CSIRO PUBLISHING
www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2006, **15**, 121–135

Science, technology, and human factors in fire danger rating: the Canadian experience

Stephen W. Taylor[A,C] *and Martin E. Alexander*[B]

[A]Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 506 W. Burnside Road, Victoria, BC, V8Z 1M5, Canada.
[B]Forest Engineering Research Institute of Canada, Wildland Fire Operations Research Group, 1176 Switzer Drive, Hinton, AB, T7V 1V3, Canada. Present address: Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 5320-122 St, Edmonton, AB, T6H 3S5, Canada.
[C]Corresponding author. Email: staylor@nrcan.gc.ca

Abstract. The present paper reviews the development of the Canadian Forest Fire Danger Rating System (CFFDRS) and its implementation in Canada and elsewhere, and suggests how this experience can be applied in developing fire danger rating systems in other forest or wildland environments. Experience with the CFFDRS suggests that four key scientific, technological, and human elements need to be developed and integrated in a national forest fire danger rating system. First among these is a sustained program of scientific research to develop a system based on relationships between fire weather, fuels, and topography, and fire occurrence, behavior, and impact appropriate to the fire environment. Development of a reliable technical infrastructure to gather, process, and archive fire weather data and to disseminate fire weather forecasts, fire danger information, and fire behavior predictions within operational agencies is also important. Technology transfer and training in the use of fire danger information in fire operations are necessary, as are cooperation and communication between fire management agencies to share resources and set common standards for information, resources, and training. These elements must be appropriate to the needs and capabilities of fire managers, and must evolve as fire management objectives change. Fire danger systems are a form of media; system developers should be careful not to overemphasize scientific and technological elements at the expense of human and institutional factors. Effective fire danger systems are readily assimilated by and influence the organizational culture, which in turn influences the development of new technologies. Most importantly, common vision and a sense of common cause among fire scientists and fire managers are needed for successful implementation of a fire danger rating system.

Additional keywords: Canada; Canadian Forest Fire Danger Rating System; fire behavior; technology transfer; wildland fire research.

Introduction

Forest fire danger rating schemes underlie all contemporary fire management systems. These systems are the principal means by which scientific knowledge of fire potential is synthesized and integrated with operational experience into practical fire management applications. Many forest fire danger rating systems have been developed throughout the world (Lin 2000; San-Miguel-Ayanz *et al.* 2003), although no universal or leading system has emerged. Fire management agencies developing new systems often look to use or adapt such well-developed existing systems as the US National Fire Danger Rating System (Deeming *et al.* 1977), the McArthur fire danger rating meters used in Australia (Luke and McArthur 1978) or the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks *et al.* 1989). The CFFDRS, for example, has been fully implemented in parts of the USA and in New Zealand, and components of the system have been used in countries such as Fiji, Argentina, Mexico, Indonesia, and Malaysia. The CFFDRS is accepted outside of Canada likely because it is relatively simple to use, robust in a variety of environments, and has strong interpretive products (i.e. posters, look-up tables, electronic data processing and display systems) that are useful in a variety of situations.

In Canada, the CFFDRS is the principal source of fire intelligence for all forest fire management agencies. It is used to support fire management decision making at strategic and tactical levels, from fire prevention to firefighter safety. The development and implementation of the CFFDRS was challenging. Canada is a large country; although boreal forests are the predominant forest-cover type, fire environments

 10.1071/WF05021 1049-8001/06/010121

range from coastal rain forests and taiga to grassland and semi-desert. Land management objectives, fire load and fire management capacities vary across the country. As well, the federal government has a limited role in operational forest and fire management, and must work with provincial and territorial agencies to implement national programs in a kind of cooperative federalism (e.g. Wilson 2000).

The objective of the present paper was to address the question 'What makes for an effective national wildland fire danger rating system?' This was done by reviewing the purpose and principles of fire danger rating, and by examining the development and implementation of the CFFDRS as a case study. Four key scientific, technical and human/institutional elements or strategies were identified that can inform the further development of fire danger rating in Canada, the use of the CFFDRS in other countries, and the development of other fire danger rating systems.

Fig. 1. Fire danger indicator road sign used in Whitehorse, Yukon Territory. Photograph by AK Beaver, Yukon Wildland Fire Management.

The purpose of fire danger rating systems

In the 5th century BC, military strategist Sun Tzu wrote that 'one who knows the enemy and knows himself will not be in danger in a hundred battles'.[1] In contemporary Canadian fire management a forest fire may be considered a threat to forest resources, property, and public safety, or an important ecological process, depending on where and when it occurs. However, Sun Tzu's principle remains valid: a fire-intelligence system is an important element of any effective fire organization (Barrows 1969). A major component of any forest fire intelligence and management system is a fire danger rating system.

Fire danger refers to an assessment of both fixed and variable factors of the fire environment (i.e. fuels, weather, and topography) that determine the ease of ignition, rate of spread, difficulty of control, and impact of wildland fires (Merrill and Alexander 1987). Fire danger rating began in the temperate and boreal forests of North America, where fire danger typically varies throughout the fire season as weather systems bring rain, and are followed by drying periods of varying frequency, intensity, and duration. In times of greater fire danger, there may be many ignitions across large areas in short periods of time, resulting in peaks in fire management service demand. In Canada, at least, fire seasons are usually of limited duration, beginning in spring after snowmelt and ending in late autumn when snow cover resumes.

Wildland fire management is principally an economic activity. Fire danger rating systems were first developed for regions where the fire environment (weather, fuels, and topography) varies in space and time, and where fire management resources are costly and limited (Beall 1967). Their purpose is to provide a way to efficiently allocate an appropriate level of resources across a region or country from day to day or place to place, on the basis of existing and forecasted fire danger levels. The process of systematically evaluating and integrating individual and combined effects of factors influencing fire potential is referred to as 'fire danger rating'. Systems that rate fire danger provide for one or more qualitative and numerical indices of ignition potential and probable fire behavior (Countryman 1966).

Fire danger measures must provide useful information to support fire management decisions. The primary role of fire danger rating systems in North America is to enable fire managers to properly judge levels of preparedness needed and corresponding suppression resources required to keep wildfire losses or adverse impacts to a minimum. To the Canadian public, fire danger indicator road signs are still the most visible evidence of the existence of a fire danger rating system (Fig. 1). However, fire danger rating system outputs are used in a variety of fire management activities. These include: prevention planning (e.g. informing the public of impending fire danger, regulating access and risk associated with public and industrial use of forest and rural areas); preparedness planning (i.e. level of readiness and pre-positioning of suppression resources); detection planning (e.g. lookout staffing and aircraft scheduling and routing); initial-attack dispatching (e.g. prioritizing of targets for air tankers and ground crews); formulating suppression plans on active wildfires (including short-range predictions of fire spread and behavior); evaluating fire behavior potential and guidelines for safe work practices for firefighters; escaped fire situation analysis (including long-range projections of fire growth and behavior); prescribed-fire planning and execution (which includes smoke management); fire and fuel management modeling and planning; and fire behavior training.

[1] 'Therefore I say: One who knows the enemy and knows himself will not be in danger in a hundred battles. One who does not know the enemy but knows himself will sometimes win, sometimes lose. One who does not know the enemy and does not know himself will be in danger in every battle' (Tzu 1963).

Table 1. Comparison of fire management with and without the use of a fire danger rating system (from Van Wilgen and Burgan 1984)

Management using formal system	Management without formal system
1. Fire danger is accurately quantified	1. Fire danger is estimated
2. Fire danger can be calculated by newly appointed staff	2. Estimations of fire danger rely largely on experience
3. Use of the system will force staff to keep records of climatic data, which are of importance to all management procedures	3. No (or very few) climatic records are kept
4. Management decisions are based on quantified indices and are therefore less variable	4. Management decisions are based on experience and vary greatly among individuals

Fire management objectives change over time and space; we can distinguish at least four developmental stages in fire management programs in Canada:

1. Unregulated use of wildland fire by rural and aboriginal peoples as a part of traditional land management practices;
2. Government agencies begin to control fires to prevent unwanted damage to timber or other state and private resources as development and competition for resources increases, and to reduce people-caused fires by instituting fire laws, education programs, and suppressing traditional practices;
3. Government agencies and private concerns attempt to control all wildfires and restrict the use of prescribed fire to fire managers; wildland fire is institutionalized;
4. Realization that it is not possible or ecologically or economically desirable to control all fires. Wildfires may be allowed to burn in some areas where they play a natural role, and prescribed fire may be used to manage fuels and maintain ecological integrity.

As fire management objectives change, fire danger rating systems must also evolve to support more complex decision making. For example, a more thorough understanding of the complexities involved in forecasting fire behavior (Alexander and Thomas 2004) is needed to decide between suppressing a fire in a natural area or letting it burn freely.

Principles of fire danger rating

A fire danger scheme, like a smoke detector, should sound an alarm before fire danger and difficulty of control reach extreme levels, thus allowing fire managers time to prepare and take preventative action. Nelson (1955) outlined five general principles for the measurement of fire danger:

1. A fairly simple method of measuring key variables such as fuel moisture, wind, and rain, and a way of integrating these variables into numerical values;
2. Close adherence to standards for fire weather station location and instrumentation that are established for the particular system in use;
3. Careful training of fire weather observers;
4. Periodic and thorough inspection of fire weather stations; and
5. Continuity of fire weather and fire danger records.

