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Advanced Information Systems in Canadian Forest Fire Control

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Abstract

Annually, in Canada, forest fires burn an area equal to that harvested. The easiest and most economical way to significantly increase our harvestable timber volume is to sharply reduce or eliminate fire losses in our industrial forest zones. Modern technology, when combined with an appropriate fire control organization structure, makes such a goal feasible for little or no increase in current expenditures.

Across Canada, provincial fire control agencies are in various states of evolution. Some have changed little since the 1950s, relying on widely-distributed, multiple-use, forestry personnel operating in a low technology environment to carry out the fire control program. In sharp contrast, however, several agencies have evolved to a highly specialized, city-fire-department-like organization structure, dependent upon integrated computerized information systems, aggressive aerial detection, and forceful, aircraft-based initial attack systems. More than a decade of experience with these organizations has shown that very substantial reductions in operating costs and losses are possible.

Over the past several decades, a foundation decision support system has been developed and implemented to serve the basic information needs of most provincial fire control agencies. Additional components, including operations research based models and expert systems, have been added to this foundation in several of the more centralized operations. The expert systems that have been developed and partially tested to date include initial attack dispatch, forest fire occurrence prediction, daily fire control resource positioning, daily aerial fire detection planning, and fire attack priority assignment. None are considered operational to date. These systems integrate object programming concepts, relational databases, rule-based structures, neural networks, traditional operations research algorithms, and modern graphic user interfaces.

The concepts underlying the Canadian approach to fire control could play a major role in reducing the terrible losses caused by Australian bush fires. However, modern fire control alone will not solve the Australian bush fire problem. A massive fuel modification program is also required at the same time to continually manage the accumulating fuel. These two components, when combined with the existing prevention program, have the potential to significantly reduce present fire losses.

Advanced Information Systems in Canadian Forest Fire Control

Forestry in Canada

Canada has 244 million ha of productive forests that produce annually $23 billion in forest product exports. Forestry is the basis for some 800000 jobs and is the country's largest source of exports, amounting to more than agriculture, mining, and fishing combined.

Ninety percent of Canada's forests are owned by the public, represented by mainly the 10 provincial governments. Forest fire control is the responsibility of each province and, unlike in Australia, huge areas fall under the jurisdiction of just one provincial fire management agency. There are 10 autonomous agencies across Canada, each with their own organization structure and slightly different approach to the problem of forest fire control.

The Canadian Fire Problem

The Boreal Forest is Canada's major forest type and it spans the entire width of Canada. It is characterized by its conifer forest types, namely black spruce and white spruce (*Picea glauca, Picea mariana*), jack pine and lodgepole pine (*Pinus banksiana, Pinus contorta*), aspen (*Poplus tremuloides*), and white birch (*Betula papyrifera*). The history of the boreal forest shows that, on average, severe fire has burned every point about every 75 to 100 years. Today, in intensively protected areas, this is more like once every 500 to 1000 years. Unlike in Australia, there is no significant ground fuel buildup; therefore, fuel modification programs are rarely used as a part of the Canadian fire management strategy. Only in a relatively small portion of the intermountain region of British Columbia are there fuel types and weather conditions that resemble those found in Australia.

There is large variance in the occurrence of severe fire-years across Canada. In the dry near desert-like conditions of interior British Columbia bad fire seasons occur on a 5- to 10-year cycle. Around the prairie areas, the frequency is about every 10 to 15 years. More typically, in much of the boreal forest, bad fire years occur every 20 to 30 years. In contrast, some areas of Australia have severe fire years every 3 to 5 years.

Annually, in Canada, 9500 forest fires burn a million ha, an area equal to that harvested. Seventy percent of these fires are started as a result of people's activities while the remaining 30% are started by lightning. Among those causes associated with people, there are relatively few arson fires and only a small percentage are caused by agriculture-related burning. Most fires are related to carelessness, recreation, and use of machinery in the forest. As in Australia, about 5% of the fires cause 95% of the suppression costs and losses. Many of our severe fires are caused by lightning; as many as 500 lightning fires can occur in a single day in a local area resulting in overtaxing the capabilities of suppression forces. Annually Canada spends about $250 million in direct and indirect suppression costs. This year, for example, British Columbia's bill for fire suppression will approach $100 million. Annual damages associated with the fires amount to an estimated $250 million. Unlike in Australia, these damages are mainly associated with lost timber, tourism, and recreation; only a small portion can be attributed to loss of life, livestock, or property.

Cultural Attitudes Toward Forest Fires

In Canada during the 1800s pioneer settlers involved with developing northern communities considered the forests more of a nuisance rather than an asset. Fire was one of the main tools for land clearing. By the early 1900s, there were many small northern mining and forestry communities established in heavy forested regions vulnerable to fire. Between 1900 and 1920, eastern Canada experienced a disastrous sequence of large forest fires, many originating from land clearing operations, that killed hundreds of people and destroyed many northern communities. These triggered an attitude change towards forest fire. Fire was no longer merely an inconvenience to be tolerated; fire became an enemy of society and was actively sought out, no matter how remote, and suppressed when and where possible.

A provincial fire control service was developed in each province and a policy of total fire exclusion was adopted. One might characterize this as an "offensive" strategy. The goal, even in the 1920s was to detect fires as soon as possible and extinguish them before they could develop into large fires. These provincial fire control services are controlled and operated by the provincial governments and are 100% funded through regular provincial taxation (Quebec Province is the one partial exception). There is no private land involved, nor is there any involvement by the insurance industry.

In addition to fire control, a successful prevention program aimed at school children was aggressively pursued from the early 1950s. Today every Canadian can tell you about Smokey the Bear and his forest fire prevention message. From the fire management perspective, however, the program has been too successful. There is an unrealistic fear of fire that is reflected by the politicians' negative attitudes towards the use of fire as a silvicultural and ecological management tool.

