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Report on Early Warning for Fire and Other Environmental Hazards

Convener of International Working Group, and first Author:

Dr. Johann G. Goldammer

Max Planck Institute for Chemistry, Biogeochemistry Department

Fire Ecology Research Group, Freiburg University

Freiburg

Germany

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EARLY WARNING FOR FIRE
AND OTHER ENVIRONMENTAL HAZARDS

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FOREWORD

In 1989, the member states of the United Nations declared the period from 1990 to the year 2000 to be the International Decade for Natural Disaster Reduction (IDNDR). Its objective is to "reduce the loss of life, property damage, and social and economic disruption caused by natural disasters, through concerted international action, especially in developing countries".

The fundamental importance of early warning for realizing this objective of disaster reduction was recognized in 1991. The IDNDR's Scientific and Technical Committee declared the subject a program target, by which the success of the Decade would be judged by the year 2000. By drawing on global scientific knowledge and practical experience, the Decade's advisory committee encouraged all countries to ensure the ready access to global, regional, national and local warning systems as part of their national development plans. The IDNDR Secretariat has since coordinated an international multi-disciplinary framework to promote this issue. In doing so, it has been able to draw on the comprehensive views and abilities of the United Nations system, needs and concerns of individual countries, and related global expert knowledge.

The critical nature of early-warning for the protection of vital resources and for addressing national development objectives was highlighted by a technical committee session devoted to the subject at the United Nations' World Conference on Natural Disaster Reduction held in Yokohama, Japan in May 1994. Several of the expert presentations cited the importance of public policy commitment for successful early warning. The primary outcome of the Conference, The Yokohama Strategy for a Safer World: Guidelines for Natural Disaster Prevention, Preparedness and Mitigation further emphasized the importance of applied scientific knowledge and the public's awareness of hazard risks as essential components for more effective early warning practices.

The IDNDR Secretariat was requested by the United Nations General Assembly in 1995 to coordinate a review of the existing early warning programs and to suggest means by which global practices could become better coordinated and made more effective. Initial information was conveyed by the Secretary General's Report on Early Warning to the Fiftieth Session of the United Nations General Assembly in October 1995. (UN Document A/50/256, 9 October 1995). At that time, a further examination of new scientific and experimental concepts for accurate and timely short-term forecasting was requested of the IDNDR for the purpose of making recommendations on the applicability and development of more effective early warning in the context of international cooperation.

For the current work, six international expert working groups were convened to study different aspects of the early warning process: geological hazards, hydrometeorological hazards including drought, fire and other environmental hazards, technological hazards, the use and transfer of related modern technologies, and national and local capabilities pertinent to the effective use of early warning. Guiding Principles for Effective Early Warning were also compiled by the conveners.

This following report of the Working Group on Early Warning Capabilities for Geological Hazards summarizes global experience and reviews the current state of knowledge and practice on the subject. Recommendations are also made for improvements and areas that require additional international attention. The conclusions reflect the views of scientific and technical experts as well as those of the United Nations departments and agencies concerned. An effort was made to ensure that views of government authorities, non-governmental organizations and other elements of civil society were also represented, particularly as they relate to factors which determine the efficacy of early warnings.

This report is one of a series issued by the IDNDR Secretariat in October 1997 to review the current state of early warning systems. By the end of the Decade, these views will contribute to final recommendations for improved, and better coordinated, practices in fulfillment of the initial

IDNDR program target for the subject. They will first be considered by an International Conference on early warning systems for the reduction of natural disasters which has been held in Potsdam, Germany in September, 1998. This technical and scientific conference focusing on the application of successful warning practices was sponsored by the Government of Germany with the collaboration of United Nations' agencies and international scientific organizations. As a major topical event of the IDNDR closing process and the consolidation of global views, the conference has identified those accomplishments and local experiences which can best improve organizational relationships and practical effectiveness for early warning into the 21st century.

The following titles compose the series of information reports of the IDNDR Early Warning Programme:

Early Warning Capabilities for Geological Hazards
Early Warning for Hydrometeorological Hazards, Including Drought
Early Warning for Fire and Other Environmental Hazards
Early Warning for Technological Hazards
Earth Observation, Hazard Analysis and Communications Tech. for Early Warning
National and Local Capabilities for Early Warning
Guiding Principles for Effective Early Warning

The Secretary General's Report on Early-warning Capacities of the United Nations System with Regard to Natural Disasters presented to the Fiftieth Session of the United Nations General Assembly, October 1995. (UN doc. A/50/526).

The Secretary General's Report on Improved Effectiveness of Early-warning Systems With Regard to Natural and Similar Disasters presented to the Fifty-second Session of the United Nations General Assembly , October 1997. (UN doc. A/52/561).

These reports may be accessed on the IDNDR web site: http://www.idndr.org or on the EWC'98 web site at http://www.gfz-potsdam.de/ewc98/ They also may be obtained from the IDNDR Secretariat, Palais des Nations, CH-1211 Geneva 10 Switzerland. or by Fax: +41-22-917-9098, or E-mail: idndr@dha.unicc.org

EXECUTIVE SUMMARY

Wildfires annually effect several hundred million hectares of forest and other vegetation of the world. In some ecosystems fire plays an ecologically significant role in biogeochemical cycles and disturbance dynamics. In other ecosystems fire may lead to the destruction of forests or to long-term site degradation. In most areas of the world wildfires burning under extreme weather conditions will have detrimental impacts on economies, human health and safety, with consequences which are comparable to the severity of other natural hazards.

Fires in forests and other vegetation produce gaseous and particle emissions that have impacts on the composition and functioning of the global atmosphere. These emissions interact with those from fossil-fuel burning and other technological sources which are the major cause for anthropogenic climate forcing. Smoke emissions from wildland fires also cause visibility problems which may result in accidents and economic losses. Smoke generated by wildland fires also affect human health and in some cases contribute to loss of human lives. Fire risk modelling in expected climate change scenarios indicate that within a relatively short period of the next three to four decades, the destructiveness of human-caused and natural wildfires will increase. Fire management strategies which include preparedness and early warning cannot be generalized due to the multi-dimensional effects of fire in the different vegetation zones and ecosystems and the manifold cultural, social, and economic factors involved. However, unlike the majority of the geological and hydrometeorological hazards included in the IDNDR Early Warning Programme, wildland fires represent a natural hazard which can be predicted, controlled and, in many cases, prevented.

Early warning systems are essential components of fire and smoke management. They rely on evaluation of vegetation dryness and weather; detection and monitoring of active fires; integrating and processing of these data in fire information systems with other relevant information, e.g. vegetation cover and values at risk; modelling capabilities of fire occurrence and behaviour; and dissemination of information.

Early warning of fire and atmospheric pollution hazard may involve locally generated indicators, such as local fire-weather forecasts and assessment of vegetation dryness. Advanced technologies, however, which rely on remotely sensed data, evaluation of synoptic weather information and international communication systems (e.g., Internet) are now also available for remote locations.

This present report of the IDNDR Early Warning Group on Wildfire and other Environmental Hazards represents global experience and reviews the current state of knowledge and practice on the subject. It provides a state-of-the-art analysis of existing and projected early warning and fire information systems which can be made accessible equally at global

Recommendations are also made for improvements and areas that require additional international attention. They include design and implementation of a global fire inventory; establishment of a Global Vegetation Fire Information System (GVFIS); establishment of a system in which real-time information on early warning of wildfire precursors and on ongoing wildfire situations across the globe is gathered and shared, e.g. through the creation of a World Fire Web; development of space borne sensors and platforms with improved early warning capabilities; establishment of an information network which includes the resource status by continuously monitoring the disposition of suppression resources; establishment of a global fire management facility under the auspices of the UN system; promotion of policies and agreements on early warning of wildfires at international levels; and coordination of research efforts with ongoing and future fire science programmes.

I. INTRODUCTION

General Remarks on Fire Hazard

Fire is an important recurrent phenomenon in all forested and non-forested regions of the globe. In some ecosystems fire plays an ecologically significant role in biogeochemical cycles and disturbance dynamics. In other ecosystems fire may lead to the destruction of forests or to long-term site degradation. As a consequence of demographic and land use changes and the cumulative effects of anthropogenic disturbances many forest types adapted to fire, are becoming more vulnerable to high-intensity wildfire. Ironically, this is often due to the absence of periodic low-intensity fire. In other forest types, however, as well as many non-forest ecosystems e.g. in savannas and grasslands, fire plays an important role in maintaining their dynamic equilibrium productivity and carrying capacity (Goldammer, 1990; Goldammer and Furyaev 1996; van Wilgen et al. 1997).

In most areas of the world wildfires burning under extreme weather conditions will have detrimental impacts on economies, human health and safety, with consequences that are comparable to the severity of other natural hazards. In all ecosystem fire needs to be managed to balance the benefits derived from burning with the potential losses from uncontrolled fires.

Fires in forests and other vegetation produce gaseous and particle emissions that have impacts on the composition and functioning of the global atmosphere (Crutzen and Goldammer, 1993; Levine, 1991, 1996; van Wilgen et al. 1997). These emissions interact with those from fossil-fuel burning and other technological sources which are the major cause for anthropogenic climate forcing. Smoke emissions from wildland fires also cause visibility problems which may result in accidents and economic losses. Smoke generated by wildland fires also affect human health and in some cases contribute to the loss of human lives.

Fire risk modelling in expected climate change scenarios indicate that within a relatively short period of the next three to four decades, the destructiveness of human-caused and natural wildfires will increase. Fire management strategies which include preparedness and early warning cannot be generalized due to the multi-dimensional effects of fire in the different vegetation zones and ecosystems and the manifold cultural, social, and economic factors involved.

However, unlike the majority of the geological and hydrometeorological hazards included in the IDNDR Early Warning Programme, wildland fires represent a natural hazard which can be predicted, controlled and, in many cases, prevented.

Recent major fire events and fire losses

Comprehensive reports with final data on losses caused by forest and other vegetation fires (wildland fires) are only occasionally available. The main reason for the lack of reliable data is that the majority of both the benefits and losses from wildland fires involve intangible non-use values or non-market outputs which do not have a common base for comparison, i.e. biodiversity, ecosystem functioning, erosion, etc. (González-Cabán, 1996).