Fire danger systems must be based on fire danger factors that are easy to measure accurately, and give consistent measures of fire danger from place to place and time to time, with approximately the same antecedent environmental conditions. Fire danger rating systems must also integrate a large number of fire danger parameters in simple, easy-to-use, and yet soundly based systems. As Van Wagner (1970) notes:

> Forest fire danger rating is a fascinating but exasperating branch of forest research. The goal is easily stated: Make an index such that any given index value will always represent the same fire behaviour, no matter what weather history leads up to it. The trouble is, one quickly outruns the available practical knowledge and theory. A liberal dose of philosophy is therefore required as well.

Thus, fire danger rating, as with other aspects of forestry, involves both science and professional judgment. Van Wagner (1971) further noted that 'if it is complicated, then the complexity should be buried out of sight, as in prepared tables or computer programs'.

Early cognitive science research suggested that the span of memory for a particular type of information is about seven items or factors (Miller 1956). While span of memory varies among individuals, the use of systems that integrate many significant factors affecting fire danger into a few indices is sound. A stronger argument is the advantage of substituting an objective method for the opinions of individuals in assessing risk and allocating resources, particularly as fire danger across a region or country is beyond any one individual's direct experience. Some advantages and disadvantages of using a fire danger rating system are listed in Table 1.

Fire danger rating systems attempt to simulate reality, but often fall short of it. In meeting the objective of simplified relationships, minor factors are neglected and systems are usually based on single sets of idealized conditions. If certain physical fundamentals are observed, this permits approximations that are close enough for many purposes – but they are approximations only. Consequently, fire danger rating

Table 2. Types of fire danger rating errors

True state of nature	Danger rating	
	Low danger	High danger
Low danger	No error	Type I error – false positive
High danger	Type II error – false negative	No error

systems tend to be applied beyond their field of usefulness. To avoid this tendency, the assumptions on which the systems are based and the range of conditions under which the systems are valid need to be defined carefully and checked frequently (Brown and Davis 1973). Most importantly, fire danger values must be correlated with empirical measures of fire occurrence or severity through experimentation and analysis of historical records (Harvey *et al*. 1986; Viegas *et al*. 1999; Cruz *et al*. 2003).

The use of fire danger systems can result in two types of error, which are illustrated for two conditions, 'High' and 'Low' fire danger levels in Table 2:

- Type I errors (errors of commission or false positives) occur when the system 'sounds an alarm', but no real potential for serious fires exists: fire danger is overestimated;
- Type II errors (errors of omission or false negatives) occur when serious fires take place prior to the system 'sounding an alarm' or when the system 'sounds no alarm at all': fire danger is underestimated.

Type I errors can result in fire management agencies overcommitting expensive resources, thereby incurring excessive pre-suppression costs. Type II errors can result in fire management agencies failing to anticipate increasing fire danger and being unprepared, leading to potential initial attack failures and incurring excessive suppression and damage costs. It is usually most important to minimize Type II errors or false negatives. However, it is also important that the system not be on high alert all the time – a fire danger system must isolate with certainty those days each season on which extreme fire danger conditions occur (Andrews 1987). In addition to weaknesses in fire danger systems or input data, human factors such as cognitive fixation – the failure to revise situation assessments as new information is received (De Keyser and Woods 1990) – may result in both Type I and II errors of interpretation.

In as much as fire danger rating systems are a form of media in McLuhan's (1994) sense of media as any extension of human powers or senses, media theory provides a useful framework for understanding the evolution and impact of fire danger rating systems. McLuhan (1994) held that 'The "message" of any medium or technology is the change of scale or pace or pattern that it introduces into human affairs'. Innis (1972) suggested that media are not only human constructs that attempt to fill perceived communication needs, but new media can influence culture and society, and in turn effect the development of further technology. McLuhan and McLuhan (1988) articulated four laws of media. Every new media extends or enhances some human ability or faculty; obsolesces an older form; builds on an older form; and reverses its properties when pushed to its limits. In this sense, new fire danger systems extend our ability to process and perceive fire danger in space and time beyond individual experience; they may displace daily weather observations as primary measures of fire potential; they build on the concept of fuel moisture integrators in the form of mathematical models; and pushed to the extreme they may reverse or amputate experiential-based judgment. While fire danger rating systems necessarily grow and change in response to changes in fire management, they may also influence how fire management is practised, and in turn affect the development of new technologies. Successful media are readily assimilated by and influence a culture – the fire management organizational culture – in the case of fire danger rating systems.

The Canadian experience in forest fire danger rating

Evolution of the CFFDRS

Systematic fire management began in North America in the early 1900s with the recognition that fire protection was essential to the development of a forest industry. Early efforts at fire danger rating attempted to describe the fire problem in relation to the moisture content of critical fuels, with emphasis on fine fuels important to ignition and early spread. Different approaches to estimating fuel moisture have been used over the years. These include: direct measurement; fuel moisture analogs such as fuel moisture sticks, duff hygrometers, and evaporation devices; correlation of fuel moisture with weather elements such as relative humidity; and cumulating the effects of current weather and past weather to describe the rate of change in fuel moisture in various fuels with different response times or timelags.

Research into forest-fuel flammability began in Canada in the mid-1920s (Williams 1964; Beall 1990). Fire danger rating pioneers James G. Wright and Herbert W. Beall produced their first set of fire danger tables in 1933. These were based on a 'Tracer Index' that related moisture content of needle litter and top-layer duff in red and white pine stands to behavior of small-scale test fires (Wright 1933). This early work led to the development of a number of regional fire danger rating tables by the 1960s (Williams 1964).

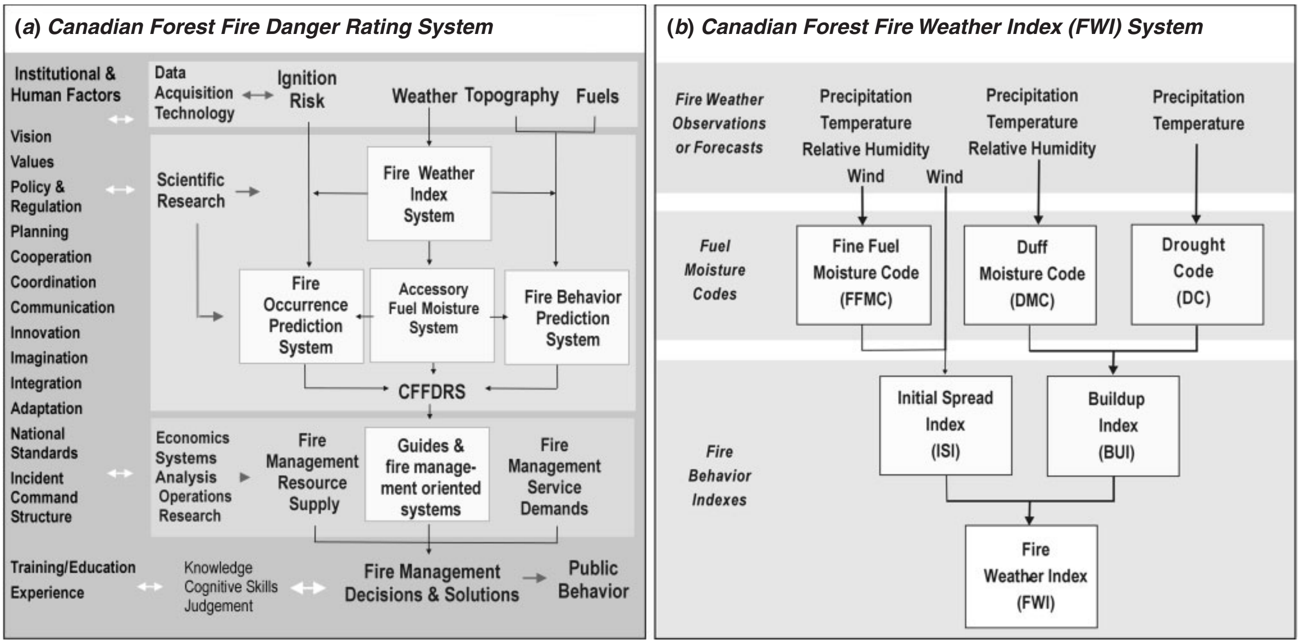

Fig. 2. (*a*) Structure of the Canadian Forest Fire Danger Rating System (CFFDRS) illustrating linkages to fire management actions and to some of the scientific, technical, human, and institutional factors that were important to its development and implementation; and (*b*) structure of the Fire Weather Index (FWI) System module of the CFFDRS.