In contrast, Australian society appears to tolerate bush fires as long as they don't threaten lives, property, and local economies such as tourism. Related to this, a "defensive" approach to fire protection has evolved centered around community protection. Several hundred thousand local volunteers are involved in fighting fires that threaten or have the potential to threaten lives, livestock, and property. There seem to be little effort directed toward prediction, detection, and timely and forceful initial attack: this is a major difference between the Canadian and Australian approach to the fire problem.

The Canadian Approach to Forest Fire Control

With only a few exceptions, Canadian fire policy is focused on excluding wildfire and it attempts to achieve this by quickly suppressing all fires while they are small. Ground firefighting crews form the backbone of the fire control effort. They are highly motivated, well trained, and very professional. Detection efforts are well organized and rely mainly on aircraft and human vision. Lookouts, although once used across the country, are now only used in some provinces.

In the past 40 years, there has been considerable emphasis on the use of aircraft for detection, transport, and water and retardant bombing. During severe fire weather it is recognized that ground access even in well roaded areas is too slow. In many cases only air attack with foam or retardant bombers can deliver the fire stopping force required before the fires become too large. On every fire, ground crews, usually transported by helicopters, are required to suppress the fire. Aircraft merely buy precious time by containing the fire until the ground crews arrive. In British Columbia, with fuel conditions not too unlike those found in Australia, and under severe fire weather conditions, air attack goals state that the first attack must be within 15 minutes of detection. This time response is achieved only by having aircraft in the air loitering in high risk areas waiting for fire reports.

In Canada, there are no volunteers involved in forest fire control. One exception is in the rural interface areas where some local volunteer fire departments have made special contract arrangements with the provincial forest fire authorities. It is recognized that these volunteer groups neither have the specialized equipment nor training to handle most forest fires. The provincial fire authorities will not rely on the volunteer groups in times of severe fire weather.

In typical mature boreal forest jack pine (*pinus banksiana*) stand fuel loadings range from 100 t/ha to 150 t/ha, whereas in Australia typical fuel loadings in heavy grass is about 7 t/ha and in forested areas heavy fuel loadings are in the 25 to 50 t/ha range. Under severe fuel moisture and wind conditions, fires in these heavier fuel types quickly crown and are near impossible to stop unless attacked before they enter their rapid spread phase. Once they enter the blowup stage, attempts at control are futile; this is a similar situation to that of Australia's blowup fires. At best, structures can be protected only through massive efforts and burning out. These large fires quit either because they run out of fuel or the weather modifies the fuel moisture.

There are no major fuel modification programs in Canada. The values associated with the forests are more or less evenly distributed over the entire forest complex. Ground fuel buildup is not a significant problem; for immature conifer stands fuel loadings are more or less uniform from the ground to the canopy. Fuel modification makes little sense under these conditions. Likewise, fire breaks are too expensive to build and maintain considering their value in stopping relatively infrequent fires. Also, spot fires can be started many kilometers downwind. There is a moderate prescribed burn program where several hundred thousand hectares are burned annually mainly for silviculture and ecological reasons.

In contrast, Australian bush itself has little commercial value. Society's values are concentrated at the rural/urban interfaces. Maintaining the vegetation in a low hazard state in broad zones around these values through an active fuel modification program is an excellent and very necessary complement to traditional fire control. Fire control alone is a poor solution. Successful fire control just further aggravates the problem of fuel buildup. In Canada, commercial harvesting of the mature timber is an alternative to nature's way of removing the fuel buildup. Aggressive fire control makes good sense if one's goal is to harvest timber.

Canadian fire control is focused on early detection and rapid and forceful initial attack when appropriate. We have reached a level of knowledge and technological ability to sharply reduce or even eliminate significant fire losses in our industrial forest zones. Modern information and fire control technology, when combined with an appropriate fire control organization structure, makes such a goal feasible for little or no increase in current expenditures.

Fire Economics

In Canada, there has been relatively few economic studies related to forest fire control. Through the 1960s there was work carried out on fire damage; many focused on timber losses. In the past decade, C.E.Van Wagner and Prof. D. L .Martell (U. of Toronto) have done excellent work on the impact of forest fires on long term timber supply. There have also been studies related to specific components of fire control. In the late 1960s, for example, the problem of lookouts versus aircraft was addressed. Canada has also had its equivalent of Project Aquarius. Prof. Martell has addressed the question of appropriate annual and daily manning policies for a provincial agency (Martell 1984).

Why have not there been more economic studies related to fire control? The answer is at least partly related to the difficulty in assessing the effects and real damage caused by fires. Intangibles represent a significant portion of the losses. What is the value of a smoke-free view of the Canadian Rocky Mountains? Perhaps the beautiful sunsets caused by smoke from distant fires make up for this loss. What's the real cost of evacuating northern communities threatened by fire; some people look forward to the "the annual shopping trip". Do the positive benefits from fire control outweigh the negative effects on the forest ecosystem? To assess the worth of a specific policy or action, we must be able to define the resulting fire effects had we not intervened. So far, our models cannot do this with any degree of credibility.

I am not aware of any major Canadian forest fire-related decision that was influenced by an economic study. I can point to a few, in fact, where the exact opposite decision was taken as that recommended. Fire control decisions affect the whole society. In Canada, most important fire-related decisions are made by the political process. The fire agencies define and evaluate scenarios but the political process makes the important decisions. What is most cost-effective for fire control may not necessarily be the best for society. Employment issues are an example. Centralization of fire control is often resisted by politicians in spite of the demonstrated savings in costs and reduced losses because it means the loss of jobs for relatively unskilled workers. The counter argument in this case is that we should be as efficient as possible in fire suppression and the savings can be redirected to more productive parts of the economy. For example, manual labor is desperately required in Canadian silviculture. In Australia, people displaced by more efficient fire control might be more effectively used on labor-intensive fuel management programs.

