CHAPTER 15

# Forest Fire Management

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## I. INTRODUCTION

Societies that are confronted with potentially destructive forest or wildland fires develop fire management organizations to modify fire's impact on people, the things they value, and the ecosystems about which they are concerned. A fire management organization's objectives are determined by the social, economic, and political institutions that control it. The extent to which it achieves its objectives depend upon (1) how well the fire and ecosystem processes and the impact of fire management are understood; (2) the degree to which the social and economic impacts of fire are understood; (3) the technology and resources society puts at the organization's disposal; (4) the knowledge, skills, and experience of the people in the organization; and (5) the challenges posed by nature.

*Forest Fires*

Most of the earlier chapters of this book have dealt with the physics, chemistry, and biology of wildland fire and its ecological impact on forest stands and landscapes. The focus has been largely what wildland fire specialists describe as fire science. Fire scientists carry out basic research (e.g., fire spread), applied research (fire danger rating system development and implementation), and a great deal of research that cannot readily be classified on the basic/applied research spectrum. Previous chapters illustrated the importance of moving beyond the development of relatively simple empirical curve-fitting models and furthering our basic understanding of fire processes and their impact on ecosystems. In this chapter, we turn our attention to the ways in which societies attempt to shape wildland fire and influence its impact on them and surrounding ecosystems. We study wildland fire from a management perspective and explore what fire managers do, why they do what they do, how they decide to do what they do, and the short, intermediate, and long-term social, economic, and ecological consequences of their actions. We focus on what is commonly referred to as *fire management*.

> *Fire Management:* The Canadian Glossary of Forest Fire Management Terms (Merrill and Alexander, 1987) defines *forest fire management* as the "activities concerned with the protection of people, property, and forest areas from wildfire and the use of prescribed burning for the attainment of forest management and other land use objectives, all conducted in a manner that considers environmental, social, and economic criteria."

Most North American wildland fire agencies were developed to combat fire in the early 1900s and for many decades they had names that included terms like *fire control* and *fire protection*. They were unabashedly fire suppression organizations, and their names reflected their view of wildland fire and its impact on the world. The current widespread use of the term *fire management* reflects a more enlightened view that wildland fire is a natural phenomenon that has a range of social, economic, and ecological impacts that should be considered when it is managed.

Fire management programs typically include prevention measures to reduce the number of people-caused fires that occur, detection systems to find fires while they are small, initial attack systems to contain fires before they burn over large areas, and large fire management systems that are designed to minimize the damage that results from large fires that are not controlled by the initial attack system. They also include fuel modification measures to mitigate the impact of fires that do occur and the use of prescribed fire to fulfill silviculture, wildlife habitat management, and other land management objectives. Fire management also calls for (albeit very infrequently in most jurisdictions) conscious decisions to allow some wildfires to burn freely or to be subjected to limited suppression action if and when the net benefit of doing so is thought to be positive.

Fire management researchers carry out basic research to further our understanding of fire management processes (e.g., the influence of suppression action on fire growth) and applied research to develop decision support systems (e.g., initial attack system models) that fire managers can use to help predict the consequences of their actions and to evaluate alternative policies, strategies, and tactics. Many fire management systems researchers use Operations Research/Management Science (OR/MS) methodologies which entail the use of mathematical models and information technology. Pollock and Maltz (1994, p. 4) characterize Operations Research "as a *process* of developing mathematical models in order to understand (and possibly influence) complex operational systems." Martell (1982) and Martell *et al.* (1998) review many of the fire management operations research publications that have appeared over the last four decades.

Physical and biological scientists can and often do study systems that are relatively isolated from human intervention, but fire management researchers must deal with large complex systems composed of natural processes, people, and machines. Fire managers must resolve decision-making problems (e.g., initial attack dispatching) as circumstances dictate and, even though they base their decisions in part on the understanding of basic physical and biological processes developed by scientists, they frequently have to deal with processes that are, at best, poorly understood. Although they can postpone some decisions (e.g., the purchase of airtankers) while they gather more information and reflect upon the possible consequences of their actions, they seldom have the luxury of postponing their decisions until researchers have developed a thorough understanding of the pertinent processes. Fire management researchers that develop decision support systems to meet their needs must therefore incorporate in their systems models what is currently known about physical, biological, social, and economic processes, empirical curve-fitting models, and the subjective assessments of designated experts. In this chapter, we will describe how they do so.

A forest fire can burn over a large area during a short period of time. When it does so, it can leave tremendous impacts on public safety, property, forest resources, and forest ecosystems in its wake. Although many fire management activities are directed at specific fires, fire management programs are designed to modify the impact of fire across vast landscapes and administrative regions over very long planning horizons that are embedded in larger ecoclimatic and administrative hierarchies that span many forest management units, districts, regions, provinces, nations, and even continents. There is no definitive spatial and temporal scale at which fire can or should be managed. One can focus on a portion of an active fire's current perimeter or one can deal with fire regimes across very large spatial and temporal scales. We will approach fire and its management from a range of spatial and temporal scales, and we will study the impact of fire and fire management on fire regimes at landscape levels embedded within political and administrative structures that span many such landscapes. We begin by clarifying our use of the term *fire regime.*

> ***Fire Regime:*** Whalen (1995) described a *fire regime* in terms of the following five basic elements: (1) fire intensity, (2) the season during which burning takes place, (3) fire size or extent, (4) fire type, and (5) fire frequency.

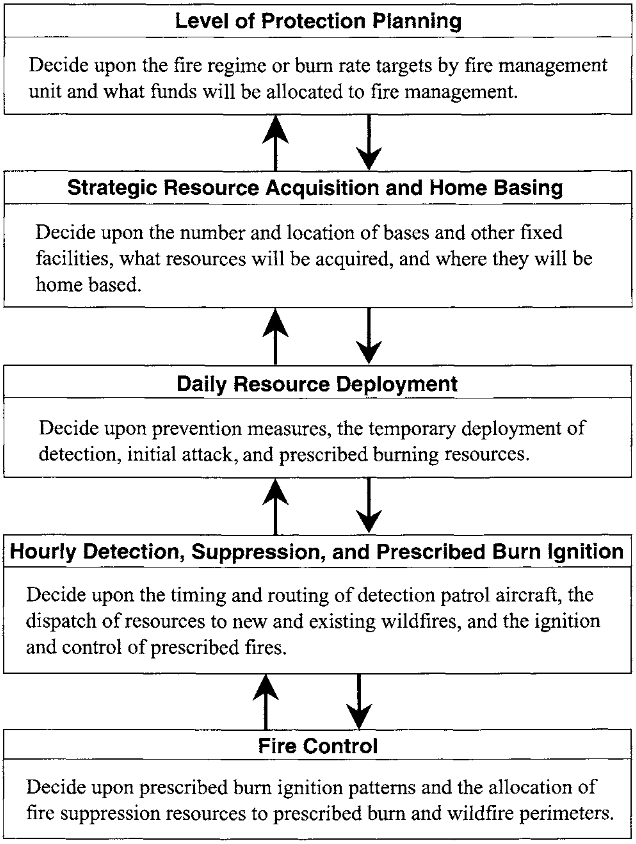
Fire management programs are designed to modify one or more of those five basic elements of a fire regime, either directly or indirectly. Prevention measures, for example, reduce fire frequency, whereas fire detection and suppression activities reduce final fire size. Prescribed burning can either increase or decrease fire intensity, size, and frequency.

In Section II we describe the relationship between fire management objectives and higher level forest land management objectives, and in Section III we deal with fire economics and the assessment of fire impacts. Section IV deals with fire management organizations, and in Section V we describe how fire managers carry out level of fire protection planning to balance the benefits of mitigating the detrimental impacts of fire and reaping its benefits with the cost of doing so. We conclude with Section VI in which we describe some of the more significant challenges that will need to be addressed as fire management agencies increasingly move away from fire exclusion to the adoption of policies that call for modified fire suppression and the use of prescribed fire.

Since we are primarily interested in fire management and its impact on fire regimes, we describe the activities associated with each subsystem, their potential impact on the basic elements of a fire regime, and their potential social, economic, and ecological impacts. We discuss the decision-making problems associated with each fire management subsystem and the management information systems and decision support systems that are designed to enhance fire management decision-making.

Figure 1 is a hierarchical view of fire management decision making which will be used to structure our investigation of fire management systems. The list of decisions included in Figure 1 is not exhaustive but is characteristic of most large North American wildland fire management agencies. Most of those agencies are still very heavily committed to fire control, but the use of prescribed fire to achieve ecological objectives is a major concern of many agencies, particularly those responsible for fire management in national parks and wilderness areas in Canada and the United States.

Sound fire management is based, in part, on the extent to which the decisions associated with any particular level in the hierarchy are compatible with the decisions taken above and below. Consider daily airtanker deployment, for example. The number of airtankers to be deployed on a particular day will be



**Level of Protection Planning**

Decide upon the fire regime or burn rate targets by fire management unit and what funds will be allocated to fire management.

**Strategic Resource Acquisition and Home Basing**

Decide upon the number and location of bases and other fixed facilities, what resources will be acquired, and where they will be home based.

**Daily Resource Deployment**

Decide upon prevention measures, the temporary deployment of detection, initial attack, and prescribed burning resources.

**Hourly Detection, Suppression, and Prescribed Burn Ignition**

Decide upon the timing and routing of detection patrol aircraft, the dispatch of resources to new and existing wildfires, and the ignition and control of prescribed fires.

**Fire Control**

Decide upon prescribed burn ignition patterns and the allocation of fire suppression resources to prescribed burn and wildfire perimeters.

FIGURE 1 Fire management decision hierarchy.

influenced by the number of airtankers the agency owns or leases for the fire season (a consequence of higher level strategic decision making) and the cost of temporarily borrowing more costly airtankers from other agencies. High borrowing costs could deter fire managers from borrowing airtankers from others, which could produce daily airtanker shortages, longer initial attack response times, and more escaped fires in the lower initial attack level of the hierarchy. Fire management poses many such challenges.

We draw heavily on our own experience with the Ontario Ministry of Natural Resources (OMNR) in the province of Ontario in Canada, and what we know about other North American wildland fire management agencies to illustrate our discussion. Most wildland fire management agencies are, for the most part, emergency response systems; however, they vary from jurisdiction to jurisdiction around the globe, and we do not attempt to capture the rich diversity of approaches, philosophies, and practices that are influenced by local ecosystems, climate, culture, economics, and political systems. For comprehensive historical accounts of the development of forest fire management in some North American jurisdictions, see, for example, Holbrook (1943), Lambert and Pross (1967), and Pyne (1982). Pyne (1997) reviews fire and fire management from a more global perspective.

It is important to note that, although private enterprise plays a significant role in wildland fire management in North America (e.g., many fire management agencies contract flying services from private companies and public corporations), fire management is ultimately a public sector endeavor and management and decision making in the public sector differs in many ways from management in the private sector. Gass (1994) describes some of the many ways in which public sector OR/MS differs from its practice in the private sector including the relative importance of political concerns, the difficulties associated with evaluating costs and benefits, and the "freedom of information" environment that makes public sector policy analysis and decision-making processes very open. He points out that, unlike their private sector counterparts that tend to focus on the "bottom line," public sector decision makers must address efficiency (the proper use of resources), effectiveness (the attaining of specified goals and objectives), and equity (the extent to which all citizens are treated alike).

## II. THE RELATIONSHIP BETWEEN FIRE AND FOREST LAND MANAGEMENT OBJECTIVES

A fire management program is usually but one of many components of a broader forest land management program. Societies develop and implement land management plans to increase the likelihood that the human activities which take place on or near designated parcels of land will be compatible with the needs and desires of the people and institutions that have jurisdiction over that land. Forest land management plans might, for example, call for some areas to be treated as wilderness in which the impact of humans is minimized to protect natural ecosystem processes, others to be designated as recreational parks in which heavy human use is tempered to reduce its impact on natural processes, and yet others that are managed primarily for industrial fiber production. Land management plans should reflect the diverse needs and interests of the many groups of people who have interests in the forest. Consequently, even though forest land management is frequently a source of bitter conflict in modern industrial societies, we will assume that societies can and ultimately do develop land management plans that reflect the way they want their forest lands to be

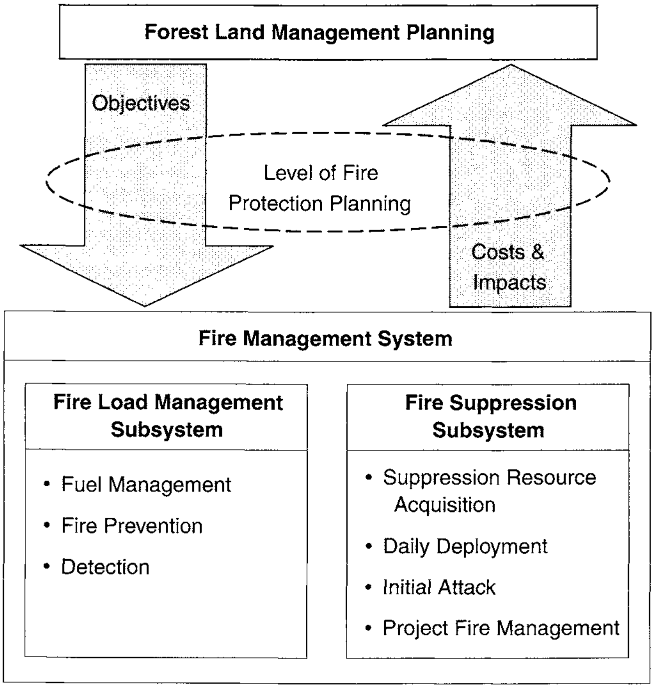


FIGURE 2 The relationship between fire and forest management planning, a refinement of the fire management systems framework presented in Martell *et al.* (1999).

managed. The fire manager's role is to develop and implement fire management plans that are compatible with and contribute to the achievement of the objectives of the higher level forest land management plans.

Figure 2 is a refinement of the fire management systems framework presented in Martell *et al.* (1999) and illustrates the hierarchical relationship between fire management and forest land management. Forest land management planners should begin by identifying fire management objectives such as average annual burned area targets and transmitting them to the fire organization. Fire managers should then determine if they can achieve those targets and develop strategies that will minimize the cost of doing so. They should then transmit their predictions concerning the cost of achieving the specified fire management targets and their assessment of the social, economic, and ecological impacts of the fire behavior that might ensue, back up to the forest land management planners. If the forest land management planners and their clients are not satisfied with those predicted costs and impacts, they should revise their fire management objectives and send the revised targets back down to the fire organization. Area burned is not simply the fortunate or unfortunate consequence of a chance process but rather the result of explicitly planned human intervention in complex natural processes. The iterative process of balancing forest land management fire needs with fire management costs and impacts to achieve a workable solution is what is known as *level of fire protection planning,* a topic we will address in Section V.