In the 1950s and early 1960s, an expanding forest industry spurred the development of federal forest research centres across Canada, and renewed efforts in fire research. In 1965, a fire danger working group, representing Canadian Forest Service (CFS) fire researchers from across the country, was formed to guide development of what is now the CFFDRS. In 1967, a modular national fire danger rating system was proposed to replace a variety of regional systems (Muraro 1968). It has two primary subsystems (Fig. 2*a*) – the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System (Stocks *et al.* 1989). Elements of an Accessory Fuel Moisture System (e.g. Lawson *et al.* 1996; Wotton *et al.* 2005) and a Fire Occurrence Prediction System, including models for predicting flaming and smoldering ignition potential (e.g. Lawson and Dalrymple 1996*a*; Lawson *et al.* 1997*a*; Otway 2005) have been developed, but they have not been implemented on a national basis.

A provisional version of the FWI System was field tested at selected locations during the 1969 fire season, and the first edition was issued in 1970. The FWI System consists of six components (Fig. 2*b*). The Fine Fuel Moisture Code (FFMC) represents the moisture content of surface litter, which is key to ignition and fire spread, and is derived from Wright and Beall's Tracer Index. The Duff Moisture Code (DMC) and Drought Code (DC) represent the moisture content of shallow and deep organic layers, respectively. These organic layers are important to surface fire intensity, crowning potential, and difficulty of control in temperate and boreal coniferous forests. Three fire behavior indexes – the Initial Spread Index (ISI), Buildup Index (BUI), and FWI (patterned after Byram's [1959] concept of fire intensity) were developed and scaled in relation to fire behavior observations of small- to moderate-scale test fires in a standard or reference fuel type (i.e. a mature jack pine or lodgepole pine stand), but can be correlated with fire behavior in other fuel types (Van Wagner 1987*a*).

The three moisture codes of the FWI System do not represent the moisture content of all components of all fuel complexes in Canada. Fuel-specific moisture content models have also been developed for rapidly wetting and drying reindeer lichen (*Cladonia* spp.) (Pech 1989) and slowly wetting and drying downed woody fuels (Van Wagner 1987*b*), but they are not implemented on a national basis. The DMC and DC components are calibrated against organic layers that differ distinctly from the standard pine type (Lawson and Dalrymple 1996*b*; Lawson *et al.* 1997*b*; Wilmore 2001; Otway 2005).

All FWI System values are calculated from four simple weather observations (Turner and Lawson 1978) – temperature, relative humidity, wind speed, and 24-h accumulated precipitation – as recorded at noon local standard time (LST), but the values represent conditions at ∼1600 LST, which is the peak fire danger period (Van Wagner 1987*a*). Other schemes have been developed to model or calculate diurnal variation in the FFMC and, in turn, the ISI and FWI components at any time of the day (e.g. Lawson *et al*. 1996; Beck and Armitage 2004).

As soon as the FWI System was released in 1970, work began on a system to quantitatively predict primary behavior characteristics (McAlpine *et al*. 1990). Experimental fires were carried out in major Canadian fuel types, including coniferous and deciduous forests and logging slash (Alexander and Quintilio 1990; Stocks *et al*. 2004), over a range of burning conditions. These data, combined with observations from selected wildfires, were correlated with FWI System components. Primary relationships between the ISI and rate of spread, and the BUI and fuel consumption were modeled. Experimental fire data from Australia were used for grasslands (Cheney and Sullivan 1997). An interim edition of this FBP System was released in 1984 (Lawson *et al*. 1985), and the first complete edition of the FBP System (Fig. 2*a*) was published 8 years later (Forestry Canada Fire Danger Group 1992).

Lin (2000) notes that most fire danger rating systems in use in the world do not account well for human factors affecting fire occurrence. Efforts have been made in some Canadian provinces to develop prediction systems for both human-caused and lightning-caused fire occurrence (Martell *et al*. 1989; Todd and Kourtz 1991; Kourtz and Todd 1992; Vega-Garcia *et al*. 1995; Anderson 2002; Wotton *et al*. 2003; Wotton and Martell 2005); however, they have not been integrated into a national system.

A number of studies relate FWI System components to daily, monthly, and annual fire occurrence and area burned across Canada. For example, Harrington *et al*. (1983) found that certain FWI System components recorded at individual fire weather stations explained from 0 to 43% of the variance in monthly area burned by Canadian provinces. Anderson (2002) found that a model of lightning-caused fire occurrence incorporating FWI System values and number of lightning strikes correctly predicted the number of lightning-caused fire starts on 56% of days over a 5-year period in Saskatchewan. This model correctly predicted low fire activity days 90% of the time.

The CFFDRS was completed largely due to the dedicated efforts of a small group of researchers in the CFS Fire Danger Group who, for more than two decades, continued a line of work that began 40 years earlier. The fact that the group represented different regions of the country no doubt contributed to the national flavor of the CFFDRS.

Although Canadian and American fire researchers have communicated frequently over many decades (Beall 1990) and share some common views (Alexander and Andrews 1989), there was little formal collaboration in the pursuit of what has amounted to two very different approaches to modeling and predicting fire danger and fire behavior. In April 1992, researchers from the CFS and US Forest Service met in Missoula, Montana, to discuss development of a common North American fire danger rating system. While this was not resolved, the discussions led to a formal Canada–USA–Australia cooperative agreement on wildland fire research (McCaw and Alexander 1994), and in part to the International Crown Fire Modeling Experiment, which took place in Canada's Northwest Territories from 1995 to 2001 (Stocks *et al*. 2004). Such cooperative work may lead to the development of common fire behavior models in North America, if not entire systems.

Implementation of the CFFDRS in Canada

The present FWI System was designed in the 1970s before computers and electronic communications technology were widely available. It was therefore designed so that simple observations from manual fire weather stations could be used and FWI System values could be determined from look-up tables (Canadian Forestry Service 1984).

One of the first ways in which the FWI System was implemented was in fire danger class schemes. Fire danger levels were based on correlations between FWI System values and fire activity developed from analyses of historical fire weather and occurrence data (e.g. Turner 1973). Fire danger levels must also be determined in relation to fire management objectives, while the kinds of interpretations depend on values put at risk by fire and on the fire management resources or tools available. In British Columbia, for example, fire danger classes were defined in terms of FWI and BUI values for three danger regions with different fire climates (BCMF 1983). The fire danger classes were incorporated into fire prevention regulations that required forest operators to take preventative measures such as the provision of watchmen and equipment, and to abide by industrial forest closures. Guidelines for resource levels, patrols, and alert status were also tied to fire danger class (BCMF 1983). Fire danger classes were an important means for guiding objective systematic decision making but, as with any tool, they required interpretation. Fire danger classes are still used in British Columbia in the form of the Forest Fire Prevention and Suppression Regulations.[2] Effectively communicating fire danger to the public and other interest groups is an important part of fire prevention programs (Dawson 1991). However, at present there is no common fire prevention message in Canada.

After its release in 1992, the first complete edition of the FBP System was implemented in several provincial fire management systems, as well as in commercial software that is primarily used by provincial and regional fire centres and by specialists. In 1994, there were several near-entrapments of firefighters in British Columbia. A safety review of the incidents recommended that fire behavior, fire potential, and safe work practices be emphasized in all training and that a firefighter safety awareness campaign be developed (BCMF 1994). In 1995, the CFS field tested a prototype field guide

[2] Forest Practices Act of British Columbia, Revised Statutes of British Columbia, 1996.

