Chapter 7
Climate Change and Early Warning Systems for Wildland Fire

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Abstract Wildland fires burn several hundred million hectares of vegetation around the world every year. A proportion of these wildland fires cause disastrous social, economic, and/or environmental impacts. Disaster fires occur in every global region and vegetated biome. Recent research suggests a general increase in area burned and fire occurrence during the last few decades, but there is much global variability. Wildland fire regimes are primarily driven by climate/weather, fuels, ignition agents, and people. All of these factors are dynamic and their variable interactions create a mosaic of fire regimes around the world. Climate change will have a substantial impact on future fire regimes. Under a warmer and drier future climate, fire management agencies will be challenged by fire weather conditions that could push current suppression capacity beyond a tipping point, resulting in a substantial increase in large fires, and a corresponding increase in disaster fires. To mitigate or prevent wildfire disaster, land and forest fire managers require early warning of extreme fire danger conditions. This allows time to implement fire prevention, detection, and presuppression action plans before disaster fires occur. Fire danger rating is the cornerstone of fire management decision-making and is commonly used to provide early warning of potential wildfires. Currently, less than half of the world has a national fire danger rating system in place. The Global Early Warning System for Wildland Fire is based on extended fire danger forecasts and aims to contribute to the Global Multi-Hazard Early Warning System evolving under the auspices of the United Nations International Strategy for Disaster

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Reduction, and contribute to implementation of the Hyogo Framework for Action. By using longer-term forecast data from advanced numerical weather models, and early warning products that are further enhanced with satellite data, the global system provides extra time to coordinate suppression resource-sharing and mobilization within and between countries in advance of disaster conditions.

Keywords Changing fire regimes • Fire danger rating • Fire weather • Forecasting • Presuppression preparedness • Wildfire disaster

7.1   Global Wildland Fire

Fire has been an integral part of the Earth system for hundreds of millions of years, affecting global biome distribution and being used by humans through history to modify the world they live in (Bond et al. 2005; Bowman et al. 2009; Pyne 2001). Fire plays an important ecological role as it influences ecosystem patterns and processes, and has substantial environmental effects with a global scale impact through its influence on the carbon cycle and climate. Fire first occurs in the charcoal record shortly after the appearance of terrestrial plants (Scott and Glasspool 2006) and throughout history, wherever humans traveled, fire soon followed. Even today, little has changed as fire occurs wherever there is vegetation and the vast majority of global area burned is the result of human-caused fire.

Charcoal evidence indicates that global wildland fire has increased since the last glacial maximum about 21,000 years ago, with increased spatial heterogeneity during the last 12,000 years (Power et al. 2008). Wildland fires currently burn 330–431 M ha of global vegetation every year (Giglio et al. 2010). Most wildland fires occur in tropical grasslands and savannahs (86 %), and a smaller amount in forests (11 %) (Mouillot and Field 2005). In the last few decades, there is evidence of greater area burned and increasing fire severity in many different global regions (Pyne 2001; FAO 2007; Bowman et al. 2009). There are varied reasons for regional increases in wildland fire activity, but the primary factors are fuels, climate/weather, ignition agents, and people (Flannigan et al. 2005, 2009b). During the last millennium, the global fire regime appears to have been strongly driven by precipitation, and shifted to an anthropogenic-driven regime during the Industrial Revolution (Pechony and Shindell 2010).

7.2   Climate Change and Future Global Fire Regimes

Future fire regimes are expected to be temperature driven (Gillett et al. 2004; Pechony and Shindell 2010) with warmer conditions and longer fire seasons leading to increased area burned and fire occurrence (Flannigan et al. 2009b) and an unprecedentedly fire-prone environment in the twenty-first century (Pechony and

Shindell 2010). In terms of fire severity and fire intensity, a review of global research papers showed mixed results in different regions (Flannigan et al. 2009a). In the boreal forest region, which represents about one-third of global forest cover, fire records document increased fire activity in recent decades (Stocks et al. 2003; Kasischke and Turetsky 2006) due to increased temperature (Westerling et al. 2006). Under current climate change scenarios, global temperature increase is expected to be greatest at northern high latitudes (IPCC 2007). For that reason, the boreal forest region is anticipated to experience the earliest and greatest increases in wildland fire activity under future climate change.

Box 7.1 Fire, Weather, and Climate Change

There are four general factors affecting wildland fire activity over a region:

1. Fuel – factors affecting flammability such as vegetation type (grass, shrub, tree species), amount, moisture, and continuity (or distribution – both horizontal and vertical) of fuel
2. Weather – temperature, rainfall, atmospheric moisture, wind speed, solar radiation, atmospheric stability, upper atmospheric patterns (e.g., blocking upper atmospheric ridges) directly affecting fuel moisture content, and ability for fire to spread
3. Ignitions – human and lightning
4. People – as a fuel modifier (reducing fuel loads by clearing or burning; planting new vegetation), and the primary source for identifying risk (homes and communities located in the wildland-urban interface) as well as conducting fire management activities

Weather, in addition to being a key factor, also influences the fuel factor via fuel moisture and the ignition factor through lightning activity. Climate change will result in changes to the day-to-day weather and, in particular, extremes; this is critical to wildland fire as much of the area burned occurs during relatively short periods of extreme fire weather. A warmer world will likely have more fire and longer fire seasons at higher latitudes; more lightning activity will lead to more lightning-caused fires; and lastly, increased evapotranspiration will lead to drier fuels unless there are significant increases in precipitation. Drier fuels will make it easier for fires to ignite and spread.

In the most recent study of future global wildland fire (Flannigan et al. 2013), the potential influence of climate change on fire season length and fire season severity was examined by comparing three General Circulation Models (GCMs) and three possible emission scenarios (nine GCM-emission scenario combinations). The GCMs used in the study were: (1) THE CGCM3.1 from the Canadian Centre for Climate Modelling and Analysis, (2) the HadCM3 from the Hadley Centre for Climate Prediction in the United Kingdom, and (3) the IPSL-CM4 from France.
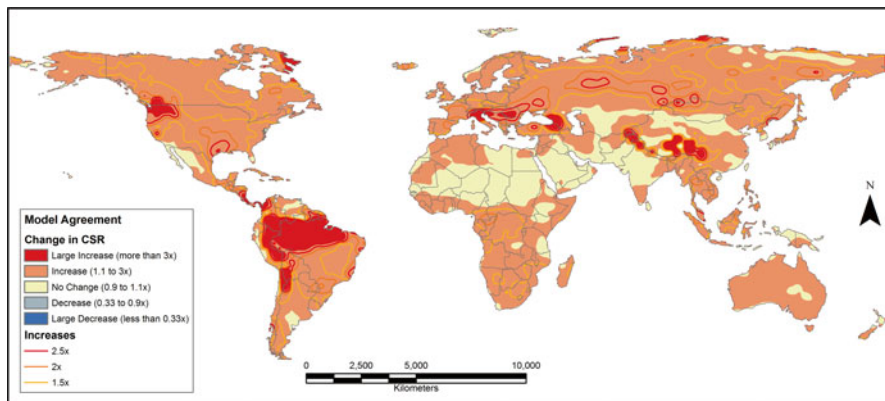
Fig. 7.1 Cumulative Severity Rating anomalies for the HadCM3 A2 scenario for 2041–2050 relative to the 1971–2000 base period (See Flannigan et al. 2013 for study design)

The models were selected to provide a range of expected future warming conditions. There are four emission scenario storylines (A1, A2, B1, and B2) that set out distinct global development direction to the end of this century (IPCC 2000). The Flannigan et al. (2013) study used the following three scenarios: A1B, representing a world of very rapid economic growth with global population peaking by mid-century, rapid development of efficient technology, and a balanced use of fossil fuel and nonfossil fuel sources; A2, representing a world of increased population growth, slow economic development, and slow technological change (business-as-usual scenario); and B1, representing the same population as A1, but more rapid change in economic structure, and moving towards service and information technology.