Just as forest management plans must vary across the landscape, so too must fire management objectives vary from time to time and place to place. Clough (1963) said that "management has been defined as the art of 'guiding the activities of a group of people toward the achievement of a common goal.'" One can think of forest fire management as *the art and science of guiding people in efforts to modify fire regimes that vary across spatial and temporal landscapes in accordance with forest land management objectives, in a cost-effective manner.* This might, for example, call for some fires to be allowed to burn reasonably freely in remote wilderness areas, the use of prescribed fire to fulfill ecological and other land management needs, the aggressive suppression of fire in areas where they pose significant threats to people and their property, and the attempts to limit fire losses in timber production areas. In Section IV, we will study the structure and functions of fire management organizations that are designed to achieve such objectives, but, before we do so, we will investigate how the social, economic, and ecological impacts of fire can be assessed.

## III. ASSESSING FIRE IMPACTS

Our discussion of forest fire management has, to this point, been predicated on an assumption that forest fire managers and their land management clients can assess the impact of fire and fire management programs on people, property, forest resources, and ecosystems, and earlier chapters addressed the impact of fire on ecosystems. Assessing the social and economic impact of fire poses many complex, largely unresolved problems and is the subject of what forest fire management specialists refer to as *fire economics.* Gorte and Gorte (1979) and Baumgartner and Simard (1982) review much of the work that has been carried out in this area. In this section we describe how such impacts are currently assessed, and we identify some of the many significant gaps that remain in this area.

Consider a forest fire management agency that strives to minimize the net destructive impact of fire subject to constraints on the resources that society puts at its disposal and the ways in which they are to be used. Funds are allocated to fire management on the assumption that the subsequent benefits will exceed the value of the money spent. Fire management costs can be assessed and expressed in monetary terms by using standard accounting procedures. Salaries and equipment costs, for example, are easily assessed as is the cost of supporting fire management personnel working in the field. Standard accounting practices will produce reasonably accurate estimates of the annual cost of fixed assets such as aircraft, fire suppression equipment, buildings, communications, and information systems. The benefits of fire management activities include the reduced losses that result from limiting the number and size of destructive wildfires and the increased forest resource productivity and enhanced environment that result from the use of prescribed fire and successfully monitoring and modifying the suppression of beneficial wildfires.

Each year forest fire managers and the governments and other organizations that fund them must decide how much money to allocate to fire management. Many attempts have been made to develop formal procedures for determining optimal, or appropriate, levels of fire protection. Fire management specialists use what is referred to as the least cost plus damage or LCD fire economics model, first developed by Sparhawk (1925), to explore such issues. We will use the simplest variant of the basic LCD model to explain the basic principles of fire economics.

## A. LEAST COST PLUS DAMAGE MODEL OF FIRE ECONOMICS

Forest fire managers use the term presuppression to describe the activities that take place before fires actually occur; for example, the hiring of fire fighters and the commitment to pay their regular salaries for the entire fire season regardless of the number of fires that actually occur. The extra costs, for example, the overtime wages earned once a fire has been reported and is being fought, are referred to as suppression expenditures.

Let us assume that a forest fire management agency must decide how much money to allocate to presuppression efforts prior to the start of the fire season. Those funds could be used to maintain fire lookout towers and other infrastructure and fire suppression equipment such as portable power pumps, hose, and hand tools. They could also be used to pay the regular salaries of fire fighters and other staff; to charter detection aircraft, airtankers, and transport helicopters; and to lease or purchase trucks and other resources that can be used to combat fires once the season begins. The more fire fighters the agency hires, the less likely shortages will occur. That will make it easier to deploy initial attack crews at bases close to areas where fires are expected to occur, in advance, before the fires are reported. The reduced response times that would result should decrease the likelihood that fires will escape initial attack and the net result should be a reduction in fire damage and suppression costs. It is reasonable to assume that suppression costs will decrease as presuppression expenditures

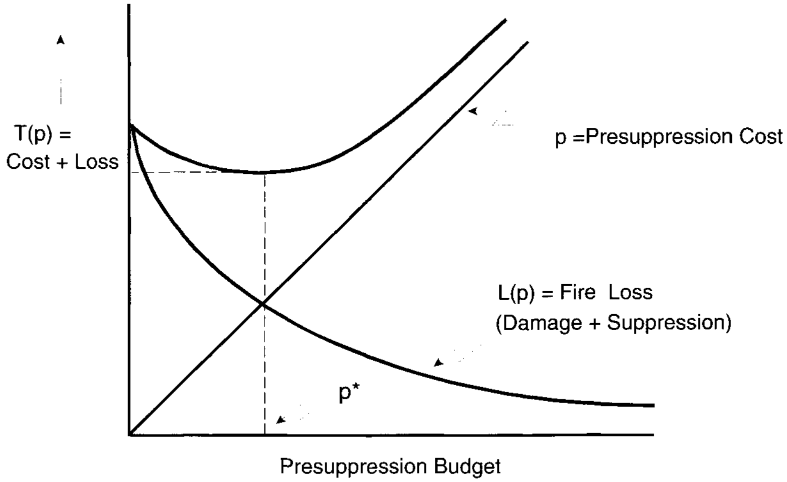


FIGURE 3 Sparhawk's (1925) least cost plus damage fire economics model.

increase but, like most human endeavors, at a decreasing rate due to decreasing marginal returns.

Figure 3 depicts the decision-making problem faced by fire managers. Let $p$ denote the presuppression budget and $L(p)$ the fire loss which includes the suppression cost (e.g., airtanker flying costs and the overtime wages of fire fighters) and the fire damage. The total cost plus loss ($T$) is $p + L(p)$ which is the sum of the $L(p)$ curve and the presuppression cost $p$. The optimum presuppression budget ($p^*$) is the value of $p$ that minimizes the total cost plus loss. Since fire is natural and sometimes beneficial, some writers allow $L(p)$ to be positive (a loss) or negative (a benefit) and refer to the LCD model as the least cost plus net value change model, but the result will be the same if benefits are treated as negative costs. The LCD principle, in its simplest form, is that a forest fire management system should be operated at such a level that the total cost of operating the system plus the fire loss (or more precisely, the net loss) is minimized (i.e., minimize cost plus loss).

In the simple case depicted in Figure 3, the total cost plus loss ($T$) is a convex function of the presuppression cost so one can easily identify its minimum by taking its derivative with respect to $p$, equating the result to zero, and solving for $p^*$, the optimum presuppression budget. Real fire management systems are far more complicated.

## 1. LCD Limitations

The LCD model illustrates the basic principles of fire economics but has many drawbacks that limit its practical use for fire management planning. It is difficult to specify a production function that relates the annual area burned to the presuppression budget. Analysis of the impact of fire management on area burned is confounded by the fact that the historical data may no longer be relevant due to changes in land use, the forest fuel complex, or even climate and fire suppression technology. Furthermore, the production function is not a univariate function of the presuppression budget as area burned depends not only on the amount of money spent on presuppression but also on how those funds are allocated to the many presuppression activities that can take place.

Consider, for example, a very simple fire management organization that has no prevention program and no airtankers. It has a fixed presuppression budget and must decide how much money to use to hire fire fighters and how much money to spend on helicopters and trucks to transport fire fighters to fires. If it chooses to charter a large number of helicopters and hire a small number of fire fighters, then fire fighters will be able to fly to fires as soon as they are reported. However, on days when many fires are reported, the supply of fire fighters will be quickly exhausted, and the fires that occur later in the day will burn freely for long periods of time while they wait for fire fighters to be released from the earlier fires or borrowed and flown in from other agencies at increased cost. If the agency hires many fire fighters and charters few helicopters, then the first few fires reported each day will be helitacked quickly, but the later fires will wait and burn freely for long periods of time as crews travel to them by truck or wait for helicopters to be released from earlier fires.

What is needed, of course, is a multidimensional fire management production function that relates the annual area burned to, for example, prevention efforts, the number and location of fire lookout towers, the number and type of detection aircraft and detection observers hired, the number and type of airtankers chartered, the number and type of transport helicopters chartered, and the number of fire fighters hired. It is not possible to develop such functions to be used in the LCD optimization framework at the present time, and it is doubtful that it will be possible to do so in the foreseeable future.

Another critical limitation of the basic LCD model is that its deterministic structure does not capture the stochastic elements that are so characteristic of forest fire management systems. Fire management success varies significantly from year to year, not only due to changes implemented by managers but more often due to variability in weather, fire ignition, and fire behavior processes.

The most significant problem that limits the practical significance of the LCD model is one that extends far beyond fire management and that is the difficulty of assessing fire impacts and expressing them in monetary terms so that the net impact of alternative fire management strategies can be assessed in monetary terms. Most forest fire management agencies have a hierarchy of objectives that guide their activities. For example, the Ontario Ministry of Natural Resources' fire management objectives are, in order of priority: (1) to enhance public safety, (2) to reduce the detrimental impact of fire on property and forest resources, and (3) to utilize the beneficial impacts of fire which may include the use of prescribed fire for silviculture purposes and modified suppression of fires in some remote areas to benefit from the impact of fire on natural ecosystems.

Historical data clearly indicate that fire management saves lives, but it is difficult to assess how it contributes to public safety. Even if it were possible to do so, it would be neither possible nor socially acceptable to assign a monetary value to the lives saved. Property loss reductions are also difficult to assess as that would entail identifying physical structures such as houses and transportation facilities that might have burned had fires not been suppressed, and using their monetary value to assess the damage averted. Even if that could be done, the human cost incurred when, for example, homes are burned exceeds the assessed cost of the structures destroyed, and it would not be possible to assess such costs.

Growing recognition that fire is a natural component of many ecosystems poses even greater challenges. Previous chapters make it eminently clear that it is difficult to assess the impact of fire on ecosystems and that such problems will persist for the foreseeable future. Add to that the need to express such impacts in monetary terms, and it is clear that such problems will not be resolved for a very long time, if ever.

Given such limitations, the LCD model provides valuable insight into the basic principles of fire economics but is of little or no practical significance. Fire managers and the political institutions that support them, therefore, rely on heuristic approaches to fire management budgeting. In the past, they typically implemented slight changes from year to year, particularly after "bad" fire seasons when people reacted to severe losses and funding levels were increased or when governments grew complacent after a few "good" years and attributed small fire losses to an "overabundance" of fire suppression resources (rather than some fortuitous combination of adequate resources, sound fire management, good weather, and good luck) and diverted funds from fire programs to other pressing needs. They relied on their intuition and allocated what they thought might be the best amount of money to spend on presuppression based on their experience and understanding. In Section V, we describe how level of fire protection planning is currently practiced, but first we will describe one fire impact that can be assessed in both physical and monetary terms—the impact of fire on industrial fiber production or timber supply.

## B. ASSESSING THE IMPACT OF FIRE ON TIMBER SUPPLY

North American forests have been, and continue to be, used extensively for industrial timber production, and most North American forest fire management agencies were developed to protect people and timber from fire damage. It is therefore not surprising that a great deal of effort has been devoted to assessing the impact of fire on timber supply and that is the impact that is perhaps best understood. Forests are now viewed as far more than industrial fiber sources and that will become even more evident in the future, but we do not know how to measure or assess the impact of fire on those other "nontimber" values. Since the methodologies developed to assess the impact of fire on timber supply might ultimately be extended to some nontimber values, this subsection is devoted to a detailed analysis of the impact of fire on timber supply.

We will use a simple hypothetical 100,000-ha jack pine forest that is used solely for industrial timber production to illustrate how one can assess the impact of fire on timber supply. Assume our hypothetical forest has the stand age class structure shown in columns 1 and 2 of Table 1 and in Figure 4.

We will assume that the merchantable volumes produced when stands are harvested vary with age as shown in column 3 of Table 1, which contains the gross merchantable volumes for Site Class II jack pine stands in the province of Ontario taken from Plonski (1974).

Suppose a fire burned 4000 ha of age class 7, 3000 ha of age class 8, 2000 ha of age class 9, and 1000 ha of age class 10. Using the gross merchantable volume

TABLE 1 Age Class Distribution and Yield of Merchantable Timber Volume for the Hypothetical Forest

| Age class (years) | Area (ha) | Gross merchantable volume ($m^3$/ha) |
|---|---|---|
| 0–10 | 18,127 | 0 |
| 10–20 | 14,841 | 0 |
| 20–30 | 12,151 | 23 |
| 30–40 | 9,948 | 68 |
| 40–50 | 8,145 | 110 |
| 50–60 | 6,669 | 147 |
| 60–70 | 5,460 | 174 |
| 70–80 | 4,470 | 190 |
| 80–90 | 3,660 | 199 |
| 90–100 | 2,996 | 203 |
| 100–110 | 2,453 | 204 |
| 110–120 | 2,009 | 204 |
| 120–130 | 1,644 | 204 |
| 130–140 | 1,346 | 204 |
| 140–150 | 1,102 | 204 |
| > 150 | 4,979 | 204 |
| Total | 100,000 | |

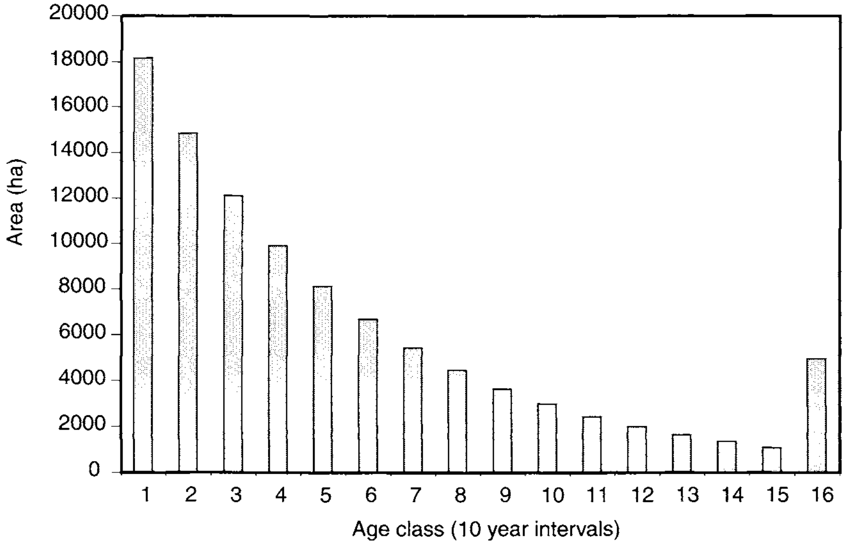


FIGURE 4 Age class distribution of the hypothetical forest.

figures in column 3 of Table 1, we find that the volume burned would be 1,867,000 $m^3$. Our first task is to assess the impact of such a fire.

Suppose the company that harvests wood from the hypothetical forest sells it at a rate of \$5.00/$m^3$. A superficial *burn site* assessment of the fire could be obtained by multiplying the merchantable volume of the wood consumed by the fire by the selling price of wood and that would produce an estimated cost of \$9,335,000 for the 10,000-ha fire. The true economic cost of the timber destroyed by the fire can differ significantly from this figure as we explain later.