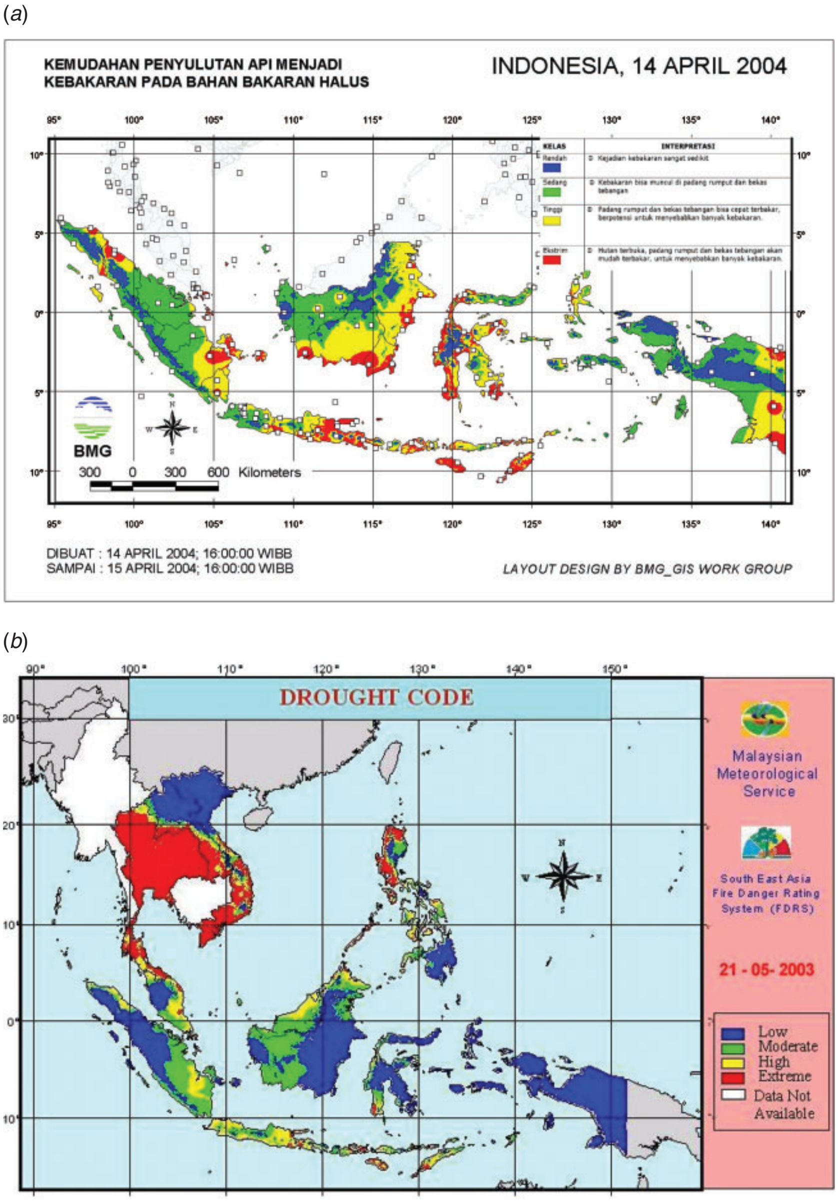

Fig. 3. Examples of daily FDRS maps showing: (*a*) Fine Fuel Moisture Code, an indicator of ignition potential, across Indonesia; (*b*) Drought Code, an indicator of smoke and haze potential, across the south-east Asia region. Maps produced by the Indonesia Meteorological and Geophysical Agency (http://www.bmg.go.id) and the Malaysian Meteorological Service (http://www.kjc.my and http://www.asean.haze-online).

to the FBP System to assist in this effort (Taylor *et al*. 1997). Reflecting on Van Wagner's (1971) advice, the guide was designed to be simple to use and formatted so that significant thresholds could be readily identified (e.g. surface- to crown-fire transition). Popularly known as the 'red book', the field guide is used at the tactical level and in training courses by all fire management agencies in Canada, enabling operational staff to make fire-behavior predictions that previously were limited to specialists. Although FBP System software is available for small computers such as palmtops, computers are not yet widely used in field operations in Canada (i.e. 'on the fireline'). In the late 1990s, the British Columbia Ministry of Forests adopted a policy of issuing fire-behavior warnings and removing crews from direct attack at the head of the fire when fire intensities are forecasted to exceed 4000 kW/m (Beck *et al*. 2002), a threshold identified in the field guide.

The development of remote automatic weather stations and communications technology in the 1980s and 1990s permitted collection of weather data from isolated locations in almost real-time on a provincial and even national basis. The effect of this automation could not have been anticipated and has been fortuitous. Automation has permitted the development of sophisticated fire management systems such as the Spatial Fire Management System to process, interpolate, and display fire weather data in concert with fuels and topographic data using geographic information system-based engines (Lee *et al*. 2002). Internet-based map displays such as the Canadian Wildland Fire Information System (Lee 1995) have also been developed to distribute text and map products to fire centres and other users across the country (http://cwfis.cfs.nrcan.gc.ca/en/index_e.php, accessed 15 September 2005), and around the world. An example of such a map display for south-east Asia is shown in Fig. 3. Systems have also been developed to guide daily and seasonal resourcing levels (e.g. Anderson and Lee 1991; Beck 2004), based in part on CFFDRS outputs and in some cases spatial statistical analyses. Computerized fire management decision support systems are very effective for communicating spatial variation in fire danger, allowing for the use of spatial analysis or visual interpretation in resource allocation decisions. They are a major reason for the expanded use and application of the CFFDRS at strategic levels.

Thus, there continues to be a place for a wide range of tools, from networks of automatic weather stations linked with sophisticated computer systems to basic weather instruments and look-up tables, to provide information on fire potential for users with different needs, capabilities, and resources.

Fire danger rating systems must also be cost effective for fire management agencies to use. According to a Government of Canada review of the CFFDRS undertaken in 1987 and 1988, for the period 1971–1982, at least $CAN 750 million in benefits (i.e. in terms of a reduction in firefighting expenditures) could be directly attributable to the system for Canada as a whole. The benefit-to-cost ratio was $\sim$3 : 1 (Moore and Newstead 1992).

Interagency cooperation in forest fire research and management

Although the CFS has led forest fire danger research in Canada, the cooperation of provincial and territorial fire management agencies has been critical to successful development and implementation of the CFFDRS. Fire management agencies lead implementation of the CFFDRS through training and operational practices. Although good working relationships between researchers and operational staff are crucial, formal working groups and cooperative agreements between federal and provincial agencies have also been important in setting policy and direction. These groups included, most importantly, the Canadian Committee on Forest Fire Control (CCFFC), later renamed the Canadian Committee on Forest Fire Management (CCFFM), which operated between 1952 and 1997 under the auspices of the National Research Council of Canada. Its membership included representatives of fire management agencies, universities and technical schools, the forest industry, and the CFS. Throughout the committee's 45 years, various subcommittees and task groups on fire research, terms definition, equipment, training, education, and communications addressed important common issues. While the CCFFC/CCFFM did not provide direct funding for fire research, it was an important vehicle for communication between the fire research community and fire management agencies across the country during the development and implementation phases of the CFFDRS.

In 1981, the Canadian Interagency Forest Fire Centre (CIFFC) was formed to manage the exchange of resources across Canada under the Mutual Aid and Resource Sharing (MARS) Agreement. Members represent federal, provincial, and territorial fire management agencies. The centre is one-third funded by the federal government, with the balance shared among the provinces. When the CCFFM was disbanded in 1996, the CIFFC's role expanded. Six CIFFC working groups – aviation, resource management, fire equipment, fire science and technology (S&T), national training, and forest and fire meteorology – formed to address common problems and issues, and resource sharing on a nation-wide basis. The three latter groups have been increasingly active in the continuing development, implementation, and application of fire danger rating in Canada.

The CIFFC S&T working group exchanges information on developments in fire science and technology, and shares funding of research and development projects of common interest. They helped acquire funding to develop PROMETHEUS, a wildland fire growth model (Tymstra 2002). The CIFFC Forest and Fire Meteorology Working Group is developing a common approach to fire weather data standards and sharing. The CIFFC National Training Working Group establishes training standards for staff exchanged under the MARS Agreement, oversees implementation of national courses, and shares resources to develop new national courses on such topics as fire behavior, firefighter safety, and fire weather (Thorburn *et al*. 2000, 2003; St John and Alexander 2004). Starting in the mid-1990s, two national training courses – Advanced Wildland Fire Behavior and Wildland Fire Behavior Specialist (Alexander and Van Nest 1995) – were developed and delivered by CIFFC members. These national courses, as well as other, regional courses (e.g. de Groot 1989), have contributed to the degree of acceptance and implementation of the CFFDRS in Canada.

Other cooperative groups formed in the 1960s–1980s, which helped bring fire management and fire research staff together at regional levels. These included the Northwest Fire Council (Alaska, Yukon, British Columbia, Washington, and Oregon), the Interior West Fire Council (Northwest Territories, Alberta, Saskatchewan, Montana, Idaho, Colorado, Utah, Wyoming, Kansas, Nebraska, North Dakota, and South Dakota), the Great Lakes Forest Fire Compact (Manitoba, Ontario, Michigan, Minnesota, and Wisconsin), and the Northeast Fire Protection Compact (Quebec, New Brunswick, Nova Scotia, Maine, Massachusetts, Connecticut, Vermont, New York, and Rhode Island). Such groups sponsored annual and biennial meetings for operational staff to discuss common problems and innovations in fire management and research (e.g. Lawson *et al.* 1989; Alexander and Bisgrove 1990).

Implementation of the CFFDRS in other countries

The CFFDRS has been implemented in whole or in part in a number of countries: these experiences provide useful lessons regarding the transfer of fire danger rating knowledge from one environment to another. New Zealand and Fiji adopted the FWI System for use in exotic pine plantations in 1980 (Valentine 1978) and 1988 (Alexander 1989), respectively. New Zealand adopted the FWI System in part because of its simplicity, the similarity of climate and topographic condition to British Columbia, and the fact that decision aids for prescribed burning of logging slash tied to the FWI System existed (Muraro 1975). For many years, little work was done on local adaptation (except for modification of the daylength influence on drying at lower latitudes) or technology transfer, and so the system's full benefits were not realized (Fogarty *et al*. 1998). Subsequently, the FWI System was used for fire danger rating in a range of vegetation types, including shrublands for which it was not designed. In 1992, a research program began to develop new models for indigenous fuel types (mainly shrublands), and to improve technology and information transfer (e.g. Fogarty 1994, 1996; Alexander and Fogarty 2002). Alexander (1994) developed fire danger classification schemes for both grasslands and exotic pine forests based on FBP System models. An evaluation of the latter indicated that the initial decision to adopt the FWI System remained valid (Pearce and Alexander 1994).

From 1981 to 1991, the Ontario Ministry of Natural Resources carried out a project to develop a model forest fire management system, including a fire danger rating system, in north-eastern China (Lynham and Stocks 1990; Thomas 1990; White and Rush 1990). This included establishing a network of Canadian-made fire weather stations, producing fuel-type maps, and implementing both the FWI System and a computer system to prepare daily strategic plans. Many of the implementation issues encountered by Canadian staff in China derived from cultural differences. Decisions related to fire suppression were often made at a very senior level. Also, the use of Canadian-made electronics and fire weather instruments posed maintenance problems.