The GCM-emission scenarios were used to calculate fire weather conditions during the next century. Fire weather data (temperature, relative humidity, wind speed, 24-h precipitation) were used to calculate daily component values of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). Fire season length was calculated using a temperature approach, with the start of the fire season defined as three consecutive days of 9 °C or greater, and the end of the fire season by three consecutive days of 2 °C or lower. Fire severity was calculated using the Daily Severity Rating (DSR), which represents the increasing difficulty of control as a fire grows (Van Wagner 1970) and is a simple power function of the Fire Weather Index component of the FWI System. Changes in fire severity were measured using the Cumulative Fire Severity (CSR), which was the sum of DSR values during the fire season divided by the fire season length. In this way, the CSR was a seasonal length-scaled version of the DSR. Changes in future fire season length and CSR were summarized by decade as anomalies from the 1971–2000 period (results were only presented for mid-century and end of century).

Figures 7.1 and 7.2 show CSR for the HadCM3 model and the A2 scenario for 2041–2050 and for 2091–2100. These examples are representative of all the GCMs and scenarios maps that show a significant worldwide increase in CSR especially for
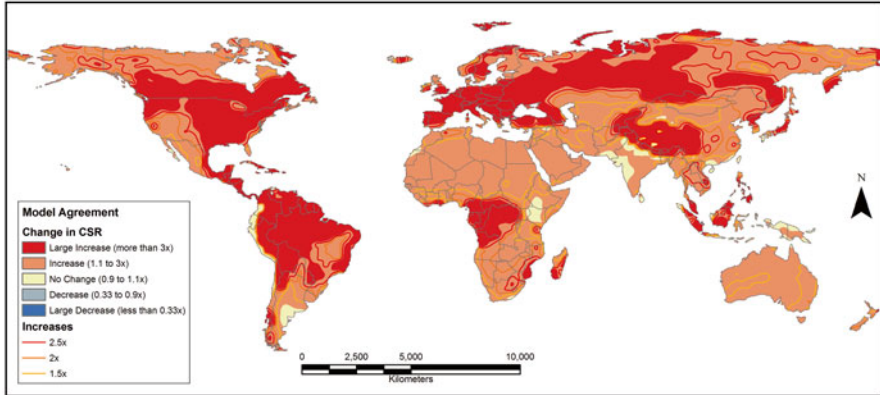
Fig. 7.2 Cumulative Severity Rating anomalies for the HadCM3 A2 scenario for 2091–2100 relative to the 1971–2000 base period (See Flannigan et al. 2013 for study design)

the northern hemisphere (Flannigan et al. 2013). With these increases, we expect more area burned, increased fire occurrence, and greater fire intensity that will result in more severe fire seasons and increased fire control difficulty. In a Canadian boreal modeling study, Podur and Wotton (2010) estimate that these future conditions will result in an increase of 200–500 % in annual area burned. The substantial increases in CSR predicted globally across climate change scenarios by the end of this century (some showing increases of up to 300 %) are truly noteworthy for wildland fire managers.

7.3   Fire Management and Disaster Fires

Many global regions have reported increasing fire activity in recent decades, which is attributed to numerous factors such as climate change-altered fire regimes, rural-urban population shifts, and land-use change affecting vegetation and fuel conditions (Mouillot and Field 2005; Marlon et al. 2008; Flannigan et al. 2009a, b). With the vast amount of fire that occurs globally, a proportion inevitably becomes uncontrolled wildfire of which some have disastrous social, economic, and/or environmental impacts. The human impacts of wildland fire are different from other natural disasters in several ways. Uncontrolled wildland fires (or wildfires) can threaten the safety of many thousands of people, but fortunately, human mortality is much lower (the highest current documented mortality is 173 lives lost in the Victoria, Australia, wildfires of 2011). However, wildfires can cause substantial human suffering for large numbers of people through the loss of shelter, food (crops), fuelwood for cooking, and perhaps even more crippling, through loss of livelihood (e.g., farm animals, grazing area). Additionally, the human health impacts from smoke pollution are much more insidious and long term (Sastry 2002; Rittmaster et al. 2006; Goldammer et al. 2009), and can be very far-reaching beyond the fire area itself (DeBell et al. 2004).

Most global fire is unmonitored and undocumented so the record of wildland fire disasters is incomplete. However, the existing record indicates that disaster fires occur in every global region and in every vegetated biome on a regular basis (Table 7.1). Disaster conditions are defined as any wildfire(s) situation that

Table 7.1 Examples of some recent wildland fire disasters and impacts around the world

Year	Location	Impacts
2013	Arizona, USA	19 lives lost
	Colorado, USA	2 lives lost
		509 homes destroyed, 17 damaged
		Estimated damage: US$90+ million
2012	Colorado, USA	3 lives lost
		594+ homes destroyed
	Global	180 lives lost
		2,938 people injured
		2,949 homes and businesses destroyed
		116,575 people evacuated
2011	Alberta, Canada	1 life lost
		433 properties destroyed, 84 damaged
		7,000 people evacuated
		Estimated damage cost: CA$1.8 billion
	Texas, USA	1,500+ homes destroyed
	Global	130 lives lost
		349 people injured
		7,193 homes destroyed
		85,723 people evacuated
2010	Western Russia	50 lives lost
		Moscow daily mortality rate doubled; estimated 56,000 premature deaths due to smoke pollution and heat stress
		5,000 homeless
		Estimated economic damage: US$15 billion
	Bolivia	State of emergency declared
		60+ homes destroyed
	Global	279 lives lost
		140 people injured
2009	Victoria, Australia	173 lives lost
		2,059 homes destroyed
	Global	374 lives lost
		160 people injured
2007	Greece	84 lives lost
		1,000+ homes destroyed
	California, USA	9 lives lost, 85 people injured
		1,500+ homes destroyed
2005	Guadalajara, Spain	11 lives lost
	Greece	13 lives lost
		Estimated economic damage: EUR744 million
	South Korea	160 homes destroyed
		2,000 people evacuated
		1,300-year-old Buddhist temple destroyed

Table 7.1 (continued)

Year	Location	Impacts
2003	British Columbia, Canada	3 lives lost 334 homes destroyed 45,000 people displaced Suppression cost: CA$700 million
	Canberra, Australia	4 lives lost 500+ homes destroyed Estimated property damage: AU$600–1,000 million
	California, USA	24 lives lost 3,640 homes destroyed 120,000 people displaced Estimated damage: USD$2 billion
	Portugal	21 lives lost 100+ homes destroyed Estimated damage cost: EUR1,000+ million
2001	Sydney, Australia	109 homes destroyed Estimated property losses: AU$75 million (~3,000 claims) Estimated suppression costs: AU$106 million
1997–1998	Southeast Asia	Estimated regional economic damage: US$8.7–9.2 billion

Sources: Goldammer (2010), Global Fire Monitoring Centre, fire statistics for Australia, Canada, Europe and USA
This represents a sample of global wildland fire disasters; many jurisdictions do not keep wildfire records or have minimal documentation

overwhelms fire suppression capacity to the point that human life, property, and livelihood cannot be protected. Besides the threat to human safety, these fires can also have serious negative impacts on human health, regional economies, global climate change, and ecosystems in non-fire-prone biomes (ADB and BAPPENAS 1999; Cochrane 2003; Goldammer et al. 2009; Flannigan et al. 2009a, b). To mitigate fire-related problems and escalate fire suppression costs, forest and land management agencies, as well as landowners and communities, require early warning of extreme fire danger conditions that lead to uncontrolled wildfires. Early warning of these conditions allows fire managers to implement fire prevention, detection, and presuppression action plans before fire problems begin.

