EARLY WARNING SYSTEMS FOR THE PREDICTION OF AN APPROPRIATE RESPONSE TO WILDFIRES AND RELATED ENVIRONMENTAL HAZARDS

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SUMMARY

Wildfires annually affect several hundred million hectares of forest and other vegetation of the world. In some ecosystems, fire plays an ecologically significant role in maintaining 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 that are of significance and severity comparable to other major 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. 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, leads to loss of human lives. Fire risk modelling

in expected climate change scenarios indicate that within a relatively short period, the next three to four decades, the destructiveness of wildfires will increase. Fire management strategies which include preparedness and early warning cannot be generalized due to the multi-directional and 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 hydro-meteorological hazards included in the International Decade of Natural Disaster Reduction (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.

The paper presents the findings of the IDNDR Early Warning Group on Wildfire and Related Hazards 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 that can be equally made accessible on a global scale.

Recommendations are also made for improvements and areas that require additional international attention: the 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 are gathered and shared, e.g. through the Global Fire Monitoring Center (GFMC); development of spaceborne 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.

INTRODUCTION

General fire hazard

General remarks

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 wildfires: often, ironically, 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 (1-3).

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. In all ecosystems, 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 (3-6). These emissions interact with those from fossil-fuel burning and other technological sources. Smoke emissions from wildland fires also cause visibility problems which may result in accidents and economic losses. Smoke generated by wildland fires affects human health and can lead to increased morbidity and mortality.

Fire risk modelling in expected climate change scenarios indicate that within a relatively short period, over 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-directional and 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 hydro-meteorological 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. (7).

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 (8). It resulted in the loss of timber values of about US$ 8.3 billion, and a total of timber and non-timber values and rehabilitation costs of about US$ 9 billion (9).

The damages caused by the fire episode of 1997-98 in Indonesia; Brazil and Central America are not yet fully assessed at the time of writing this report. According to the interim results of a study conducted by the World Wide Fund for Nature (WWF) in the framework of the Economy and Environment Program for South East Asia (EEPSEA), the economic damages caused by fire in Indonesia during 1997 are in the region of US$ 2.8 billion, and additional costs arising due to fire and haze in Indonesia and in the neighbouring countries are in the region of US$ 1.6 billion. Total damage assessed at about US$ 4.5 billion includes short-term health damages, losses of industrial production, tourism, air, ground and maritime transportation, fishing decline, cloud seeding and fire-fighting costs, losses of agricultural products, timber, and direct and indirect forest benefits and capturable biodiversity (10).

The Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore, currently investigates the total area affected by land-use fires and wildfires on the islands of Sumatra and Borneo during the 1997-98 fire season based on the high-resolution SPOT (Système pour la Observation de la Terre) satellite data (11). Preliminary data (which were based on the EEPSEA/WWF study) suggest that a total area affected by fire exceeds 4-5 million hectares.

The economic and environmental damages caused by fires in Latin America (Brazil and Central America) during early 1998 are not yet assessed. Figures released by Mexican authorities in May 1998 indicate that the reduction of industrial production in Mexico City, which was imposed in order to mitigate the additional smog caused by forest fires, involved daily losses of US$ 8 million (12).

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, a 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) were estimated to be A$ 5.7 million (on the basis of 1976-77 prices), and the estimated net costs of the 1983 bushfires to the government sector were A$ 33 million (13).

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 about 12 million hectares (14). The burning of about 40,000 hectares of coffee plantations, 60,000 hectares of cocoa plantations, and some 10,000 hectares 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 and 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 (15). In the same period, satellite-derived information reveals that about 14.5 million hectares of forest were affected by fire in the neighbouring Soviet Union, predominantly in the Siberian boreal forests, which have a composition similar to Northeast China (16).

The last major fire episode in central Eurasia occurred in Mongolia between February and June 1996. A total of 386 forest and steppe fires burned over an area of 2.3 million hectares of forest and 7.8 million hectares of pasture land, resulting in the loss of 25 human lives, more than 7000 livestock, 210 houses, 560 communication facilities, and 576 facilities for livestock; the cost of the damage based on the preliminary assessment was about US$ 2 billion (17). Recent evaluation of fire data from Mongolia reveals that 2.47 million hectares of forest were burned in 1993 (18).

The 1988 fires in the Yellowstone area of the United States cost around US$ 160 million to suppress and an additional estimated loss of US$ 60 million in tourist revenues between 1988 and 1990 (19). In the longer term, however, the increased biodiversity created by the fires in Yellowstone National Park may well yield benefits that outweigh these losses.

Reliable statistical data on occurrence of wildland fires, areas burned and losses incurred are available for only a limited number of nations and regions. Within the northern hemisphere, the most complete dataset 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 USA and Canada. The last data set covers the period 1995-97 (20). 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 (21, 22). 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 (23).