The Alaska wildland fire community adopted the CFFDRS in 1990 (Alexander and Cole 1995), mainly because of the similarity between fuel types in Alaska and northern Canada. Since then, other northern USA states, such as Minnesota and Michigan, have adopted portions of the system. Despite similar environments, adjustments for particular conditions may need to be considered. For example, in Alaska, the effect of permafrost on wetting and drying processes with respect to the DMC and DC requires investigation (Wilmore 2001; Jandt *et al*. 2005), and local interpretive guidelines tied to FWI System component values still need to be developed (Alexander and Cole 2001).

The CFFDRS has been used, in part, in the development of computerized fire management decision-support systems in Mexico, Florida (Brenner *et al*. 1998), and south-east Asia, largely because of its simplicity and its strong interpretive products (Lee *et al*. 2002). In 1999, the CFS began a 5-year project to implement a danger rating system in south-east Asia based on the CFFDRS. The CFFDRS was adapted to serve as an early warning system for haze events, because of their serious negative impacts on regional health and economy (Field *et al*. 2004). Through early warning, strategies to reduce open burning during critical periods were developed with local agencies. The CFFDRS was adapted using airport visibility data to calibrate the DC as a smoke-potential indicator, using grass ignition and hotspot data to calibrate the FFMC as an ignition indicator, and using the FBP System O-1 fuel type rate of spread model to indicate difficulty of controlling grassland fires (de Groot *et al.* 2005, 2006).

In Argentina, the National Fire Management Plan began to implement the FWI System in three pilot areas in 2000. In a review of the project, Taylor (2001) suggested that institutional mechanisms be created and strengthened to enhance communication and cooperation between national and provincial agencies before implementing the system nationally. Taylor (2001) also noted that countries implementing the CFFDRS would probably go through similar steps to develop a fire danger rating system as Canada has gone through, although perhaps over a shorter time period.

Several European countries, including Sweden (Granstrom and Schimmel 1998), Portugal, and Spain, have also adopted portions of the CFFDRS. Viegas *et al*. (1999) found that FWI System components were correlated with fire activity in southern Portugal, Spain, France, and Italy, even though the vegetation, fuel types, and dry Mediterranean climate differ from those in Canada. Not surprisingly, the FWI was found to be a good predictor of ignition in pine and spruce forests in Finland (Tanskanen *et al*. 2005), which are more similar to the Canadian boreal forest.

Discussion and conclusions

Although forest fire danger rating systems have their origins some 80 years ago they continue to be one of the most important means by which scientific knowledge of wildland fire is applied in fire management. It is important to understand what underlies their successful and unsuccessful application.

Experience with fire danger rating in Canada and elsewhere (e.g. Peet 1980) reveals important lessons. Developing a national fire danger rating system and implementing it across a number of fire management agencies is a long and complex process, with scientific, technological, human, and organizational/institutional dimensions. Four elements need to be integrated in national fire danger rating systems (Fig. 2*a*).

A modular system of fire danger indicators or models of fire occurrence and behavior in important fire environments developed through a sustained program of scientific research and based on relationships between fire weather, fuels, topography, and ignition sources

Fuels wet and dry according to the same physical processes regardless of location, and fires respond to variation in the same physical influences of fuel, weather, and topography. Although the CFFDRS was designed for boreal and temperate forest fuel and weather conditions, in other regions where conditions are different, elements of existing fire danger systems, such as the CFFDRS, can often be successfully applied. The key to adapting an existing fire danger rating system is to identify moisture models that represent the fuels that are important to fire behavior in the new environment, and to develop new relationships or modify existing ones as necessary. This process begins with identification of fuel types of most concern, and fuel elements within them that are important to ignition, spread, difficulty of control, and impact of wildfires. Seasonality of fuel conditions and diurnal variations should also be investigated and addressed (McArthur 1971).

Developing a national fire danger rating system is a lengthy process: countries adopting such systems will likely go through many of the same stages to develop fire danger rating systems as Canada has gone through. It is important for adopting countries carrying out their own research to test and adapt their systems, to develop local interpretive products, and to participate in the international fire research community. This requires a long-term commitment to fire research and training by fire management and science agencies. A dedicated professional staff must remain committed to the work over a long period. Timelines and expectations must be realistic. Canada has a long and rich history of fire danger rating research. This foundation of knowledge and experience has been an important factor in getting Canadian fire management organizations to accept and use fire danger rating. Nevertheless, there was a lag time of about 5–10 years, from time of introduction of research products to full implementation in operational regulations, guidelines, procedures, and training courses.

National fire danger rating systems must continue to evolve. Improvements occur as research and operational experience continue, as fire management organizations become more sophisticated, as problems and opportunities change, and as technology advances. The current CFFDRS, for example, represents the fifth generation of fire danger rating methods developed in Canada by the CFS (Stocks *et al*. 1989).

A reliable technical infrastructure to gather, process, disseminate, and archive fire weather data and forecasts (weather instruments/stations, standards, communication) and fire danger predictions (text and map displays) within operational agencies

Fire danger indexes, such as the FWI System components, are usually calculated from one weather observation per day to represent a large administrative area that may include many different fuel types and variable topography. This is difficult to do well. Two of the most significant general assumptions concerning any fire danger rating system are that: (1) the observations made at a particular fire weather station, and the simulated fuel moistures calculated from these observation, are representative of the area being assessed (i.e. they ignore spatial variations in fire danger); and (2) the time of day on which the index is based is valid (i.e. it ignores temporal variations in fire danger due to diurnal wetting, drying, and wind speed).

Spatial fire management systems have been developed to interpolate between weather stations and to integrate spatial variability in fuel, weather, and terrain data. These computer systems are effective tools for interpolating and portraying fire danger over large spatial scales, and they allow for powerful spatial analysis. Nevertheless, the accuracy of these systems may be limited by data inputs such as local variability in rainfall amounts and wind speed in complex terrain. High-resolution numerical weather models have promise for forecasting winds in complex terrain. Stull *et al.* (2004) ran four models in nested grids of 104, 36, 12, and 4 km for southern British Columbia and 2 km for the Vancouver area on a daily basis. However, high-resolution forecast models have not as yet been explicitly included in spatial fire management systems in Canada.

Useful information can also be obtained in the field using simple weather instruments and look-up tables. Use of electronic and computer technology requires ongoing training and maintenance, which may not be available or appropriate in all situations. It is often possible and cost effective to 'sense' weather conditions between fire weather stations or for particular locations by using remote sensing (including precipitation radar), installing additional rain gauge sites, and using inexpensive fire weather instruments for measuring temperature, relative humidity, and rain, and the Beaufort wind scale for estimating wind velocity.

Fire danger information will not be used if it is only disseminated from the top down – if fire managers in remote, rural locations perceive it to be coming from a central or regional office some distance away, it may be questioned. End users must feel ownership and have input into determining fire danger at the local level – by collecting weather data or by determining weather station location, for example. Effective means are also needed to communicate fire danger to the public and other interest groups.

Guidelines, decision aids, and training for fire managers in the application of fire danger indicators appropriate to the needs and capabilities of operational agencies based on research and operational experience

As a form of media, fire danger rating systems should be appropriate not only for the fire environment but also for the human environment – the organizational and institutional structures, culture, economic circumstances, and technological capability – that influence the capability and decision making of the implementing fire management agencies. The importance of developing suitable technology transfer plans cannot be overemphasized (Kiil *et al*. 1986; de Groot 1989; Fogarty *et al*. 1998).

Fire danger rating systems will be useful only where fire managers have authority to make pro-active decisions about resource allocation based on fire danger and values at risk. The transfer of North American fire danger systems will be most successful in organizations with organizational structures similar to those found in North American fire management agencies: a centralized command structure with well-trained professional firefighters empowered to make operational decisions (e.g. an Incident Command System), and a systematic allocation of resources depending on fire danger and values at risk. A fire danger rating system is of little use where decisions are reactive or where operational resources are allocated at a political level.

A national system should be sufficiently flexible that it can be implemented at varying degrees of intensity and complexity in different regions, depending on local importance of the fire problem and capacity of fire management agencies. Various interpretive media, from posters (e.g. Alexander 1995; Cole and Alexander 1995; Stocks and Hartley 1995) and look-up tables (Canadian Forestry Service 1984; Taylor *et al*. 1997) to computer displays (Lee *et al*. 2002), are useful in providing fire danger information depending on the background, literacy, numeracy, and culture of fire management staff. The CFFDRS supports decision making by providing real-time fire danger information that is useful at multiple operational levels. System developers often encounter contradictory responses to their attempts to satisfy user demands: models and systems aren't accurate enough, *v.* models and systems are too complicated (Rothermel 1987). Presumably, simple but reliable decision aids are needed at the field level.