Market values such as loss of timber or tourism activity have been calculated in some cases. The large wildfires in Borneo during the drought of 1982-83, which was caused by the El Niño Southern Oscillation (ENSO), affected a total of more that 5 million hectares of forest and agricultural lands (Goldammer et al., 1986). It resulted in the loss of timber values of ca. US$8.3 billion, and a total of timber and non-timber values and rehabilitation costs of US$ 9.075 billion (Schindele et al., 1989). The damages caused by the fire episode of 1997 in Indonesia are not yet known at the time of writing this report.

The 1988 fires in the Yellowstone area of the United States cost around US$ 160 million to suppress and caused an estimated loss of US$ 60 million in tourist revenues between 1988 and 1990 (Polzin et al., 1988). In the longer term, however, the increased biodiversity created by the fires in Yellowstone National Park may well yield benefits that outweigh these losses.

Australia's Ash Wednesday Fires of 1983, which were also linked to the ENSO drought of 1982-83, resulted in a human death toll of 75, the loss of 2539 houses and nearly 300,000 sheep and cattle. In South Australia alone the estimated direct losses of agricultural output (sheep, wool, lambs, cattle, pasture, horticulture) of the Ash Wednesday fires were estimated AUS$ 5.7 million (on the basis of 1976-77 prices), and the estimated value of the net costs to the Government Sector of South Australia of the 1983 bushfires were AUS$ 33 million (Healey et al., 1985).

Wildfire damage to agricultural lands, particularly in the tropics, may have tremendous impact on local and regional famine. In 1982-83 the West African country Côte d'Ivoire was swept by wildfires over a total area of ca. 12 million ha (Goldammer, 1993). The burning of ca. 40,000 ha of coffee plantations, 60,000 ha of cocoa plantations, and some 10,000 ha of other cultivated plantations had detrimental impacts on the local economy. More than 100 people died during this devastating fire period.

The "Great Black Dragon Fire" of 1987 in the People's Republic of China burned a total of 1.3 million hectares of boreal mountain forest, the houses of 50,000 inhabitants and resulted in a human death toll of 221, mostly caused by high carbon monoxide concentrations in the forest villages. The long-term statistics in China reveal that between 1950 and 1990 a total of 4,137 people were killed in forest fires (Goldammer, 1994).

The last large fire event occurred in Mongolia between February and June 1996. A total of 386 forest and steppe fires burned over an area of 2.3 million ha of forest and 7.8 million ha of pasture land, involving the loss of 25 human lives, more than 7000 livestock, 210 houses, 560 communication facilities, and 576 facilities for livestock; the preliminary damage assessment was ca. US$ 2 billion (Naidansuren, 1996).

Reliable statistical data on occurrence of wildland fires, areas burned and losses are available for only a limited Number of nations and regions. Within the northern hemisphere the most complete data set on forest fires is periodically collected and published for the member states of the Economic Commission for Europe (ECE). It includes all Western and Eastern European countries, countries of the former Soviet Union, the U.S.A. and Canada. The last data set covers the period 1993-95 (ECE/FAO 1996). In the European Union a Community Information System on Forest Fires has been created on the basis of information collected on every fire in national databases. The collection of data on forest fires (the common core) has become systematic with the adoption of a Commission Regulation in 1994. The Community Information System on Forest Fires currently covers 319 provinces (departments, states) of Portugal, Spain, France, Italy, Germany and Greece (European Commission, 1996; Lemasson, 1997). It contains information on 460,000 fires recorded between 1 January 1985 and 31 December 1995 involving a total of six million hectares. Other countries from outside the ECE/EU region report fire statistics in the pages of International Forest Fire News or are included in the FAO report on global wildland fires (FAO, 1992).

In many countries (e.g. Australia) where fire is used as a management tool by the indigenous population, graziers and managers of forests and natural areas it is impossible to discriminate between management fires and wildfires. Statistics for wildfires are usually available only for production forest and national park lands.

A global data set has been developed on the basis of active fires detected by the NOAA AVHRR sensor. The "Global Fire Product" of the International Geosphere-Biosphere Programme Data and

Information System (IGBP-DIS; further details are provided below in the section on Global Fire Monitoring).

Impacts of fire on the environment

From the perspective of the IDNDR wildland fires may affect two basic environmental problem areas, (1) atmospheric pollution (direct impact of smoke on human health and economies; influence of gaseous and particle emissions on the composition and functioning of the atmosphere), and (2) biodiversity, ecosystem functioning, and landscape stability. These both can have deleterious consequences for the severity of other hazards.

Atmospheric pollution

Human fatalities and health

Smoke pollution generated by wildland fires occasionally creates situations during which human lives and local economies are affected. Fatalities in the general public caused by excessive carbon monoxide concentrations have been reported from various fire events, e.g. the large forest fires in China in 1987. Firefighters who are regularly subjected to smoke are generally at higher health risk.

The use of fire in forest conversion and other forms of land clearing and wildfires spreading beyond these activities are very common in tropical countries. In the 1980's and 1990's most serious pollution problems were noted in the Amazon Basin and in the South East Asian region. The most recent large smog episodes in the South East Asian region were in 1991, 1994 and 1997 when land-use fires and uncontrolled wildfires in Indonesia and neighbour countries created a regional smog layer which lasted for several weeks. In 1994 the smoke plumes of fires burning in Sumatra (Indonesia) reduced the average daily minimum horizontal visibility over Singapore to less than 2 km; by the end of September 1994 the visibility in Singapore dropped to as low as 500 metres. In the same time the visibility in Malaysia dropped to 1 km in some parts of the country. A study on asthma attacks among children revealed a high concentration of fire-generated carbon monoxide (CO), nitrogen dioxide (NO_2) and inhalable suspended particulate matter (PM10) was responsible for the health problems (ASEAN, 1995a). The smog situation in September 1997 caused the worst smoke pollution in the region, reflected by a value of 839 of the Pollutant Standard Index (PSI, for further details see the Section below on Atmospheric Pollution Warning) in the city of Kuching (Sarawak Province, Malaysia); the government was close to evacuating the 400,000 inhabitants of the city.

In the same regions, the smoke from fires caused disruption of local and international air traffic. In 1982-83, 1991, 1994 and 1997 the smog episodes in South East Asia resulted in the closure of airports and marine traffic, e.g. in the Strait of Malacca and along the coast and on rivers of Borneo. Smoke-related marine and aircraft accidents occurred during September 1997. The loss of an air plane and 234 human lives in September 1997 in Sumatra was partially attributed to air traffic control problems during the smog episode.

Wildfires burning in radioactively contaminated vegetation lead to uncontrollable redistribution of radionuclides, e.g. the long-living radionuclides caesium (^{137}Cs), strontium (^{90}Sr) and plutonium (^{239}Pu).[1] In the most contaminated Regions of the Ukraine, Belarus and the Russian Federation (the Kiev, Zhitomir, Rovmo, Gomel, Mogilev and Bryansk Regions), the prevailing forests are young and middle-aged pine and pine-hardwood stands with high fire danger classes. In 1992 severe wildfires burned in the Gomel Region (Belorussia) and spread into the 30-km radius zone of the

[1] Radionuclides of plutonium are found mainly within the 30-km zone around the Chernobyl Power Plant. Radionuclides of strontium have contaminated a number of districts in the Kiev Region (Belarus) and in the Bryansk Region (Russian Federation). Radionuclides of caesium account for the largest contaminated areas in these states. In the Russian Federation, the soil surface, in which caesium radionuclide contamination exceeds 37 GBq/km^2 (37 Gigabequerel = 3.7×10^{10} Bq), totals 4.9 million hectares within 15 Regions. The areas in which the radiocaesium contamination density is 555 GBq(= 0.555 TBq)-1,5 TBq/km^2 and higher, are mainly in the Bryansk Region (ca.250,000 ha).

Chernobyl Power Plant. Research reveals that in 1990 most of the ^{137}Cs radionuclides were concentrated in the forest litter and upper mineral layer of the soil. In the fires of 1992 the radionuclides were lifted into the atmosphere. Within the 30-km zone the level of radioactive caesium in aerosols increased 10 times (for more details on resuspension of radioactive matter from forest fires, see Dusha-Gudym, 1996).

Fire emissions, atmosphere and climate

In recent years increasing attention has been given to the role of vegetation fires in biogeochemical cycles and in the chemistry of the atmosphere (Crutzen and Goldammer, 1993). According to recent estimates some 1.8-4.7 billion tons of carbon stored in vegetation may be released annually by wildland fires and other biomass burning (Crutzen and Andreae, 1990). It must be noted that not all of the biomass burned represents a net source of carbon in the atmosphere. The net flux of carbon into the atmosphere is due to deforestation (forest conversion with and without involving the use of fire) and has been estimated by Houghton (1991) to be in the range of 1.1-3.6 billion tons per year. Important contributions to the total world wide biomass burning, which are included in the numbers mentioned above, are fires in savannas, shifting agriculture, agricultural waste burning and firewood consumption (Andreae and Goldammer, 1992).

Although the emissions from tropical vegetation fires are dominated by carbon dioxide [CO_2], many products of incomplete combustion that play important roles in atmospheric chemistry and climate are emitted as well, e.g., a number of gases that influence the concentrations of ozone and hydroxyl radicals and thus the oxidation efficiency of the atmosphere, in particular NO, CO, CH_4 and reactive hydrocarbons. The influence of these emissions affects especially the southern hemisphere during the dry (winter) season, i.e. during August - November, and manifests itself in strongly enhanced tropospheric ozone concentrations, extending from the regions regularly affected by biomass burning in Brazil and southern Africa across the Atlantic and the Indian Ocean all the way down to Tasmania (Andreae et al., 1993; Journal of Geophysical Research, 1996; van Wilgen et al., 1997). Other gases whose atmospheric concentrations are strongly dominated by biomass burning are CH_3Cl and CH_3Br, which together with CH_4 play a significant role in stratospheric ozone chemistry (Manö and Andreae, 1994).

Biodiversity, ecosystem functioning, and landscape stability

The impacts of wildfires on the functioning and stability of ecosystems has been described widely in numerous publications, covering the full range of geographical, ecological, socio-cultural and economic conditions of the globe. The magnitude of phenomena resulting from wildfires prohibits any detailed review in the context of this report.