The harvesting activities that take place in a forest that is managed for timber production will be governed by a timber harvest scheduling plan that stipulates when each stand is to be cut. The economic value of the timber is the present net worth of all the economic returns associated with the harvesting activities that are scheduled to occur over the planning horizon. Suppose future costs and revenues are discounted at an annual rate of 3%. The present value of a cubic meter of wood that is to be sold 5 years from now is not \$5 but rather $\$5/(1.03)^5$ or \$4.31. The economic value of the timber in a forest is therefore determined by the harvest schedule, but when fire burns stands that are scheduled to be harvested, that schedule will have to be revised. The cost of a fire is therefore the economic value of the timber as determined by the preburn harvest schedule minus the economic value of the timber determined by the revised postburn harvest schedule.

Van Wagner (1979) was one of the first to focus attention on forest-level fire and timber supply issues, and he used computer simulation models to do so. Forest managers have developed and used a myriad of techniques to develop timber harvest schedules, and linear programming optimization models are often used for such purposes. Johnson and Scheurman (1977) describe what they refer to as the standard Model I and Model II forms of the timber harvest scheduling model. Timber harvest scheduling linear programming (LP) models are deterministic models, but the need to account for the variability of fire leads to stochastic forest level problems that are complex, largely mathematically intractable problems. Fortunately, Reed and Errico (1986) developed a mean value formulation of the forest-level problem in which one assumes some constant average fire loss occurs each year. Although this approach ignores the variability that complicates forest management under uncertainty, their mean value formulation of the problem produces timber harvest scheduling solutions that are close to those solutions which more detailed stochastic models would produce for sufficiently large forest management units. The Reed and Errico (1986) model is similar in structure to Model II, but it is different enough to merit recognition as a new form, Model III. One of the most appealing aspects of Model III is that it is well suited for dealing with flammable forests.

The form of Model III we use here is identical to the model presented in Martell (1994) which is a variant of the basic Reed and Errico (1986) model. A 300-yr planning horizon is partitioned into 30 10-yr periods, and the forest stands are aggregated into 10-yr age classes. Let $x_{i,t}$ denote the area of the forest in age class $i$ at the start of period $t$, and let $h_{i,t}$ denote the area of age class $i$ harvested during period $t$. Assume that some constant fraction of the forest (0.2%) burns each year, that harvesting takes place before burning in each period, and that the burned area is uniformly distributed over the forest. Stands are assumed to regenerate naturally to jack pine after harvesting or burning. The harvest flow is constrained to be constant and a terminal constraint that the merchantable volume growing in the forest at the end of the 300-yr planning horizon average 40.2 $m^3$ $ha^{-1}$ is imposed to ensure the entire forest is not clear cut at the end of the planning horizon.

The Model III LP model can be used to assess the impact of a fire (and fire management) on our hypothetical forest. The economic impact of a fire on the timber value of a forest is the timber value of the forest given the prefire timber harvest schedule less the postfire value under a revised plan. Neither plan has to be optimal, but it makes little sense to evaluate fire impacts using suboptimal timber harvest schedules. The optimal preburn Model III timber harvest schedule for our 100,000-ha hypothetical forest produces an annual allowable cut of 2.41 $m^3$ $ha^{-1}$ $yr^{-1}$ and a present net worth of $407/ha. The optimal postburn timber harvest schedule produced by running Model III with a revised age class structure (all the burned area is moved into age class 1) produced an annual allowable cut of 2.37 $m^3$ $ha^{-1}$ $yr^{-1}$ and a present net worth of $399/ha, a loss of 2%. Thus a fire that burns 10% of the area and 21% of the volume reduces the value of the forest by only 2%. It is important to note, however, that this numerical result is specific to this particular hypothetical forest and the relative sizes of the burn fraction and that loss cannot be generalized to other fires and forests with different age class structures, growth and yield functions, and harvest flow constraints.

Timber harvest scheduling models can also be used to help evaluate and set initial and extended attack priorities. Suppose that two fires were burning out of control and threatening to grow even larger in two distinctly different parts of a forest. One could assess the pre- and postburn values of the forest for both fires and determine which of the two fires would have a greater impact on the economic value of the timber in the forest. Such information could be used to inform decisions concerning the allocation of scarce suppression resources to escaped fires.

Timber supply models can also be used to evaluate fire management programs. Figure 5 is a graph that relates the annual allowable cut to the average annual burn fraction in our hypothetical forest. Suppose that the average annual burn rate of the natural fire regime in our hypothetical forest was 2% and that fire management reduced that to 0.2%/yr. That would increase the an-

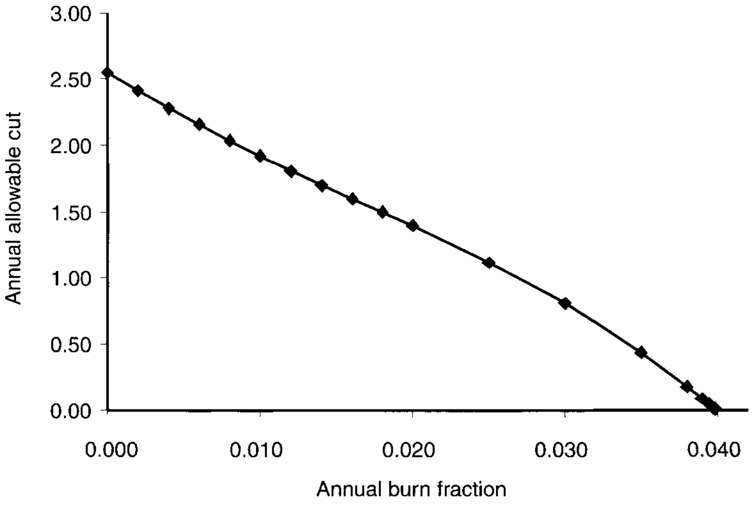


FIGURE 5 The impact of the annual burn fraction on the annual allowable cut in the hypothetical forest.

nual allowable cut from 1.40 $m^3\ ha^{-1}\ yr^{-1}$ (a present net worth of $236/ha) to 2.41 $m^3\ ha^{-1}\ yr^{-1}$ (with a present net worth of $407), an increase of 72% in the timber production value of the forest. Since that present net saving of $171/ha would be realized over a 300-yr planning horizon, it can be transformed (using a 3% discount rate) into an equivalent annual saving of $5 $ha^{-1}\ yr^{-1}$.

Timber is but one of many forest-based values that benefit people, but some of the lessons we have learned about evaluating the impact of fire on timber supply may be applicable to other values. Boxall *et al.* (1996), for example, have studied the impact of fire on the attractiveness of recreational canoe routes. When a fire burns through an area through which a canoe route passes, that fire will alter the vegetation of some portion of the larger network of canoe routes in ways that are not evident by looking at the burn site itself. To assess the impact of such a fire, one would have to evaluate the canoe route network before and after the fire. Clearly, scale is important when assessing fire impacts and stand- or burn-site specific assessments are not appropriate for assessing the impact of fire on timber supply. The management unit is an appropriate scale at which to assess the impact of fire, but it is important to recognize that it is based on an assumption that management units are independent entities. That may well be the case when they are owned or managed by competing enterprises, but companies or governments can pool management units for risk management purposes, and that possibility means that there is nothing inherently sacrosanct about management boundaries.

If one wishes to assess the ecological impact of fire, it is clear that one must look beyond the burn itself, but it is not obvious how far one must look. One can, as is the case with timber production and management units, identify the habitat utilized by some species of interest and attempt to identify a scale which captures the true impact of fire on those populations. Clearly, the appropriate scale will vary by species and the communities of interest.

It is also important to note that, when the impact of a specific fire is assessed, assessment should be carried out within a context of the underlying on-going fire regime. Using a Model III LP model pays explicit recognition to the fact that, were you to save some forest stand from destruction due to fire today, your "saving" will be measured with respect to the fact that the stand might well burn in the near future despite your most recent intervention. The fire regime embedded in Model III accounts for that factor. The larger the average annual burn fraction, the smaller the economic impact of a specific fire, since increased annual burn fractions decrease the values of both the pre- and postburn forests. The ecological impact of fire must also be assessed in such contexts.

Finally, it is important to note that fire impacts need not be expressed in monetary terms. The impact of fire on timber supply can be evaluated in terms of its impact on projected harvest flow or dollars, and both are legitimate measures that may be of interest to fire management clients. Since it would be difficult, if not impossible, to assess the ecological impact of fire or its impact on environmental services in monetary terms, fire managers and their clients need to identify what measure or measures to use and then develop multiattribute evaluation procedures for evaluating fire management programs, a challenge that lies well beyond the scope of this chapter.

## IV. FOREST FIRE MANAGEMENT ORGANIZATIONS

Forest fire management organizations are emergency response systems but, unlike urban fire, police, and ambulance services, they deal with natural processes that can have both beneficial and detrimental impacts on people, property, forest resources, and ecosystems. Since it is virtually impossible to exclude fire from most forests and attempts to do so can be very costly, fire management agencies use the resources allocated to them to minimize what they and their land management clients collectively judge to be the net detrimental impact of fire.

A fire regime will produce a spatial and temporal distribution of burn patches embedded in a larger forest landscape composed of many patches that have been shaped and influenced by both human and natural processes. Consider the simplest case in which we focus on one very simple result of a fire regime, the average annual fraction of the fire management area or fire region burned each year. That burn fraction should be compatible with the forest management objectives, and the role of the fire manager is to develop and implement a fire management plan that will achieve that average annual burn fraction at a reasonable cost. Fire managers often partition the area under their jurisdiction (the *fire region*) into zones or compartments that are reasonably homogeneous with respect to ecosystem processes, land use activities, and values at risk and then specify their fire management objectives in terms of fire regimes or the level of fire protection they will attempt to achieve in each zone.

The forest fire management planning process can then be viewed as comprising four basic steps:

1. Partition the fire region into zones or compartments that are reasonably homogeneous with respect to forest ecosystems, land use patterns, and values at risk;
2. Assess the potential beneficial and detrimental impacts of fire in each zone;
3. Select an appropriate level of protection or fire regime for each zone and develop a plan to minimize the cost of achieving that objective;
4. Implement, monitor, and revise the fire management plan over time.

Forest fire management objectives vary from agency to agency, a reflection of the variability of both societies and the ways in which they interact with the ecosystems that envelop them. The Aviation, Flood, and Fire Management Branch of the Ontario Ministry of Natural Resources, the agency responsible for forest fire management in the province of Ontario in Canada, is representative of many large North American forest fire management agencies. The OMNR is responsible for fire management on more than 85 million hectares and spends roughly $85 million a year on its activities. A permanent staff of 220 is augmented by 640 fire fighters that are hired each fire season. The agency also operates an aircraft fleet that includes 9 large CL-415 airtankers and 5 smaller Twin Otters that can serve as airtankers. Approximately 14 helicopters, 15 detection aircraft, and 7 bird-dog aircraft (that carry air attack officers that direct airtanker operations over the fire) are hired each season, but those figures vary from year to year. The OMNR participates in national and international mutual aid agreements that make it possible for it to share its fire suppression resources with other North American fire management agencies and to borrow resources from other agencies when the need arises.

During the years 1976–1999, the number of forest fires in Ontario ranged from 735 to 3970 per year with an average of 1713 fires per year and a median of 1588 fires per year. The area burned each year during that period ranged from 9444 to 611,939 ha with an average of 241,734 ha/yr and a median of 176,462 ha/yr. The year-to-year variation in the number of fires and area burned are illustrated in Figures 6 and 7.

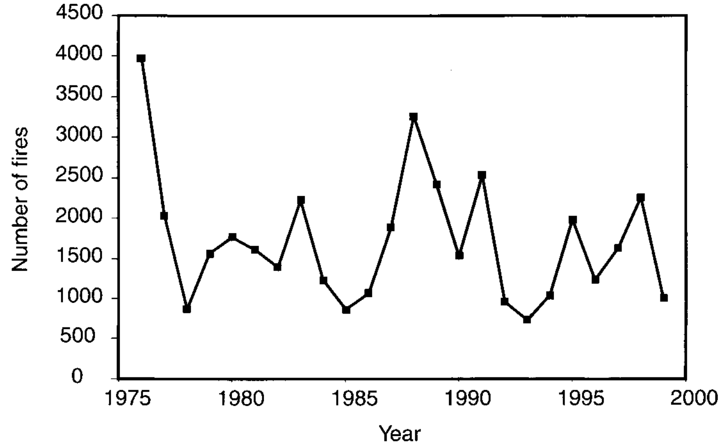


FIGURE 6 Number of forest fires in Ontario, 1976–1999.

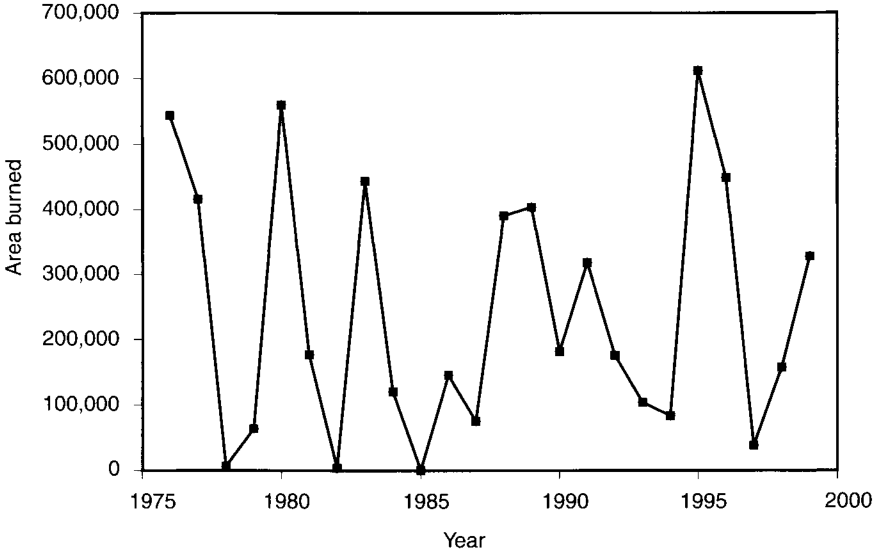


FIGURE 7 Area burned by forest fires in Ontario, 1976–1999.

## A. A Simple Fire Suppression Model

Societies allocate funds to fire management on the assumption that the allocation will reduce the damage that results from wildfire and enable them to reap some of fire's benefits. In this section, we present a simple conceptual model of the fire suppression process which will illustrate how such activities can influence final fire size that, in turn, influences the economic impact of fires.