In North America, fire management organizations have adapted their operations to changing technology. When new technologies are introduced, it takes time for organizational practices to change and implement the technology effectively. Implementation issues surrounding new fire danger applications range from rejecting what is not 'home grown' to too-ready acceptance of 'black box' predictions. While developing some fire management applications of fire danger rating systems or indices can be easy, in other cases applications come about as a result of long operational experience (e.g. Melton 1989, 1996).

No fire danger rating decision aid can replace an individual's local knowledge of the fire environment and influence on fire behavior, fire-suppression and prescribed-burning experience, or skill and common sense. A fire danger rating system is simply a decision aid that is available to fire managers who choose to use it. It is not a solution for all fire management problems and decisions and should not amputate good judgment. In this regard, Nelson (1955) made a very apropos statement:

> I do not want to leave the impression that I think a good system of [fire] danger measurement is the answer to all fire control and management problems. It can be a guide, and a very useful one, but it can never take the place of cool, calculating, and experienced judgement.

Nelson's observation is confirmed by recent research that reveals the importance of experience and intuition in decision making in emergency situations (Klein 1998).

Cooperation between fire management agencies and with research agencies to foster communication, to share resources, and to set common standards for information, resources, and training (policies, cost-sharing agreements, national training courses, working groups)

To fully realize a national system, formal institutional mechanisms are often needed to coordinate implementation among agencies and between regions. Cooperative mechanisms also facilitate communication between researchers and operations staff (Alexander 2003). Researchers must understand the skills, capabilities, and needs of fire managers, and managers and operations staff must have realistic expectations for research products and time frames. Formal agreements and working groups composed of federal and provincial research and operational staff play important roles in setting policy and direction, as well as in setting standards and sharing information and resources. Perhaps most importantly, common vision and a sense of common cause between fire scientists and fire managers is needed to successfully realize a national fire danger rating system.

Technological innovation in communications and computing has greatly changed the volume and speed by which fire danger information is gathered and disseminated in Canada, as elsewhere, and has allowed for the incorporation of increasingly sophisticated scientific models in fire management systems. However, as the volume and complexity of available fire danger information increases, a better understanding of the influence of cognitive and other human factors on the use of such information in decision making is needed (Weick and Sutcliffe 2001). Indeed, fire danger rating systems exist within and to serve the larger fire management environment. Thus it is important to create or support the human and institutional infrastructure needed to make a fire danger system work in a particular organizational and cultural environment, as well as the science and technology infrastructure appropriate for the fire environment (Fig. 2*a*).

Acknowledgements

Many thanks to Brad Hawkes, Bill de Groot, Brad Stennes, Brian Stocks, Peter Engelfield, and three anonymous reviewers for reviewing an earlier draft of this paper and to Monique Keiran for editorial help. Thanks also go to María del Carmen Dentoni and staff of the Plan Nacional del Manejo del Fuego of Argentina for their hospitality and for conversations about the CFFDRS, which provided impetus for this work.

References

Alexander ME (1989) Fiji adopts Canadian system of fire danger rating. *International Forest Fire News* **II**, 3.

Alexander ME (1994) 'Proposed revision of fire danger class criteria for forest and rural areas in New Zealand.' Circular 1994/2. (National Rural Fire Authority: Wellington)

Alexander ME (1995) 'New Zealand fire danger classes.' Poster with text. (National Rural Fire Authority: Wellington and New Zealand Forest Research Institute: Rotorura)

Alexander ME (2003) Technology transfer and wildland fire management/research. *Fire Management Today* **63**(2), 41–42.

Alexander ME, Andrews PL (1989) Wildland fire behavior occurrence and behavior analysis in the year 2000 and beyond. *Fire Management Notes* **50**(4), 35–37.

Alexander ME, Bisgrove GF (Tech. coords) (1990) 'The art and science of fire management.' Proceedings of the first Interior West Fire Council annual meeting and workshop. Forestry Canada, Information Report NOR-X-309. (Northern Forestry Centre: Edmonton)

Alexander ME, Cole FV (1995) Predicting and interpreting fire intensities in Alaskan black spruce forests using the Canadian system of fire danger rating. In 'Managing forests to meet peoples' needs'. Proceedings of 1994 Society of American Foresters/Canadian Institute of Forestry Convention, pp. 185–192. SAF Publication 95-02. (Society of American Foresters: Bethesda, MD)

Alexander ME, Cole FV (2001) Rating fire danger in Alaska ecosystems: CFFDRS provides an invaluable guide to systematically evaluating burning conditions. *Fireline* **12**, 2–3.

Alexander ME, Fogarty LG (2002) A pocket card for predicting fire behaviour in grasslands under severe burning conditions. Fire Technology Transfer Note No. 25. (Natural Resources Canada, Canadian Forest Service: Ottawa, ON)

Alexander ME, Quintilio D (1990) Perspectives on experimental fires in Canadian forestry research. *Mathematical and Computer Modelling* **13**(12), 17–26. doi:10.1016/0895-7177(90)90095-5

Alexander ME, Thomas DA (2004) Forecasting wildland fire behavior: aids, guides, and knowledge-based protocols. *Fire Management Today* **64**(1), 4–11.

Alexander ME, Van Nest TA (1995) National fire behavior training. In 'Canadian Interagency Forest Fire Centre/Canadian Committee on Forest Fire Management, 4th annual joint meeting'. 21–24 November 1995, Edmonton, AB, Canada.

Anderson K (2002) A model to predict lightning-caused fire occurrences. *International Journal of Wildland Fire* **11**, 163–172. doi:10.1071/WF02001

Anderson KR, Lee BS (1991) Linear programming techniques for initial attack resource deployment. In 'Proceedings of the 11th conference on fire and forest meteorology'. SAF Publication 91-04. (Eds PL Andrews, DF Potts) pp. 1–8. (Society of American Foresters: Bethesda, MD)

Andrews PL (1987) The National Fire Danger Rating System as an indicator of the fire business. In 'Conference papers: Ninth Conference on fire and forest meteorology'. pp. 57–62. (American Meteorological Society: Boston, MA)

Barrows JS (1969) Intelligence systems for forest fire control. In 'Proceedings of the sixth world forestry congress, Volume 2'. pp. 1934–1940. (Spanish Ministry of Agriculture: Madrid)

BCMF (1983) 'Fire weather indices – decision aids for forest operations in British Columbia.' Forest Protection Handbook 12. (British Columbia Ministry of Forests, Protection Branch: Victoria, BC)

BCMF (1994) 'Safety review team report – a summary of the 1994 fire season.' (British Columbia Ministry of Forests, Protection Branch: Victoria, BC)

Beall HW (1967) Research in the measurement of forest fire danger. Canada Department of Forestry and Rural Development, Forest Fire Research Institute, Ottawa, Ontario. Information Report FF-X-8. [First published 1947]

Beall HW (1990) Fire research in Canada's federal forestry service – the formative years. In 'The art and science of fire management'. Proceedings of the first Interior West Fire Council annual meeting and workshop. (Tech. coords ME Alexander, GF Bisgrove) pp. 14–19. Forestry Canada, Information Report NOR-X-309. (Northern Forestry Centre: Edmonton)

Beck J (2004) The effectiveness of Alberta's presuppression preparedness planning system. Forest Engineering Research Institute of Canada Advantage Report Volume 5, No. 14.

Beck JA, Armitage OB (2004) Diurnal fine fuel moisture and FFMC characteristics at northern latitudes. In 'Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Fire in temperate, boreal, and montane ecosystems'. (Eds RT Engstrom, KEM Galley, WJ de Groot) pp. 211–221. (Tall Timbers Research Station: Tallahassee, FL)

Beck JA, Alexander ME, Harvey SD, Beaver AK (2002) Forecasting diurnal variations in fire intensity to enhance wildland firefighter safety. *International Journal of Wildland Fire* **11**, 173–182. doi:10.1071/WF02002

Brenner JD, Herbster C, Lee BS, Brackett DP, Arvanitis LG (1998) GIS-based fire management in Florida. In 'Proceedings of the first international conference on geospatial information in agriculture and forestry, Volume I'. pp. 140–147. (ERIM International: Ann Arbor, MI)

Brown AA, Davis KP (1973) 'Forest fire: control and use.' 2nd edn. (McGraw-Hill: New York)

Byram GM (1959) Combustion of forest fuels. In 'Forest fire: control and use'. (Ed. KP Davis) pp. 61–89. (McGraw-Hill: New York)

Canadian Forestry Service (1984) 'Tables for the Canadian Forest Fire Weather Index System.' 4th edn. Environment Canada, Forestry Technical Report 25. (Canadian Forestry Service: Ottawa, ON)

Cheney P, Sullivan A (1997) 'Grassfires: fuel, weather and fire behaviour.' (CSIRO Publishing: Collingwood)

Cole FV, Alexander ME (1995) 'Head fire intensity class graph for FBP System Fuel Type C-2 (Boreal Spruce).' Poster with text. (Alaska Department of Natural Resources, Division of Forestry: Fairbanks, AK and Natural Resources Canada, Canadian Forest Service: Edmonton, AB)

Countryman CM (1966) Rating fire danger by the multiple basic index system. *Journal of Forestry* **64**, 531–536.

Cruz MG, Alexander ME, Wakimoto RH (2003) Assessing the probability of crown fire initiation based on fire danger indices. *Forestry Chronicle* **79**, 976–983.