Because economics and politics are so closely intertwined, the fire research group at the Petawawa National Forestry Institute (PNFI) has concentrated on short term information and decision support systems. These systems are designed to help fire agencies be more effective given their current resources and funding. Some of these systems are described later.

A question posed frequently by Canadian fire control mangers is how best to spend the available money and to utilize the existing resources (people, equipment, aircraft, and facilities). Management is a balancing act. There is one economic model (theory of the firm) that is helpful in keeping the various components of fire management in proper balance. One can identify the major components of the fire management business: the information system, detection, initial attack, large-fire suppression, prevention, fuel management, etc. The theory of the firm views these components as factors needed to produce a product. In fire management's case the product or goal is related to minimizing the negative aspects of fire on society. Furthermore, the theory tells us we should continue to invest or redistribute effort in each component until the marginal contribution of each component toward the common goal is equalized. The returns obtained from the last dollar spent on each component must be equal. For example, the last dollar spent on detection should be equally rewarding as the last dollar spent on initial attack or prevention or any other component in the system.

Note that no component can be studied in isolation from the total fire control system. For instance, we cannot study the use of airtankers independent of detection. The fire control agency might be far more productive if money were shifted from initial attack to detection, for instance. If next to nothing is being spent on detection, even a small increase in effort in detection could make a huge improvement in total productivity. Such is likely the case for many agencies in Canada. Some have huge investments in initial attack capability but rely upon the public to report the fires. The public, of course, will sooner or later report all significant fires but they may be hopelessly out of control by the time they are reported. In Australia's situation related to airtankers, these cannot be studied in isolation from detection and ground force components.

The difficulty with the theory is measuring the contribution of the components to the final goal. We can use a "proximate" criterion related to our ultimate goal, say, to allocate effort to detection and initial attack in a way that minimizes the number of fires that escape the initial attack forces. Probably the best way to define the marginal productivities of components in terms of the proximate criterion is to use a small group of unbiased experts. With luck these people may be able to define the necessary iso-effectiveness curves given a set of fixed budgets.

Canadian Fire Management Agency Organization Types

Across Canada, provincial fire control agencies are in various states of evolution. Some have changed little since the 1950s, relying on widely-distributed, multiple-use, forestry personnel operating in a low technology environment to carry out the fire control program. In sharp contrast, however, several agencies have evolved to a highly specialized, city-fire-department-like organization structure dependent upon computerized information systems. More than a decade of experience with such an organization, supported by advanced information systems, has shown that very substantial reductions in operating costs and losses are possible.

Integrated vs. Non-integrated Fire Control

Quebec and Ontario both operate non-integrated, separate, fire management agencies. Like a city fire department, each employee's work-day is dedicated to fire management activities. This structure is much more suited to anticipating daily fire problems, to positioning resources before the fires occur, and to carrying out an aggressive aerial detection and aircraft-based initial attack programs. Such structures can capitalize on the benefits of modern information technology, are less reliant on large labor pools, and have a higher level of training and professionalism. The obvious criticisms of this form of organization include higher costs, lots of idle time, and the difficulty integrating fire management into timber, recreation, and wildland management.

In all the other provinces, fire control operations are integrated with provincial forest management operations. When the firebell rings, the timber, wildlife, recreation, and inventory people are temporarily drafted into the fire service. These integrated operations were developed in a time when fire control was mainly labour intensive and often involved in fighting large fires. The main advantages of this structure are the large pool of people available in times of crisis and the productive use of idle fire fighters between fires. The weakness is the high and recurrent training costs and, most important, the lack of interest and preparedness for severe fire situations with the result that often the agencies must deal with fires hopelessly out of control.

Government vs. Private

Only in the Province of Quebec is fire control run by a private company. There, all individuals, private companies, and government agencies that use the forest or that have logging or recreation rights must, by law, belong to the private, non-profit cooperative. The cooperative has the authority to tax the members (shareholders) for operation costs in proportion to the interest that each member has in the forest. Regional advisory boards are set up to represent the social and economic interests of the local communities. The cooperative manages all presuppression and suppression facilities and equipment, including Quebec's waterbomber fleet of 15 CL215s, a fleet of 30 detection aircraft, a dozen helicopters, and some 400 permanent and seasonal employees. It operates a large provincial command center, four regional bases, and about 15 to 20 temporary bases that are manned as needed. The provincial government assists the company by paying a portion of the actual fire fighting costs for fires above a certain size. The size-related subsidy is cleverly worked out so that it is in the company's interest to keep the fires small.

The advantages of a privately operated fire management organization centre around its responsiveness to change, economic factors, and its effectiveness. Government organizations resist change, whereas a private company appears to be able to easily adapt to new economic and social realities. Twenty years of experience with the Quebec private company indicates that, given proper incentives, it can be much more effective at reducing fire losses and at the same time less costly. A private company will invest in capital rather than labour. In Canada, fire fighters are highly unionized and demand high wages and reasonable working conditions. It is less expensive to utilize modern information technology, aircraft, helicopters, and modern detection technology in place of a traditional labour intensive operation.

The trend in Canada is to downsize government operations and to privatize what it can. Fire control on provincial and privately owned forests can be transferred easily and effectively to the private sector, as experience in Quebec has demonstrated.