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 dataset has been developed on the basis of active fires detected by the National Oceanic and Atmospheric Agency (NOAA)'s Advanced Very High Resolution Radiometer (AVHRR) sensor. The "Global Fire Product" is an activity of the International Geosphere-Biosphere Programmme Data and Information System (IGBP-DIS; for details see section on "Global fire monitoring, p. 43).

Impacts of fire on the environment

From the perspective of the IDNDR, wildland fires may affect two basic environmental problem areas: (i) atmospheric pollution (direct impact of smoke on human health and economies; influence of gaseous and particle emissions on the composition of the atmosphere); and (ii) biodiversity, ecosystem performance, and landscape stability. Both these areas 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 1980s and 1990s, most serious pollution problems were noted in the Amazon Basin and in the South East Asian region. The most recent large smoke episodes in the South East Asian region were in 1991, 1994 and 1997 when land-use fires and uncontrolled wildfires in Indonesia and neighbouring countries created a regional smoke 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 (PM_{10}) was responsible for the health problems (24). The worst smoke pollution in the region occurred in September 1997, as reflected by a value of 839 of the Pollutant Standard Index (PSI; see section on "Atmospheric pollution warning", p. 35) in the city of Kuching (Sarawak state, Malaysia); the Malaysian government was on the verge of 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 1997-98, the smoke episodes in South East Asia resulted in closing of airports and marine traffic, e.g. in the Straits of Malacca and along the coast and on rivers of Borneo. Several smoke-related marine and aircraft accidents occurred during late 1997. The loss of an airplane and 234 human lives in September 1997 in Sumatra was partially attributed to air traffic control problems during the smoke episode.

Wildfires burning in radioactive-contaminated vegetation has led 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 of the high-fire-danger classes. In 1992, severe wildfires burned in the Gomel region (Belorussia) and spread into the 30-km radius zone of the 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 reports by Dusha-Gudym (25).

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 (4). 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 (26). 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 (27) to be in the range of 1.1-3.6 billion tons per year. Important contributions to the total worldwide biomass burning, which are included in the numbers mentioned above, are fires in savannas, shifting agriculture, agricultural waste burning and firewood consumption (28).

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

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[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 are the largest contributors in the contaminated areas in these states. In the Russian Federation, the soil surface, in which caesium radionuclide contamination exceeds 37 GBq/km^2 [(1 GBq (gigabequerel) = 10^9 Bq], totals 4.9 million hectares within 15 regions. The areas in which the radiocaesium contamination density is between 0.55 and 1.5 TBq/km^2 [1 TBq(terabequerel) = 10^{12} Bq) and higher, are mainly in the Bryansk region (about 250,000 hectares).

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 (3,29,30). 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 (31).

Biodiversity, ecosystem performance, and landscape stability

The impacts of wildfires on the performance 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 the phenomena resulting from wildfires prohibits any detailed review in the context of this paper.

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 the 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 escaping 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 (32).

In the Krasnoyarsk region, Russian Federation, an on-going mass outbreak of the Siberian gipsy moth (*Dendrolimus superans sibiricus*) since 1989 has meanwhile affected a total of 1 million hectares of boreal forest (33). It is expected that large wildfires will occur in the partially or completely killed stands within the next few years.

Early warning systems in fire 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;

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[2] For clarification of terminology used in this report, the terms "fire management", "prescribed burning" and "smoke management" are briefly explained (34):

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

- 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 programmes 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). They are equally subjected to high wildfire risk because of the abundance of human fire sources or the lack of human resources to control fires, respectively.

This paper provides a state-of-the-art analysis of existing and projected early warning and fire information systems which can be equally made accessible on a global scale.

Relations to other activities of the IDNDR early warning programme

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

The conclusions of a 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 (35). 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 early warning and management of disasters.

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 also provides capabilities for detecting new wildfires, monitoring ongoing active wildfires, and, in conjunction with fire-weather forecasts, an early warning tool for estimating extreme wildfire events.

Fire danger rating (fire risk assessment)

Introduction

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 (36).

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 as guides in a variety of fire management activities, including early warning of fire threat. Different systems of widely varying complexity, which have been developed throughout the world 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 starting a fire [e.g. the Angstrom index (36)]. 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 (37-39). The most complex systems have been developed in Canada (40) and the United States (41) which combine measures of fuel, topography, weather and risk of ignition (both caused by lightning and human activity), 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: 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 US 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 some places, this may be complicated by the introduction of exotic forest species (e.g. the establishment of eucalypti forests on formerly oak woodland savannas 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 through 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 population centres 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 reduces the moisture content of the green foliage. 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 extreme drought is combined with severe fire weather variables.