Forest fires are ignited by people or some natural agent such as lightning, and they smolder or burn with an active open flame and emit smoke until they are either extinguished due to a lack of combustible fuel or detected and reported to the duty officer or initial attack dispatcher who decides what suppression resources will be dispatched to the fire. The initial attack crew travels to the fire by truck or by air, sets up its suppression equipment at or near the fire, and begins suppression action as soon as possible. The ground crew may or may not be assisted by airtankers that drop water or fire retardant on, or just ahead of, the active fire front.

The effectiveness of the initial attack force will depend upon its composition, how soon it arrives at the fire, the fuel and terrain in which the fire is burning, and the fire's behavior. Most North American forest fires are contained when they are relatively small, but some escape initial attack and can grow to very large sizes. Such fires are usually classed as escaped fires and, when they become large, they can seldom be controlled until favorable weather conditions arrive and persist long enough for the fire fighters to establish control lines that are strong enough to contain the fire if and when weather conditions subsequently deteriorate.

Forest fire management agencies use fire control status classification systems to identify a fire's control status and important points and intervals of time in its life cycle. We combined the fire control status classification system used by the Ontario Ministry of Natural Resources with the formal mathematical model and graphical representation of the life cycle of a fire developed by Parks (1964) and modified the combined system slightly to produce the formal description of the life cycle of a wildland fire presented in Table 2 and Figure 8.

The sooner a fire is detected and reported, the larger the initial attack force; and the quicker it arrives at the fire, the more likely the fire will be contained at a small size. Some fires, however, are so large and/or intense that they cannot be contained regardless of the size of the initial attack force, and they can burn freely until a significant change in fuel, weather, topography, or some combination of these factors occurs and the fire intensity decreases to levels where fire fighters can work safely to contain their spread.

TABLE 2 **Fire Control Status Classification System**

| Event | Description | Time | Time interval |
|---|---|---|---|
| Ignition | Fire is ignited. | $T_{IGN}$ | — |
| Detection | Fire is detected by the public or the fire management agency. | $T_{DET}$ | Detection interval $= T_{DET} - T_{IGN}$ |
| Report | Fire is reported to the duty officer or the initial attack dispatcher. | $T_{REP}$ | Report interval $= T_{REP} - T_{DET}$ |
| Dispatch | Initial attack resources dispatched to the fire. | $T_{DISP}$ | Dispatch interval $= T_{DISP} - T_{REP}$ |
| Arrive | Initial attack forces arrive at or near the fire perimeter. | $T_{ARR}$ | Travel time $= T_{ARR} - T_{DISP}$ |
| Attack | Initial attack suppression action begins. | $T_{ATT}$ | Response time $= T_{ATT} - T_{REP}$ |
| Being Held | Fire classed as being held (BHE). The fire is no longer spreading but has the potential to resume spreading in the near future. | $T_{BHE}$ | Time to containment $= T_{BHE} - T_{ATT}$ |
| Under Control | Fire classed as under control (UCO). The fire is no longer spreading and is not expected to resume spreading in the future. | $T_{UCO}$ | Control interval $= T_{UCO} - T_{ATT}$ |
| Out | Fire is declared out (OUT). | $T_{OUT}$ | Mop up $= T_{OUT} - T_{UCO}$ |

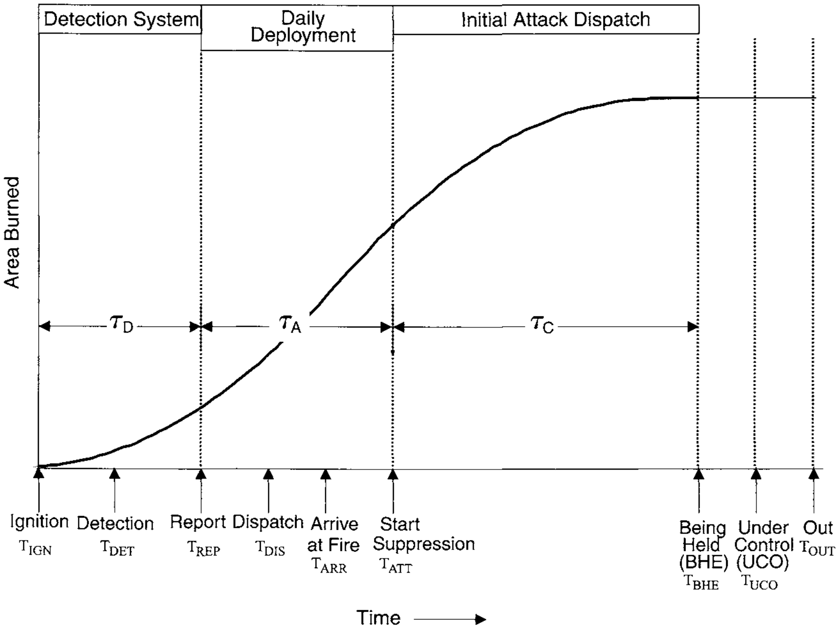


FIGURE 8 The life cycle of a forest fire.

Parks (1964) developed a simple single fire suppression model that can be used to illustrate how the components of a fire management system interact to determine the final area burned. He assumed that fires were reported as soon as they were detected, and he defined the detection interval $\tau_D = T_{DET} - T_{IGN}$ as the time between ignition and detection. He assumed that the initial attack force begins suppression action as soon as it arrives at the fire, and he defined the attack interval, $\tau_A = T_{ATT} - T_{REP}$, as the elapsed time from detection (report) until fire suppression action begins. He defined the control interval, $\tau_C = T_{BHE} - T_{ATT}$, as the time to contain the spread of the fire.

Parks began by ignoring fire geometry and developed a very simple aspatial fire spread model. He assumed that, in the absence of suppression activity, the growth of a free-burning fire (area/unit time) at the time it is detected ($T_{DET}$) can be represented by the following differential equation:

$$\frac{dy}{dt} = G_D + Ht \qquad y(0) = y_D \tag{1}$$

where $y$ is the area burned, $dy/dt$ is the rate of fire growth, $t$ is the elapsed time measured from the time the fire is detected, $y(0)$ is the size of the fire when it is detected, $G_D$ is the fire's growth rate when it is detected, and $H$ is the acceleration component of fire growth.

Let $y_A$ denote the size of the fire at time $T_{ATT}$ when suppression action begins. Then

$$y_A = y(\tau_A) = y_D + G_D\tau_A + \tfrac{1}{2}H\tau_A^2 \tag{2}$$

and at that time the fire will continue to grow at a rate

$$G_A = y'(\tau_A) = G_D + H\tau_A \tag{3}$$

Consider, for example, the simple case in which a fire burns freely on a flat area in the absence of wind in the shape of a circle with a radius that increases at a constant rate which depends on the current condition of the forest fuel complex and the weather. Let $R = r\tau_D + rt$ denote the radius of the fire at time $t$ where $r$ is its constant radial rate of spread and $t$ denotes the elapsed time from the time the fire was detected (and reported). If $A(t)$ denotes the area of the fire at time $t$, then

$$A(t) = \pi r^2\tau_D^2 + 2\pi r^2\tau_D t + \pi r^2 t^2 \tag{4}$$

and

$$\frac{dA(t)}{dt} = 2\pi r^2\tau_D + 2\pi r^2 t \tag{5}$$

so

$$y_D = \pi r^2\tau_D^2 \tag{6}$$

$$G_D = 2\pi r^2\tau_D \tag{7}$$

and

$$H = 2\pi r^2 \tag{8}$$

Parks (1964) modeled the growth of a fire that is being fought as follows. Let $x$ denote the number of units of fire suppression resource allocated to the fire, and assume that those resources decelerate the growth of the fire. Let $E$ denote the efficiency factor for the fire suppression resources. Parks assumed that the effect of the suppression force is to decelerate the rate of growth of the fire at some rate which is a linear function of the size of the force and the time it works. The growth of the fire at time $t$ after $T_{ATT}$, the time suppression begins, is, therefore,

$$\begin{aligned}\frac{dy}{dt} &= G_D + Ht - E(t - \tau_A)x \qquad t \geq \tau_A \\ &= G_A - (Ex - H)(t - \tau_A)\end{aligned} \tag{9}$$

Let $\tau_C = T_{BHE} - T_{ATT}$ denote the elapsed time interval from the start of initial attack until the fire is declared as being held or contained (BHE). It can be shown that the area burned from the time suppression action begins until the fire ceases to spread is

$$y_C - y_A = \frac{G_A^2}{2(Ex - H)} \tag{10}$$

The growth of the fire is composed of two parabolic portions, one when the fire is burning freely and accelerating until suppression action begins, and a second after suppression action begins when it begins to decelerate. Note that the number of suppression units allocated to the fire must be greater than $H/E$ to bring the fire under control. Parks' model is illustrated in Figure 8. In his case, there is no delay between detection and report so $T_{DET} = T_{REP}$ and no delay between when the crew arrives at the fire and starts suppression so $T_{ARR} = T_{ATT}$.

Others have studied the fire suppression process and developed mathematical models to predict the final size and shape of a fire depending upon its behavior, the productivity of the suppression force, and their interaction. Fried and Fried (1996) reviewed some of the many models that have been developed and developed a containment model that overcomes many of the limitations inherent in earlier models. They showed how their model can be applied and solved numerically to predict the final size and shape of an elliptical fire that is subjected to direct attack by ground crews.

One of the most appealing features of the Parks (1964) model is that the final size of the fire can be expressed as an explicit function of fire behavior and fire suppression productivity parameters. It indicates that the more resources devoted to detection, the faster the fire is detected, the smaller $\tau_D$ is, and the smaller the final size of the fire is. The more money allocated to initial attack transport (the use of helicopters rather than trucks, for example), the smaller $\tau_A$ is and the smaller the final fire size is, assuming that there are always fire fighters available to be dispatched whenever a fire is reported (an issue we address later in this chapter). The more suppression resources dispatched to the fire, the shorter $\tau_C$ is and the smaller the final fire size is. The more resources devoted to mop up, the less likely the fire will escape once it has been declared BHE. Such predictions are compatible with what fire managers believe about real fire suppression processes.

The next step is to explore the economics of fire suppression, and Parks (1964) did just that. He defined the following components of the cost of a fire:

$C_F$ = the fixed cost of maintaining the fire suppression organization ($ per fire)
$C_S$ = cost of dispatching a unit of fire suppression resource to a fire (e.g., the cost of transporting the resources to the fire) ($ per unit of suppression resource)

$C_T$ = cost incurred by the need to increase the fire organization's readiness while the fire is burning out of control ($ per unit time)
$C_B$ = cost of fire damage incurred per unit area burned ($ per unit area)
$C_X$ = suppression cost incurred while the fire is burning out of control ($ per unit resource per unit time)

Let $x_0 = H/E$ denote the minimum suppression force required to contain the fire, $x$ be the size of the suppression force, and $z = x - x_0$ denote the number of suppression units above $x_0$ sent to the fire.

The fire will be contained and declared BHE or reach its final size when it stops growing or $dy/dt = 0$. Given Eq. (9), it can be shown that the fire stops growing when $\tau_C = t - \tau_A$ is given by the following expression:

$$\tau_C = \frac{G_A}{(Ex - H)} \tag{11}$$

The total cost of the fire is, therefore,

$$C = C_F + C_S x + C_T \tau_C + C_B y_C + C_X \tau_C x \tag{12}$$

or

$$\begin{aligned} C = C_F + C_S x + C_X \frac{G_A}{(Ex - H)} x + C_B \left[ y_A + \frac{G_A^2}{2(Ex - H)} \right] \\ + C_T \left[ \frac{G_A}{(Ex - H)} \right] \end{aligned} \tag{13}$$

If we let

$$C_R = C_B + \left[ 2 \frac{C_T}{G_A} \right]$$

then

$$C(z) = C_0 + C_S z + \frac{(C_X G_A H/E^2) + (C_R G_A^2/2E)}{z} \tag{14}$$

where

$$C_0 = C_F + \frac{C_S H}{E} + \frac{C_X G_A}{E} + C_B y_A$$

Parks (1964) showed that the optimal number of suppression resources to allocate to a fire is given by the following expression:

$$z^* = \sqrt{\frac{C_R G_A^2 E + 2 C_X G_A H}{2 E^2 C_S}} \tag{15}$$

### 1. A Numerical Example

Consider a fire for which $G_D = 2.0$ ha hr$^{-1}$, $H = 1.5$ ha hr$^{-2}$, $E = 0.5$ ha hr$^{-2}$ per suppression unit, $y_D = 0.25$ ha, and $\tau_A = 0.57$ hr. Suppose that $C_F = 0$, $C_S = 100$, $C_X = 3.0$, $C_B = 500$, and $C_T = 0$. Using the expression for the optimum suppression effort given above, $x_0 = 3.0$, $z^* = 7.0$, and the optimum suppression effort for this fire is 10 units. Figure 9 illustrates how the total cost plus loss for this fire varies as the fire suppression effort varies.

Parks (1964) applied his model to some specific fire shapes (e.g., direct and indirect attack on rectangular fires that burn freely on one side like a fire burning up a canyon). He also extended his model to deal with the optimization of two simultaneous fires under certainty, and he solved a simple stochastic fire suppression problem which he modeled as a Markov decision process.

Fire managers must weigh the costs and potential benefits of deciding how many resources to allocate to each activity and each fire, and, when they do so, they must consider other fires that are burning or might be reported in the near future. Given the number of factors that must be considered and the uncertainty involved, this clearly is a daunting task. Although the Parks (1964) single and multiple fire suppression process models provide valuable insight into the behavior of fire suppression systems, they are not robust enough to serve the prac-

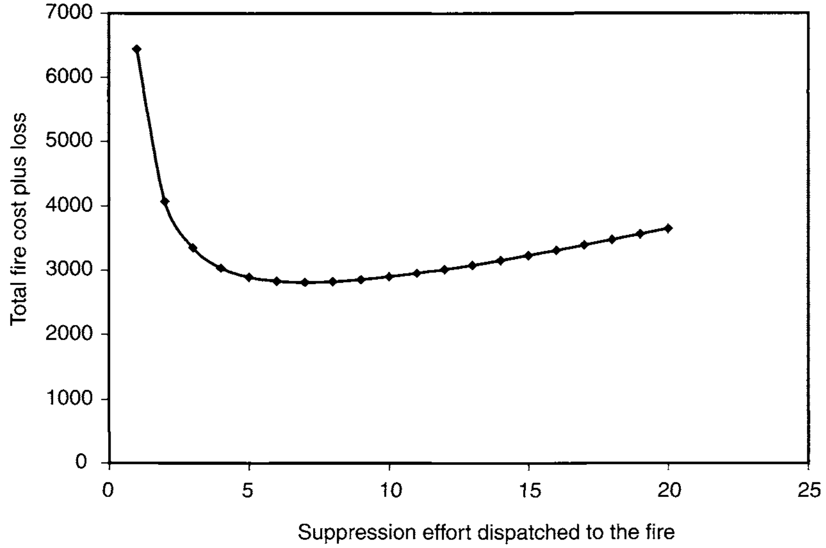


FIGURE 9 Numerical example of Parks' (1964) single fire suppression model.

tical needs of fire managers. We will now describe the basic components of a modern forest fire management system and study how fire managers deal with such problems. We begin with the fire load management subsystem depicted in Figure 2.