Decentralized vs. Centralized

Up to the 1960s all provinces operated highly decentralized fire suppression organizations. The provincial forest was divided into regions, districts, and divisions. Typically there were five to 10 regions, each with about five districts and each district with five or so divisions. Each division typically had a small fire fighting crew, vehicles for transport, and the necessary hand tools and water pumps. Air detection and attack operations usually were controlled at the district and regional levels. The historical record clearly indicates that the decentralized approach to fire control was flawed. Many large fires occurred and continued to occur in areas protected by agencies with this philosophy. Proponents of this approach argue that large fires will occur regardless of the effort expended to control them and that such losses are inevitable. Meanwhile these same people continue to spend millions of taxpayers' dollars on fires hopelessly out of control.

Through the mid-1970s Quebec and Ontario led the way in developing more centralized organizations. The number of regions was reduced to five, many districts were consolidated, and the divisions eliminated. Success with this resulted in even further consolidations. Today, Quebec operates with one provincial command centre, four regions, and no districts. Ontario presently has a provincial fire center, two regional centres, and about 40 "attack bases". Presently, both agencies delegate initial attack authority to the regions or attack bases on a daily basis. In the near future it is conceivable that even initial attack decisions could be made at the provincial level. We have the information technology to enable this but the political will to do it is presently lacking. All remaining provinces are rapidly evolving towards some form of a more centralized management structure.

The benefits of a centralized structure center around the reduced resources required, the ability to see the "big picture" as the situations develop, and to anticipate the fire situation of the next few days and allocate resources accordingly. The central command center is able to see the developing fire situation and to position appropriate resources before fires occur. Resource positioning in anticipation of fire activity is the key to fire control effectiveness. The approach totally depends on early detection and effective aircraft-based initial attack. The cost reductions come not from the information technology itself but rather from the "leaner" organization that the technology permits. Far fewer people, ranger stations, pumps, hose, and aircraft are required. Provincial mobility of all resources is essential. More than 10 years of experience with this structure in Quebec indicates that it is one third to one half less expensive and the area burned for the same period has been more than cut in half.

Resource Mobility & Sharing

No provincial agency, no matter how well equipped, can afford the equipment, aircraft, and crews needed to deal with the worst fire situation. Canada is large enough that a severe fire situation is usually isolated to a few provinces at any given time. Resources from the remaining provinces are made available through mutual aid agreements with all other provincial fire agencies. The Canadian Interagency Fire Centre (CIFC) oversees the operations of these agreements and, at the request of the province in need, will arrange the transfer of the desired resources on a daily basis. Each province daily supplies CIFC with a list of resources available for any province in need.

There is a special arrangement for the interprovincial movement of 49 CL-215 waterbombers. For example, this summer CL215s from Quebec and Ontario spent considerable time in British Columbia. The CIFC also has a very active agreement for resource sharing with the U.S. through the Boise Interagency Fire Center. Canada frequently borrows the BIFC fire mapping equipment and the U.S. often uses Canadian fire control teams and aircraft.

Fire Management Systems in Canada

Overview

There is an intimate link between organization structure and information technology. Decentralized integrated fire control operations have little need for advanced information technology. These organizations served us well when we had poor communications, difficult transportation, and low labour costs. The local ranger knew his small area well and relied upon his own staff and equipment to carry out fire control. On the other hand, a modern centralized organization cannot function without an information system. Just as a military command centre needs information about its war environment and the state of its own forces and those of the enemy, so does a modern fire control centre. Vital to its operations is information about fuel, terrain, weather, fuel moisture, crew and aircraft status, likely fire occurrence and fire behavior, detection demand, and resource prepositioning. This information must be summarized in a timely fashion for the few decision makers.

Key tasks in the central control philosophy include:

- monitoring the ever-changing fire environment,
- predicting fire occurrence and potential fire control work load,
- positioning sufficient initial attack forces well before fires occur,
- focusing aerial detection efforts to ensure appropriate early detection,
- dispatching enough force to guarantee containment on every fire at initial attack time.

During the past 25 years the Petawawa National Forestry Institute has worked at developing a decision support system for a centralized fire control operation. This work involved the integration of many disciplines including forestry, fire science, meteorology, remote sensing, operations research, computer science and, lately, artificial intelligence.

This work has produced a large collection of computer programs and databases referred to as a fire management system. These computer programs are designed to be used in fire control centres that protect large areas such as a province or a large provincial region. It focuses mainly on short term decision making (minute-by-minute to next-day forecasts) and aims at making the best use of currently available fire control resources. The programs collect and manage information on the current and near-future state of the forest environment including the monitoring and display of weather, fuel moisture, lightning and rainfall occurrence, and fuel type and terrain. Models predict both lightning and people-caused fire occurrence, fire behavior, and a specific fire's growth. Manual and remote weather stations, weather forecasts, precipitation radars, lightning sensors, Landsat satellites, and forestry geographic information systems provide the data for the system. It has a resource tracking component designed to keep track of important resources whether they be in warehouses, at fires, or intransit. Also there are algorithms for daily detection planning, positioning initial attack resources in anticipation of fire occurrence, and for dispatching resources to a specific fire.

Computing and Communications

There are many versions of the programs running on UNIX workstations, DOS and/or Windows PCs, Mac PCs, and VAXs. Presently the PNFI group is converting existing programs and developing new ones for Pentium 90 PCs served by a DEC Alpha AXP. Most of the provincial forest fire networks use 486-based PCs linked to VAXs. The existing programs are written in "C" and VISUAL BASIC. Future programs will likely be developed in VISUAL C. In the past our databases used a combination of existing commercial products such as INGRES, supported by homemade structures designed to speed retrievals. Colour graphics and windows environment tools are important in such a system. We have had considerable experience with X Windows, TCL/TK and, lately, VISUAL BASIC.