On the one hand fire is an integrated element which contributes to the stability, sustainability, high productivity and carrying capacity of many ecosystems. On the other hand wildfire, in conjunction or interaction with land use systems and exploitation of natural resources, leads to the loss of forest and agricultural products and can have negative impacts on biodiversity, ecosystem function and land stability. For example, in the dry forests of Australia low-intensity fire is regularly applied to maintain understorey plant species and habitat for native fauna as well as to reduce surface fuels to mitigate against the impacts of high-intensity wildfires. During the dangerous summer period all fires are suppressed as quickly as possible both to reduce damage to forest values and to reduce the chance of wildfire burning out of the forest and causing severe losses to houses and structures in the built environment.

Many plant and animal species, e.g. in the tropical lowland rain forest ecosystems and elsewhere, are susceptible to fire influence and are easily destroyed by fire and replaced by less species-rich communities. Human-induced fire regimes in tropical rain forests result in degraded vegetation types (grasslands, brushlands) which are less stable and productive, both from an ecological and economic point of view. Fires may also lead to the depletion of soil cover, resulting in increased runoff and erosion, with severe downstream consequences, e.g., mudflows, landslides, flooding or siltation of reservoirs.

Fires often interact with other disturbances, e.g. extreme storm events (hurricanes) or insect outbreaks. The extended rain forest fires of 1989 in Yucatan (Mexico) represent a typical example because they were a result of a chain of disturbance events. Hurricane "Gilbert" in 1987 opened the closed forests and increased the availability of unusual amounts of fuels. The downed woody fuels were then desiccated by the subsequent drought of 1988-89, and the whole of the forest area was finally ignited by escaped land clearing fires. None of these single three factors, the cyclonic storm, the drought, or the ignition sources, if occurring alone, would have caused a disturbance of such severity and magnitude on an area of 90,000 hectares (Goldammer, 1992).

In Krasnoyarsk Region, Russian Federation, a mass outbreak of the Siberian Gipsy Moth (*Dendrolimus superans sibiricus*) going on since 1989 has meanwhile affected a total of 1 million hectares of boreal forest (Baramchikov, 1997). It is expected that large wildfires will occur in the partially or completely killed stands within the next years.

Early warning systems in fire management and smoke management

Early warning (fire intelligence) systems are essential components of fire and smoke management [2]. They rely on

- evaluation of vegetation dryness and weather;
- detection and monitoring of active fires;
- integrating and processing of these data in fire information systems with other relevant information, e.g. vegetation cover and values at risk;
- modelling capabilities of fire occurrence and behaviour; and
- dissemination of information.

Early warning of fire and atmospheric pollution hazard may involve locally generated indicators, such as local fire-weather forecasts and assessment of vegetation dryness. Advanced technologies, however, which rely on remotely sensed data, evaluation of synoptic weather information and international communication systems (e.g., Internet) are now also available for remote locations.

In this report the large variety of standards, methods and technologies of fire and smoke management which are used in national programs cannot be described in detail. Generally speaking, however, it is obvious that, due to the lack of resources, fire management systems are disproportionately less available in developing countries.

In some industrialized countries, e.g. in Central and Northern Europe, wildfires have been largely eliminated due to high-intensity land use, improved accessibility of potentially threatened land and the availability of infrastructures and advanced fire management technologies. Regions with less developed infrastructures are found in densely populated lands (e.g., in the tropics and subtropics) and in sparsely inhabited regions (e.g., in the northern boreal forests) as well. They are

[2] For clarification of terminology used in this report the terms fire management, prescribed burning and smoke management are briefly explained (FAO, 1986):

Fire management embraces all activities required for the protection of burnable forest values from fire and the use of fire to meet land management goals and objectives. This includes fire prevention, early warning of fire risk, detection and suppression of fires, and the application of prescribed burning.

Prescribed burning is the controlled application of fire to wildland fuels in either their natural or modified state, under specified environmental conditions which allow the fire to be confined to a predetermined area and at the same time to produce the intensity of heat and rate of spread required to attain planned resource management objectives.

Smoke management is the application of knowledge of fire behaviour and meteorological processes to minimize air quality degradation during prescribed fires.

equally subjected to high wildfire risk because of the abundance of human fire sources or the lack of human resources to control fires respectively.

Relation to Other IDNDR Early Warning Working Group Reports

Some of the issues described in this report are closely related to other IDNDR Early Warning Working Group reports, e.g. the reports on hydrometeorological hazards, on technological opportunities, and on local perspectives. The cross-cutting issues show that there are areas of potential common activities and programmes.

The conclusions of the most recent global wildland fire forum, the "Second International Wildland Fire Conference" (Vancouver, Canada, May 1997), clearly underscored the fact that unlike other natural disasters, fire is one of the few natural disturbances that can be forecast and mitigated (Anonymous, 1997). This fact may explain why forecasting fire events and the potential of mitigating fire impacts are comparably better developed as compared to other natural disasters. The description of the early warning systems for wildfires, which are available, in the development stage or proposed, may therefore serve as examples for other local, regional and international mechanisms of cooperation in disaster early warning and management.

II. HAZARD ASSESSMENT AS THE BASIS OF RISK ANALYSIS

Early warning systems for fire and smoke management for local, regional, and global application require early warning information at various levels. Information on current weather and vegetation dryness conditions provides the starting point of any predictive assessment. From this information the probability of risk of wildfire starts and prediction of the possibility of current fire behaviour and fire impacts can be derived. Short- to long-range fire weather forecasts allow the assessment of fire risk and severity within the forecasting period. Advanced space borne remote sensing technologies allow fire weather forecasts and vegetation dryness assessment covering large areas (local to global), at economic levels and with accuracy which otherwise cannot be met by ground-based collection and dissemination of information. Remote sensing provides also capabilities for detecting new wildfire starts, monitoring ongoing active wildfires, and, in conjunction with fire-weather forecasts, providing an early warning tool for escalating, extreme wildfire events.

Fire Danger Rating (Fire Risk Assessment)

Fire danger rating systems have been devised by fire authorities to provide early warning of conditions conducive to the onset and development of extreme wildfire events. The factors that predispose a particular location to extreme wildfire threat change over time scales that are measured in decades, years, months, days and hours. The concept of fire danger involves both tangible and intangible factors, physical processes and hazard events. By definition:

"Fire danger" is a general term used to express an assessment of both constant and variable fire danger factors affecting the inception, spread, intensity and difficulty of control of fires and the impact they cause (e.g., Chandler et al., 1983).

The constant factors in this definition are those which do not change rapidly with time but vary with location e.g. slope, fuel, resource values, etc. The variable factors are those which change rapidly with time and can influence extensive areas at one time and these are primarily the weather variables which affect fire behaviour. All the potentials referred to in the definition must be present.

If there is absolutely no chance of ignition - there is no fire danger. If fuels are absent or cannot burn - there is no fire danger. If fires can start and spread but there are no values at risk as may be perceived for remote areas managed for ecological diversity, there is no fire danger for values at risk.

Fire danger rating systems produce qualitative and/or numerical indices of fire potential that can be used for guides in a variety of fire management activities including early warning of fire threat. Different systems of widely varying complexity have been developed throughout the world which reflect both the severity of the fire climate and the needs of fire management. The simplest systems use only temperature and relative humidity to provide an index of the potential for fire starts (e.g. see the Angstrom index, cf. Chandler et al., 1983). Fire danger rating systems of intermediate complexity combine measures of drought and weather as applied to a standard fuel type to predict the speed of a fire or its difficulty of suppression (e.g., McArthur 1966, 1967; Sneeuwjagt and Peet, 1985). The most complex systems have been developed in Canada (Forestry Canada Fire Danger Group, 1992) and the United States (Deeming et al., 1978) which combine measures of fuel, topography, weather and risk of ignition (both lightning and human-caused) to provide indices of fire occurrence or fire behaviour which can be used either separately or combined to produce a single index of fire load.

While a single fire danger index may be useful to provide early warning of wildfire activity over broad areas it is impossible to communicate a complete picture of the daily fire danger with a single index. Therefore, it is necessary to break fire danger rating into its major components to appreciate where early warning systems for single factors fall into the overall picture of fire danger rating. These fall into three broad categories of changes in fuel load; changes in fuel availability or combustion and changes in weather variables that influence fire spread and intensity.

Early warning of fire precursors

Changes in fuel load

In all fire danger rating systems fuel load is assumed to be constant although specific fuel characteristics may be formulated for specific forest or other vegetation types as in the Canadian fire danger rating system or for specific fuel models i.e. combinations of vegetation and fuel with similar characteristics as in the U.S. National Fire Danger Rating System. These fuel models may overlook major shifts in total fuel loads which may be changing over periods of decades or even centuries. Fuel changes start immediately after the cessation of cultural or agricultural burning. This change usually runs in parallel with increased suppression efficiency whereby small fires under moderate fire danger conditions are suppressed early in their life. In this scenario fire authorities and the general public may be lulled into a false sense of security because the potential for high-intensity forest fires is not manifest except under rare events of extreme weather. In places this may be complicated by the introduction of exotic forest species (e.g. the establishment of eucalypt forests on formerly oak woodland savannahs in central California) and a shift of the population from living in relatively low-fuel areas which were maintained either by frequent burning through cultural or agricultural practices, or though frequent low-intensity wildfires.

Thus, the first element of early warning for a potential fire risk is a major shift in the total forest fuel complex towards denser forests with a large build up of surface debris and a change in vulnerability of the population by living more intimately with these fuels. Over the last 20 years this change has occurred in the urban/forest intermix associated with most of the centres of population located in forest regions of many of the more developed countries.

Fuel availability

The seasonal change in fuel availability as fuels dry out during the onset of the fire danger period sets the stage for severe wildfires. Under drought conditions more of the total fuel complex is available for combustion. Deep litter beds and even organic soils may dry out and become combustible. Large fuels such as downed logs and branches may burn completely. Drought stress on living vegetation not only reduces the moisture content of the green foliage but also dried plant matter such as leaves and bark can be shed adding to the total load of the surface fuel. Under extreme drought conditions normally moist areas such as swamps and creek lines dry out and are no longer a barrier to the spread of fires as might be expected in a normal fire season. Long-term moisture deficiency in itself cannot be used to forecast critical fire situations because if the smaller fine fuels are wet or green, serious fires will not occur at any time of the year. However, most devastating fires occur when severe fire weather variables are combined with extreme drought.

