the fundamental mechanisms of fire in the global environment, including the reconstruction of the prehistoric and historic role of fire in the genesis of planet Earth and in the co-evolution of the human race and nature.

However, at this stage we have to examine the utility of the knowledge that has been generated by a dedicated science community. We have to ask this at a time when it is becoming obvious that fire plays a major role in the degradation of the global environment. It follows from the statement of Pyne (2001) "*Fire has the capacity to make or break sustainable environments. Today some places suffer from too much fire, some from too little or the wrong kind, but everywhere fire disasters appear to be increasing in both severity and damages*" that we must ask whether wildland fire is becoming a major threat at the global level? Does wildland fire at a global scale contribute to an increase of exposure and vulnerability of ecosystems to secondary / associated degradation and even catastrophes?

The regional analyses provided in this paper reveal that environmental destabilization by fire is obviously accelerating. This trend goes along with an increasing vulnerability of human populations. Conversely, humans are not only affected by fire but are the main causal agent of destructive fires, through both accidental, unwanted wildfires, and the use of fire as a tool for conversion of vegetation and reshaping whole landscapes.

This trend, however, is not inevitable. There are opportunities to do something about global fire because – unlike the majority of the geological and hydro-meteorological hazards – wildland fires represent a natural hazard which in most regions of the world is primarily human-made, can be predicted, controlled and, in many cases, prevented.

Here is the key for the way forward. Wildland fire science has to decide its future direction by answering a number of basic questions: What is the future role of fundamental fire science, and the added value of additional investments? What can be done to close the gap between the wealth of knowledge, methods and technologies for sustainable fire management and the inability of humans to exercise control?

From the perspective of the author the added value of continuing fundamental fire science is marginal. Instead, instruments and agreed procedures need to be identified to bring existing technologies to application. Costs and impacts of fire have to be quantified systematically to illustrate the significance of wildland fire management for sustainable development.

This implies that scientific focus has to be shifted. The fire domain for a long time has been governed by inter-disciplinary natural sciences research. Engineering research has contributed to a high level of development in the industrial countries. What is needed in future is a research focus at the interface between the human dimension of fire and the changing global environment. The new fire science in the third millennium must be application-oriented and understood by policy makers.

This recommendation is reflected by the establishment of a dedicated Working Group on Wildland Fire of the United Nations. The Working Group operates in support of the Inter-Agency Task Force for Disaster Reduction of the United Nations International Strategy for Disaster Reduction (ISDR) and brings together an international consortium of UN agencies and programmes, representatives from natural sciences, humanities, fire management agencies and non-government organizations (ISDR 2001). The terms of reference of this group is, among others, to advise policy makers at national to international levels in the reduction of the negative effects of fire in the environment, in support of sustainable management of the Earth system. The activities include a major global networking activity – the Global Wildland Fire Network – facilitated through the Global Fire Monitoring Center (GFMC 2003) and supported by the science community.

The UN Working Group also intends to develop a proposal for internationally acceptable criteria, with common procedures and guidelines, for the collection of data on fires in a consistent manner, with the intention of compiling accurate estimates of wildland fire globally that can be used by various user communities locally, nationally, regionally and globally.

The contribution of global wildland fire science to the way forward must lead towards the formulation of national and international public policies that will be harmonized with the objectives of international conventions, protocols and other agreements, e.g., the Convention on Biological Diversity (CBD), the Convention to Combat Desertification (UNCCD), United Nations Framework Convention on Climate Change (UNFCCC) and the UN Forum of Forests (UNFF). The wildland fire community has begun working on efficient, internationally-agreed-upon solutions to respond to wildland fire disasters through international cooperative efforts. The first International Wildland Fire Summit (Sydney, Australia, 8 October 2003) has provided the ground for enhancing the international dialogue on cooperation in wildland fire management.

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