Linked to the database is a geographic information system. PNFI has chosen to use the U.S. military's GRASS system. It runs on UNIX and DOS platforms, is well supported and, best of all, it is almost free. We are presently building a sophisticated TCL/TK user interface to the GRASS displays that will run in either the UNIX or 486/Pentium environments. All geographic information sets and model outputs will be displayed using this combined tool. With this approach we hope to avoid the never ending need to develop new graphic user interfaces and displays every time a new language, operating system, or hardware platform is introduced.

A key part of the information system is the computer communications sub-system. The system inexpensively links all attack bases and regional and provincial computers into a common network so that data and model results can be viewed at the local level as well as at the provincial level. For example, in British Columbia, there are about 45 PCs linked to a central VAX in the city of Victoria. In addition to the PC network, each province operates a network of real-time lightning sensors whose outputs are directed into the PC network. British Columbia has invested heavily in remote weather stations. For example, there are 500 fire weather stations reporting automatically into the computer network. Two hundred of these report each hour. Most provinces use a combination of regular telephone lines, provincial microwave networks, and digital radio links to network their sensors and computers. B.C. is presently experimenting with a communications scheme that takes advantage of available over capacity on a cable/satellite TV transmission system. Also, the province is experimenting with meteor-burst communications for reporting the GPS locations of its aircraft every few minutes. Quebec is using its voice air-to-ground UHF channels to transmit aircraft locations automatically to the command centre computers.

Foundation Decision Support System

The foundation of our fire management decision support system includes a huge information acquisition, storage, and retrieval system. Data types include lists, tables, point data, geographic rasters, vectors, and images. The following summarizes the items that can be stored in the database structure. No one province has all these features but they all exist in at least one provincial database.

- hourly and daily weather station data (manual and some automatic input)
- fire report data on all fires (manual/network input)
- detection reports of new fires (manual/network input)
- predicted weather (one day ahead)
- interpolated raster weather maps of current and predicted weather
- current and predicted fire weather index values for each weather station (values generated by the Canadian Fire Weather Index program)
- interpolated raster maps of the past, current, and predicted indexes
- forest fire fuel maps (vector or raster inputs from GIS timber maps, Landsat, etc.)
- fire behavior maps (raster) for the current and predicted situation (values generated by the Canadian Fire Behavior Program)
- lightning flash locations (automatically loaded from LLP or LPATS sensors)
- lightning and people-caused fire prediction maps (raster maps from prediction model)
- digital or analog terrain maps (i.e. DTM elevations every 50 meters or map images)
- initial attack resource status by fire centre and attack bases (manual input)
- current aircraft location (automatic GPS location reporting Quebec and B.C. trials)
- culturally important features such as roads, lakes, rivers, boundaries, etc. (point and vector data)
- detection planning system maps showing daily detection demand, zones of operation, current aircraft locations, and suggested patrol routes.

Some Examples of Models Developed at PNFI

Over the past several decades, foundation decision support systems have been developed and implemented to serve the basic information needs of most provincial fire control agencies. Operations research-based models and expert systems have been added to this foundation in several of the more centralized operations. These include forest fire occurrence prediction, initial attack dispatch, daily fire detection planning, daily fire control resource positioning, and a sophisticated fire growth model that can simulate multiple ignitions and control line construction with back burning. None are considered operational to date. These programs integrate object programming concepts, relational databases, rule-based structures, neural networks, traditional operations research algorithms, and X-window graphics. The following is a brief description of our various fire predictions, and initial attack and detection planning models.

Conventional People-Caused Fire Occurrence Prediction

PNFI has developed several people-caused and lightning-caused fire occurrence prediction models, beginning in the early 1970s. These models divide the region of interest into raster cells each approximately 100 to 200 sq. km in size. A prediction of the expected number of fires or chance of one or more fires is made one day in advance for each cell. Expected occurrence rates are classified usually into four classes and displayed as a colour map.

In the most commonly used people-caused prediction program, historical fire occurrence is correlated with fire weather indexes and fuel types for each specific cell location. The mean fire occurrence rate is used as the base prediction and this is further adjusted to consider short and medium trends in actual fire occurrence in each cell's vicinity. We assume that fires occur according to a Poisson distribution whose parameters themselves have a Gamma distribution that are adjusted though a Bayesian scheme based on actual fire occurrence in the past few days or weeks (Todd and Kourtz 1991). The prediction program has been customized for the provinces of B.C., Manitoba, Ontario, and Quebec and has been used quite successfully for many years.

The Fuzzy People-Caused Fire Occurrence Predictor

In an attempt to improve our ability to predict fires, a new approach was developed in 1987. It was known that a few experienced fire personnel could rather accurately predict fire occurrence for the next day. We interviewed these people and attempted to discover the rules they used. Some 2000 rules were identified and these were encoded first as a PROLOG program and later as a NEXPERT program linked to a sophisticated graphic user interface.

The expert system uses fuzzy logic and considers the factors related to why, where and when fires were being started by people (Kourtz, 1989). Like the conventional fire prediction models, a large region is divided into cells and a forecast is made for each. Five causes of forest fires are recognized: forest operations, recreation, residents, industrial activity, and railways.

The expert system required not only the traditional fuel type, fuel moisture, and weather data from existing raster databases but also a large set of spatial data not found in any geographic information system. A mouse-driven "painter" routine is provided to the expert user that enables one to quickly enter spatial perceptions, in the form of coloured maps, of some 24 factors related to fire occurrence. Included in this list are perceptions of the location of forestry operations, rural and urban interface regions, risky recreation areas, risky public works, railway fire problem areas, phenological greenup state, restricted fire zones, garbage dump locations, and areas of special prevention activities. Some 1000 rules assign the degree of belief that each cell would have fires started by each of the causes for that specific day. Here, day-of-the-week, season, special holidays, niceness of the weather, and fuel moisture states provide some of the dynamics to the system. This was the risk portion of the expert system.