7.3.1   Fire Danger Rating and Early Warning

Fire danger rating[1] is the systematic assessment of fire risk and potential impact, and it is the cornerstone of contemporary fire management programs. It is used to determine suppression resource levels (fire fighters, equipment, helicopters, fixed wing airtankers), mobilization, and strategic prepositioning; to define safe and acceptable prescribed burn prescription criteria; and to establish fire management budgets

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[1] Fire danger is a measure of the potential for a fire to start, spread, and do damage.

based on long-term fire danger statistics, and to justify increased funding during times of wildfire disaster. Fire danger rating research has been ongoing since the 1920s, resulting in operational fire danger rating systems being available for about four decades in Canada (Stocks et al. 1989), the United States (Deeming et al. 1977), and Australia (Luke and McArthur 1978). Numerous other weather-based systems and indices have been developed worldwide, although the Canadian Forest Fire Weather Index (FWI) System remains the most widely used fire danger rating system internationally (Table 7.2). Current fire danger rating systems in the world are wide-ranging in their scientific/technical basis and operation; they are discussed in this chapter in general terms only.

Fire danger rating systems were primarily designed to support landscape-level decision-making in fire management. Continuing research in this field has also led to more detailed, smaller-scale models of fire behavior, fire spread, and fire effects that simulate at the forest stand level. Despite the considerable progress that has been made in fire danger rating and related sciences in the last eight to nine decades, less than half of the world's countries has a national fire danger rating system in place to support fire management. Most countries that do not have an operational fire danger rating system are in that situation because of a lack of institutional and/or financial capacity to build a national system. Ironically, fire danger rating systems need not be expensive, as very simple and reliable systems can be developed from existing science and technology with minimal capital costs. The only real expense necessary is the cost of technology transfer, specifically training to use fire danger information in fire management operations.

Using real-time actual weather data, fire danger rating systems normally provide a 4- to 6-h advanced warning of the highest fire danger for any particular day that the weather data is supplied. However, extended early warning (i.e., 1–2 weeks) can be provided by using forecasted conditions from advanced numerical weather models. This extra time allows for greater coordination of resource-sharing and mobilization within and between countries. Early warning systems are usually comprised of a number of different short-term (1 day to 2 weeks in advance) and long-term (seasonal fire danger forecasts estimated many months in advance) products that are based primarily on predicted fire danger. Early warning products are typically enhanced with remotely sensed spectral data on land cover and fuel conditions that reflect different fuel types and flammability. Near-term early warning products are also usually enhanced with satellite-detected hot spots as these indicate current active fires (prescribed burning and wildfires) that are ignition sources that could potentially become disaster fires. Long-term early warning products provide fire agencies with information in a large-scale management context, i.e., how does the extended outlook for the current fire season compare to the experiences of previous fire seasons? Short-term early warning at the 1–2 week scale is information useful for strategic decision-making such resource-sharing between countries, or across large landscapes. Short-term early warning at the scale of 1–3 days is most useful for tactical decision-making such as resource mobilization within country, between priority fires, or to different sectors of a fire.

Table 7.2 Summary of commonly referenced weather-based systems and indexes for national fire danger rating (documented systems only)

Index or system	Country or region of application[a]	Weather parameters	References
Canadian Forest Fire Weather Index System	Argentina, Canada, China, Chile, Fiji, Indonesia, Malaysia, Mexico, New Zealand, Portugal, South Africa, Spain, Sweden, Thailand, United Kingdom, USA (Alaska, some northern states), Venezuela; Europe and North Africa, Eurasia, global, Southeast Asia, Southern Africa	Temperature, rainfall amount, relative humidity, wind speed	Van Wagner (1987)
Fire Danger	Brazil, South America	Temperature, relative humidity, precipitation	Setzer and Sismanoglu (2012)
F Index	USA, Australia	Wind speed, FMI (Fuel Moisture Index)	Sharples et al. (2009a, b)
Forest Fire Danger Index	Australia, South Africa, Spain	Temperature, relative humidity, wind speed, Keetch-Byram Drought Index, rainfall amount, days since rain	McArthur (1966, 1976), Luke and McArthur (1978)
Fosberg Fire Weather Index	USA, Australia, global	Temperature, relative humidity, wind speed	Fosberg (1978), Goodrick (2002)
Grassland Fire Danger Index	Australia, South Africa, USA	Temperature, relative humidity, wind speed	McArthur (1976), Luke and McArthur (1978)
Haines Index	USA	Lower atmosphere temperature and dew point	Haines (1988)
Keetch-Byram Drought Index	USA, Australia, Indonesia	Temperature, rainfall amount, mean annual precipitation	Keetch and Byram (1968)
Lowveld Fire Danger Index	South Africa	Temperature, relative humidity, wind speed, rainfall	Meikle and Heine (1987)
National Fire Danger Rating System	USA, South Africa	Temperature, relative humidity, rainfall amount and duration, wind speed, cloud cover	Deeming et al. (1972, 1977)
Nesterov Index	Russia	Temperature, dew point, days since rain	Nesterov (1949)
PV 1 Index	Russia	Temperature, relative humidity, pressure, wind speed, precipitation	Vonsky et al. (1975)

Many other national and subnational systems are used around the world, although technical and scientific documentation, and history of operational use is often limited

[a]Documented applications, in whole or in part

Early warning at the scale of minutes to hours, which could be used for evacuation and is typically understood as "early warning" in other natural disaster disciplines (tsunami, flood, hurricane, mudslide), may be more accurately described as "very short-term" early warning in the context of wildland fire. It is an area of relatively recent research and experience. The Advanced Fire Information System[2] is the first operational system providing near real-time warning of fires to desktop computers and cell phones. Warnings are provided based on satellite-detected hot spots (MODIS and MSG) and user-selected location. It was developed in South Africa and has been running there operationally since 2004.

7.3.2   *The Global Early Warning System for Wildland Fire*

Following the recommendations of the UN World Conference on Disaster Reduction (WCDR) in Kobe, Japan, January 2005, and the proposal of the UN Secretary General to develop a Global Multi-Hazard Early Warning System (GEWS), a call for project proposals for building a GEWS was issued in preparation for the 3rd International Conference on Early Warning (EWC-III) (27–29 March 2006, Bonn, Germany), sponsored by the United Nations International Strategy for Disaster Reduction (UNISDR) and the German Foreign Office (www.ewc3.org/). An international consortium of institutions cooperating in wildland fire early warning research and development (de Groot et al. 2006) submitted a proposal for a Global Early Warning System for Wildland Fire (EWS-Fire), and it was selected for presentation at EWC-III. The outcomes of the discussions reveal the high interest in and endorsement by government and international institutions.[3]

The global wildland fire community recognizes that no individual country is capable of solving the problem of increasing fire activity and disaster fire occurrence on its own, and that greater international cooperation is required. The Global EWS-Fire is one component of *A Strategy to Enhance International Cooperation in Fire Management* (FAO 2006). The objective of the Global EWS-Fire is to provide a scientifically supported, systematic procedure for assessing current and future fire danger that can be applied from local to global scales. The system is not intended to replace the many different fire danger rating systems currently in use, but rather to support and build on existing national and regional fire management programs by providing:

- New longer-term predictions of fire danger based on advanced numerical weather models
- Common global fire danger metrics to support international fire management cooperation, including resource-sharing during times of fire disaster
- A fire danger rating system for the many countries that do not have a national system in place

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[2] More information is available at http://afis.co.za.

[3] Documented on the GFMC Early Warning Portal (www.fire.uni-freiburg.de/fwf/EWS.htm).

The primary purpose of the Global EWS-Fire Project is to develop a globally consistent suite of fire danger and early warning products to support international collaboration and reduce wildfire disaster. As part of this process, fire danger and early warning information will be made widely available to all countries through open access. As well, the Global EWS-Fire Project actively supports projects to assist countries with limited fire management capacity in the local use and application of fire danger and early warning information. The Global EWS-Fire was officially launched and made publicly available in May 2011, and system development is ongoing as new products are being designed.