There are a number of bookkeeping methods of monitoring the seasonal development of drought. The Keetch-Byram (1968) Drought Index is a number representing the net effect of evapotranspiration and precipitation in producing a cumulative measure of moisture deficiency in the deep duff and soil layers. It is a continuous index which can be related to the changes in fuel availability mentioned above and the occurrence of severe fires. The Index has proved to be a useful early warning tool and is now incorporated into the US National Fire Danger Rating System (Pyne et al., 1996) and the Australian Forest Fire Danger Rating System (McArthur, 1967).

There are a number of similar drought indices used elsewhere in the world. For example, the drought code component of the Canadian Fire Weather Index System (Forestry Canada Fire Danger Group, 1992), the Australian Mount Soil Dryness Index (Mount, 1972) and the Drought Index used in France (Orieux, 1974, cited from Chandler et al., 1983).

Although drought indices can be built into a broader fire danger rating system they are most effective as an early warning system when they are maintained separately and charted to illustrate the progressive moisture deficit for a specific location. This allows the fire manager to compare the current season with historical records of past seasons. The fire manager can also make associations between level of drought index and levels of fire activity which are specific to the region. This overcomes the problems caused by variation of both forest and soil type which can mask the recognition of severe drought when a drought index is applied across broad areas.

Weather Variables

Regular charting of bookkeeping-type systems such as the Keetch-Byram Drought Index or the Mount Soil Dryness Index are particularly useful in monitoring the effects of below-average rainfall during the normal wet or winter season. Moisture deficits from the previous dry season may be carried over winter. As the next fire season develops, high levels of drought may occur early in the season when, under the normal seasonal pattern, large and intense fires rarely occur. In some parts of the world there are indices which indicate the changes in the global circulation patterns which may provide warning as much as 6 to 9 months in advance of extremely dry conditions. One of these is the Southern Oscillation Index which records the difference in atmospheric pressure between Darwin in the north of the country and Melbourne in southern Australia which can be related to the El Niño events in the southern Pacific Ocean. When the Southern Oscillation Index is strongly positive wetter than normal conditions are expected in south-eastern Australia; when the index is strongly negative drought conditions are forecast for the south-east of Australia.

Early warning of fire behaviour

The fire spread component of fire danger rating systems is designed to combine the weather elements affecting fire behaviour and provide a prediction of how fires will change hourly during the day. Most indices use 24 hour precipitation, and daily extremes or hourly measurements of temperature, relative humidity, and wind speed to predict the rate of spread of forest fires. In some systems, notably the U.S. National Fire Danger Rating System and the Canadian Fire Weather Index System, indices of fire spread are combined with a long-term measure of drought to provide an index of the total severity of the fire. This is termed a Burning Index in the United States system or a Fire Weather Index in the Canadian system.

In some systems the risk of ignition from either lightning activity or human activities is calculated to form an index of fire occurrence which can be combined with a Burning Index to give an overall Fire Load Index (e.g. Deeming et al., 1978). These are rarely used in the U.S.A. today

(Pyne et al., 1996). The risk of ignition by lightning is calculated separately and areas with historical records of high human-caused ignitions are mapped as a constant fire danger variable and are used in concert with a burning index to calculate fire threat in a wildfire threat analysis system.

Fire spread indices are essentially weather processors (Andrews, 1991) and the data required to provide early warning of severe fire conditions, depends primarily on the ability to provide adequate space and time forecasts of the weather. The synoptic systems which are likely to produce severe fire weather are generally well known but the ability to predict their onset depends largely on the regularity of movement and formation of atmospheric pressure systems. In Australia the genesis of severe fire weather synoptic systems has, at times, been recognised up to three days in advance; more often less than 24 hours warning is available before the severity of fire weather variables can be determined. Extended and long range forecasts contain greater uncertainty, and there is less confidence in fire severity forecasts at these time scales. Even so, these forecasts are useful in fire management in that the forecasts can be used to develop contingency plans, that is, developing options, but not implementing them until the forecasts are more certain.

As improved fire behaviour models for specific fuel types are developed there is an increasing need to separate the functions of fire danger and fire spread (Cheney, 1991). A regional fire weather index based on either fire spread or suppression difficulty in a standard fuel type and uniform topography is required to provide public warnings, setting fire restrictions, and establishing levels of readiness for fire suppression. At a local level, fire spread models which predict the development and spread of a fire across the landscape through different topography and through a number of fuel types are required for suppression planning and tactical operations. However, these systems can be confusing on a broader scale by providing too much detail. They may be influenced by atypical variations of critical factors at the measuring site and may lose the broad-scale appreciation of regional fire danger that is required for early warning purposes.

Use of Satellite Data to Help Assess Fire Potential

The amount of living vegetation, and its moisture content, has a strong effect on the propagation and severity of wildland fires. The direct observation of vegetation greenness is therefore essential for any early warning system. Current assessment of living vegetation moisture relies on various methods of manual sampling. While these measurements are quite accurate, they are difficult to obtain over broad areas, so they fail to portray changes in the pattern of vegetation greenness and moisture across the landscape.

The current polar orbiting meteorological satellites provide the potential for delivering greenness information and other parameters needed for fire management and fire impact assessment at daily global coverage at coarse spatial resolution (cf. Following section on Active Fire Detection by Satellite Sensors; see also Kendall et al., 1997). This is achieved using wide angle scanning radiometers with large instantaneous fields of view, e.g. the NOAA Advanced Very High Resolution Radiometer (AVHRR) instrument which measures reflected and emitted radiation in multiple channels including visible, near-infrared, middle-infrared, and thermal (Kidwell, 1991). Because of its availability, spatial resolution, spectral characteristics, and low cost, NOAA AVHRR has become the most widely used satellite data set for regional fire detection and monitoring. Currently, AVHRR data are used for vegetation analyses and in the detection and characterization of active flaming fires, smoke plumes, and burn scars.

Since 1989 the utility of using the Normalized Difference Vegetation Index (NDVI) to monitor seasonal changes in the quantity and moisture of living vegetation has been investigated (Tucker, 1977, 1980; Tucker and Sellers, 1986; Holben, 1986; Tucker and Choudhury, 1987; Goward et al., 1990). Daily AVHRR data are composited into weekly images to remove most of the cloud and other deleterious effects, and an NDVI image of the continental U.S. is computed by the U.S. Geological Survey's Earth Resources Observation Systems Data Center (EDC). These weekly images are obtained via the Internet and further processed into images that relate to fire potential

(Burgan and Hartford, 1993; Burgan et al., 1996) and that are more easily interpreted by fire managers.

Vegetation greenness information: An early warning indicator

Four separate images are derived from the NDVI data -- Visual Greenness, Relative Greenness, Departure from Average Greenness, and Live Shrub Moisture.

Visual greenness is simply NDVI rescaled to values ranging from 0 to 100, with low numbers indicating little green vegetation. Relative greenness maps portray how green each 1 km square pixel is in relation to the historical range of NDVI observations for that pixel. The Departure from Average Greenness maps portray how green the vegetation is compared to the average NDVI value determined from historical data for the same week of the year. Use of this map, along with the Visual and Relative Greenness maps, can give fire managers a good indication of relative differences in vegetation condition across the nation and how that might affect fire potential.

Live Shrub Moisture: The National Fire Danger Rating System (NFDR) used by the United States requires live shrub and herbaceous vegetation moisture as inputs to the mathematical fire model (Burgan and Hartford, 1996). For this reason, and to help fire managers estimate live shrub moistures across the landscape, Relative Greenness is used in an algorithm to produce live shrub moistures ranging from 50 to 250 percent.

These maps may be viewed at http://www.fs.fed.us/land/wfas/welcome.html.

Development of fire hazard maps

Improvement in the spatial definition of fire potential requires use of a fire danger fuel model map to portray the spatial distribution of fuel types. In the U.S.A. the Geological Survey's Earth Resources Observation Systems Data Center (EDC) used a series of eight monthly composites of NDVI data for 1990 to produce a 159 class vegetation map of the continental U.S. at 1 km resolution (Loveland et al., 1991). Data from 2560 fuel observation plots randomly scattered across the U.S. permitted the development of a 1 km resolution fuel model map from the original vegetation map. This fuel model map is now being used in two systems to provide broad scale fire danger maps.

Integration of satellite data into fire danger estimates

The state of Oklahoma in the United States provides a good example for early warning of wildfires. The state operates an automated weather station network that consists of 111 remote stations at an average spacing of 30 km. Observations are relayed to a central computer every 15 minutes. Cooperative work between the Intermountain Fire Sciences Laboratory (U.S. Forest Service) and the Oklahoma State University resulted in development of a fire danger rating system that produces map outputs (Carlson et al., 1996). The satellite-derived NFDR fuel model map is used to define the fuel model for each 1 km pixel, and the weekly Relative Greenness maps are used to calculate live fuel moisture input for the fire danger calculations. This results in a fire danger map showing a smooth transition of fire danger across the state. These maps may be viewed at http://radar.metr.ou.edu/agwx/fire/data.html.

A goal of fire researchers in the U.S. is to expand the techniques provided for Oklahoma to other states and nations. An alternative method of estimating fire potential has been developed (Burgan and others, in prep.) using just the 1 km resolution fire danger fuel model map, relative greenness, and interpolated moisture for dead fuels about 1.25 cm in diameter. This map was found to be highly correlated with fire occurrences for California and Nevada for the years 1990 to 1995 (Klaver et al., 1997). It is now being, or will be, further tested by Spain, Chile, Argentina, and Mexico as part of an effort between the Intermountain Fire Sciences Laboratory and the EDC, sponsored by the Pan American Institute for Geography and History. The Fire Potential Map is updated daily and can be seen at http://www.fs.fed.us/land/wfas/welcome.html under "experimental products".