Another large set of rules was used to determine the degree of belief that firebrands occurring in each cell would survive and develop into visually detectable fires. This was the hazard side of the system. The fuzzy logic product on a cell basis, of the risk and hazard degrees of belief, is the fire prediction and is displayed as a coloured map.

The fuzzy fire predictor was tested at the Maniwaki and Thunder Bay fire centres during a 3-year period beginning in 1988. At Maniwaki, the system received strong support from the principal users. At Thunder Bay, users recognized the potential of the system but wanted major changes specifically in the area of final outputs. They wanted numerical outputs rather than fuzzy output classes and were not prepared to spend the time each day to enter the appropriate "painter" maps. This process could take up to 15 minutes each day. Common to both centres was the complaint that the program took too long to execute. If the VAX were idle, the execution time was about 30 minutes. Since these trials the program has been ported to NEXPERT and modified to include numerical fire predictions. Computer time was reduced to 5 minutes on a Sun Sparc 1+ and plans were made to retest the program. Unfortunately, the field organizations never evolved to UNIX and this approach had to be abandoned. Plans are in the works to port the program the Pentium/Windows PC which is much faster, less expensive, and easier to maintain than the older Sun/UNIX workstations.

NePeNet (Neural People-caused Network)

Yet another approach to people-caused fire prediction is being investigated. The main concepts of the fuzzy fire predictor have been reworked as an hierarchical set of neural networks. Eventually the new program will recognize five forest fire causes, and for each cause, there will be a separate set of neural networks summarizing historical occurrence rates, the present use of the forest by people and the current fire behavior characteristics of the forest fuel types. Separate neural networks combine and summarize these risks and hazard components and the output represents the fire occurrence prediction.

The program depends on historical fire and weather data for training the neural networks and on current inputs of fire and weather data for execution. It is presently running on a Sun Sparc station but will be ported to our new Pentiums shortly. Field trials of this program should begin in the summer of 1995.

Lightning-Caused Fire Occurrence Predictor

Lightning is the most dangerous cause of forest fires in Canada. Hundreds of lightning fires can occur in a local area almost simultaneously. A fire agency that is not prepared can be easily overtaxed and the result, more often than not, is one or more large fires hopelessly out of control. Predicting the arrival of lightning fires many hours in advance is an essential component of a successful suppression strategy.

A network of automated lightning sensors provides the locations and the number of cloud-to-ground lightning flashes. It is not enough to know that lightning has occurred; this is merely a necessary condition for fires. A typical severe-storm day in a large region can produce in excess of 20000 flashes but there will be no fires ignited. At other times a small storm can have five flashes and two fires will result. Our lightning fire prediction procedure builds a likely scenario for every flash registered by the lightning location system. Appropriate weather, fuel type, and moisture data are combined with models of the ignition, smouldering, and detectability processes. The ignition model predicts the chance of the flash causing ignition. The smouldering model tells us the chance that the fire will survive overnight (usually in a smouldering state). The detectability model forecasts the probability of a fire being visually detectable during the burning period.

Because fires can remain dormant for long periods, each flash that occurred during the previous 10 days is considered a potential fire. Potential fires predicted to have been ignited on a previous day are subjected to a self-extinguishing and detection removal process where their numbers are decreased each successive day until the present. Remaining expected fires are combined with newly ignited potential fires and subjected to a smoke-related detection model to give the likely number of arrivals (detectable fires) for the current day (Kourtz and Todd 1992).

In general, the model produces fair to good results for most days. The main weakness is the inaccuracy of the lightning sensors and the lack of precipitation data for the storm. Work is underway to develop a modern lightning sensor that is capable of detecting those flashes that have long continuing current flow: the flashes that can ignite a fire. Quebec and British Columbia are addressing the rainfall distribution problem through the use of precipitation radar. Quebec now has three units specifically designed for forest fire use. They plan an eventual network of about 15 radar units. In the meantime, PNFI is beginning work on two new lightning fire prediction programs. One will use an hierarchy of neural networks much like the people-caused program. The other will attempt to identify historical patterns of weather and fuel conditions leading up to lightning fire events. We hope to use a new pattern recognition tool called "Sparse Distributed Memory" to store and retrieve appropriate patterns and possibly to self-calibrate through an automatic learning and forgetting process.

Initial Attack Dispatch

The purpose of the initial attack expert system is to dispatch water bombers, crews, and helicopters to a newly reported fire. It is intended to be used as an operational aid for the initial dispatch to a fire and is a means to incorporate agency policy and opinions of the experts. Most important, it provides an agency with a standard response guide usable by even inexperienced personnel. Two versions of the program have been created. The first is a complex program that reasons about the state of all initial attack resources, shortages and possible substitutions of resources when either the force level or time response goals could not be met. The second version of the program deals with defining the ideal response and does not consider the availability of resources. It is designed for agencies without real-time inventories of their initial attack resources.

Both programs begin with a computerized fire report describing factors related to the fire's potential for spread, the likely difficulty of control, and potential damage. The information contained in those fire reports that originate from trained observers is used directly to classify the situation in terms of the ideal maximum response time and numbers of crews and bombers needed. Hundreds of expert rules reflecting agency policy are used to train an hierarchical set of neural networks to provide these outputs. This "ideal response" version of the program has been customized for and implemented in four provinces and is presently undergoing field trials.

The more complex version considers the reliability of the fire report. When the fire report is judged to be unreliable or only partially reliable, fire growth simulations using a simple elliptical fire growth model are carried out using fuel type, fuel moisture, terrain and weather data available from existing databases. Rules relate the simulation results to the desired ideal response. Two dynamic programming algorithms determine the best bomber and crew-helicopter sets available. Substitutions, defined by agency policy, of bombers for crews and crews for bombers are considered if the ideal dispatch is not possible. If suitable substitutions are not possible, resources further away are considered. In the end, the program dispatches the best set of resources possible under the current time, substitution, and operating policy constraints. In 1988, this program could compute a typical dispatch in about 30 seconds. More complex dispatches took several minutes.