## B. FIRE LOAD MANAGEMENT

The term *fire load* refers to the magnitude of the suppression task associated with fires that occur in a designated area during some specified time interval, typically a day. The more fires that occur and the larger and more intense they are when detected, the greater the fire load is. The objective of the fire load management subsystem is to reduce the fire load to be managed. This can be accomplished by preventing fires from occurring, modifying the forest fuel complex to temper the behavior of fires that do occur, and detecting and reporting wildfires soon after they are ignited so that they are small when the initial attack fire suppression force arrives.

### 1. Fuel Management

The objective of the fuel management subsystem is to modify forest vegetation or fuel complexes to reduce the likelihood that fires will occur and to stop or slow the spread of fires and thereby reduce the social, economic, and biological impacts of fires that do occur. It includes the construction and maintenance of fuel breaks, extensive understory thinning or fuel modification, and the use of prescribed fire to modify fuels to reduce their flammability, for silvicultural purposes, or to enhance wildlife habitat. Fire is a natural component of many forest ecosystems, and agencies that are responsible for fire management in some parks and wilderness areas may use prescribed fire in an attempt to sustain natural ecosystem processes. Fuel management influences the *type* and *intensity* aspects of a fire regime directly, but it also indirectly influences its *fire size* or *extent*. Martell (1982) described some of the decision support systems that have been developed to enhance fuel management decision making, but our understanding of fuel management is ultimately based on the extent to which we understand how fire spreads through heterogeneous fuel complexes that include patches and strips that have been modified to influence fire behavior.

### 2. Fire Prevention

Since the objective of the fire prevention program is to reduce the number of people-caused fires that occur in designated areas, it can reduce the *fire frequency* characteristics of a fire regime. Fire prevention specialists must decide how to encourage people to refrain from starting fires intentionally or accidentally. They use media advertising campaigns to transmit prevention messages to the public, invoke site-specific land use restrictions such as forest closures that prohibit travel in designated areas, or ban the use of campfires by recreationists to reduce the likelihood that accidental fires will occur. They carry out fire investigations to determine how specific fires were started and sometimes invoke law enforcement measures to sanction people who start fires. Martell (1982) described some of the prevention studies that have been carried out in the past. However, human behavior is influenced by media advertising that reaches them throughout their lives, beginning with fire prevention programs directed at young school children as well as localized special advertising and land use restrictions invoked during hazardous fire weather conditions. Therefore, it is very difficult to assess the effectiveness of prevention measures. As a consequence, fire prevention processes are not well understood, and there are few decision support systems to enhance the cost effectiveness of prevention programs.

## 3. Predicting Daily Fire Occurrence

Prevention planners need to know when and where people-caused fires might occur so that they can focus their efforts where they will have their greatest impact. Detection planners need to know when and where both people and lightning-caused fires are likely to occur so that they can direct their detection patrols to fly near those fires soon after they ignite. Later in this chapter, we will illustrate the importance of daily fire occurrence predictions to fire managers who must deploy their initial attack resources close to fires before they are reported to minimize initial attack response times. In this section, we will discuss daily fire occurrence prediction, one of the key components of a fire management information system. We will deal primarily with people-caused fires to explore the basic principles of daily fire occurrence prediction, but we will also summarize very briefly some of the lightning-caused fire occurrence and fire arrival prediction systems that have been developed.

### *a. Predicting Uncertain Events*

The daily occurrence of forest fires can be characterized as a random or chance process. Just as we are uncertain whether heads or tails will result when a coin is tossed, we are almost always uncertain how many fires will occur each day. On some days fire occurrence predictions can be made with greater certainty than on others; for example, that no fires will occur on a rainy day with no lightning. Nevertheless, there is almost always some degree of uncertainty involved.

### *b. Forest Fire Ignitions and Arrivals*

It is important to distinguish between the occurrence and arrival of forest fires. The occurrence time is the time a fire is ignited. Another important time is the time the fire is first reported to the fire management agency or it "arrives" and demands the organization's attention. Given the hold-over behavior of some fires that may smolder undetected for several days before they are detected, particularly those caused by lightning, it is important to distinguish between predictions concerning fire occurrences and fire arrivals. Not all fires that occur will eventually arrive since some of them will be extinguished naturally by weather or a lack of fuel.

### *c. Probabilistic Models of People-Caused Fire Occurrence*

The binomial probability distribution can be used to model the daily occurrence of people-caused fires in a specific area. The binomial distribution is applicable to processes with repeated independent trials (e.g., Blake, 1979) such as people subjecting forest fuels to firebrands. Suppose that there are $n$ people in a forested area during a particular day and that each of those people subjects the forest fuel complex to a single firebrand. Let each firebrand represent an independent trial which results in success (a fire occurs) or failure (a fire does not occur). Let $\theta$ denote the probability that a trial results in a fire, and assume that it is the same for all the people in the forest. If the probability of success is constant and the trials are independent (people do not influence each other), the probability distribution of the number of fires that will occur is binomial with parameters $n$ and $\theta$:

$$\begin{aligned} b(x; n, \theta) &= P\{x \text{ successes in } n \text{ trials}\} \\ &= \frac{n!}{x!(n-x)!}\theta^x(1-\theta)^{n-x} \qquad x = 0, 1, 2, \ldots n \end{aligned} \tag{16}$$

In most jurisdictions, it would be very difficult to determine how many people are present in a designated area each day. It is, therefore, difficult to use historical data to estimate $\theta$ and to determine $n$ to predict fire occurrence during any particular day. Fortunately, it can be shown (e.g., Blake, 1979), that the Poisson probability distribution is the limiting form of the binomial distribution as $\theta$ becomes very small, $n$ becomes very large, and $n\theta$ remains constant. That is, lim as $\theta \rightarrow 0$, $n \rightarrow \infty$, and $n\theta$ remains constant,

$$b(x; n, \theta) \cong \frac{\lambda^x e^{-\lambda}}{x!} \tag{17}$$

where $\lambda = n\theta$ is the expected number of fires per day.

Since there are usually many people in the forest and the probability that any one of them will start a fire is very small, it is reasonable to use the Poisson distribution to model daily people-caused forest fire occurrence. Cunningham and Martell (1973) studied daily people-caused forest fire occurrence in the Sioux Lookout area of northwestern Ontario and found that it was reasonable to use the Poisson distribution to model fire occurrence there.

The Poisson distribution is a single parameter distribution and

$$P(x) = \frac{\lambda^x e^{-\lambda}}{x!} \qquad \text{for} \quad x = 0, 1, 2 \ldots \tag{18}$$

where $P(x)$ = probability that $x$ fires will occur and $\lambda$ = expected number of fires per day. If one accepts the validity of the Poisson model, the task is to develop operational procedures for estimating $\lambda$ for each fire management compartment each day.

### *d. A Simple People-Caused Forest Fire Occurrence Model*

Daily people-caused forest fire occurrence is influenced by many factors including the number of people present in the forest, their behavior which is influenced by the land use activities in which they are engaged and the prevention measures they have encountered, and the condition of the forest fuel complex.

The major factors which influence the occurrence of people-caused forest fires are the ease of ignition of the fine fuel and the potential number of sources of ignition to which that fuel is exposed. The Fine Fuel Moisture Code (FFMC) is one of the component indices of the Canadian Forest Fire Weather Index (Van Wagner, 1987). Since the FFMC was designed as a measure of the moisture content of the fine fuels, one would expect it to have an important effect upon people-caused fire occurrence. Previous research results (e.g., Cunningham and Martell, 1973) indicate that this is the case.

One of the simplest procedures for predicting daily people-caused fire occurrence is to use daily records of the observed FFMC and the corresponding number of fires that occurred to estimate $\lambda$, the expected number of fires per day. This can be accomplished by compiling historical fire occurrence and fire weather data into the format shown in the following numerical example.

### *e. A Numerical Fire Occurrence Prediction Example*

Suppose that one analyzed a set of historical data and obtained the results shown in Table 3. If the current day's forecast FFMC is 83, then using the for-

TABLE 3 Relationship between Average Daily People-Caused Fire Occurrence and the FFMC for a Hypothetical Area

| Category | FFMC | Days | Fires | Average number of fires per day |
|---|---|---|---|---|
| 1 | 0–74 | 200 | 2 | 0.01 |
| 2 | 75–79 | 150 | 9 | 0.06 |
| 3 | 80–84 | 120 | 18 | 0.15 |
| 4 | 85–89 | 100 | 24 | 0.24 |
| 5 | 90–100 | 90 | 32 | 0.36 |

mula for the Poisson distribution with an average of 0.15 fires per day, one would obtain the probabilistic prediction shown in Table 4.

Some forest fire management agencies use more sophisticated daily fire occurrence predictions such as the logistic regression analysis procedure developed by Martell *et al.* (1987) which can be used to predict daily people-caused fire occurrence by subseason and the procedure developed by Martell *et al.* (1989) which models seasonality explicitly. Poulin-Costello (1993) used Poisson regression techniques to relate the expected number of fires per day to fire danger rating indices. The development of lightning stroke counters and lightning strike location systems has resulted in a substantial improvement in the quantity and quality of information available for predicting lightning-caused forest fire occurrence, and analogous lightning-caused fire occurrence prediction models have been developed. For example, Kourtz and Todd (1992) developed a daily lightning fire occurrence prediction model that uses fuel moisture and lightning stroke data to predict fire ignitions. The holdover smoldering process is modeled to predict how many "detectable" fires are burning undetected in an area each day.

TABLE 4 Probabilistic People-Caused Fire Occurrence Prediction for a Category 3 FFMC Day with an Expected Value of 0.15 Fires per Day

| Number of fires | Probability |
|---|---|
| 0 | .8607 |
| 1 | .1291 |
| 2 | .0097 |
| 3 or more | .0005 |

## 4. Fire Detection

The objectives of the forest fire detection system are to find and report fires while they are small and to provide the initial attack dispatcher with information that will enable him or her to prioritize fires as they are reported and to tailor the initial attack response to the potential impact of each fire. The sooner the fire is reported and the better the information concerning its precise location, accessibility, its current size, its spread rate, its intensity, the fuel complexes ahead of the fire, and the values at risk, the more likely that threatening fires will be contained while they are still small.

The fire detection system's primary effect is on the *size* or *extent* component of the fire regime. However, since fire detection measures increase the likelihood that a fire will be contained soon after it is ignited and while it remains small, they reduce the likelihood that fire will continue to burn during later periods when more severe fire weather prevails or through more hazardous fuel complexes located elsewhere on the landscape. Fire detection activities, therefore, indirectly decrease the area burned by intense fire and thereby influence the *intensity* aspects of the fire regime as well.

During the years 1976–1999 the detection size of forest fires in Ontario ranged from less than 0.1 ha to 20,000 ha, but 0.1 ha or less is the smallest detection size that is assigned to a fire on an official fire report form in Ontario. The average detection size was 6.4 ha, but the distribution was highly skewed with a median of 0.1 ha and a mode of 0.1 ha. Of the fires, 95% were less than or equal to 3.4 ha when first detected. The skewness is largely a result of a few large fires in the extensive protection zone in the far north.

Forest fire management agencies use fixed lookout towers and patrol aircraft to detect fires, but they also depend upon the public to find and report fires in and near populated areas. Each agency's strategy is driven by the relative cost effectiveness of the different modes of detection and the values at risk. Towers and patrol aircraft comprise what is commonly referred to as the *organized* detection system, and the public constitutes the *unorganized* detection system. Those terms reflect the belief that, although fire managers can influence the behavior and effectiveness of the public, they have much more direct control over the performance of the organized detection system.

Satellites equipped with infrared scanners and other remote sensing devices can detect forest fires, but the resolution of currently publicly available satellite technology is such that satellites cannot find fires until they grow to sizes that are considered too large for effective initial attack. Satellites are, therefore, used primarily to monitor large, on-going fires in some remote low-priority areas where they can provide fire size information with some delay at less cost than conventional fixed-wing aircraft.

### a. *The Unorganized Detection System*

In most jurisdictions, the public views fire as a potentially destructive force and assumes it has a civic duty to report fires that are burning out of control in forested areas. Given such attitudes, fire management agencies need not devote scarce resources to searching for fires that will be detected and reported by the public while they are still small. It makes little sense, for example, to build a fire lookout tower at the edge of a forested community or to fly a detection patrol aircraft along a highway as the public will find and report most of the fires that occur in such areas before they are detected by trained detection observers, but at little or no cost. Fire management agencies are therefore free to let the public detect fires in and near populated areas and to devote their efforts to more remote areas where fires might burn undetected for long periods of time.

Fire managers can and should devote some resources to the unorganized detection system and enhance its cost-effectiveness by influencing public attitudes and enhancing the communications infrastructure to facilitate the reporting of fires, thereby reducing the time interval between detection and formal reporting. Fire management agencies, therefore, publicly stress the importance of reporting fires and use both print and broadcast media to publicize how to report forest fires. The unorganized detection system has benefitted from the increasing availability of cellular telephone technology in many rural areas in recent years. Since the cost-effectiveness of the unorganized detection system has not been well studied, fire managers must rely upon their intuition and experience when they decide how to influence the behavior of the people and thus the performance of the unorganized detection system in their area.

### b. *The Organized Detection System*

Most forest fire management agencies use fire towers or lookouts located atop high hills or mountains, patrol aircraft, or mixed systems with both towers and patrol aircraft, for fire detection purposes. Towers are fixed and expensive to construct and operate, but they provide constant surveillance of an area when the observer is in the tower. Tower systems, therefore, provide excellent but costly coverage.

Aerial detection systems are very flexible because patrol routes can vary from day to day or even hour to hour as fire weather conditions vary, and a patrol aircraft can be diverted from its planned route to enable the onboard observer to check suspicious smokes reported by the public. Although aircraft are expensive to charter or own and operate, most North American forest fire management agencies that rely on aircraft are satisfied with aerial coverage levels that cost less than the former towers would cost had they remained in service. However, detection aircraft provide intermittent surveillance, and once they pass over a specific area, any fires they miss or any new fires that occur before they pass near that area again can burn freely undetected and have the potential to remain undetected so long that they cannot be controlled by the initial attack force. While this problem can, to a large extent, be addressed by using many aircraft to fly almost continuous patrols over areas where potentially destructive fires are likely to occur, detection patrols never really provide the continuous coverage possible with extensive tower networks.

Kourtz and O'Regan (1968) studied the economics of fire detection systems and concluded that tower systems are best for high-value areas under intensive forest management and that aircraft are best for less-valuable extensive forest management areas with relatively small detection budgets.