While these examples, and many other published papers (Chuvieco, 1995), indicate the usefulness of current satellite data for fire management purposes, it is obvious that satellite data will become ever more useful and accurate. Instruments that will be flown on the "Mission to Planet Earth" hold great promise for several fire management requirements, such as fire detection, fuel mapping, monitoring seasonal greening and curing.

Fire Weather Forecasts

Improved fire weather forecasts are needed at a variety of time and space scales. At large space and time scales, accurate fire weather forecasts have potential for long range planning to allocate scarce resources. At smaller time and space scales, accurate fire weather forecasts have potential use in alerting, staging and planning the deployment of fire suppression crews and equipment. At the smallest time and space scales, accurate fire weather forecasts can be helpful in fighting fires as well as determining optimal periods for setting prescribed silvicultural fires (Fosberg and Fujioka, 1987; Roads et al., 1991, 1997).

Current U.S. fire weather forecasts are prepared from short-range weather forecasts (1-2 days) by the Eta model of the National Center for Environmental Prediction (NCEP), other model output statistics, and human judgement. These fire weather forecasts include information about precipitation, wind, humidity, and temperature.

To test whether even longer range forecasts focused on fire weather products would be useful, an experimental modelling system, developed at the U.S. National Center for Environmental Prediction (NCEP) for making short-range global to regional weather forecasts, is currently being developed at the Scripps Experimental Climate Prediction Center (ECPC). Although this system is currently focused on making and disseminating experimental global to regional fire weather forecasts focused for Southern California, it could be easily transported and applied anywhere else in the world.

Global to regional fire-weather forecasts

At the largest space and time scales, a modelling system utilizes NCEP's MRF or GSM (global spectral model; see Kalnay et al. 1996). A high resolution regional spectral model (RSM; see Juang and Kanamitsu, 1994) is nested within the global model by first integrating the GSM which provides initial and low spatial resolution model parameters as well as lateral boundary conditions for the RSM. The RSM then predicts regional variations influenced more by the higher resolution orography and other land distributions within a limited but high resolution domain (Kalnay et al., 1996).

Global to regional forecasts of the fire weather index and precipitation are currently displayed on the world-wide web site of the ECPC at http://meteoral.ucsd.edu/ecpc/special/globaltoregional/.

Due to bandwidth limitations of the Internet, only the complete initial and 72-hour forecasts for the global model are transferred four times daily (at 0000, 0600, 1200, 1800 hrs. UCT). From these global initial and boundary conditions, regional forecasts at 25 km resolution are then made and also displayed.

Future work

New features are under development. Besides beginning development of longer-range monthly global to regional forecasts, the current fire weather forecasting methodology will be validated. Experimental global to regional forecasts for other regions are also under development. Provision of additional output of corresponding land surface variables such as snow, soil and vegetation moisture are now being extracted and may soon be provided as part of the forecasts. These additional variables are needed to transform fire weather indices into fire danger indices, which include vegetation stresses.

Active Fire Detection by Satellite Sensors

The middle-infrared and thermal AVHRR bands of the NOAA polar-orbiting satellites have been used for identifying fires. Several techniques are currently used to detect active fires at regional scales using multi-spectral satellite data. A comprehensive validation of AVHRR active fire detection techniques through a range of atmospheric and surface conditions has not yet been performed. A number of studies, however, have provided some level of validation.

Limitations in AVHRR fire detection

Even in full configuration, with two NOAA satellites in operation, the AVHRR data provides only a limited sampling of the diurnal cycle. The orbital characteristics of the satellites result in two daytime and two nighttime orbits per location. The afternoon overpass provides the best coverage in terms of fire detection and monitoring in tropical and subtropical regions (Justice and Dowty, 1994). In addition, the afternoon overpass enables detection of the full range of parameters described (i.e. vegetation state, active fires, burn scars, smoke).

Perhaps the most fundamental problem to AVHRR fire detection is that analysis is limited to relatively cloud-free areas. This can be a serious issue in tropical and sub-tropical regions. Cloud cover can cause an underestimation in the extent and frequency of burning, and limits the ability to track vegetation parameters. This issue is not limited to the NOAA satellite system. Dense clouds will prevent detection of the surface by all visible and infrared sensors. A satisfactory methodology for estimating the amount of burning missed through cloud obscuration has yet to be developed.

Due to characteristics of the NOAA meteorological satellites described it is possible to collect near real-time information to support fire management activities.

Automatic fire alerts

A prototype software has been developed in Finland for automatic detection of forest fires using NOAA AVHRR data. Image data are received by the Finnish Meteorological Institute. From each received NOAA AVHRR scene a sub-scene covering as much as possible of the monitoring area is extracted (approximately 1150 square km).

The processing includes: detection and marking of image lines affected by reception errors, image rectification, detection of "hot spots", elimination of false alarms, and generation of alert messages by e-mail and telefax.

A fully automatic system has been developed to detect forest fires using data from NOAA AVHRR. The prototype system has been developed in Finland and tested in four experiments in 1994-1997 in Finland and its neighbouring countries Estonia, Latvia, Russian Carelia, Sweden and Norway. For each detected fire, a telefax including data on the location of the fire, the observation time and a map showing the location, is sent directly to the local fire authorities. Nearly all detected fires were forest fires or prescribed burnings.

The screening of false alarms is an essential technique in fire detection if the results are to be used in fire control. Effective screening enables fully automatic detection of forest fires, especially if known sources of error like steel factories are eliminated. In the experiments in 1994-96, most of the detected fires that were in areas where verification was possible, were real fires. This shows that space borne detection of forest fires has potential for fire control purposes.

Atmospheric Pollution Warning

The drought and fire episodes in Southeast Asia between 1992 and 1994 and again now in 1997 (September-October) resulted in severe atmospheric pollution. The regional smog events of 1991 and 1994 triggered a series of regional measures towards cooperation in fire and smoke management. In 1992 and 1995 regional workshops on "Transboundary Haze Pollution" were held in Balikpapan (Indonesia) and Kuala Lumpur (Malaysia). This was followed by the establishment of a "Haze Technical Task Force" during the Sixth Meeting of the ASEAN Senior Officials on the Environment (ASOEN) (September 1995). The task force is chaired by Indonesia and comprises senior officials from Brunei Darussalam, Indonesia, Malaysia, and Singapore. The objectives of the work of the task force is to operationalize and implement the measures recommended in the ASEAN Cooperation Plan on Transboundary Pollution relating to atmospheric pollution, including particularly the problem of fire and smoke (ASEAN, 1995a,b; Goldammer, 1997a,b).

First regional cooperation plans include the use of satellite data to predict smoke pollution from wildfires based on detection of active fires and smoke plumes and the forecast of air mass trajectories. In addition, some Southeast Asian countries have developed an air quality index for early warning of smoke-generated health and visibility problems.

In Singapore air quality is monitored by 15 permanent stations and reported using the Pollutant Standard Index (PSI), a set of criteria devised by the U.S. Environmental Protection Agency (EPA). The PSI value of 100 equals legal air quality standard (or limit) and is based on risk to human health (primary standard) or non-human health (animals, plants; secondary standard). Under this system, the levels of key pollutants like sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3) and respirable suspended particles (PM10) are used to come up with a single index, the PSI. The PSI is a health-related index, averaged over a 24-hour period, on a scale of 0-500.[3]

Another potentially useful tool for analysing fire-generated smoke sources, as detected or monitored by space borne sensors, is the rose-diagram technique (Brivio et al., 1997). In conjunction with trajectory analysis this spatial analysis technique allows to establish the relationships between smoke pollution and the potential sources, e.g. wildfires vs. industrial pollution.

Climate-change and Fire Risk Modelling

The Intergovernmental Panel on Climate Change (IPCC) has recently concluded that "the observed increase in global mean temperature over the last century (0.3-0.6°C) is unlikely to be entirely due to natural causes, and that a pattern of climate response to human activities is identifiable in the climatological record" (IPCC, 1995). In Canada and Russia, for instance, this pattern of observed changes has taken the form of major winter and spring warming in west-central and northwestern Canada and virtually all of Siberia over the past three decades, resulting in temperature increases of 2-3°C over this period (Environment Canada, 1995).

Numerous General Circulation Models (GCMs) project a global mean temperature increase of 0.8-3.5°C by 2100 AD, a change much more rapid than any experienced in the past 10,000 years. Most significant temperature changes are projected at higher latitudes and over land. While GCM projections vary, in general summer temperatures are expected to rise 4-6°C over much of Canada and Russia with a doubling of atmospheric carbon dioxide. In addition, changes in the regional and

[3] A PSI value <50 is good (no health effects; no cautionary actions required), 50-100 is moderate, 100-200 "unhealthy" (irritation symptoms; no vigorous outdoor activities recommended), 200-300 "very unhealthy" (widespread symptoms in population with heart or lung diseases; elderly and sick persons should stay indoors), and PSI >300 is "hazardous" (aggravation of symptoms, premature death; elderly and sick persons stay indoors and keep windows closed, general population to avoid outdoor activities). Malaysia is using a similar system for early warning of smoke-caused health problems (Malaysian Air Quality Index [MAQI]).

temporal patterns and intensity of precipitation are expected, increasing the tendency for extreme droughts associated with an increase of fire risk and severity.

In the lower latitudes and in coastal regions the expected changes in temperatures, precipitation and dry season length will be less pronounced than in higher latitudes and in continental regions. However, the manifold interactions between changing climate and human-caused disturbances of ecosystems may result in change of fire regimes in the densely populated regions of the tropics and subtropics (Goldammer and Price, 1997; see para.4.6.3).

Modelling climate change and forest fire potential in boreal forests

Despite their coarse spatial and temporal resolution, GCMs provide the best means currently available to project future climate and forest fire danger on a broad scale. However, Regional Climate Models (RCMs) currently under development (e.g. Caya et al., 1995), with much higher resolution, will permit more accurate regional-scale climate projections. In recent years GCM outputs have been used to estimate the magnitude of future fire problems. Flannigan and Van Wagner (1991) used results from three early GCMs to compare seasonal fire weather severity under a $2xCO_2$ climate with historical climate records, and determined that fire danger would increase by nearly 50% across Canada with climate warming. Wotton and Flannigan (1993) used the Canadian GCM to predict that fire season length across Canada would increase by 30 days in a $2xCO_2$ climate. An increase in lightning frequency across the northern hemisphere is also expected under a doubled CO_2 scenario (Fosberg et al., 1990; Price and Rind, 1994). In a recent study (Fosberg et al., 1996) used the Canadian GCM, along with recent weather data, to evaluate the relative occurrence of extreme fire danger across Canada and Russia, and showed a significant increase in the geographical expanse of the worst fire danger conditions in both countries under a warming climate.