There are a number of book-keeping methods of monitoring the seasonal development of drought. The Keetch-Byram Drought Index is a number representing the net effect of evapo-transpiration and precipitation in producing a cumulative measure of moisture deficiency in the deep duff and soil layers (42). 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 (43) and the Australian Forest Fire Danger Rating System (38). Most recently, the index has been used to establish a user-friendly early warning system in Indonesia (44).

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 (40), the Mount Soil Dryness Index of Australia (45) and the Drought Index used in France [quoted in (33)].

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.

Regular charting of bookkeeping-type systems such as the Keetch-Byram Drought Index (42) or the Mount Soil Dryness Index (45) 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 six to nine 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 and Melbourne in the south of Australia. This index 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 US National Fire Danger Rating System (43) and the Canadian Fire Weather Index System (40), 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 (41). These are rarely used in the USA today (46). 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 (47), 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 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 (48). 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

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

Introduction

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 [see section on "Active fire detection by satellite sensors", (p. 32) and (49)]. 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 ones (50). Because of its availability, spatial resolution, spectral characteristics, and low cost, NOAA AVHRR has become the most widely used satellite dataset 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 (51-56). Daily AVHRR data are composited into weekly images to remove most of the cloud and other deleterious effects, and an NDVI image of continental US is computed by the US 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 (57, 58) so that they 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.

As for Live Shrub Moisture, the National Fire Danger Rating System (NFDR) used by the United States requires live shrub and herbaceous vegetation moistures as inputs to the mathematical fire model (59). 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.

The above maps may be viewed at this Internet site:
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 USA, the Geological Surveys Earth Resources Observation Systems Data Center (EDC) used a series of 8 monthly composites of NDVI data for 1990 to produce a 159 class vegetation map of continental

US at 1 km resolution (60). Data from 2560 fuel observation plots randomly scattered across the US 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 broadscale fire danger maps.

Integration of satellite data into fire danger estimates

The state of Oklahoma 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 (US Forest Service) and the Oklahoma State University resulted in the development of a fire danger rating system that produces map outputs (61). 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 this Internet site: http://radar.metr.ou.edu/agwx/fire/data.html.

A goal of fire researchers in the US is to expand the techniques provided for Oklahoma to other states and nations. An alternative method of estimating fire potential has been developed (62) 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 (63). 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 this Internet address: under "experimental products".

http://www.fs.fed.us/land/wfas/welcome.html

While these examples, and many other published papers (64), 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 were presented at the IDNDR Early Warning Conference 1998 in Potsdam, e.g. the satellites and sensors BIRD and FOCUS of the DLR, hold great promise for several fire management requirements, such as fire detection, fuel mapping, monitoring seasonal greening and curing (65).

Fire weather forecasts

Introduction

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 of allocation of 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 (66-68).

Current US fire weather forecasts are prepared from short-range weather forecasts (1-2 days) by the Eta model of the US 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 NCEP for making short-range global to regional weather forecasts, is currently being developed at the Scripps Experimental Climate Prediction Center (ECPC) (69). Although this system is currently focused for Southern California on making and disseminating experimental global to regional fire weather forecasts, it could be easily transferred to 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 Global Spectral Model (GSM) (70). A high resolution regional spectral model (RSM) (71) 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 (70).

Global to regional forecasts of the fire weather index and precipitation are currently displayed on the world-wide web site of the ECPC as follows:

> http://meteora.ucsd.edu/ecpc/ (hit the predictions button, then the ecpc/ncep button)

Due to bandwidth limitations of the Internet, only the complete initial and 72-hour forecasts 4 times daily (00, 06, 12, 18 UCT) for the global model are transferred. From these global initial and boundary conditions, regional forecasts at 25 km resolution are then made and also displayed.

Future work

New forecast methods are being developed. Besides preliminary 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 being prepared. 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

Introduction

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 multispectral 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

Data are sensed by all channels simultaneously at 1.1 km spatial resolution. Data acquired by the instrument are resampled on board the satellite to 4 km spatial resolution and recorded for later transmission to one of two NOAA Command Data Acquisition (CDA) stations, at Gilmore Creek, Alaska, and Wallops Island, Virginia. This is known as the Global Area Coverage (GAC) mode of transmission. In addition, the full spatial resolution 1.1 km data can be recorded for previously scheduled areas of the world, in the Local Area Coverage (LAC) mode, or can be received directly from the satellites by suitably equipped receiving stations, in the High Resolution Picture Transmission (HRPT) mode.

Even in full configuration, with two NOAA satellites in operation, the AVHRR data provide 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 (72). 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.

Within these limitations, it is possible, due to the characteristics of the NOAA meteorological satellites described, 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. The prototype system has been 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 (73).

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 1994-97, 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 1998 resulted in severe atmospheric pollution. The regional smoke events of 1992 and 1994 triggered a series of regional measures towards