Dawson MP (1991) Fire bans and public perception of danger. In 'Conference on bushfire modeling and fire danger rating systems: Proceedings'. pp. 32–42. (CSIRO: Canberra)

Deeming JE, Burgan RE, Cohen JD (1977) 'The National Fire-Danger Rating System – 1978.' USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-39. (Ogden, UT)

de Groot WJ (1989) Technology transfer in Saskatchewan: operational use of the Canadian Forest Fire Danger Rating System. In 'Proceedings of the 10th conference on fire and forest meteorology'. (Eds DC MacIver, H Auld, R Whitewood) pp. 327–332. (Forestry Canada and Environment Canada: Ottawa, ON)

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

de Groot WJ, Field RD, Brady MA, Roswintiarti O, Mohamad M (2006) Development of the Indonesian and Malaysian Fire Danger Rating Systems. *Mitigation and Adaptation Strategies for Global Change*, in press.

De Keyser V, Woods DD (1990) Fixation errors: failures to revise situation assessment in dynamic and risky systems. In 'System reliability assessment'. (Eds AG Colombo, A Saiz de Bustamante) pp. 231–251. (Kluwer Academic: Amsterdam)

Field RD, Wang Y, Roswintiarti O, Guswanto (2004) A drought-based predictor of recent haze events in western Indonesia. *Atmospheric Environment* **38**, 1869–1878. doi:10.1016/J.ATMOSENV.2004.01.011

Fogarty LG (1994) Fire problem, what fire problem? A review of 'Fire danger ratings associated with New Zealand's major pine plantation wildfires' by HG Pearce and ME Alexander. Fire Technology Transfer Note No. 3. (New Zealand Forest Research Institute: Rotorura and National Rural Fire Authority: Wellington)

Fogarty LG (1996) A summary and status of the 'Proposed revision of fire danger class criteria for forest and rural areas in New Zealand' by Martin E. Alexander. Fire Technology Transfer Note No. 7. (New Zealand Forest Research Institute: Rotorua and National Rural Fire Authority: Wellington)

Fogarty LG, Pearce HG, Catchpole WR, Alexander ME (1998) Adoption vs. adaptation: lessons from applying the Canadian Forest Fire Danger Rating System in New Zealand. In 'Proceedings III international conference on forest fire research/14th conference on fire and forest meteorology, Volume I'. (Ed. DX Viegas) pp. 1011–1028. (University of Coimbra: Coimbra)

Forestry Canada Fire Danger Group (1992) Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Information Report ST-X-3. (Science and Sustainable Development Directorate: Ottawa, ON)

Granstrom A, Schimmel J (1998) 'Utvardering av det kanadensiska brandrisksystemet—testbranningar och uttorkningsanalyser. [Assessment of the Canadian forest fire danger rating system: test fires and drying rate analyses.]' Publication P21–244/98. (Swedish Rescue Services Agency: Karlstad)

Harrington JB, Flannigan MD, Van Wagner CE (1983) A study of the relation of components of the Fire Weather Index to monthly provincial area burned by wildfire in Canada, 1953–80. Environment Canada, Canadian Forestry Service, Information Report PI-X-25. (Petawawa National Forestry Institute: Chalk River, ON)

Harvey DA, Alexander ME, Janz B (1986) A comparison of fire weather severity in northern Alberta during the 1980 and 1981 fire seasons. *Forestry Chronicle* **62**, 507–513.

Innis HA (1972) 'Empire and communications.' (University of Toronto Press: Toronto)

Jandt R, Allen J, Horschel E (2005) Forest floor moisture content and fire danger indices in Alaska. BLM-Alaska Technical Report 54. (USDI Bureau of Land Management: Anchorage, AK)

Kiil AD, Quintilio D, Alexander ME (1986) Adaptation of a national system of fire danger rating in Alberta, Canada: a case study in technology transfer. In 'Proceedings 18th IUFRO world congress, division 6: General subjects'. pp. 410–421. (International Union of Forest Research Organizations: Vienna)

Klein G (1998) 'Sources of power: how people make decisions.' (MIT Press: Cambridge, MA)

Kourtz P, Todd B (1992) Predicting the daily occurrence of lightning-caused forest fires. Forestry Canada, Information Report PI-X-112. (Petawawa National Forestry Institute: Chalk River, ON)

Lawson BD, Dalrymple GN (1996*a*) Probabilities of sustained ignition in lodgepole pine, interior Douglas-fir, and white spruce-subalpine fir forest types. Canadian Forest Service, FRDA Handbook 12 Supplement 1. (Pacific Forestry Centre and British Columbia Ministry of Forests, Research Branch: Victoria, BC)

Lawson BD, Dalrymple GN (1996*b*) Ground-truthing the Drought Code: field verification of overwinter recharge of forest floor moisture. Natural Resources Canada, Canadian Forest Service, FRDA Report 268. (Pacific Forestry Centre and British Columbia Ministry of Forests, Research Branch: Victoria, BC)

Lawson BD, Stocks BJ, Alexander ME, Van Wagner CE (1985) A system for predicting fire behavior in Canadian forests. In 'Proceedings of the 8th conference on fire and forest meteorology'. SAF Publication 85-04. (Eds LR Donoghue, RE Martin) pp. 6–16. (Society of American Foresters: Bethesda, MD)

Lawson BD, Hawkes BC, Dalrymple GD (1989) 'Fire management in a climate of change: Proceedings of the 1988 Northwest Fire Council annual meeting.' (Northwest Fire Council)

Lawson BD, Armitage OB, Hoskins WD (1996) Diurnal variation in the Fine Fuel Moisture Code: tables and computer source code. Natural Resources Canada, Canadian Forest Service, FRDA Report 245. (Pacific Forestry Centre and British Columbia Ministry of Forests, Research Branch: Victoria, BC)

Lawson BD, Frandsen WH, Hawkes BC, Dalrymple GN (1997*a*) Probability of sustained smouldering ignition for some boreal forest duff types. Canadian Forest Service, Forest Management Note 63. (Northern Forestry Centre: Edmonton, AB)

Lawson BD, Dalrymple GN, Hawkes BC (1997*b*) Predicting forest floor moisture contents from Duff Moisture Code values. Natural Resources Canada, Canadian Forest Service, Technology Transfer Notes No. 6. (Pacific Forestry Centre: Victoria, BC)

Lee BS (1995) The Canadian Wildland Fire Information System. In 'Proceedings of 9th annual conference on geographic information systems in forestry, environment and natural resources management'. pp. 639–646. (GIS World Inc.: Fort Collins, CO)

Lee BS, Alexander ME, Hawkes BC, Lynham TJ, Stocks BJ, Englefield P (2002) Information systems in support of wildland fire management decision making in Canada. *Computers and Electronics in Agriculture* **37**, 185–198. doi:10.1016/S0168-1699(02)00120-5

Lin C-C (2000) The development, systems, and evaluation of forest fire danger rating: a review. *Taiwan Journal of Forest Science* **15**, 507–520.

Luke RH, McArthur AG (1978) 'Bushfires in Australia.' (Australian Government Publishing Service: Canberra)

Lynham TJ, Stocks BJ (1990) Suitability of the Canadian Forest Fire Danger Rating System for use in the Daxinganiing Forestry Management Bureau, Heilongliang Province, China. In 'Proceedings of the 10th conference on fire and forest meteorology'. (Eds DC MacIver, H Auld, R Whitewood) pp. 232–246. (Forestry Canada and Environment Canada: Ottawa, ON)

Martell DL, Bevilacqua E, Stocks BJ (1989) Modelling seasonal variation in daily people-caused forest fire occurrence. *Canadian Journal of Forest Research* **19**, 1555–1563.

McAlpine RS, Stocks BJ, Van Wagner CE, Lawson BD, Alexander ME, Lynham TJ (1990) Forest fire behavior research in Canada. In 'Proceedings of international conference on forest fire research'. pp. A.02: 1–12. (University of Coimbra: Coimbra)

McArthur AG (1971) 'Aspects of fire control in the *P. caribaea* & *P. elliottii* plantations of northwestern Viti Levu, Fiji Islands.' (Commonwealth of Australia, Forestry and Timber Bureau, Forest Research Institute: Canberra)

McCaw WL, Alexander ME (1994) Tripartite agreement on wildland fire science research signed. *International Forest Fire News* **11**, 27–29.

McLuhan M (1994) 'Understanding media: the extensions of man.' (MIT Press: Cambridge, MA) [First published 1964]

McLuhan M, McLuhan E (1988) 'Laws of media: the new science.' (University of Toronto Press: Toronto)

Melton M (1989) The Keetch/Byram Drought Index: a guide to fire conditions and suppression problems. *Fire Management Notes* **50**(4), 30–34.

Melton M (1996) The Keetch-Byram Drought Index revisited: prescribed fire applications. *Fire Management Notes* **56**(4), 7–11.

Merrill DF, Alexander ME (Eds) (1987) 'Glossary of forest fire management terms.' 4th edn. National Research Council of Canada, Publication NRCC No. 26516. (Canadian Committee on Forest Fire Management: Ottawa, ON)

Miller GA (1956) The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review* **63**, 81–97.