The Global EWS-Fire is a project of the Global Observation of Forest Cover and Global Observation of Landcover Dynamics (GOFC-GOLD) Fire Implementation Team, which is comprised of numerous international wildland fire, remote sensing, and weather agency representatives. The Global EWS-Fire is actually a system of fire danger modeling systems. All early warning products will be accessible at the home directory of the GOFC-GOLD Fire IT website.[4] Additional and more detailed information can be found at other system websites hosted by the Global Fire Monitoring Centre,[5] the European Forest Fire Information System,[6] the Desert Research Institute,[7] and the Canadian Forest Service.[8]

7.3.3   Global System Structure

As stated earlier, the purpose of the Global EWS-Fire is to link the wide range of uniquely calibrated, national fire danger rating systems currently in operation, with a single set of fire danger indices that have globally consistent calibration. These global indices allow weather-based comparisons of fire danger across national borders and continents over a spectrum of time scales. They are provided as a supplement to national systems and serve to support large-scale bilateral fire management decisions such as suppression resource-sharing and resource mobilization in advance of disaster conditions, similar to the centralized decision-making of national fire management agencies with nationally calibrated systems. For the many countries in the world that do not have the internal capacity to develop a national fire danger rating system, the Global EWS-Fire provides an operational fire danger rating system that can be calibrated to regional conditions.

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[4] http://gofc-fire.umd.edu/index.php.

[5] http://www.fire.uni-freiburg.de/gwfews/forecast_ews.html.

[6] http://forest.jrc.ec.europa.eu/effis/.

[7] http://www.cefa.dri.edu/CFS/fwi.php.
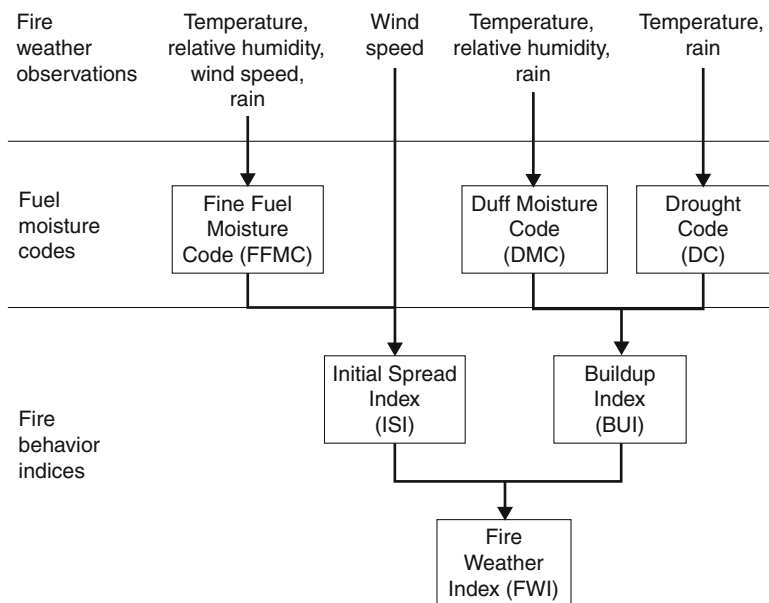
[8] http://cwfis.cfs.nrcan.gc.ca/.

Fig. 7.3 Structure of the Canadian Forest Fire Weather Index (FWI) System. See Box 7.3 for system description

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Box 7.2 Time Scales and Early Warning

Long-term early warning products (or seasonal forecasts) provide an indication of anticipated global trends in fire danger over the course of the upcoming fire season. Short-term early warning products (1–2 weeks) provide information for large-scale tactical decision-making that requires "spool-up" time to implement fire management action plans such as arranging the transfer of helicopters, fixed-wing air tankers, or fire fighters and equipment across international borders. Early warning of 1–7 days provides information for strategic decision-making, such as prepositioning suppression resources in the most critical areas to most effectively control new fires and contain ongoing fires.

The Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) was used for the Global EWS-Fire since it is the most widely used system, internationally (Table 7.2). As a brief summary, there are six components in the FWI System that reflect fuel moisture and general fire behavior at a landscape scale, as influenced by weather (see Fig. 7.3). There are three fuel moisture codes representing the moisture content of litter and other dead fine fuels (Fine Fuel Moisture Code, FFMC), surface organic matter of moderate density, such as the F layer of forest soils (Duff Moisture Code, DMC), and deep, compact soil organic layers, such as the H layer of forest soils (Drought Code, DC). The fuel moisture codes are also

Fig. 7.4 Calibrating the Fine Fuel Moisture Code (FFMC) with satellite-detected hot spots to construct a fire start predictor, or "Ignition Potential" indicator. This example uses 1 year of MODIS hot spot data for sub-Saharan Africa and corresponding FFMC data for the hot spot location. Similar calibrations have been done for SE Asia and for Central and South America resulting in very similar FFMC scale calibrations
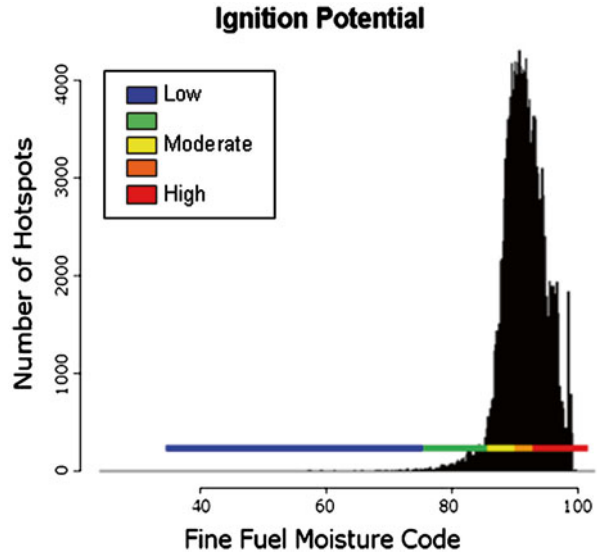
used to represent the moisture content of dead woody debris of different diameter classes. FFMC fuels are present in virtually all fuel types, and represent the component of the fuel complex where fires start and spread. As such, the FFMC serves as a universal indicator of potential fire occurrence, particularly for human-caused fires (de Groot et al. 2005; Wotton 2009, Fig. 7.4). The DMC is used as a lightning fire predictor in northern forests where lightning ignitions can smolder in the duff accumulated on the forest floor (Wotton 2009). DC is an indicator of potential for deep burning fires and difficulty of extinguishment. DMC and DC fuels are not found in the fuel complex of all fuel types, as this depends on vegetation litterfall and dead organic matter decomposition rates. Therefore, the FFMC has global application and the DMC and DC are only relevant in fuel types with significant organic soil development or dead woody debris fuel load. The FWI System also has three fire behavior indices, which are general indicators of rate of fire spread (Initial Spread Index, ISI), fuel available for combustion within a moving flame front (Buildup Index, BUI), and head fire intensity (Fire Weather Index, FWI). The FWI component is also used as a general indicator of fire danger. The Daily Severity Rating (DSR) is a power function of the FWI that represents difficulty of fire control (Van Wagner 1970).

The Global EWS-Fire uses ground-based and remotely sensed data to prepare early warning products. Fire danger is calculated with Global Forecast System data from the US National Centers for Environmental Prediction (NCEP).[9] The Global EWS currently provides 1–7 day forecasted FWI System data that are calibrated to commonly used threshold values that identify low to extreme conditions

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[9] For further information, see Global Forecast System details at http://www.emc.ncep.noaa.gov.

Box 7.3 The Canadian Forest Fire Weather Index (FWI) System

The FWI System is based on the effects of weather parameters on forest floor fuel moisture conditions and generalized fire behavior that can be expected in a typical jack pine (*Pinus banksiana* Lamb.) forest stand (Van Wagner 1987). Fire weather observations are used as inputs for three Fuel Moisture Codes, which represent three classes of forest fuel with different drying rates, nominal fuel depths, and nominal fuel loads (see properties Table below). The Fine Fuel Moisture Code (FFMC) represents the moisture content of dead fine fuels and litter on the forest floor. The Duff Moisture Code (DMC) represents the moisture content of loosely compacted decomposing organic matter. The Drought Code (DC) represents the moisture content of deep compact organic matter of moderate depth. The three Fuel Moisture Codes are each calculated with a daily time-step and include their previous day's value as an input to the current day's value. It is through this feedback mechanism that antecedent information is incorporated into the FWI System and each new day's moisture level is determined. A measure of the fuel drying speed is the time lag at which the fuel loses $1-e^{-1}$ (about two-thirds) of its free moisture content above equilibrium.