In a recent study (Stocks et al., 1997), Canadian and Russian fire weather data from the 1980's were used, the warmest decade on record in Canada (Gullet and Skinner, 1992), in conjunction with outputs from four recent GCMs, to compare the spatial distribution of current seasonal levels of fire weather severity across both countries with those projected under a $2xCO_2$ climate.

Daily May - August weather data was collected for the 1980's for 224 Russian and 191 Canadian climate stations. Local noon measurements of temperature, relative humidity, windspeed and precipitation were used to calculate the component codes and indices of the Canadian Fire Weather (FWI) System (Van Wagner, 1987) for each station. Daily FWI values were then converted to Daily Severity Rating (DSR) values using a technique developed by Williams (1959) and modified by Van Wagner (1970). This severity rating technique permits the integration of fire severity over periods of various lengths, from daily (DSR) through monthly (MSR) to seasonal (SSR) values. In this analysis both MSR and SSR values are used. The FWI System provides an assessment of relative fire potential based solely on weather observations, and does not take forest type into consideration.

The following shows an example of possible conclusions: The monthly progression of modelled MSR under a $2xCO_2$ climate indicates an earlier start to the fire season, with significant increases in the geographical extent of extreme fire danger in May. The month of June shows the most significant increase, however, with virtually all of Siberia and western Canada under extreme fire danger conditions during that period. A more modest increase is observed in July and August. The seasonal pattern changes indicate an earlier annual start of high to extreme fire severity, and a later end to the fire season across Canada and Russia as a whole, although there are important regional variances from this pattern.

Changes in the area in each fire danger class are perhaps more important than absolute value changes in MSR. Dramatic changes in the areal extent of high to extreme fire danger in both countries under a doubled CO_2 climate were observed. In general, there is a decrease in moderate MSR and SSR levels, and a significant increase in the area experiencing high to extreme MSR and SSR levels under a warmer climate. This is particularly true in June and July, but increases in the area under extreme fire danger (and therefore greatest fire potential) are common to all months. Significantly, two to three-fold increases are projected for Russia during the June-July period.

Although hampered somewhat by coarse spatial and temporal resolution, the four GCMs utilized in this study show similar increases in fire danger levels across much of west-central Canada and Siberia under a warmer climate. While shifts in forest types associated with climate change were not considered in this analysis, these increases in fire danger alone will almost certainly translate into increased fire activity, and, as fire management agencies currently operate with little or no margin for error, into large increases in area burned. The result will be more frequent and severe fires, shorter fire return intervals, a skewing of forest age class distribution towards younger stands, and a resultant decrease in the carbon storage of northern forests (cf. Kurz et al., 1995).

A warmer climate, in combination with severe economic constraints and infrastructure downsizing, will decrease the effectiveness, and thus the area protected, by fire management agencies. This then means that a new reality in forest fire impacts is on the horizon. There is a strong need to continue modelling future climates, using higher-resolution models as they become available, so that future development of long-range early warning systems and fire management planning can be accomplished in the most informed manner possible.

Assessing impacts of climate change and human population growth on forest fire potential in the tropics

With growing population pressure and accelerating change of land use in tropical vegetation -- i.e., conversion of tropical forested ecosystems into farming and pastoral ecosystems -- fire is being used increasingly. While certain tropical dry forests and savannas have been adapted to anthropogenic fire use for millennia and show typical features of sustainable fire ecosystems, the opening and fragmentation of tropical evergreen forests has increased the risk of wildfires that will have destructive impacts on biodiversity and sustainability of these forest ecosystems.

An assessment of potential impacts of climate change on fire regimes in the tropics based on GCMs and a GCM-derived lightning model (Goldammer and Price, 1997) recently concluded that there is a high degree of certainty that land use and climate features under conditions of a $2xCO_2$ atmosphere will influence tropical fire regimes.

In this respect, tropical closed evergreen forests will become increasingly subjected to high wildfire risk because of land-use changes (opening and fragmentation of closed forest by logging and conversion), increasing fire sources (use of fire as land clearing tool), and climate change (prolongation of dry seasons, increasing occurrence of extreme droughts, increase of lightning as fire source). Tropical dry forests and savannas in regions with predicted reduction of average total annual precipitation and average prolongation of dry seasons will be subjected to higher fire risk. However, the reduction of net primary production (NPP) and the increasing impacts of farming and grazing systems will lead to formation of open and sparse vegetation cover with restricted capability to support the spread of fires (discontinuity of fuelbed).

Tropical dry forests and savannas in regions with a predicted increase of average total annual precipitation and average reduction of dry season length will be subjected to higher fire risk due to the fact that increased NPP will lead to the build-up of more continuous fuelbeds that may carry more frequent and larger-sized wildfires.

Long-range forecasting of fire potential: conclusions

The models and assumptions described in this section clearly exceed the time horizon of early warning systems. However, the Working Group strongly suggests that relevant follow-up processes, in conjunction with other international activities, programmes and agreements, will consider this extended time horizon. The disaster management community needs to be prepared for managing situations which, in the near future, may require the development of innovative technologies and the preparedness of administrations to accomplish tasks that may differ from today's situation. While warning of potential disaster implies a high level of confidence, a second level, or alert level, with lower level of confidence is useful from the standpoint of strategic or contingency planning. This alert level is intended to convey the message that the potential for disaster has increased, but that actions would be limited to planning.

Towards A Global Wildland Fire Information System

A demonstration concept

One demonstration project is the Canadian Wildland Fire Information System (CWFIS), developed by the Canadian Forest Service. The CWFIS is a hazard-specific national system envisioned as a prototype system that is adaptable to other countries. Establishing and linking a number of compatible national systems could provide the nucleus of a global fire information network. Following the conceptual design of CWFIS, future early warning systems would have three goals:

i) Facilitate information sharing among all agencies through a national network.
ii) Facilitate inter-agency sharing of resources by providing national fire information.
iii) Facilitate the application of fire research results through an interoperable platform.

The CWFIS incorporates several functions: weather observations, weather forecasts, fire danger, fire behaviour, fire activity, resource status, situation reports, decision support systems, technology transfer, and information exchange.

Weather observations

The system automatically downloads weather observations from a national satellite network. Although Canadian weather data are not mapped, exported systems (ASEAN, Florida) provide this capability. Data needed for daily fire-danger calculations are extracted from a larger set of hourly weather observations. Most countries operate national weather observing networks. The World Meteorological Organization maintains a global network of synoptic weather stations which is accessible through satellite downlinks. Nationally, research is underway to produce automated spot fire-weather forecasts using a Regional Atmospheric Modelling System (RAMS). When operational, users will be able to submit coordinates for a specific fire and obtain computer-generated hourly forecasts for that location.

Weather forecasts

At global and national scales, forecasts are important because large-scale mobilization requires one or more days to accomplish. The CWFIS accesses 3 days of numeric forecast data generated by the Canadian Meteorological Centre (CMC). In Florida, a Regional Atmospheric Modelling System (RAMS) is used to forecast weather on a finer scale than that available nationally. Many countries operate similar national weather forecasting systems. Alternatively, the CMC (or other major national agencies) can generate a numeric weather forecast for any region on earth (see also **Fire Weather Forecasts** section, above).

Fire danger

Weather data are transformed into components of the Canadian Forest Fire Danger-Rating System. Station data are converted to national contour maps with an ARC/INFO GIS processor. The maps are converted to GIF images and stored on a World-Wide Web server. Daily maps overwrite those from previous days and date indices are automatically updated. Fire-danger maps are retained for seven days to provide backup.

Fire behaviour

Digital fuel and topographic databases enable calculating absolute fire behaviour potential such as rate of spread, head-fire intensity, fuel consumption, and fire type. The CWFIS uses a 16-class satellite-derived land-cover classification to approximate a national fuel map which is not directly available. The fire-behaviour maps are in a cell format, reflecting the underlying fuel database.

Satellite-based land cover classifications should be derivable for most countries. The system provides seven days of history, current observations, and three days of forecasts.

Fire activity

Fundamental to any fire information system is compiling and disseminating fire statistics such as number of fires and area burned. Although this currently requires manual reporting, tabulation, and graphing, it could be automated by having data entered directly into a remote database. A project has been proposed to develop an automated national satellite monitoring and mapping system for fires >200 ha. This system would transmit large-fire maps and associated statistics directly to the CWFIS for distribution via the web server (see also ***Global Fire Monitoring***, below).

Resource status

It is important to continuously monitor the disposition of suppression resources. This includes the location and status of individual resources as well as potential availability for inter-agency mobilization. Manual systems are in place for monitoring resource status at agency and national levels; this information could be displayed by the CWFIS.

Situation reports

It is useful to provide public information on the status of individual fires on the world-wide web. Providing an alternate media access point reduces the workload of public information officials during fire emergencies. Nationally, an overall synopsis of the current situation and prognosis for the near future is useful for senior executives, policy analysts, and governments. Reports are prepared manually and distributed through the Internet.

Decision support systems

Decision-support systems (DSS) are often used for complex tasks, such as resource prepositioning, detection route planning, fire prioritization, and dispatch. Most agencies in Canada operate such systems.

Technology transfer

A web-based fire information system provides an interoperable platform to inform users about scientific results and technological developments. It also allows users to test and evaluate new systems. Accessibility through the web allows system developers to focus on underlying technology while avoiding system-specific idiosyncrasies. The CWFIS accomplishes this through a link to the Canadian Forest Service Fire Research Network, where emerging technologies such as hourly and seasonal fire growth models can be tested.

Information exchange

The most important aspect of the CWFIS may be its use as an example and a platform that enables fire management agencies to exchange information among themselves. The CWFIS also provides a national node that links individual fire agencies to the global fire community and vice versa. Similar national nodes in other countries could be linked readily to form a global forest fire information network. For example, FireNet (Australia) has proven invaluable as the principle server for a global fire community discussion group.