Strategic detection planners must decide how many lookout towers are required and where they will be constructed. Computer-based spatial analysis techniques (see Mees, 1976, for example) can be used to assess the "seen area" surrounding each potential tower site and the number and type of fires that have occurred within the seen areas in the past.

**Detection Patrol Route Planning** Many forest fire management agencies use patrol aircraft to search for fires, and each day detection planners must decide the times at which airborne patrols will leave specified airports and the routes they will follow. Since the time and location of fires is uncertain, this constitutes a very difficult stochastic combinatorial planning problem.

Forest fire managers use the term *visibility* to describe the ability of an observer to see a *smoke,* the smoke plume that rises above a small fire burning under a forest canopy. In Ontario's boreal forest region, the visibility is usually assumed to be roughly 24 km either side of a patrol aircraft in good weather. Visibility varies from day to day and depends upon many factors including vegetation, atmospheric haze conditions, the location of the sun with respect to the observer and the fire, the altitude of the observer, the characteristics of the fire (fuel, weather, size, diurnal variation), and the observer.

Aerial detection observers do not detect every smoke they pass, and the fire detection process can be modeled as a stochastic process for planning purposes. Detection planners can divide the fire region into many small cells and define the *detection probability* as the conditional probability that the observer finds a fire when he or she looks in a cell, if there is one fire burning undetected in that cell. The detection probability depends upon the visibility factors described earlier. The following problem is a very simplified example of a daily detection patrol route planning problem which illustrates some of the basic principles of daily detection patrol aircraft management.

**A Simple Detection Patrol Routing Problem** Suppose that a fire is known to be burning in one of a number of cells some distance from the initial attack

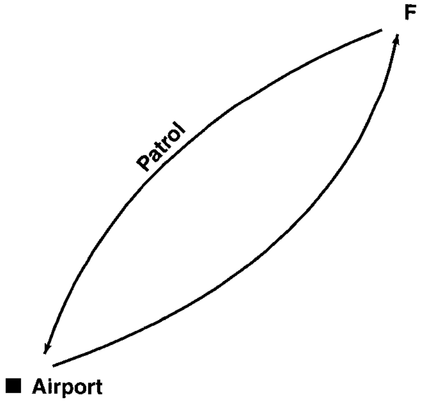


FIGURE 10 Detection patrol routing.

base but the precise cell in which the fire is located is unknown [as depicted in Figure 10]. The duty officer must know the precise location and behavior of the fire before dispatching an initial attack force. Should he/she use a patrol aircraft or rely on the public to provide that information?

The detection planner must decide whether to send a detection aircraft to look for the fire and, if so, at what time that patrol should be dispatched. To simplify the problem, we will assume that (1) the fire started at 08:00, (2) the fire spreads in the shape of a circle and the radius increases at a constant rate of 36 m $\mathrm{hr}^{-1}$, and (3) the fire damage is \$200/ha based on the size of the fire when it is detected. Given these parameters, the fire loss depending upon the time the fire is found is shown in Table 5.

Assume that the detection probability varies throughout the day as shown in Table 6 and Figure 11. The expected cost if a patrol is dispatched early enough to look in the cell at 10:00 A.M. is

$$(1000 + 320)(0.2) + (1000 + 11{,}720)(1 - 0.2) = 10\,440$$

TABLE 5 Fire Loss Assuming Fire Is Circular

| Time found (hr) | Hours burned | Area (ha) | Fire cost ($) |
|---|---|---|---|
| 10:00 | 2 | 1.6 | 320 |
| 12:00 | 4 | 6.5 | 1,300 |
| 14:00 | 6 | 14.7 | 2,940 |
| 16:00 | 8 | 26.1 | 5,220 |
| 18:00 | 10 | 40.7 | 8,140 |
| 20:00 | 12 | 58.6 | 11,720 |

TABLE 6 Detection Probability Function

| Look time | Aircraft detection probability | Public detection probability |
|---|---|---|
| 10:00 | 0.2 | — |
| 12:00 | 0.4 | — |
| 14:00 | 0.6 | — |
| 16:00 | 0.8 | — |
| 18:00 | 0.6 | — |
| 20:00 | — | 1 |

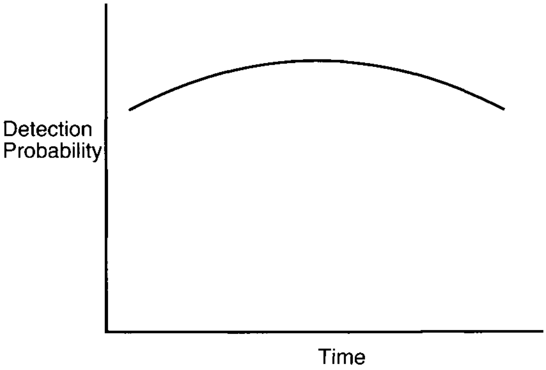


FIGURE 11 Detection probability function.

The expected costs associated with detection flights dispatched at later times are shown in Table 7. The expected cost plus loss is convex, as shown in Figure 12. The optimum solution is to dispatch a detection patrol to look in the cell at 14:00 hours.

The tactical detection patrol routing problems faced by detection planners are much more complex than this simple patrol timing problem. One can ap-

TABLE 7 Expected Cost Plus Loss

| Time the detection observer looks in the cell | Flying cost ($) | Expected cost plus loss ($) | |
|---|---|---|---|
| 10:00 | 1000 | 10,440 | |
| 12:00 | 1000 | 8,552 | |
| 14:00 | 1000 | 7,452 | **Optimum** |
| 16:00 | 1000 | 7,520 | |
| 18:00 | 1000 | 10,572 | |
| Public finds fire at 20:00 | 0 | 11,720 | **Do not fly** |

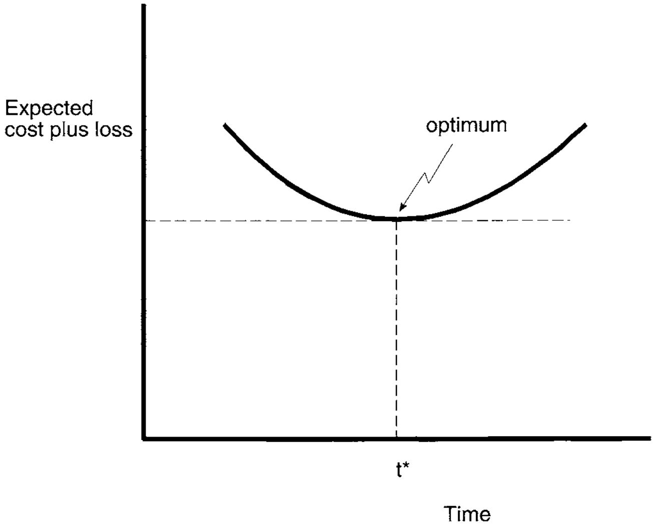


FIGURE 12 Expected detection cost plus loss function.

proach such problems by partitioning the fire region into a large number of small rectangular cells and predicting the expected number of fires or the parameters of the probability distribution of the number of new fires that occur in each cell each hour of the day. Forest vegetation or fuel type maps, weather and fire danger rating indices, and "values at risk" maps can be used to help identify potentially critical cells that "must" be visited. The task is then to design "good" sets of patrol routes that will route aircraft over or close to the critical cells.

Kourtz developed and field tested many novel approaches to daily detection routing problems, many of which were reviewed by Martell (1982). His most recent approach (Kourtz and Mroske, 1991) was to formulate the problem as what operational researchers refer to as a multiple salesperson-traveling salesperson problem, and he used a simulated annealing algorithm to solve such problems on a daily basis.

## C. FIRE SUPPRESSION

Free-burning fires grow in size, become more difficult to control, and, if they are destructive, cause more damage over time. In the simplest case, a fire on flat terrain covered with a homogeneous fuel complex will burn in the shape of a circle in the absence of wind. The perimeter and therefore the difficulty of containing the fire will increase as a linear function of time. One can view fire suppression as a race between a fire that produces burning perimeter and fire fighters that produce fire line. The fire is contained when the amount of fire line constructed by the initial attack crew is greater than or equal to the perimeter of the fire. Since the perimeter of a free-burning fire increases as a linear function of time, the greater the head start of the fire and the faster it is spreading, the longer it takes to contain the fire.

If one assumes fire damage is a linear function of the area burned, then fire damage increases as a quadratic or nonlinear function of time, as illustrated in Figure 8. Fire management systems are, therefore, designed to predict when and where those fires are likely to occur, deploy fire fighters, helicopters, airtankers, and other suppression resources close to areas where fires are expected to occur, find and report fires soon after they are ignited, dispatch initial attack resources to fires soon after they are reported, carry out suppression action to contain fires as quickly as possible, and minimize the damage of large potentially destructive escaped fires that result when fires are not controlled by the initial attack force. In the following sections, we describe each of these fire suppression subsystems, the decision making associated with their management, and some of the planning models and decision support systems that have been developed to enhance their performance.

Fire suppression systems act on individual fires, but we are primarily interested in their impact on landscape fire regimes. Presuppression planning measures to support decision making concerning fire suppression resource acquisition, home basing, and daily deployment help fire managers design and operate their initial attack system to minimize response times and decrease the number of fires that escape initial attack and grow to large sizes. They influence the *fire size* or *extent* component of a fire regime directly but, like detection, they also have an indirect impact on *fire intensity*.

### 1. Fire Suppression Resource Acquisition and Strategic Deployment

Strategic fire suppression resource management entails deciding how many permanent initial attack bases and other facilities will be established and where they will be located, the number and type of airtankers and transport aircraft that will be purchased and kept for long periods of time, the number of fire fighters that will be hired, and the number and type of aircraft that will be chartered for a particular fire season. The more resources acquired, the less likely the agency will have to pay premium rates for aircraft chartered for short periods of time and the less likely they will have to incur the transportation costs and waiting times associated with short-term aircraft charters and borrowing fire fighters and equipment from other agencies. Once a base has been established, it is difficult to relocate it. Airtankers are very effective but costly to own and operate, and, since they do not fly long hours each year, they can last for many years. Well-trained fire fighters are essential skilled personnel that cannot readily be replaced. The way such strategic decision-making problems are resolved, therefore, has significant impacts that can ripple throughout a fire organization for many years.

It is difficult to determine how much of each type of fire suppression resource to acquire and where to base those resources so that they are readily available to be dispatched to fires as they are reported. Fire management agencies often use large computer-based decision support systems to help resolve such decision-making problems. Martell (1982) described some of the many strategic planning models, most of which focused on airtanker operations, that have been developed. We discuss the use of such models in Section V where we study level of fire protection planning.

Fire management planning is a hierarchical process, and decisions concerning the mix of resources required depends upon where those resources will be permanently based, how they will be repositioned or deployed each day as fire occurrence ebbs and flows across the protected area, how they will be dispatched to fires, and how they will be used on each fire. Fire management systems are so large and complex that managers must decompose them into hierarchical systems of decisions such that decisions made at any level within a hierarchy are compatible with decisions being made above and below that level in the hierarchy, as described in Section I.

Consider, for example, the decision of where to home-base airtankers. Fire occurrence processes vary significantly over both time and space, and the demand for fire suppression resources shifts from day to day and place to place. Fire suppression resources are very mobile, and fire managers move them from their home bases to areas where they are most needed on a daily basis. In the province of Ontario, for example, it is not uncommon to require a large number of fire fighters and airtankers in different areas, and, when such needs arise, resources are quickly moved or deployed from their home bases or their current locations to the areas where they are most needed. Once the agency has decided how many and what type of airtankers to purchase or lease, it must decide where to home-base them. Given their mobility and the fact that they can be shared with other agencies, fire managers attempt to develop home-basing strategies that will minimize the time and flying costs incurred while meeting shifting daily deployment needs.

Greulich (1976) developed an integrated airtanker home-basing/daily deployment model for two bases in California, but his model would not have been mathematically tractable for the number of airtankers and bases used in Ontario. MacLellan and Martell (1996) decomposed the problem into separate home-basing and daily deployment decision-making systems and developed a mathematical programming model which the Ontario Ministry of Natural Resources used to help decide how it should home base its airtankers. They dealt with daily airtanker deployment needs by consulting fire managers and asking them to express their daily airtanker deployment needs in terms of the number of airtankers required at each base as a function of the forecasted fire weather and the number of fires expected to occur in the area surrounding each base. Their mathematical programming model accounted for historical fire weather and fire occurrence patterns and identified home-basing strategies (how many airtankers should be home-based at each airport) to minimize the cost of satisfying the daily airtanker deployment rules identified by the fire managers. That home-basing system is only as good as the daily deployment rules embedded in the model and, since they and the Ontario fire managers that developed the model opted to use subjective deployment rules, it begs the question: How should airtankers be deployed at each base each day? Daily airtanker deployment poses many complex challenges due to the need to deal with stochastic fire occurrence and behavior processes that vary over both time and space, so it is reasonable to approximate the deployment practices fire managers will use as an interim measure. In the next section, we describe how daily suppression deployment needs can be formally modeled and assessed.

## 2. Initial Attack Resource Deployment

Fire occurrence rates vary over both time and space, and each day fire managers must decide where to deploy their initial attack resources to minimize initial attack response times. They must, for example, decide how many fire fighters to place on initial attack standby at each base each day. The more crews they place on alert, the more costs they will incur, but the less likely they will experience crew shortages. They can reduce the number of crews on initial attack standby but, if they do so, they run the risk of experiencing shortages which will mean delays in acquiring crews from other bases or agencies, extra costs in transporting them in to the area experiencing the shortage, and an increased likelihood that fires will escape initial attack. They face similar decision-making problems associated with the daily deployment of airtankers and transport aircraft. Martell (1982) described some of the models that have been developed to enhance daily deployment decision-making.

Initial attack resource deployment analysis is complicated by uncertainty concerning the timing and location of fires and interactions *between* fires. For example, if the response time to one fire is excessive, that fire will grow as it waits, and its size at attack will increase. Initial attack resources will be required on that fire for a longer period of time so that the *next* fire that arrives may have to wait even longer. A delayed response to one fire can therefore produce impacts that can ripple over both time and space and affect the ability of the initial attack system to respond to far-distant fires several days later. That calls for systems-level approaches to deployment analysis.

Many service systems are designed such that, when the number of customers that require service is greater than the number of servers, the surplus customers join a queue where they wait for service. Queues are prevalent in our society, and we are accustomed, for example, to queueing for supermarket cashiers, automatic banking machines, and airline ticket agents. Service system managers must balance the cost of service (more servers cost more money) with the cost (or inconvenience) to customers associated with waiting for service. For an introduction to the basic principles of queueing theory, see Ross (1985).