The program was first installed and tested at the Outaouais fire control center at Maniwaki, Quebec in 1986 (Kourtz 1987) and later, in 1988, it was tested at the North Central Regional Fire Centre of the Ontario Ministry of Natural Resources at Thunder Bay, Ontario. Both command centres were responsible for dispatching to fires in areas spanning more than 80000 sq. km. At that time both sites used VAX 750 computers.

Much of the testing focus was at the Thunder Bay fire centre where the program was operated in parallel with existing manual dispatch procedures. By 1989, it was generally concluded that the program could make dispatches as well or better than the operational dispatchers. However, it was not fast enough to be operational at that time. We plan to convert this program to operate on a Pentium PC in the near future. A major limitation is its dependence on a timely and accurate inventory of initial attack resources. So far no provincial agency has a suitable inventory system but this should be soon rectified.

Daily Detection Planning for Aerial Detection

The detection planning expert system is to be used, on a daily basis, to control the placement and use of a fleet of 33 detection aircraft in the Province of Quebec. Fifteen airports are available at which up to five aircraft can be temporarily assigned. Each aircraft operates out of one of four home regions and can be moved to any airport within their home region for only the cost of travel. Moving an aircraft outside of its home region incurs a small foreign basing charge in addition to the travel cost. Sequential shifts of aircraft will be common, such as a general movement of aircraft from east to west across the Province.

Five separate steps are involved in making tomorrow's detection plan. The first step defines tomorrow's level of detection effort required. The number of patrols required tomorrow in each 15 minute (latitude and longitude) cell is the criterion used to express the need or demand for detection. Ideally we wish to visit each cell often enough so that the chance of having a fire escape initial attack is reduced to some acceptable level. The factors that presently are important in determining the number of patrols over each cell are:

- The likely number of fires predicted to occur in the cell and its nearby vicinity. If no fires are predicted for the cell or for its neighbors, there should be less need or "demand" for detection. In general, the more fires predicted, the more detection effort is needed so that none will escape from the initial attack effort.
- The likely rate-of-spread of fires that may occur. Slow spreading fires generate less detection demand since they can be easily suppressed. On the other hand, fast spreading fires require more detection effort. They must be detected sooner if they are to be stopped by the initial attack effort. Fire spread rate is a function of the fuel type, season of the year (phenology), fuel moisture, wind speed, and slope of terrain.
- The likely intensity of the fires that may occur. Low intensity fires are easier to suppress and therefore detection patrols over a cell can be less frequent. When high intensity fires are expected, more frequent patrols must be made in order to catch the fires before they become expensive to suppress. The intensity of a fire is a function of the fuel type and fuel moisture.
- The value at risk. Where values are low, such as in unused, non-commercial forest, i.e., taiga, detection frequency should be less compared to similar conditions within cells having high value timber stands, structures, human life at risk, or high wildlife and recreation values. This must always be balanced with the effort required to suppress the resulting fires. In some cases, even though no losses are occurring, it may be best to suppress fires immediately to prevent significant suppression costs and eventual high losses associated with large fires.

These relationships are complex and difficult, if not impossible, to quantify in an objective manner. An expert system has been created to assign the number of patrols that should be flown over a specific cell given the class level of each of the above factors. It is based on the opinions of fire detection experts and reflects the current policies and operations procedures of the provincial fire control agency. The response of the expert system can be modified as policies change or as better operating procedures are worked out.

The rules in the expert system are encoded as a neural network. To train the network, a complete set of possible states and their corresponding number of patrols were used. There were four classes of predicted fires, rate-of-spread and fire intensity. Two classes of values-at-risk were used. The total number of possible states was 128.

Fifteen airports across the province have been identified as possible locations for detection aircraft operations. In step 2, the planning process deals with the identification of an appropriate subset of airports from which to operate tomorrow and the zone of operation for each. Aircraft assigned to these airports are moved to them in time to carry out the day's detection patrols. Every 15-minute (latitude and longitude) cell in the province's protected area is assigned to the most appropriate airport of the subset of airports to be operated.

The identification of the appropriate subset of airports and each airport's zone of operation is treated as an operations research "warehouse positioning" problem (Woolsey and Huntington 1969). Key to the problem's solution is the definition of reward associated with patrolling a specific cell from an aircraft located at a specific airport. Arbitrarily, a cell's detection demand is defined to be the number of patrols needed times 25. Detection demand therefore varies from 0 to 100. The reward for visiting a cell is the amount of reduction in demand associated with such a visit. This reward is assumed to be a function of cell's detection demand, its distance from the airport, and the visibility within the cell.

Cells at distances greater than 300 km or cells requiring 0 patrols have zero reward. Visibility of less than 5 km reduces the reward by one third. Visibility of more than 15 km neither reduces nor increases the reward. Little reward is assigned for visiting a cell very distant from an airport. Likewise there is only a small reward for visiting a cell with poor visibility, even if it is in urgent need of detection and is only a moderate distance away from the airport.

To apply the warehouse location algorithm we assume the cells in the province are like customers wanting some service supplied from a group of warehouses (airports). We wish to establish from one to 15 warehouses to best meet the needs of our customers. Money is tight and we really only want to establish the fewest number of warehouses as possible while still keeping our customers reasonably satisfied. In our case, the value in providing service from a specific warehouse to a specific customer is the associated detection reward (or equivalently, the reduction in demand for detection).