Canadian experience has shown that exchanging information among fire agencies is a precursor to developing mutual understanding. This, in turn, fosters agreements to exchange resources as no agency or nation can be an island unto itself in fire management. Prior inter-agency and intergovernmental agreements are the key to avoiding bureaucratic delays that can preclude effective resource exchanges. The process begins slowly and increases gradually as mutual trust develops among agencies. Implementing resource exchanges also fosters common standards for equipment and training; exchanging people fosters technology transfer. The overall result is enhanced fire management effectiveness and efficiency among all participants.

Global fire monitoring

It is currently technically feasible technically to use the described earth observation and information systems to collect, analyse and share information on wildfire throughout the world on a daily basis. The Monitoring of Tropical Vegetation Unit of the Space Applications Institute at the EC Joint Research Centre has been working on a global fire dataset based on the NOAA AVHRR products (Malingreau and Grégoire, 1996; Grégoire et al., 1996). The "Global Fire Product", in its first phase, is generating a dataset for the 21 months of global daily coverage from April 1992 to December 1993. Because of the significance of the dataset for global change studies, the latest state-of-the art report was produced under the umbrella of the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) (Malingreau and Justice, 1997).

Malingreau (1996) recently proposed the creation of the World Fire Web in which a network of centres with facilities to receive and process fire observation data from satellites, will be connected via the World Wide Web (WWW). Through the World Fire Web scientists, managers, and policy makers can have instant access to local, regional and world data; they can exchange experience, methods and trouble-shoot with each other. The World Fire Web, in conjunction with the space borne evaluation of vegetation dryness and fire-weather forecasts can provide a powerful early warning and disaster preparedness and management tool.

III. CONCLUSIONS AND RECOMMENDATIONS

The recommendations given by the IDNDR Early Warning Working Group on fire and other environmental hazards build on a series of previous international efforts which addressed the needs of international collaboration in providing and sharing information and technologies. In so doing, these efforts can create the institutional mechanisms necessary to fulfill the overall goals of the IDNDR as related to fire disasters. The recommendations are in agreement with, and legitimised by, international initiatives of scientific, management and policy institutions. They address a broad scale of fire management issues which will be mentioned because they are prerequisites for operational early warning systems. Summary recommendations of the IDNDR Early Warning Working Group are given at the end of this chapter.

International initiatives and non-binding international guidelines

The methodologies, systems, and procedures in early warning of fire and atmospheric pollution, as in the preceding chapter, are not equally available world wide. Furthermore, some information systems, such as the global fire data set, global coverage of fire-weather prediction, or real-time monitoring of active fires are still in the phase of being tested and further developed.

Several recent international initiatives in fire science and policy planning have developed concepts and visions for collaboration in fire science and management at international level. The recommendations of the UN FAO/ECE Seminar "Forest, Fire, and Global Change", Shushenskoe, Russian Federation, August 1996 (ECE/FAO/ILO, 1996), acknowledged by the resolution of the International Wildland Fire '97 Conference, Vancouver, British Columbia, Canada, May 1997 (Clevette, 1997; Anonymous, 1997), and presented at the 11th World Forestry Congress, Antalya, Turkey, October 1997 (Goldammer, 1997c), underscored the need of providing international agreements which address the following issues:

i) **Quantifiable information on the spatial and temporal distribution of global vegetation fires is urgently needed relative to both global change and disaster management issues**.

Considering the various recent initiatives of the UN system in favour of global environmental protection and sustainable development, the ECE/FAO/ILO Seminar on Forest, Fire and Global Change strongly urges the formation of a dedicated United Nations unit specifically designed to use the most modern means available to develop a global fire inventory, producing a first-order product in the very near future, and subsequently improving this product over the next decade. This fire inventory data will provide the basic inputs into the development of a Global Vegetation Fire Information System. The FAO should take the initiative and coordinate a forum with other UN and non-UN organizations working in this field, e.g. various scientific activities of the International Geosphere-Biosphere Programme (IGBP), to ensure the realization of this recommendation. (See also Recommendations of ECE/FAO and the international fire science community [Anonymous, 1995]).

ii) **The development of a satellite dedicated to quantifying the geographical extent and environmental impact of vegetation fires is strongly supported**.

iii) **A timely process to gather and share information on ongoing wildfire situations across the globe is required.**

iv) **Mechanisms should be established that promote community self-reliance for mitigating wildfire damages and that would also permit rapid and effective resource-sharing between countries as wildfire disasters develop**.

It is recommended that the UN prepare the necessary measures in this regard, which should follow the objectives and principles of the International Decade for Natural Disaster Reduction (IDNDR).

v) **The unprecedented threat of consequences from fires burning in radioactively contaminated vegetation, and the lack of experience and technologies of radioactive fire management, requires a special, internationally concerted research, prevention and control programme**.

The International Tropical Timber Organization of the UN took a first step in its development of "Guidelines on Fire Management in Tropical Forests" (ITTO, 1997). They provide comprehensive guidance targeted at the situation in the economically less developed regions of the tropics. Among other comments, the guidelines state:

"Assessment, prediction and monitoring of fire risk and means of quantification of forest fires and other rural fires are prerequisites for fire management planning purposes. Statistical data sets can also be used to call attention of authorities, policy makers and the general public. In the tropics such information is difficult to be gathered by ground based-methods. Air- and space borne sensors offer possibilities to monitor less accessible and sparsely populated land areas with inadequate ground-based infrastructures."

Accordingly, ITTO recommends:

i) **Seeking access to meteorological information from ground stations and space borne systems and the utilization of this information for fire intelligence (fire risk assessment).**

ii) **Use of existing orbital remote sensing systems for fire detection and prediction which provide real-time information on the geographic location of fires.**

iii) **ITTO member countries should join others in supporting the development of international mechanisms to predict wildfires (early warning systems).**

iv) **The United Nations Commission on Sustainable Development (CSD) should ensure that in the implementation of Agenda 21 for forests, due attention is given to forest fires in relation to arrangements that may be developed to harmonize and promote international efforts to protect the world's forests.**

v) **A UN-sponsored Global Fire Research and Management Facility which includes a Global Vegetation Fire Information System and the capabilities to provide support on request to any nation in fire management and prevention and management of wildfire disasters should be considered by the CSD**.

The ITTO guidelines provide general recommendations which will need to be fine-tuned to meet specific national requirements. In Indonesia, for instance, ITTO is sponsoring the development of the "National Guidelines on Protection of Forests against Fire" which will be finalized in December 1997. This initiative is particularly important in light of the repeated smog episodes in South East Asia caused by land-use fires and wildfires. Other countries, such as Namibia, aim to base their national programmes on the ITTO guidelines.

The first regional initiative is underway in the region of member states of the Association of South East Asian Nations (ASEAN). The resolution and recommendations of the ASEAN Conference on "Transboundary Pollution and the Sustainability of Tropical Forests: Towards Wise Forest Fire Management" in Kuala Lumpur, Dec. 1996, stated (ASEAN, 1997):

"The Conference recognised the International Tropical Timber Organization (ITTO) Guidelines on Fire Management in Tropical Forests which has been adopted by most of the ASEAN member countries".

It further recommended that,

"A collaborative meteorological and air monitoring information network and workable partnership in ASEAN should be further explored. The network would make use of up-to-date remote sensing and communication technologies in order to provide regional assessment of fire risk, fire and smoke events and early warning systems. The related existing national and regional institutions should form a core group of agencies that could be coordinated by a regional centre, such as the AIFM. This centre will take the lead in the organisation of such a network, and to assist the ASEAN Senior Officials on Environment (ASOEN) Haze Technical Task Force, as required in the ASEAN Cooperation Plan on Transboundary Pollution."

Another regional initiative is proceeding in the Baltic Basin. The First Baltic Conference on Forest Fire (4-8 May 1998, Poland) is designed to improve the cooperation in early warning of fire and fire management among the countries bordering the Baltic Sea; candidate warning and alert systems are described above in the section on Automatic Fire Alerts.

Science and technology development

Fire research and technology development have received considerable stimulation by scientific projects conducted under the umbrella of the International Geosphere-Biosphere Programme (IGBP) and other programmes devoted to global change research (see e.g. Andreae et al., 1993; Journal of Geophysical Research Special Issue, 1996; FIRESCAN Science Team, 1996;

Malingreau and Justice, 1997; van Wilgen et al., 1997). While the scope of global change research is not necessarily directed towards requirements of operational management systems, e.g. early warning of natural hazards, the spin-offs of basic science nevertheless have a considerable potential for management solutions.

However, the application of existing technologies, methods, and procedures of information gathering, processing and distribution has revealed that many of the existing systems must be developed further in order to meet the requirements of precise and real-time application for early warning and management of fire and other environmental hazards.

Communication systems for early warning information dissemination are generally advanced since they rely on the technology progress in the civilian telecommunication sector. Space borne sensing and collection of real-time data for early fire warning purposes generally depend on systems which were not specifically designed for sensing fire precursors, active fires, and fire effects. Thus, a short overview is given below on the most important sensors which are currently designed or are in progress of construction.

New space borne sensors for early warning of fires and atmospheric pollution

In accordance with the analysis of Kendall et al. (1997) it is obvious that the remote sensing fire community, in addition to continuing experimentation and refinement of methods, needs to provide the operational monitoring data sets, at regional and global scales, to contribute to early warning of fire hazard, to fire and smoke management, and to earth system studies. The development of operational automated monitoring techniques and the provision of consistent long term data sets is a challenge that the remote sensing community is now facing. Issues associated with prohibitive data costs, computing resources, data management, data archival, and distribution need to be addressed.

Data set development is being undertaken with satellite sensing systems which were not designed for fire monitoring purposes. The current suite of sensors suitable for fire monitoring have problems such as calibration, saturation, spatial resolution, orbital overpass time, and coverage, which need to be taken into account in the data processing and data set compilation. It is critical that the user community fully understands the limitations of the data and its utility. New sensors are being designed and built which will reduce or eliminate some of these problems, but they will introduce new, and in some cases unanticipated, problems. The development of new satellite data sets is an iterative process and one which needs to be undertaken in close collaboration with the user community. The planned sensing systems will certainly provide a challenge to the remote sensing community in terms of data volume. The challenge will be to render the raw data to a volume and information content suited to the user community.