The Fuel Moisture Codes provide input to the Fire Behavior Indices. The Initial Spread Index (ISI) estimates the combined influence of wind speed and the FFMC on fire spread. The Buildup Index (BUI) is a combination of the DMC and the DC, representing the combustibility of heavier fuels, such as deeper organic forest floor layers or larger-sized dead roundwood fuels (branches, logs). The ISI and the BUI are combined to determine the value of the Fire Weather Index (FWI), representing the head fire intensity of a spreading fire during the peak burning period of the day.

The FWI System is used operationally as an indicator of landscape-level fire danger, as influenced by weather. Although it was originally designed using jack pine as a baseline fuel type, it has been calibrated using local fire and weather data to represent general fuel moisture and fire behavior conditions for fire regimes in many different global regions.

General properties of the three Fuel Moisture Codes (exact rates vary with environmental conditions)

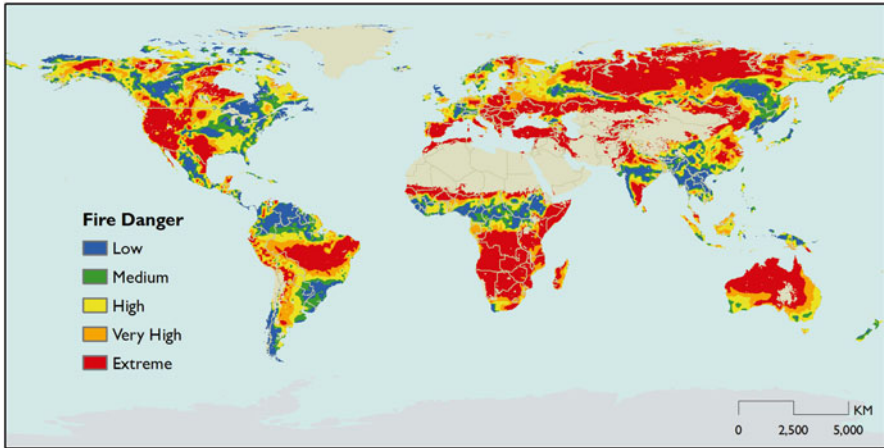| Fuel Moisture Code	Time lag (days)	Water capacity (mm)	Nominal fuel depth (cm)	Nominal fuel load (kg m^{-2})
FFMC	2/3	0.6	1.2	0.25
DMC	15	15	7	5
DC	53	100	18	25

Fig. 7.5 Example of a global-level product, indicating the Fire Weather Index (FWI) of the Canadian Forest Fire Weather Index System for 28 July 2013

(see Fig. 7.5). By using a globally consistent scale, the Global EWS provides a means of interpreting and comparing relative fire danger conditions across countries, continents, and biomes. All fire danger maps are supplemented with MODIS hot spot data for visual comparison with current fire activity. Global level products are made available via the Global Fire Monitoring Centre website, and the GOFC-GOLD Fire IT website. In future, early warning products will also be provided by the European Commission – Joint Research Centre (JRC), which provides the European Forest Fire Information System (EFFIS). The JRC is developing 1–14 day forecast global fire danger (FWI System) products calculated using data from the European Centre for Medium-Range Weather Forecasts (ECMWF).[10] Those products (which will be available on the EFFIS and GOFC-GOLD Fire IT websites) will provide a second estimation of future fire danger. Comparison of global fire danger by the two forecast models (NCEP and ECMWF) can be made on the GOFC-GOLD Fire IT website. It is envisioned that Global EWS-Fire products will be tailored in the future to meet specific international information needs for agencies such as the UNISDR, Food and Agriculture Organization, World Health Organization, and the United Nations Environment Program.

Global EWS-Fire products can be used to compare fire danger around the world because they use a globally consistent calibration. As stated previously, this type of information is useful for making large-scale fire management decisions by understanding future fire danger trends across continents and over longer time periods. However, a single fire danger value has different meanings (in a fire management context) in different parts of the world because of differences in the local fire regime. For example, a Drought Code value of 500 may be interpreted as an extreme fire danger condition in northern boreal forests where there usually is frequent seasonal

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[10] http://www.ecmwf.int/.

rainfall, but it may be considered a moderate or low value in drier biomes. For that reason, there is additional value in understanding fire danger in relation to the "local" fire regime, which includes the influences of fuel, ignition sources, climate, fire management/suppression policy, etc. The next stage in development of the Global EWS-Fire is regional calibration to adjust the fire danger scales using historical fire data (primarily remotely sensed) and weather data. This procedure will calibrate the Global EWS-Fire to provide operational-level information such as potential for fire starts and difficulty of control. Regional calibration will be a collaborative effort with regional and national agencies.

7.3.4   Regional Early Warning Systems

Organized regional fire groups, such as the Regional Networks of the UNISDR Global Wildland Fire Network[11] and the GOFC-GOLD Regional Networks,[12] have the mandate to promote regional fire management collaboration and provide national support in the practical application of wildland fire science and technology. As such, regional groups and agencies serve as a formal linkage between global and national levels. Regional systems are often an efficient way to operate a system for many countries in an area with common values and fire issues. Several prototype examples of regional products have been demonstrated during the development of the Global EWS-Fire (see Figs. 7.6, 7.7, and 7.8).

There are a number of regionally operating fire danger rating systems covering Europe and North Africa,[13] South East Asia,[14] Southern Africa,[15] Eastern Europe and Northern Asia,[16] and South America[17] (Table 7.2). Some of these regional fire danger rating systems are actively being expanded to become early warning systems by incorporating longer-term fire danger forecasts and enhancing fire danger products with additional satellite data on fire activity and fuel conditions.

7.3.5   National Systems and Local Level

For centrally organized fire management agencies, the national or subnational level (provinces, states, and/or territories) is the point of primary decision-making. Fire

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[11] http://www.fire.uni-freiburg.de/GlobalNetworks/globalNet.html.

[12] http://gofc-fire.umd.edu/RegNtwks/index.php.

[13] http://forest.jrc.ec.europa.eu/effis/.

[14] http://haze.asean.org/.

[15] http://wamis.meraka.org.za/products/fire-danger.

[16] http://www.fire.uni-freiburg.de/fwf/eurasia1.htm.

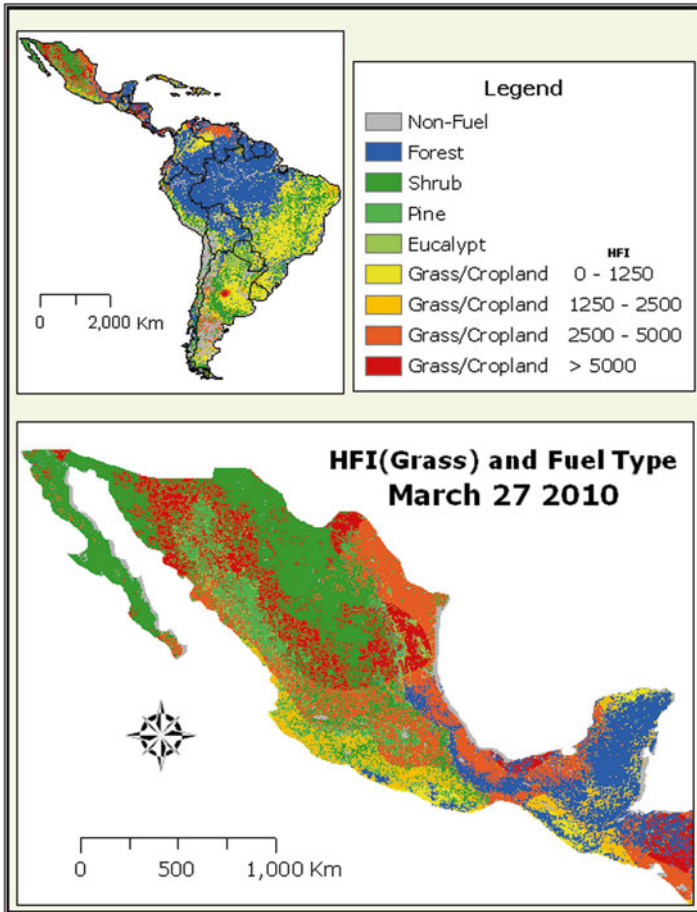[17] http://www.inpe.br/queimadas/abasFogo.php.