### *a. Initial Attack Queues*

There are many queueing systems in forest fire management systems, one example of which is an airtanker initial attack system in which fires are customers and airtankers are servers. The initial attack queue is a list of fires that require initial attack action. Airtanker systems are complex queueing systems since fires arrive at rates that vary over the course of the day, fires grow and their service times can increase as they wait in the queue, and the airtanker servers must fly out to serve their customers where they are burning.

To model the behavior of a queueing system, we need to model the customer arrival process, the queue, the service discipline, and the service process. The arrival of customers that need service (fires) can be modeled as a Poisson process.

One must also describe the queue where customers wait for service. The initial attack queue is a list of fires with an infinite capacity and the queueing discipline describes how waiting customers are selected for service. It may be a first-come-first-served (FCFS) discipline, or it may be a priority queue. If it is a priority queue, the high-priority customers may preempt lower priority customers that are in service when they arrive.

The description of the service process includes the number of service channels and the service time distribution which is typically exponential or Erlang. Interarrival times and service time distributions are often modeled as exponential distributions because their Markovian or memoryless property simplifies the mathematical analysis of queueing systems (see Ross, 1985, p. 190).

Let $T$ be a random variable with an exponential distribution.

$$\begin{aligned} f_T(t) &= \mu e^{-\mu t} \qquad t \geq 0 \qquad \text{Probability density function} \\ &= 0 \qquad t < 0 \end{aligned} \tag{19}$$

$$\begin{aligned} F_T(t) &= 1 - e^{-\mu t} \qquad t \geq 0 \qquad \text{Cumulative distribution function} \\ E(T) &= 1/\mu \qquad \mathrm{Var}(T) = 1/\mu^2 \end{aligned} \tag{20}$$

Queueing models can provide a rich variety of performance measures including the expected time a customer waits in the queue, the probability that a customer has to wait for service, and the expected number of customers in the queue.

The simple *M/M/s* queueing system model is a model of a system in which customers arrive according to a Poisson process which has parameters that remain constant over time, the service time is exponential, and there is one queue in front of *s* servers. More complex models can be developed to deal with situations in which the fire arrival rate varies over the day due to diurnal variation in fire occurrence and behavior processes and long travel times make it inappropriate to use exponential service time distributions.

**A Simple Daily Airtanker Deployment Problem** Consider a simple case in which the fire region depicted in Figure 13 is partitioned into two sectors, and each sector has one airtanker base that houses all the airtankers that respond to fires within the sector. Assume that airtankers cannot be dispatched to fight fires outside the sector in which they are based.

We ignore diurnal variation in the fire arrival rates and the fact that finite travel time is incompatible with the use of an exponential service time distribution and model each sector as an independent *M/M/s* queueing system. It can be shown that $W_q$, the expected waiter time in the queue for an *M/M/s* queue, is given by the following formula (see Blake, 1979, p. 346):

$\lambda$ = average fire arrival rate (fires/hr)
$1/\mu$ = average time to fight (service) a fire (hr)
$\rho = \lambda/\mu$
$P_0$ = probability the system is empty

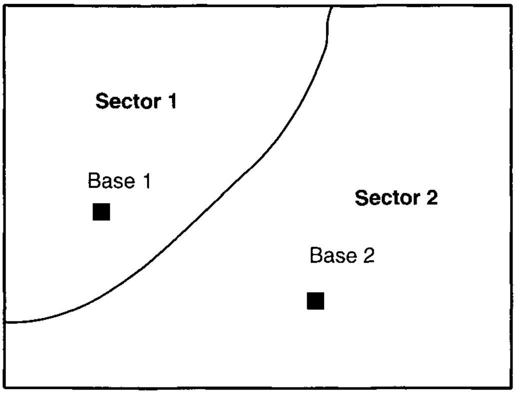


FIGURE 13 A hypothetical fire region with two airtanker bases.

$$P_0 = \left[ \sum_{k=0}^{s-1} \frac{\rho^k}{k!} + \frac{\rho^s}{(s-1)!\,(s-\rho)} \right]^{-1} \tag{21}$$

$W_q$, the expected waiting time in the queue, is

$$w_q = \frac{P_0}{\mu} \left( \frac{\rho^s}{(s-1)!\,(s-\rho)^2} \right) \tag{22}$$

Suppose that the fire management policy for the area calls for a fire waiting time of 0.10 hr or less. The expression for $W_q$ can be used to determine how many airtankers (servers) are required in sectors 1 and 2 to achieve that goal. Response time targets by sector are $W_{q1} \leq 0.10$ and $W_{q2} \leq 0.10$. The results presented in Table 8 indicate we would need 5 + 9 or 14 airtankers.

To demonstrate the importance of resource sharing, we could aggregate the sectors 1 and 2 into 1 region with $\lambda_R = \lambda_1 + \lambda_2$. The results for the aggregate region are shown in Table 9.

We would need only 12 airtankers to achieve the same level of service for two cooperating bases. It should be noted, however, that we have ignored the "extra" travel time required to move between sectors, so 12 is actually a lower bound estimate of the number of airtankers required and the true number may be greater than 12.

The queueing models we have described are for simple steady state *M/M/s* queueing systems with single bases. It is possible to develop queueing models of more realistic fire management systems. Martell and Tithecott (1991) applied an *M(t)/M/s* for airtankers at a single base when the fire arrival rate varies over the course of the day. They used numerical methods to solve the differential equations that described the system and produced time-dependent performance measures. They developed software that enabled them to field-test the

**TABLE 8** **Airtanker Response Time by Sector**

| Sector | Fire arrival rate ($\lambda$ fires/hr) | Fire service rate ($\mu$ fires/hr) | Number of airtankers, s | Expected waiting time in the queue ($W_q$ hr) |
|---|---|---|---|---|
| 1 | 2 | 0.75 | 1–2 | Undefined |
| | | | 3 | 3.19 |
| | | | 4 | 0.38 |
| | | | 5* | 0.09 |
| 2 | 4 | 0.75 | 1–5 | Undefined |
| | | | 6 | 1.43 |
| | | | 7 | 0.33 |
| | | | 8 | 0.11 |
| | | | 9* | 0.04 |

TABLE 9 **Airtanker Response by Region**

| Fire arrival rate ($\lambda$ fires/hr) | Fire service rate ($\mu$ fires/hr) | Number of airtankers, $s$ | Expected waiting time in the queue ($W_q$ hr) |
|---|---|---|---|
| 6 | 0.75 | 1–8 | Undefined |
| | | 9 | 0.87 |
| | | 10 | 0.27 |
| | | 11 | 0.11 |
| | | 12 | 0.05 |

use of the model in the northwestern region of Ontario. Managers indicated that, since it did not model base interaction, it would not satisfy their needs. Islam (1998) subsequently studied initial attack airtanker systems and developed several models for spatial airtanker queueing systems with time-dependent arrivals and interaction between bases, one of which is described in Islam and Martell (1998).

### 3. Initial Attack Dispatching

As soon as a fire has been reported, the initial attack dispatcher or duty officer must decide what suppression resources will be dispatched to that fire and when they will depart for the fire. Fires are placed in the initial attack queue as they are reported, and some have higher priorities than others depending upon their location and the threats they pose to public safety, property, and other values. Initial attack dispatching is complicated by uncertainty concerning what might happen later in the day. While airtankers are quite mobile and can readily be diverted from one fire to another as the need arises, initial attack crews are not as flexible. If an initial attack crew is allocated to a fire, it will not be available to fight higher priority fires that might be reported later that same day and, since crews are usually tied up on fires for several days, today's initial attack dispatching effects can ripple throughout the organization for the next several days.

### 4. Initial Attack

Once the initial attack crew arrives at the fire, the initial attack fire boss must assess the situation and devise a suppression strategy. The current fire behavior, surrounding vegetation, values at risk, number and type of resources currently available, and the forecast weather will influence his or her decision concerning the attack strategy. He or she may, for example, opt to have the initial attack crew set up a power pump, lay hose up to the fire, and gradually work around the fire perimeter while extinguishing the flame front. If there is insufficient water available, the crew may use hand tools such as axes, shovels, and other specialized line building equipment. Airtankers may drop water or special fire-spread-retarding chemicals on the fire while the initial attack crew is traveling to the fire, and helicopters slinging buckets that can hover and drop water precisely might work with them as they construct fire line and attack hot spots near the fire perimeter. The decision making associated with initial attack operations is the domain of skilled and experienced fire fighters, and there have been few attempts to develop decision-making aids to enhance their effectiveness.

During the years 1976–1999 the fire size at the start of initial attack in Ontario ranged from less than 0.1 ha to 27,774 ha, but 95% of the fires were attacked at less than 5.5 ha. The average fire size at attack was 24.8 ha, but the distribution is highly skewed with a median of 0.1 ha and a mode of 0.1 ha. Again, the skewness is largely a result of a few large fires in the extensive protection zone in the far north.

## 5. Large Fire Management

In many jurisdictions, a very small proportion of the fires burn a large portion of the area that is burned each year. In the province of Ontario, for example, 95% of the fires burned to a final size of 33 ha or less during the years 1976–1999. The average final fire size was 141.1 ha, but the distribution was highly skewed with a median of 0.2 ha and a mode of 0.1 ha. Fires that are not controlled by the initial attack force are classed as escaped fires, and they have the potential to grow to very large sizes and cause considerable damage. However, the small number of large fires can have very significant impacts, some of which are beneficial, on natural forest ecosystems.

Large fires are difficult and very costly to contain, and observers sometimes question what may appear to be futile suppression activities. One reason, of course, is that most agencies operate under what are essentially fire exclusion policies in much of their area, and they and the governments that fund them might be found legally liable if they simply admitted defeat and decided not to attempt to control large fires. Nevertheless, many fire managers believe that they can limit the damage caused by large fires in a cost-effective manner. Their rationale is as follows.

Large fires are driven across the landscape by weather and in many regions (e.g., the boreal forest region of Canada) suppression action may not only be ineffective but also very dangerous to fire fighters while high intensity fast-spreading fires are moving on wide fronts. Large fires can move as fast as 7 km $hr^{-1}$ on fronts as wide as several kilometers with flame fronts in excess of

50 m in the boreal forest. It makes little or no sense to attempt to contain fires while they are making such runs. Under such circumstances, fire fighters sometimes carry out what they refer to as value protection measures. For example, they may use portable power pumps, hose, and irrigation sprinklers to establish sprinkler lines around isolated cottages and other valuable structures in the paths of such fires.

Fire fighters also combat running wildfires by burning out from natural or human-made barriers. For example, they may use helicopters equipped with helitorches to fly close to a lake or river in the fire's path, ignite fire at the edge of the lake, and then continue to light fire progressively closer to the advancing fire. Their objective is to augment an existing barrier, the lake or river, and thereby create a much wider fuel break in the hope that they can stop the progress of the fire when it reaches that barrier.

Fire suppression organizations often simply monitor and project the growth of running fires but, while they do so, they identify strategic areas where they hope to establish control lines. They move suppression resources up close to the fire and establish base camps from which they can launch their attack when weather conditions turn in their favor and the fire intensity subsides. Fires that are allowed to burn freely in the largely continuous fuel complexes of the boreal forest have the potential to continue burning until the advent of winter snowfall and, in some cases, they have even been known to smolder in the deep duff under the snow during particularly bad drought years. But such fires usually move in short fast-paced bursts. As fire weather conditions worsen, the fire becomes more active. If the drying continues for a sufficiently long time, the fire will, usually under the influence of a strong wind, move rapidly for part of a day or more until the weather changes and it settles down to smolder until burning conditions worsen yet again. The fire manager's objective is to mobilize his or her resources so that the fire can be contained during one of those lulls. If and when such efforts are successful, the damage that might have been incurred during subsequent high-burning-hazard periods will be averted.

Large fire suppression teams may have to determine what values to sacrifice during burning out operations to enhance the likelihood that they can control the fire at a later date. They carry out what they refer to as escaped fire situation analyses (EFSA) to evaluate alternative strategies for dealing with large escaped fires.

## V. LEVEL OF FIRE PROTECTION PLANNING

The least cost plus damage model provides valuable insight into the potential long-term economic impact of fire management, and supplementary models like the fire and timber supply model augment that understanding with detailed information concerning the timber supply implications of fire management from landscape and regional perspectives. But fire management objectives should be based on the potential social, economic, and ecological impacts of fire, and we have, at best, only begun to scratch the surface in terms of our understanding and ability to quantify such impacts. Fire management policy analysts and others will ultimately have to provide land managers and the public with comprehensive planning models that can be used to assess the impact of fire and fire management on social systems and forest ecosystems. It will take considerable time and effort to develop our understanding sufficiently to assess the social, economic, and ecological impacts of fire management. But the public safety, property, and timber supply concerns that lead to the development of variants of current policies remain, and fire managers must continue to suppress fire, albeit with more discretion than was the case in the past, until the policies that govern their agencies direct them to do otherwise. Fire managers and their many diverse clients, therefore, need pragmatic interim solutions that can be refined as time passes and our knowledge and understanding grow.

In 1935, the U.S. Forest Service developed an effective fire exclusion policy by using what it referred to as the 10:00 A.M. policy—that all fires should be contained by 10:00 A.M. the day following the day the fire is detected (Pyne, 1982, p. 116). That surrogate initial attack objective guided their prevention, detection, and suppression activities to minimize area burned for many years. Most North American forest fire management agencies developed and implemented variants of the 10:00 A.M. rule. Some agencies recognized explicitly that they need not and cannot achieve such objectives on all fires, particularly those that occur in remote areas and do not threaten people, property, and timber supplies. The Ontario Ministry of Natural Resources, for example (see Martell, 1994), partitioned their fire region into intensive, measured, and extensive protection zones. All wildfires that occur in the intensive protection zone are attacked aggressively until they are controlled. Fires in the extensive protection zone are not attacked unless they pose significant threats to people or property. Initial attack action is taken on all fires that occur in the measured protection zone. Measured protection zone fires that are not controlled by the initial attack force are subjected to an escaped fire situation analysis that may call for continued aggressive suppression, modified suppression, or continued monitoring without suppression. Even though such zoning schemes suited the needs of the OMNR and other fire management organizations well in the past, the small number of very large zones are no longer adequate to meet the complex needs of fire management agencies that will have to assess social, economic, and ecological impacts of their activities in far more detail than was ever the case in the past.

Martell and Boychuk (1994) described conceptually how zoning schemes can be refined to suit the needs of the many diverse clients that want fire management on tracts of land they deem as being important. One can begin by partitioning the fire region into a large number of zones that are reasonably homogeneous with respect to forest ecosystems, land use, and values at risk and by specifying an average annual burn fraction for each zone. Such fractions could then be used to help quantify the potential impacts of fire on public safety and property, and they could readily be incorporated into timber supply models to assess the timber supply implications of the proposed burn fractions by zone. Ecologists who study fire regimes recognize the average fire return interval and burn fraction as important components of fire regimes and will no doubt develop models that relate ecological impacts to burn fractions.