Some of the sensing systems which are in the planning and/or construction phase are facing financial constraints. The user community which requires new space borne technologies for early warning applications therefore underscores the need to realize these planned satellite programmes:

MODIS Imaging System

The Moderate Resolution Imaging Spectroradiometer (MODIS) is planned for launch as part of NASA's Earth Observing System (EOS) in 1998. This system will provide new capabilities over the currently utilized coarse resolution sensors. Thirty-six spectral bands are planned between 0.4µm and 14.3µm at resolutions ranging from 250m to 1000m. Currently, two MODIS instruments are planned with the first platform providing a 10:30 am and pm overpass and the second providing a 2:30 am and pm overpass. For fire monitoring, the one kilometre infrared channels at 3.96µm and 11.0µm bands will have increased saturation levels, 500K and 335K respectively, which will permit improved active fire monitoring. Full resolution MODIS fire products will have 1 km resolution, and the data will be summarized for coarser grids. In the post launch period, emphasis will be placed on validating the fire product and developing and testing automated burn scar detection techniques. The improved spatial and radiometric resolution of

MODIS at 250m in the visible and near-infrared bands will permit more accurate area estimate of burn scars.

BIRD Satellite Observation

BIRD will be a small satellite mission for early warning of vegetation conditions and fires. Starting from their FIRES proposal (Jahn et al., 1996) the DLR (Deutsche Forschungsanstalt für Luft- und Raumfahrt) had proposed a new approach in the design of a small satellite mission dedicated to hot spot detection and evaluation. The new approach is characterized by a strict design-to-cost philosophy. A two-channel infrared sensor system in combination with a Wide-Angle Optoelectronic Stereo Scanner (WAOSS) shall be the payload of a small satellite (80kg). The unique combination of a stereo camera and two infrared cameras gives the opportunity to acquire both more precise information about leaf mass and photosynthesis for the early diagnosis of vegetation condition and changes, as well as real time discrimination between smoke and clouds. The primary objectives of the planned BIRD mission are:

- test of a new generation of infrared array sensors adapted to earth remote sensing objectives by means of small satellites;
- detection and scientific investigation of hot spots, including forest fires, volcanic activities, burning oil wells or coal seams; and
- thematic on-board data processing, and testing a neuronal network classificator in orbit.

Next generation geosynchronous satellites

The next generation of geosynchronous satellites will provide improved fire monitoring capabilities with continued high temporal coverage. This means that a better understanding of the diurnal cycle of fire in a range of ecosystems will be possible. For monitoring North and South America, the GOES NEXT (I-M) series of satellites was launched in 1994. The new GOES satellites offer greater radiometric sensitivity and spatial resolution along with improved geolocation. Preliminary results from GOES-I data indicate enhanced capabilities in the identification of fires and the quantification of associated haze. Geosynchronous coverage of Africa and Europe will also be improved in the coming years as the METEOSAT Second Generation (MSG) satellites are launched in 1998. MSG will offer a significant improvement in biomass burning monitoring capabilities through increased spectral coverage. The new sensors will provide 3 km scale coverage every fifteen to thirty minutes with a spectral range similar to that provided by the NOAA-AVHRR. With the addition of a middle-infrared channel (3.8µm), an opportunity for thorough investigation of the diurnal cycle of fire in African ecosystems will be feasible at last.

Future Challenges: Multi-spectral and multi-temporal sensing of early warning parameters

Early warning, monitoring and inventory of wildfire needs to be accompanied by monitoring and inventory of those ecological characteristics which lead to fire. Disturbances, such as insect or disease outbreak, wind throw of trees, forestry practices and other land use activities frequently are precursors to fire events, fire patterns and resulting severity. Insects and disease stress ecosystems, resulting in partial mortality and production of dead materials, particularly foliage and other fine materials which are critical to fire ignition and behaviour. Post-fire vegetation recovery is important to predict fire-return intervals.

Advanced early warning systems will need to integrate these parameters into multi-layer fire information systems. Geographic information systems (GIS) technology, combined with decision support systems (expert systems), offer feasible, cost-efficient, and user-friendly solutions.

International fire research programmes

The fire research programmes conducted under the International Geosphere-Biosphere Programme (IGBP) offer a suitable mechanism to provide the scientific perspectives for the IDNDR. As it is anticipated that the consequences of global change in general and climate change in particular will increase global natural hazards, the merging of joint interests between the IGBP and IDNDR communities seems to be advisable.

Recommendations by the IDNDR Early Warning Working Group on Fire and Other Environmental Hazards

In accordance with the conclusions and recommendations given by the various international initiatives, the IDNDR Early Warning Working Group on Fire and other Environmental Hazards comes to the following recommendations for priority activities:

i) **A global fire inventory must be designed and implemented, producing a first-class product in the very near future, in order to provide a basis for early warning systems. Subsequently, this product then must be improved for standardized application over the next decade.**

Fire inventory data is necessary to provide the basic inputs into the development of a future relational (geo-referenced) global fire database within the proposed Global Vegetation Fire Information System (GVFIS). FAO should take the initiative and coordinate a forum with other UN and non-UN organizations working in this field, including various scientific activities of the International Geosphere-Biosphere Programme (IGBP) and the mechanisms of the Intergovernmental Panel on Climate Change (IPCC, 1997).

ii) **A timely process to gather and share real-time information about ongoing wildfire situations on a global basis is required.**

This follows a proposal to create the World Fire Web in which a network of centres with facilities to receive and process fire observation data from satellites will be connected via the World Wide Web (WWW). Through the World Fire Web scientists, managers, and policy makers can have instant access to local, regional and world data so that they can can exchange experiences, methods and trouble-shoot with each other. The World Fire Web, in conjunction with the space borne evaluation of vegetation dryness, fire-weather forecasts and the possibility of forecasting fire danger and fire behaviour may provide a powerful early warning and disaster preparedness and management tool at national, regional and global scales. The information network should include the resource status by continuously monitoring the disposition of suppression resources. This includes the location and status of individual resources as well as potential availability for inter-agency and international mobilization.

iii) **Technology transfer and information exchange on early warning and fire management decision support systems must be provided through international collaborative agreements or technical assistance programmes.** Such programmes must support countries in fire-prone regions of the tropics and subtropics where advanced fire management systems are not yet fully available.

iv) **The development of space borne sensor technologies devoted to the specific tasks of recognizing wildfire disaster precursors, fire activities, and the**

impacts of fire (ecological, atmospheric, chemical) must receive high priority.

v) **Additional fire research is needed in those locations where existing early warning systems cannot be applied due to the particular relationships between vegetation, local/regional weather and prevailing socio-economic or cultural conditions which contribute to wildfires and their secondary damages, such as atmospheric pollution.**

South East Asia is one of the less explored regions in which fire research must receive adequate attention as proposed by the ASEAN Transboundary Haze Pollution initiative as well as by the IGBP global-change oriented science programmes. These include the South East Asian Fire Experiment (SEAFIRE) and the SARCS Integrated IGBP/IHDP/WCRP Study on Land-use Change in Southeast Asia.

vi) **Policies and agreements on environmental protection at international levels should ensure that in the implementation of Agenda 21 for forests, due attention is given to forests fires in relation to arrangements that may be developed to harmonize and promote international efforts to protect the world's forests.**

vi) **The suggestion of ITTO to establish a UN-sponsored facility for global fire research and management is endorsed to facilitate the development of the proposed Global Vegetation Fire Information System**. This is considered essential in order to provide support on request to any nation in early warning, prevention, management and mitigation of wildfire disasters.

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V. LIST OF CONTRIBUTORS

Convener and first Author:

Dr. Johann G. Goldammer
Max Planck Institute for Chemistry
Biogeochemistry Department

Fire Ecology Research Group
c/o Freiburg University
D - 79085 Freiburg, Germany
Fax: 49-761-808012
Tel: 49-761-808011
e-mail: jggold@ruf.uni-freiburg.de

Contributors:

Dr. Robert E. Burgan
Research Forester
Rocky Mountain Research Station
Intermountain Fire Sciences Laboratory
PO Box 8089
Missoula, MT 59807, U.S.A.
Tel: 1-406-329-4864
Fax: 1-406-329-4825
e-mail: rburgan/int_missoula@fs.fed.us

Dr. Phil Cheney
CSIRO Division of Forestry and Forest Products
Bushfire Research Unit
Box E 4008
Kingston, A.C.T 2604 Australia
Fax: 61-6-281-8348
Tel: 61-6-281-8379
e-mail: phil.cheney@ffp.csiro.au

Dr. Michael A.Fosberg
Director, IGBP-BAHC Core Project Office
Potsdam Institute for Climate Impact Research (PIK)
Telegrafenberg
P.O.Box 60 12 03
D - 14412 Potsdam, Germany
Fax: 49-331-288-2547
Phone: 49-331-288-2649
e-mail: mike.fosberg@pik-potsdam.de

Prof. Vaino Kelhä
Space Technology
VTT Automation
P.O.Box 13002
02044 VTT, Finland
Fax: 358-9-456-6475
Tel: 358-9-456 4330
e-mail: vaino.kelha@vtt.fi

Dr. John Roads
Scripps Institution of Oceanography
Experimental Climate Prediction Center
UCSD 0224
8605 La Jolla Shores DR., NH 441
La Jolla, CA 92093-0224 U.S.A.
Fax: 1-619-534-8561
Tel: 1-619-534-2099
e-mail: jroads@ucsd.edu

Dr. Al Simard
Canadian Forest Service
580 Booth St., 7th floor
Ottawa, Ontario K1A 0E4, Canada
Fax: 1-613-947-9090
Tel: 1-613-947-9023
e-mail: asimard@AM.NCR.FORESTRY.CA

Brian J. Stocks
Forest Fire Research
Great Lakes Forestry Center
Canadian Forest Service
Sault Ste. Marie, Ontario P6A 5M7, Canada
Fax: 1-705-759-5700
Tel: 1-705-949-9461
e-mail: bstocks@am.glfc.forestry.ca