Fig. 7.6 Example of Regional Early Warning System products for Central and South America. In this example, fuel types have been interpreted from landcover data (ESA GlobCover Project). Hear fire intensity (HFI, kW/m) in grasslands is identified using a fire danger-based fire rate of spread model (Forestry Canada Fire Danger Group 1992) and an estimated grassland fuel load of 3 t/ha

danger information is used to support many different short- to long-term fire management activities: daily resource mobilization at ongoing wildfires, presuppression resource positioning to initial attack new fire starts, prescribed burn planning (prescription determination), justification of operational budgets, predicting post-fire effects, carbon emissions accounting, long-term fire and forest management planning, modeling fire and climate change impacts, and resource-sharing within country and bilaterally. In terms of daily operational fire management decisions, fire danger information is applied to nationally derived guidelines for fire control and use (Table 7.3). For countries that have national fire danger rating systems in place, daily fire danger information is usually produced by collecting data from national
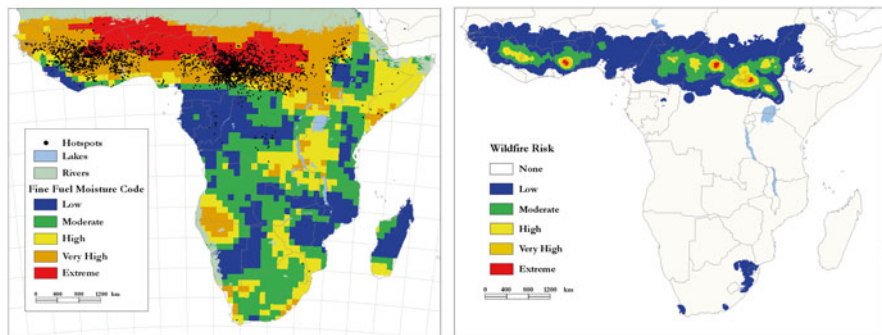
Fig. 7.7 Examples of fire early warning products from a sub-Saharan demonstration study. The left map indicates future fire danger for 23 January 2007, as represented by the Fine Fuel Moisture Code (FFMC), in relation to current prescribed fire activity, as indicated by hot spots. The right map is a presentation of FFMC and hot spot data in a different form (for 27 January 2007), illustrating areas where the highest hot spot density intercepts with areas of highest fire danger. Both products can be used to guide fire management decision-making by indicating areas where prescribed fire can be safely used, and areas where current burning should be restricted
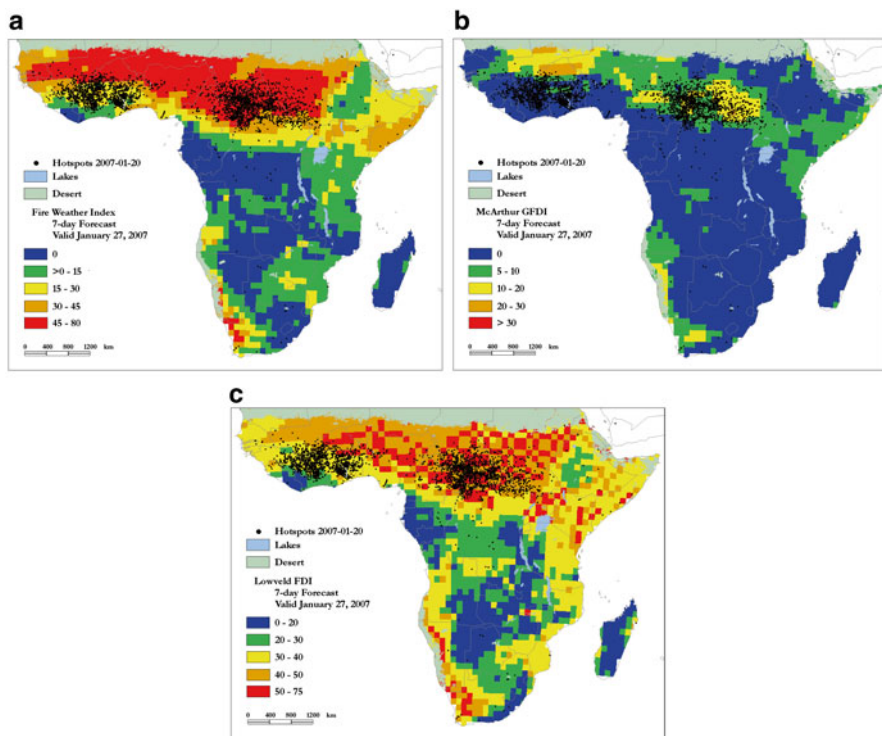

Fig. 7.8 Examples of Regional Early Warning System products for Africa using MODIS hot spots and 7-day forecasted fire danger conditions available on 20 January 2007 for (**a**) the Canadian Fire Weather Index, (**b**) McArthur's Grassland Fire Danger Index, and (**c**) the South African Lowveld Fire Danger Index

Table 7.3 Examples of fire danger-based decision-aids for (**a**) prescribed fire, (**b**) fire prevention and detection, and (**c**) fire suppression planning

a

Fire danger level	Prescribed fire activity	Fire severity	Period
Low	Nil to wet	Nil	All day
Moderate	Centre fire ignition	Low	1,000–1,4000 h
	Strip ignition	Moderate	1,400–1,800 h
High	Strip ignition	Moderate	0800–1,200 h
	Strip ignition during low winds only	High	1,200–2,000 h
Extreme	Strip ignition during low winds only	High	Before 1,000 h
	Prescribed fire ban	Extreme	1,000–2,000 h

b

Potential ignition level	Prevention activity	Detection	
		Activity	Period
Low	None	None	None
Moderate	Post-local waming signs	Towers	Mid-day
High	Local media warnings	Towers	All day
	Prescribed fire restrictions	Vehicle patrol	Mid-day
Extreme	TV and radio warnings	Towers	All day
	Prescribed fire restrictions	Vehicle Patrol	All day
	Local community meetings	Aircraft patrol	Mid-day

c

Fire danger level	Resources on standby	Alert period	Dispatch time
Low	Crews, hand tools	Mid-day	60 min
Moderate	Crews, hand tools	All day	30 min
	Pumps, water tanks	Mid-day	60 min
High	Crews, hand tools	All day	15 min
	Pumps, water tanks	All day	30 min
	Control line-building equipment	Mid-day	60 min
Extreme	Crews, hand tools	All day	15 min
	Pumps, water tanks	All day	15 min
	Control line-building equipment	All day	30 min
	Aircraft, burn out equipment	Mid-day	60 min

synoptic and/or fire weather station networks, and is calculated once or twice daily. Fire danger may be updated hourly during extreme conditions. National fire danger forecasts of 1–3 days are typical, although a few countries provide longer-term forecasts. National fire weather networks generally provide timely and reliable data because they usually have high station density, are well distributed, and can be remotely queried many times each day, if required.

Most daily operational fire management decisions are made with short-term (typically 1–3 days) early warning information. Many countries use national and subnational fire weather networks and forecasts very successfully to serve their early warning needs for within-country fire management. For fire management decisions that involve other countries such as cross-border wildfire suppression or international resource-sharing, national fire danger rating systems seldom provide the required long-range early warning capacity that extend beyond local national boundaries, which is needed to make decisions that affect multiple jurisdictions and take longer to implement. The Global EWS-Fire fills this gap by providing longer-term, international fire early warning information using common fire danger metrics across all countries, and enhanced with additional satellite data on fire and fuels. Additionally, the Global EWS-Fire provides a daily operational fire danger rating system for the many countries that do not have the capacity to implement a national fire weather station network and forecasting program.