The interested stake holders in each zone could then consider the potential impact of the proposed burn fraction and the ecosystems in those zones and arrive at a decision, preferably a consensus, as to what average annual burn fraction is acceptable in each zone. The next step would be for the fire management agency to use a strategic level of protection planning model to determine how they could meet that objective and the cost of doing so.

Many fire management agencies use modern information technology and OR/MS methodologies to guide their planning. One approach is to decompose the fire management system into many small relatively simple subsystems and then develop large comprehensive computer simulation models that predict the consequences of specified fire management program alternatives and are used for fire management budget planning purposes. Examples include LEOPARDS (McAlpine and Hirsch, 1999), National Fire Management Analysis System (NFMAS), and California Fire Economics Simulator (CFES) (Fried and Gilless, 1988). Figure 14 is a schematic representation of the basic structure of a fire suppression computer simulation model. Such models are designed to enable managers to specify what fire suppression resources they would hire and then simulate how the proposed system would perform were those resources to be used to fight historical fires or representative sets of hypothetical fires. The key issue is model validity or the extent to which such models can truly represent the real world, and increased effort is expected to be devoted to the development, testing, and use of such models in the near future.

Martell *et al.* (1984) developed an initial attack simulation model (IAM) which the Ontario Ministry of Natural Resources used to help determine the number and type of airtankers required in Ontario. That model predicts several measures of system performance including the fraction of fires that escape initial attack depending upon the number and type of airtankers, fire fighters, and transport aircraft allocated to fire suppression. Martell *et al.* (1995) later modified IAM to produce LANIK, a modern desktop computer implementation of IAM, to facilitate its use for strategic level of protection planning in Ontario.

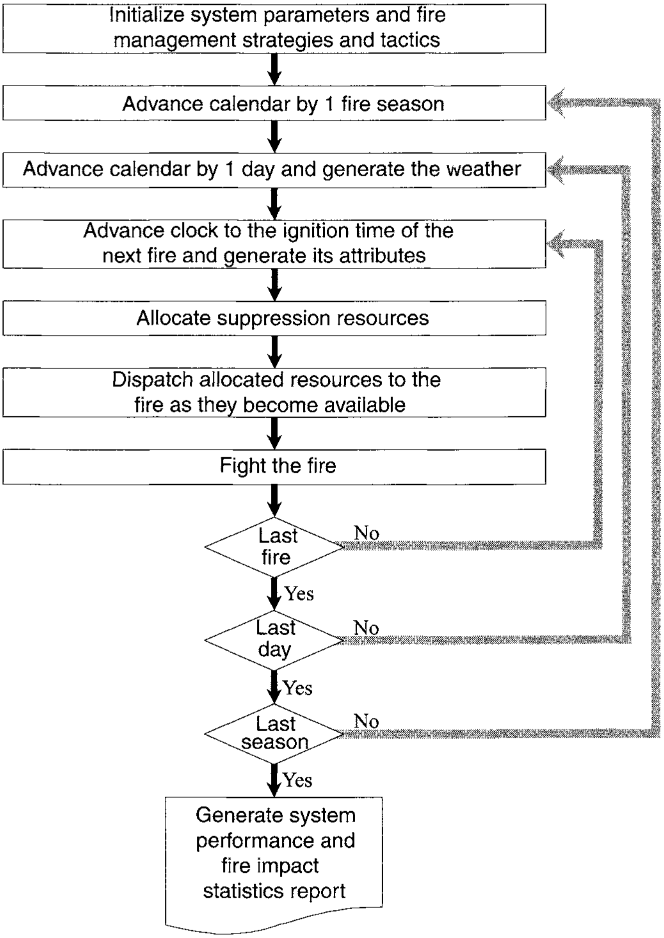


FIGURE 14 Structure of a forest fire management system computer simulation model.

McAlpine and Hirsch (1999) later extended LANIK and embedded it in a GIS to produce a Windows'95 model called LEOPARDS.

LEOPARDS has since been used for a variety of planning purposes including an assessment of the potential implications of climate change, changes in initial attack fire crew staffing levels, and the upgrading of the OMNR's airtanker fleet with modern CL-415s. Many other forest fire management agencies have developed similar systems (e.g., the U.S. Forest Service's NFMAS, the California Division of Forestry's CFES, and Chile's KITRAL [Pedernera and Julio, 1999]).

There is no reason to believe that all the stake holders will agree with the fire management costs that will emerge when they engage in detailed zonal level of protection planning exercises, so iterative procedures that hopefully converge to an acceptable agency wide strategy will have to be used.

After the burn fractions have been specified by zone, they collectively can be used as a strategic objective to be met by the fire organization. Its task then becomes one of determining a detailed site-specific plan for minimizing the cost of achieving that objective. Level of protection planning models could again be used to help transform those objectives into a refined fire management plan.

Strategic models like LANIK, LEOPARDS, NFMAS, and KITRAL are aggregate models that will need to be enhanced or replaced as time passes. Fire managers can incorporate simple proposed strategies and tactics in such models in the form of rules that govern the use of fire suppression resources, but it will be difficult to translate those strategies and tactics into precise operational deployment, initial attack, and large fire suppression in each zone. They will have to develop simple operational guidelines for prevention, detection, initial attack, and large fire suppression that vary by fire danger as measured by, for example, fire danger rating indices. For example, they will have to specify daily detection size and initial attack response time objectives by zone given the fire danger.

## VI. SOME CHALLENGES

The development and implementation of a fire exclusion policy is relatively simple and straightforward when compared with the challenges that fire managers will have to deal with in the 21st century. It is, of course, no mean feat to decide what fire-fighting resources are required and where they should be based, predict daily fire occurrence, deploy fire suppression resources close to areas where fires are expected to occur, find the fires that do occur while they are still small, dispatch initial attack resources to fight those fire and contain them quickly and at small sizes, and deal with any large escaped fires that result. These are enormous and potentially costly logistic problems, but they are manageable given the widespread acceptance that fire is destructive and that fire managers must minimize the cost of achieving specified fire control. But such challenges quickly fade when compared with the need to understand the social and ecological impacts of fire and how human intervention will shape forest landscapes and the animal populations that will struggle to survive there and to resolve the many conflicts that different constituencies will bring to the table as society attempts to develop site-specific fire management strategies for every significant parcel of forest land. We address some of those issues on the following pages.

## A. RELATING OUTCOMES TO STRATEGIES

Fire management programs produce fire regimes that forest management clients and others affected can use to assess the impact of fire management on what they do and the things they value. It is, however, difficult to predict the fire regime consequences of specified fire management strategies, and even more difficult to determine how best to achieve a specified fire management regime. Consider, for example, the simplest case of a small forest management region that functions independently. It would indeed be difficult to predict what regime would result by using a specified set of fire management resources according to some specified sets of rules. Researchers can and have, of course, developed planning models that are designed to help resolve such problems. Examples include NFMAS, CFEES, and LEOPARDS, all of which have already been discussed. But these systems are primarily initial attack planning tools that focus on initial attack operations, and their ability to model large fires that escape initial attack is either nonexistent or, at best, very simplistic.

We can expect progress in this area, but the real challenge lies in the fact that fire management units are not independent units. Consider the case of two interdependent fire management units that lie adjacent to each other and suppose airtankers are used for initial attack purposes in both units. One form of fire management might call for specified initial attack time targets that vary by compartment and fire weather within each unit. If there is a shortage of airtankers in one unit, then fires will have to wait longer in the initial attack queue during which they will grow and demand even longer service times. That will reduce the likelihood that the busy unit can share its resources with the adjacent unit which will increase the likelihood that fires escape initial attack in the adjacent unit. In turn, that will lead to an increase in the need for suppression resources in the adjacent unit and produce shortages in both units that may last for days or even weeks. Thus, a particularly troublesome fire or a shortage of fire suppression resources in one unit can have significant impacts that percolate across time and space. Furthermore, fire management agencies can borrow resources from other provinces, states, and countries. The availability of such resources will vary depending upon the weather in those jurisdictions. The first challenge is that the set of empirical data required to document what strategies were used in the past on some designated area is enormous. For example, if the fire regime is thought to be a function of the initial attack response time strategy, one needs to know how easy it was to borrow resources from other agencies to meet initial attack response time targets. Equally challenging is the fact that when a manager sets initial attack response time targets for one management unit, he or she needs to model the ability of that unit to borrow resources from other widely scattered agencies.

## B. DEALING WITH UNCERTAINTY

Fire is a stochastic disturbance agent that introduces enormous uncertainty into forest land management planning. Forest managers recognized that fire threatened their ability to exploit forest resources and took measures to limit its extent and impact. They developed contingency plans that were designed to enhance their ability to cope with fire losses, but their understanding of fire and the lack of mathematical modeling techniques and computing resources made it impossible for them to incorporate fire loss explicitly in their planning systems in anything other than a rudimentary fashion. Reed and Errico (1986) developed a forest-level timber harvest scheduling model that makes it possible to account for fire loss in large forest management units if fire losses are not severe and some deterministic average fire loss is assumed to occur each year. Boychuk and Martell (1996) showed how stochastic programming methods could be used to deal with variability in fire processes, but stochastic modeling methodologies and computer technology limit the ability to do so. There is, of course, a need to enhance stochastic programming planning methods, but even more important is the need for forest-based societies to learn to live in harmony with the variability that is characteristic of natural forests.

Gunn (1996) has suggested that replanning after significant uncertain events have taken place is a reasonable strategy for coping with uncertain fire losses and, assuming forests are not "pushed to the limit" with respect to timber production, they may be robust enough to "respond." One cannot maintain both natural ecosystems and stable timber harvest flows simultaneously. Societies must develop site-specific compromises for such problems, and they have to learn to cope with the variability that will result. That might, for example, call for explicit recognition that harvest levels will rise and fall and the aggregation of relatively small independently owned forest management units into larger woodsheds in which forest landowners agree to share their resources with those that suffer loss so that each of them enjoys a measure of insurance concerning resource flows. We will also have to learn how to deal with the problems that will arise when we embed islands of flammable "natural" forest landscapes that are designed to provide habitats for rare and endangered species in larger landscapes that are not so well endowed with suitable habitat. To date the forest fire management research community has focused on timber production under uncertainty. It is essential that ecologists and land management planners work together to deal with the much more complex issues of wildlife conservation in managed forests that are expected to provide both resources and suitable wildlife habitats.

## C. MOVING BEYOND FIRE EXCLUSION

Most modern wildland fire management agencies were established and developed in response to threats to public safety, property, and timber production. Despite the growing recognition that fire is a natural component of many forest ecosystems and that it is neither economically nor ecologically sound to attempt to exclude it completely from forested landscapes, there has not been a significant shift away from traditional fire exclusion practices in most jurisdictions. Fire has, of course, been "reintroduced" into some areas, primarily parks and wilderness areas where the desire to maintain or restore natural ecosystem processes is paramount and the land managers responsible believe that they can increase the amount of fire on the landscape without undermining public safety and property significantly.

Choosing not to fight all fires aggressively does, however, pose significant challenges to the managers who must develop and implement such policies, the fire fighters who must deliver them, and the public who must live with the consequences. The primary motivation for fire exclusion is the desire to reduce uncertainty and minimize the risk that significant losses will be incurred in the near future. While fire exclusion may lead to hazardous fuel buildups and potentially even more destructive fires in the distant future in some biomes, every wildfire that is not extinguished represents a potential short-term threat to public safety, property, and timber. Historical accounts of wildland fire disasters in North America during the early decades of the 1900s describe how hundreds of lives were lost as fires swept across the landscape and engulfed entire communities and the rural homesteads between them, almost without warning (see, for example, Holbrook, 1943; Lambert and Pross, 1967; Pyne, 1982). There is no simple common explanation for all such tragedies, but, in many cases, small land clearing and lightning-caused fires had been left to burn largely unattended across the landscape. That posed no significant threat as long as benign fire weather conditions prevailed, but from time to time nature conspired to produce several good drying days and one or more days with high temperatures, low relative humidities, and high winds. The heretofore small benign fires then began to spread, joined up, and raced across the landscape on wide fronts pushed by strong winds. The surveillance, telecommunications, and transportation systems were not up to the task, and the resulting damage precipitated calls for fire exclusion that largely persist to the present.

Modern forest fire management agencies have the capability to monitor ongoing fires, and they can rely on meteorologists to forecast weather so that they can predict potential fire behavior some days in advance. They can, in principle, predict when fires are about to make a run, intervene, and extinguish them before that happens. If and when they are unable to do so, they can use modern transportation technology to evacuate threatened communities. The irony is that, since such policies would not produce the large burned areas characteristic of natural fire regimes, it is questionable what environmental benefits would be gained by such practices.

There are no simple answers. Martell (1984) addressed this issue as it pertains to the boreal forest region of Canada and advocated the adoption of what he described as "fire impact management policies" whereby decisions concerning wildfire suppression and the use of prescribed fire are based on sound social, economic, and ecological principles. He also discussed some of the practical problems that would complicate the development and implementation of such policies.

The simple truth is that fire cannot be reintroduced into fire-prone landscapes without significant threat to public safety, property, and other values. A fire manager that cannot control what proves to be a destructive fire will not be criticized if he or she is judged to have done his or her best to deal with the situation in a professional manner. However, if he or she decides to let what ultimately proves to be a destructive fire burn with little or no significant suppression, he or she and the agency that employs him or her will no doubt be liable for civil litigation. The issue is not unlike the concern Howard *et al.* (1972) identified when they realized that decisions to seed hurricanes to diminish their destructive potential should be tempered by the possibility that a change in the storm's characteristics might, rightly or wrongly, be attributed to the seeding operation and could open the government to civil litigation.

Mitchell (1995, p. 4) explains that the precautionary principle that emerged from the Earth Summit in Rio de Janeiro in 1992 recognizes that even though "uncertainty creates a serious dilemma for resource and environmental managers. . . . incomplete understanding should not be used as an excuse for delaying action when environmental degradation appears imminent." Some might well be tempted to use the precautionary principle to support calls for nonexclusion policies, but that must be tempered by concern for public safety and property damage and the possibility that, although fire is natural, some forest ecosystems may have been so perturbed by humans that "natural" fire regimes would simply hasten their demise. Fire management is ecosystem management over massive spatial and temporal landscapes, and it is fraught with considerable uncertainty concerning what will happen in the next few days, weeks, decades, or centuries. Given the importance of fire in natural ecosystem processes, we cannot afford to simply continue on with the way we in North America have behaved for the last century. It should all make for an interesting future.

## ACKNOWLEDGMENTS

J. Beverly and A. Tithecott provided helpful comments on earlier versions of this chapter. The Aviation, Flood and Fire Management Branch of the Ontario Ministry of Natural Resources pro-

vided a digital file of their 1976-1999 fire report data that was used to compute the Ontario fire statistics reported in this chapter.

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