Moore W, Newstead R (1992) Evaluation of research and development accomplishments: Northern Forestry Centre. *The Canadian Journal of Program Evaluation* **7**, 41–51.

Muraro SJ (1968) A modular approach to a revised national fire danger rating system. In 'Contributions to the development of a national fire danger rating system'. Canada Department of Fisheries and Forestry, Forestry Branch, Information Report BC-X-37. (Forest Research Laboratory: Victoria, BC)

Muraro SJ (1975) 'Prescribed fire predictor/planner.' Environment Canada, Canadian Forestry Service, slide-rule with text. (Pacific Forest Research Centre: Victoria, BC)

Nelson RM (1955) The principles and uses of fire danger measurement. In 'Modern forest fire management in the South. Proceedings of the fourth annual forestry symposium'. pp. 37–45. (Louisiana State University: Baton Rouge)

Otway SG (2005) Aspen forest duff moisture depletion and ground fire potential. MSc Thesis, University of Alberta.

Pearce HG, Alexander ME (1994) Fire danger ratings associated with New Zealand's major pine plantation wildfires. In 'Proceedings of the 12th conference on fire and forest meteorology'. SAF Publication 94-02. pp. 534–543. (Society of American Foresters: Bethesda, MD)

Pech G (1989) A model to predict the moisture content of reindeer lichen. *Forest Science* **35**, 1014–1028.

Peet GB (1980) Forest fire management planning, Kenya: fire danger rating for forest areas. Food and Agriculture Organization of the United Nations, FAO Document FO:DP.KEN/74/024 Technical Report 1. (FAO: Rome)

Rothermel RC (1987) Fire behavior research: where do we go from here? In 'Conference papers: Ninth conference on fire and forest meteorology'. pp. 19–22. (American Meteorological Society: Boston, MA)

San-Miguel-Ayanz J, Carlson JD, Alexander M, Tolhurst K, Morgan G, Sneeuwjagt R, Dudfield M (2003). Current methods to assess fire danger potential. In 'Wildland fire danger estimation and mapping – the role of remote sensing data'. Series in Remote Sensing Volume 4. (Ed. E Chuvieco) pp. 21–61. (World Scientific Publishing: Singapore)

St John P, Alexander ME (2004) Canadian Forest Fire Weather Index System: training now available on CD-ROM. *Fire Management Today* **64**(2), 54–55.

Stocks BJ, Hartley GR (1995) 'Fire behavior in three jack pine fuel complexes.' Natural Resources Canada, Canadian Forest Service, Poster with text. (Great Lakes Forestry Centre: Sault Ste Marie, ON)

Stocks BJ, Lawson BD, Alexander ME, Van Wagner CE, McAlpine RS, Lynham TJ, Dube DE (1989) The Canadian Forest Fire Danger Rating System: an overview. *Forestry Chronicle* **65**, 450–457.

Stocks BJ, Alexander ME, Lanoville RA (2004) An overview of the International Crown Fire Modelling Experiment (ICFME). *Canadian Journal of Forest Research* **34**, 1543–1547. doi:10.1139/X04-905

Stull R, Modzelewski H, Deng X, Zhou Y, Huang L, Cannon T, Hicks G, II, Storey D, Holmes M, Charbonneau J (2004) Multimodel fine-resolution ensembles for short-range forecasts in mountainous terrain. In 'Proceedings of the 16th conference on numerical weather prediction'. (American Meteorological Society: Boston, MA)

Tanskanen H, Venäläinen A, Puttonen P, Granström A (2005) Impact of stand structure on surface fire ignition potential in *Picea abies* and *Pinus sylvestris* forests in southern Finland. *Canadian Journal of Forest Research* **35**, 410–420. doi:10.1139/X04-188

Taylor SW (2001) Considerations for applying the Canadian Forest Fire Danger Rating System in Argentina. Natural Resources Canada, Canadian Forest Service, Contract report. (Pacific Forestry Centre: Victoria, BC)

Taylor SW, Pike RG, Alexander ME (1997) Field guide to the Canadian Forest Fire Behavior Prediction (FBP) System. Natural Resources Canada, Canadian Forest Service, Special Report 11. (Northern Forestry Centre: Edmonton, AB)

Thomas B (1990) The Jiagedqui Project: Forest fire control in China. *Forestry Chronicle* **66**, 266–270.

Thorburn RW, MacMillan A, Alexander ME (2000) The application of interactive multimedia CD-ROM technology to wildland fire safety training. *Forestry Chronicle* **76**, 953–959.

Thorburn RW, MacMillan A, Alexander ME, Nimchuk N, Frederick KW, Van Nest TA (2003) 'Principles of Fire Behavior': a CD-ROM based interactive multimedia wildland fire training course. *Fire Management Today* **63**(2), 43–44.

Todd B, Kourtz PH (1991) Predicting the daily occurrence of people-caused forest fires. Canadian Forestry Service, Information Report PI-X-103. (Petawawa National Forestry Institute: Chalk River, ON)

Turner JA (1973) A fire load index for British Columbia. Environment Canada, Canadian Forestry Service, Information Report BC-X-80. (Pacific Forest Research Centre: Victoria, BC)

Turner JA, Lawson BD (1978) Weather in the Canadian Forest Fire Danger Rating System: a user guide to national standards and practices. Fisheries and Environment Canada, Canadian Forestry Service, Information Report BC-X-177. (Pacific Forest Research Centre: Victoria, BC)

Tymstra C (2002) PROMETHEUS: the Canadian wildland fire growth model. *Initial Attack* **2002**(Spring), 8–9.

Tzu S (1963) 'The art of war.' (Transl. SB Griffith) (Oxford University Press: London)

Valentine JM (1978) Fire danger rating in New Zealand: review and evaluation. New Zealand Forest Service, Forest Establishment Report No. 123. (Forest Research Institute: Rotorua)

Van Wagner CE (1970) New developments in forest fire danger rating. Environment Canada, Information Report PS-X-19. (Canadian Forestry Service, Petawawa Forest Experiment Station: Chalk River, ON)

Van Wagner CE (1971) Two solitudes in forest fire research. Environment Canada, Canadian Forest Service, Information Report PS-X-29. (Petawawa Forest Experiment Station: Chalk River, ON)

Van Wagner CE (1987*a*) Development and structure of the Canadian Forest Fire Weather Index System. Environment Canada, Forestry Technical Report 35. (Canadian Forestry Service: Ottawa, ON)

Van Wagner CE (1987*b*) A moisture content model for medium-sized logging slash. In 'Proceedings of the 9th conference on fire and forest meteorology'. pp. 34–40. (American Meteorological Society: Boston, MA)

Van Wilgen BW, Burgan RE (1984) Adaptation of the United States Fire Danger Rating System to fynbos conditions. Part II. Historic fire danger in the fynbos biome. *South African Forestry Journal* **129**, 66–78.

Vega-Garcia C, Woodard PM, Titus SJ, Adamowicz WL, Lee BS (1995) A logit model for predicting the daily occurrence of human caused forest fires. *International Journal of Wildland Fire* **5**, 101–111. doi:10.1071/WF9950101

Viegas DX, Biovio G, Ferreira A, Nosenzo A, Sol B (1999) Comparative study of various methods of fire danger evaluation in southern Europe. *International Journal of Wildland Fire* **9**, 235–246.

Weick KE, Sutcliffe KM (2001) 'Managing the unexpected: assuring high performance in an age of complexity.' (Jossey-Bass, A Wiley Company: San Francisco)

White RA, Rush MF (1990) The Jiagedaqui fire management project (JIAPRO): an example of international assistance. In 'The art and science of fire management'. Proceedings of the first Interior West Fire Council annual meeting and workshop. (Tech. coords ME Alexander, GF Bisgrove) pp. 287–296. Forestry Canada, Information Report NOR-X-309. (Northern Forestry Centre: Edmonton, AB)

Wilmore B (2001) Duff moisture dynamics in black spruce–feathermoss stands and their relation to the Canadian Forest Fire Danger Rating System. MSc Thesis, University of Alaska.

Williams DE (1964) 'Forest fire danger manual.' Publication No. 1027. (Canada Department of Forestry: Ottawa, ON)

Wilson K (2000) Health care, federalism and the new Social Union. *Canadian Medical Association Journal* **162**, 1171–1174.

Wotton BM, Martell DL (2005) A lightning fire occurrence model for Ontario. *Canadian Journal of Forest Research* **35**, 1389–1401. doi:10.1139/X05-071

Wotton BM, Martell DL, Logan KA (2003) Climate change and people-caused forest fire occurrence in Ontario. *Climatic Change* **60**, 275–295. doi:10.1023/A:1026075919710

Wotton BM, Stocks BJ, Martell DL (2005) An index for tracking sheltered forest floor moisture within the Canadian Forest Fire Weather Index System. *International Journal of Wildland Fire* **14**, 169–182.

Wright JG (1933) 'Forest fire hazard tables for mixed red and white pine forests, eastern Ontario and western Quebec regions.' (Canada Department of the Interior, Dominion Forest Service: Ottawa, ON)