Although there are substantial differences between wildfire and other natural disasters, one aspect is common: for an early warning system to work successfully, it must be implemented at the local level (i.e., the last mile). Community-based fire management is used in many parts of the world as an approach to involve landowners and local communities in the proper application of land-use fires (e.g., to control weeds, pests, and plant disease; to generate income from natural resources; to create forage) and in wildfire control (FAO 2011). Field-level decisions about fire prevention, detection, and suppression activities are made by the community using locally derived guidelines for prescribed fire and fire control (e.g., Table 7.3). Training and basic technology transfer in using such fire danger rating-based guidelines for fire management are critical to local capacity building and implementation of early warning systems at the local level. National land and forest management organizations may or may not be able to provide early warning information to the local level, either directly to the community or through subnational or regional levels. Forecasted data of 1–3 days may be provided, but there is generally limited access to long-term forecasted data at the community level. For the many wildland areas under community-based fire management that have limited or no access to early warning information, the Global EWS-Fire fills this information gap by providing short- to long-term early warning, however, access to the Internet is required.

Early warning information is critical at the local level because it takes time to implement action plans within a community. For example, the vast majority of global wildfire is human-caused due to the wide use of prescribed fire for a variety of land management purposes. Therefore, in many parts of the world, fire prevention is often the most effective means to reduce uncontrolled wildland fire. Prescribed burning by community members can be safely managed with burning restrictions,

but it takes time to communicate the prevention message throughout the community. Early warning provides the advance information needed to implement prevention action plans before dangerous burning conditions occur. When a wildfire does occur locally and there is imminent threat to human life, very short-term (or last minute) early warning systems such as AFIS can be very effective at the local level to rapidly inform people.

7.3.6   Future Global System Development and Implementation

There are a number of satellite data and modeling enhancements to the Global EWS-Fire that are being explored. Advances in measuring spatial precipitation from space likely offer the single largest improvement to the accuracy of fire danger maps and could reduce or eliminate the need for spatial interpolation of precipitation from ground-based point sources. Remotely sensed fuel mapping is also being pursued to develop a global fuel type map, which would be a first step towards developing global fire behavior prediction models. Monitoring of live fuel moisture (Ceccato et al. 2003) can contribute to establishing fuel flammability and seasonal criteria that are important to fire behavior models and monitoring/modeling of fuel consumption, fire spread rate, and carbon emissions. The use of remotely sensed fire radiative energy to estimate fuel consumption and carbon emissions is currently being studied (Wooster 2002; Wooster et al. 2003). Fuel consumption could also potentially be combined with satellite-monitored daily fire spread data to calculate fire intensity.

7.4   Climate Change, Early Warning Systems, and Future Fire Management

Current climate change models are in agreement that there will be increases in both fire occurrence and severity, resulting in larger fires and more area burned, which raises serious doubts over the ability of fire management agencies to effectively mitigate future fire impacts. The substantial increases in fire severity predicted globally across climate change scenarios by the end of this century are truly noteworthy for wildland fire managers. Increases of up to 300 % in cumulative seasonal fire severity, particularly in the northern circumpolar region, will place unprecedented demands on fire suppression resources. Some of the seasonal fire severity increase is due to longer fire seasons (about 20–30 days), but the vast majority of the increase is due to increased fire intensity and subsequent control difficulty. Fire suppression action most often fails during high intensity crown fires (Stocks et al. 2004), and the climate change scenarios of the most recent studies indicate that this type of fire behavior will occur with greater frequency in the future. Many countries of the world operate highly efficient fire management organizations that have a high fire

control success rate. However, climate change may cause a disproportionate increase in uncontrolled fires because many fire management organizations already operate at near to optimum efficiency; thus, any further increase in fire control difficulty will force many more fires beyond a threshold of suppression capability (cf Flannigan et al. 2009b; Podur and Wotton 2010). Perhaps we are already experiencing what is to come with many recent disastrous fires.

Increased wildland fire on the landscape in the future will force fire management agencies to reassess policy and strategy. All wildland areas cannot be protected from fire, and many high value areas that are managed with a policy of fire exclusion will be threatened by wildfire. Forest fire management agencies currently operate with a very narrow margin between suppression success and failure, and a warmer and drier climate will result in more fires escaping initial attack efforts and becoming large campaign wildfires (Stocks 1993). With greater occurrence of large wildfires, in combination with increasing exposure of people to fire on the landscape (due to population increase and community expansion further into wildland areas), an increase in wildfire disaster occurrence can be expected in the coming century. The international fire management community understands that greater collaboration in fire management is a key strategy in combating the increasing threat of wildland fire, particularly through the sharing of fire suppression resources. Early warning systems will play a critical role in identifying future periods of extreme burning conditions, allowing agencies to implement resource-sharing agreements, and activating fire prevention, detection, and suppression action plans before disaster fires occur.

References

Asian Development Bank (ADB), National Development Planning Agency (BAPPENAS) (1999) Causes, extent, impact and costs of 1997/98 fires and drought. Final report, Annex 1 and 2. Planning for Fire Prevention and Drought Management Project. Asian Development Bank TA 2999-INO Fortech. Pusat Pengembangan Agribisnis

Bond WJ, Woodward FI, Midgley GF (2005) The global distribution of ecosystems in a world without fire. New Phytologist 165:525–538

Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, DeFries RS, Doyle JC, Harrison SP, Johnston FH, Keeley JE, Krawchuk MA, Kull CA, Marston JB, Moritz MA, Prentice IC, Roos CI, Scott AC, Swetnam TW, van der Werf GR, Pyne SJ (2009) Fire in the Earth system. Science 324:481–484

Ceccato P, Leblon B, Chuvieco E, Flasse S, Carlson J (2003) Estimation of live fuel moisture content. In: Chuvieco E (ed) Wildlife fire danger estimation and mapping. World Scientific Publishing Co, Singapore, pp 63–90

Cochrane MA (2003) Fire science for rainforests. Nature 421:913–919

de Groot WJ, Wardati, Wang Y (2005) Calibrating the Fine Fuel Moisture Code for grass ignition potential in Sumatra, Indonesia. Int J Wildland Fire 14:161–168

de Groot WJ, Goldammer JG, Keenan T, Lynham TJ, Brady MA, Justice CO, Csiszar IA, O'Loughlin K (2006) Developing a global early warning system for wildland fire. In: Viegas DX (ed) Proceedings of the IV international conference on forest fire research (Coimbra, Portugal), CD-ROM. Elsevier BV, Amsterdam

DeBell LJ, Talbot RW, Dibb JE, Munger JW, Fischer EV, Frolking SE (2004) A major regional air pollution event in the northeastern United States caused by extensive forest fires in Quebec, Canada. J Geophys Res 109. doi:10.1029/2004JD004840

Deeming JE et al (1972) National fire-danger rating system. US For Serv Res Paper RM-84:165

Deeming JE, Burgan RE, Cohen JD (1977) The National Fire Danger Rating System – 1978, USDA For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah, Gen. Tech. Rep. INT-39

FAO (2006) Fire management review: international cooperation. Fire Management Working Paper 18. Food and Agriculture Organization, United Nations, Rome

FAO (2007) Fire management – global assessment 2006. Forestry paper 151. Food and Agriculture Organization, United Nations, Rome

FAO (2011) Community-based fire management. Forestry Paper 166. Food and Agriculture Organization, United Nations, Rome

Flannigan M, Logan K, Amiro B, Skinner W, Stocks B (2005) Future area burned in Canada. Clim Change 72:1–16

Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009a) Implications of changing climate for global wildland fire. Int J Wildland Fire 18:483–507

Flannigan MD, Stocks BJ, Turetsky MR, Wotton BM (2009b) Impacts of climate change on fire activity and fire management in the circumboreal forest. Global Change Biol 15:549–560

Flannigan MD, Cantin AS, de Groot WJ, Wotton BM, Newbery A, Gowman LM (2013) Global wildland fire season severity in the 21st century. Forest Ecol Manag 294:54–61