The algorithm proceeds by first operating all warehouses and then recursively eliminating the next least productive warehouse until a certain minimum situation is reached. Within any set of remaining warehouses, there is one specific warehouse that can best service each customer. In our case, there is an airport that can provide the greatest detection reward (reduction in detection demand) for each cell. The next warehouse or airport to be eliminated is the one associated with the least reduction in total detection demand. The algorithm provides a simple way to quickly determine which warehouse should be dropped.

As airports are dropped, detection service deteriorates. We wish to stop eliminating airports when a minimum provincial standard in detection service is reached. Currently we arbitrarily stop eliminating airports when the next, least costly, airport closure will cause an increase in total provincial detection demand of more than 2000 units. This scheme selects a subset of airports that serve as focal points of the provincial detection effort for the day. These selected airports are nearest the concentrations of cells with the most detection demand. As a side benefit to this approach, a zone map is produced showing the cells serviced by each remaining airport. In the next phase of the planning process, this map is used to determine the number of aircraft to position at each of the airports to be operated.

Step 3 in the planning process defines the number of aircraft required for each airport. We wish to position enough aircraft at each operating airport such that a minimum provincial standard in detection service is supplied to all cells uniformly across the province. Once again, the criterion or measure of effectiveness of our aircraft allocation is the detection demand defined as the number of patrols needed in a cell times 25. Without detection, the provincial total demand is the sum of the 3700-cell patrols required times 25. A single aircraft carrying out a patrol from a specific airport reduces this demand by an amount equal to the number of cells (times 25) that can visited in about a 3-hour patrol considering the visibility. Within the zone of coverage of a specific airport, as a rough approximation of the value of more than one aircraft, the current program assumes that the same reduction in demand as used for the first aircraft is used for each successive aircraft until demand reaches zero. At this point, there is no further benefit to adding additional aircraft at the airport of interest. Thus, one can calculate the reduction in detection demand for each airport zone associated with from 0 to n aircraft operating from the airport. This matrix of aircraft assignments and associated rewards for each airport is the basis for a dynamic programming solution to finding the best allocation of the provincial detection fleet to specific airports for tomorrow.

Step 4 determines the routing plan for each aircraft. The problem of how to route aircraft to specific cells is treated as a multiple-salesmen, constrained-subtour, travelling salesman problem where both simulated annealing and Lin Kernighan algorithms are used to find good routing solutions. The program determines the least-cost flight path for each aircraft under minimum and maximum time constraints and a zero route-crossing contraint. Output from the program is a map showing the location of the best set of patrols.

The final step determines the least costly plan for shifting aircraft to tomorrow's airports. A network algorithm is used to determine the least cost transfer plan of n detection aircraft, distributed among m airports, given the current distribution of aircraft, the desired airport requirements, and the cost of moving any aircraft from any airport to any other airport (Kourtz 1984). This algorithm has been coded into a program for use in planning the daily transfers of aircraft necessary to meet the predicted airport/aircraft requirements for the next day within Quebec. It specifies which aircraft to move in order to meet our aircraft/airport objectives in the least costly manner. To run it, the current and desired location of the fleet is needed in terms of numbers of aircraft at each airport in the province.

Conclusion

Canada's approach to forest fire control is very different than that taken by Australia. The reasons for these differences are related to different patterns of ownership, economic values at risk, fuel loadings, ground fuel accumulations, presence of vulnerable communities, and cultural attitudes toward fire. In Canada, in the intensively protected regions, small fires are aggressively sought out and suppressed. In times of severe burning conditions, emphasis is on early detection and forceful initial attack.

Fire control is financed very differently in Canada than in Australia. Provincial fire control agencies are financed exclusively through provincial taxes except in Quebec where it carried out by a cooperative company funded jointly through government subsidies and membership levies. There is no involvement in fire control by the insurance industry nor are there any volunteer firefighters. Unlike in Australia, there is a heavy reliance on aircraft for detection, transport, and retardant bombing especially during severe fire weather. Relatively few people are involved in actual fire fighting and there is almost no use of fire trucks. Although there are small prescribed burning programs in some provinces, mainly aimed at silviculture and ecology objectives, there are no general fuel modification programs. In the industrial forests, harvesting effectively removes the long-term fuel buildup.

Several Canadian provinces are rapidly evolving toward highly centralized organizations. This approach is characterized by a capital-intensive, resource-mobile operation that manages a large area with few personnel. Essential to this form of organization is a modern information system. Computers, sensing systems, and digital communications are used to gather information on the state of the fire environment and fire control resources. Decision support models predict the likely fire occurrence, fire behavior, and fire growth. Other models assist in detection planning, initial attack dispatch, and resource positioning in anticipation of fire activity.

The concepts underlying the Canadian approach to fire control can play a major role in reducing the terrible losses caused by Australian bush fires. But, in the long term, reliance solely on an aggressive fire control program would surely fail. Soon greatly increased fuel loadings would develop and, eventually, there would be disastrous fires. The solution involves the proper mix of prevention, fuel management, and modern fire control.

In Australia, fuel management on a massive scale is needed. Prescribed burning under conditions chosen by humans is a much preferred option compared to nature's alternative. Although Australia's famous aerial ignition technology would play an important role, ground support is essential. The skills and tools of the fire brigades are ideal for this task. The labour force displaced by a modern approach to fire control could be gainfully employed in a national fuel management program. Modern aerial fire fighting techniques also have an important role to play in a fuel modification program. Strong air attack capability in support of large scale burning is good insurance. Also, a fuel modification program will require state-of-the-art information technology to support the complex planning processes associated with prescribed burning. Our present fire management system already incorporates many of the needed decision support tools.

Appropriate Canadian forest fire control systems, information technology, knowledge, and experiences are readily available. A cooperative program between Australia and Canada to share fire management information technology would be welcomed by the Canadian Forest Service.

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