Forestry Canada Fire Danger Group (1992) Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Ottawa. Inf Rep ST-X-3

Fosberg MA (1978) Weather in wildland fire management: the fire weather index. In: Proceedings of the Conference on Sierra Nevada Meteorology, 19–21 June, Lake Tahoe. Bull Am Meteor Soc Boston 1–4

Giglio L, Randerson JT, Van der Werf GR, Kasibhatla PS, Collatz GJ, Morton DC, DeFries RS (2010) Assessing variability and long-term trends in burned area by merging multiple satellite fire products. Biogeosciences 7:1171–1186

Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD (2004) Detecting the effect of climate change on Canadian forest fires. Geophys Res Lett 31:L18211.18211–L18211.18214

Global Fire Monitoring Center (GFMC). Global wildland fire fatalities and damages reports 2009-2012. IFFN/GFMC Global Wildland Fire Network Bulletins: http://www.fire.uni-freiburg.de/media/bulletin_news.htm

Goldammer JG (2010) Preliminary assessment of the fire situation in Western Russia in 2010 by the Global Fire Monitoring Center, 15 August 2010. Presented at the State Duma, Moscow, 23 Sep 2010. IFFN 40:20–42

Goldammer JG, Statheropoulos M, Andreae MO (2009) Impacts of vegetation fire emissions on the environment, human health, and security: a global perspective. In: Bytnerowicz A Arbaugh MJ, Riebau AR, Andersen C (eds) Wildland fires and air pollution, vol 8. Krupa SV (series ed) Developments in environmental science. Elsevier, Amsterdam, pp 1–36

Goodrick SL (2002) Modification of the Fosberg fire weather index to include drought. Int J Wildland Fire 11:205–211

Haines DA (1988) A lower atmospheric severity index for wildland fire. Natl Weather Dig 13(2):23–27

IPCC (2000) Emissions scenarios. Cambridge University Press, Cambridge

IPCC (2007) Climate change 2007: synthesis report. In: Core Writing Team, Pachauri RK, Reisinger A (eds) Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change . IPCC, Geneva, p 104

Kasischke ES, Turetsky MR (2006) Recent changes in the fire regime across the North American boreal region-Spatial and temporal patterns of burning across Canada and Alaska. Geophys Res Lett 33, L09703

Keetch JJ, Byram GM (1968) A drought index for forest fire control. USDA Forest Service, Asheville. Res Paper SE-38. 32 pp. (Revised 1988)

Luke RH, McArthur AG (1978) Bushfires in Australia. CSIRO Div. For. Res., Australian Gov. Publ. Serv., Canberra

Marlon JR, Bartlein PJ, Carcaillet C, Gavin DG, Harrison SP, Higuera PE, Joos F, Power MJ, Prentice IC (2008) Climate and human influences on global biomass burning over the past two millennia. Nat Geosci 1:697–702

McArthur AG (1966) Forest fire danger meter, Mk4. For. and Timber Bur., For. Res. Dist., Canberra

McArthur AG (1976) Fire danger rating systems. FAO Consultation on Fires in the Mediterranean Region, Rome. FO:FFM/77/3-01, France

Meikle S, Heine J (1987) A Fire Danger Index system for the Transvaal Lowveld and adjoining escarpment area. S Afr For J 55–56

Mouillot F, Field CB (2005) Fire history and the global carbon budget: a 1°×1° fire history reconstruction for the 20th century. Global Change Biol 11:398–420

Nesterov VG (1949) Combustibility of the forest and methods for its determination. USSR State Industry Press, Moscow, 76 p. (In Russian)

Pechony O, Shindell DT (2010) Driving forces of global wildfires over the past millennium and the forthcoming century. Proc Natl Acad Sci U S A 107:19167–19170

Podur J, Wotton BM (2010) Will climate change overwhelm fire management capacity? Ecol Model 221:1301–1309

Power M, Marlon J, Ortiz N, Bartlein P, Harrison S, Mayle F, Ballouche A, Bradshaw R, Carcaillet C, Cordova C, Mooney S, Moreno P, Prentice I, Thonicke K, Tinner W, Whitlock C, Zhang Y, Zhao Y, Ali A, Anderson R, Beer R, Behling H, Briles C, Brown K, Brunelle A, Bush M, Camill P, Chu G, Clark J, Colombaroli D, Connor S, Daniau AL, Daniels M, Dodson J, Doughty E, Edwards M, Finsinger W, Foster D, Frechette J, Gaillard MJ, Gavin D, Gobet E, Haberle S, Hallett D, Higuera P, Hope G, Horn S, Inoue J, Kaltenrieder P, Kennedy L, Kong Z, Larsen C, Long C, Lynch J, Lynch E, McGlone M, Meeks S, Mensing S, Meyer G, Minckley T, Mohr J, Nelson D, New J, Newnham R, Noti R, Oswald W, Pierce J, Richard P, Rowe C, Sanchez Goni M, Shuman B, Takahara H, Toney J, Turney C, Urrego-Sanchez D, Umbanhowar C, Vandergoes M, Vanniere B, Vescovi E, Walsh M, Wang X, Williams N, Wilmshurst J, Zhang J (2008) Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Climate Dyn 30:887–907

Pyne SJ (2001) Fire: a brief history. University of Washington Press, Seattle

Rittmaster R, Adamowicz WL, Amiro B, Pelletier RT (2006) Economic analysis of health effects from forest fires. Can J For Res 36:868–877

Sastry N (2002) Forest fires, air pollution, and mortality in Southeast Asia. Demography 39:1–23

Scott AC, Glasspool IJ (2006) The diversification of Paleozoic fire systems and fluctuations in atmospheric oxygen concentration. Proc Natl Acad Sci U S A 103:10861–10865

Setzer AW, Sismanoglu RA (2012) Risco de Fogo: Metodologia do Cálculo – Descrição sucinta da Versão 9. http://queimadas.cptec.inpe.br/~rqueimadas/documentos/RiscoFogo_Sucinto.pdf. Accessed 24 July 2013

Sharples JJ, McRae RHD, Weber RO, Gill AM (2009a) A simple index for assessing fire danger rating. Environ Model Software 24:764–774

Sharples JJ, McRae RHD, Weber RO, Gill AM (2009b) A simple index for assessing fuel moisture content. Environ Model Software 24(5):637–646

Stocks BJ (1993) Global warming and forest fires in Canada. For Chron 69(3):290–293

Stocks BJ, Lawson BD, Alexander ME, Van Wagner CE, McAlpine RS, Lynham TJ, Dube DE (1989) Canadian Forest Fire Danger Rating System: an overview. For Chron 65:258–265

Stocks BJ, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR (2003) Large forest fires in Canada, 1959–1997. J Geophys Res 108:8149

Stocks BJ, Alexander ME, Lanoville RA (2004) Overview of the international crown fire modeling experiment (ICFME). Can J For Res 34:1543–1547

Van Wagner CE (1970) Conversion of Williams severity rating for use with the fire weather index. Can. Dep. Fisheries and For., Petawawa Forest Expt. Stn., Petawawa

Van Wagner CE (1987) Development and structure of the Canadian forest fire weather index system. Canadian Forest Service, Ottawa

Vonsky SM, Zhdanko VA, Korbut VI, Semenov MM, Tetjusheva LV, Zavgorodhaja LS (1975) Compiling and using the local scales of fire danger in the forest (in Russian). *LenNIILH, Leningrad*

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. Science 313:940–943

Wooster MJ (2002) Small-scale experimental testing of fire radiative energy for quantifying mass combusted in natural vegetation fires. Geophys Res Lett 29(21):2027. doi:10.1029/2002GL015487

Wooster MJ, Zhukov B, Oertel D (2003) Fire radiative energy for quantitative study of biomass burning: derivation from the BIRD experimental satellite and comparison to MODIS fire products. Remote Sensing Environ 86:83–107

Wotton B (2009) Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. Environ Ecol Stat 16:107–131