Levels of Fire Protection for Sustainable Forestry in Ontario: A Discussion Paper

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ABSTRACT

This discussion paper was prepared to provide background material for the participants in a Level of Fire Protection Workshop held in Sault Ste. Marie, Ontario, in September of 1993. A brief historical overview of forest fire management in the province of Ontario is followed by a discussion of several potentially useful level of protection measures. A hypothetical forest is described and used to illustrate how very simple fire management subsystems can interact to produce complex system behavior that is sometimes difficult to understand and manage. An overview of the basic principles of fire economics, planning under uncertainty, and traditional approaches to level of protection planning provides an analytical foundation for fire management planning. An integrated fire/forest management framework that can be enhanced and used for level of protection planning in Ontario is presented. Finally, several important issues that should be addressed when assessing Ontario's level of fire protection needs are briefly discussed.

RÉSUMÉ

Ce document de travail a été établi pour donner des renseignements de base aux participants d'un atelier portant sur le degré de protection-incendie, tenu à Sault-Sainte-Marie (Ontario) en septembre 1993. Un historique de la lutte contre les feux de forêt dans la province de l'Ontario est suivi d'une étude de plusieurs mesures potentiellement utiles en matière de protection. Une forêt hypothétique est décrite et utilisée pour illustrer comment de très simples sous-systèmes de lutte contre les incendies peuvent interagir pour produire un système complexe dont l'évolution est parfois difficile à comprendre et à gérer. Un aperçu de principes fondamentaux des aspects économiques des incendies, de la planification en situation d'incertitude et des modes traditionnels de planification de la protection constitue une base analytique de la planification de la lutte contre les incendies. Un cadre intégré d'aménagement forestier et de lutte contre les incendies, qui peut être amélioré et utilisé pour la planification de la protection en Ontario, est présenté. Enfin, plusieurs questions importantes à aborder pour évaluer les besoins de protection-incendie en Ontario sont brièvement examinées.

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INTRODUCTION

The Ontario Ministry of Natural Resources (OMNR) currently spends approximately $80 million per year on forest fire management. This money is used to fund a broad array of activities: including, fire prevention, detection, suppression, and the use of prescribed fire to support other land management programs such as timber production and wildlife management.

Ontario's first Fire Act was passed in 1878 and the OMNR's predecessor, the Ontario Forestry Branch, was formed in 1917 in response to a series of wildfire disasters that killed many people and threatened the economic development of northern Ontario. The OMNR's fire management program subsequently grew; primarily in response to demands that it reduce wildfire threats to people and property, and that it minimize the impact of fire on the timber resources of Ontario. Recent years have witnessed a growing recognition that fire is a natural component of many of Ontario's forest ecosystems and its impact is not entirely destructive. At the same time, the Government of Ontario has experienced growing pressure to reduce its expenditures. That combination of environmental and economic pressures has created a need to carefully reconsider Ontario's forest fire management policy, how much money the government should devote to fire management, and how those funds should be spent. These types of questions are often collectively referred to as "level of protection" issues.

The OMNR's forest fire management program, administered by its Aviation, Flood and Fire Management Branch (AFFMB), is designed to meet the needs of other branches and government agencies (e.g., timber and wildlife management). It must also meet the needs of many external clients, including the forest industry, residents of communities that are surrounded by flammable forests, and other groups and individuals that derive benefits from Ontario's forests. It is difficult for fire managers and governments to evaluate fire management program alternatives because the interests of the many internal and external clients are very diverse. There is also a wide range of benefits that flow from Ontario's forests. Finally, there is the high degree of uncertainty that makes it impossible to transform fire management plans into precise deterministic predictions concerning the social, biological, and economic impacts of fire management programs. The task of this project was to develop a fire management decision support system framework that can be used to help resolve decisions concerning the level of protection (e.g., how much area will be allowed to burn on average) and resource allocation (e.g., how the fire management budget will be allocated to fire management activities) in order to achieve specified levels of protection.

The project's primary objective, to help the OMNR develop a widely understood and acceptable means of selecting and achieving a level of protection for fire management programs, can be expressed in terms of three secondary objectives:

1. Improve the Ontario forestry community's understanding of the concept of level of fire protection.
2. Improve the degree of understanding within the forestry community of the relationship between fire and forest management.
3. Develop analytical procedures, based on level of protection measures and compatible with Ontario's forest management objectives, which can be used to help resolve decisions concerning the allocation of resources between components of the fire management program.

To accomplish this task it was essential to consult with fire managers and their clients and to encourage them to identify and discuss issues that should be addressed when plans are developed and implemented. As such, a workshop was convened to facilitate consultation with fire management specialists and representatives of other OMNR programs influenced by fire management.

The workshop objectives were:

1. Education: Describe some of the basic principles of fire management planning to the workshop participants so they can share a common body of knowledge and understanding.
2. Consultation: Have the workshop participants identify and discuss level of protection issues and measures that might be used to enhance forest fire management in Ontario.

The purpose of this discussion paper was to provide workshop participants and other interested readers with an introductory overview of some of the basic principles of forest fire management planning, to stimulate thought about fire management, and to provide a common foundation of knowledge concerning level of protection.

AN HISTORICAL PERSPECTIVE

Changing Attitudes Toward Forest Fire Management in North America

Public attitudes and government policies in North America have gone through a number of distinct phases since the first arrival of European settlers. **Phase I (Let the Forests Burn)** lasted until near the end of the 19th century, and was characterized by the carefree use of fire and the attitude that forest resources were so abundant that fires could be allowed to burn freely without having a detrimental impact on society. Although attempts were made to exclude fire from highly populated areas, little effort was taken to suppress all forest fires. Fire was used extensively to clear land for agricultural purposes and the presence of smoke was considered to be a sign of progress. Forest harvesting operations created hazardous accumulations of slash. Land-clearing fires and logging fires often escaped control and resulted in destructive conflagrations.

Phase II (Fire Exclusion) began near the turn of the century and persisted until recently. Fire was thought to be totally destructive and forest fire protection agencies (note the name!) implemented fire exclusion policies. Fire managers attempted to minimize the area burned subject to somewhat flexible (but increasingly rigid) constraints on fire control resource availability and use. This era is perhaps best symbolized by Smokey Bear.

Fire is a natural component of many North American forest ecosystems, and fire suppression operations can be very costly. If attempts to exclude fires from the boreal forest are successful, fuel buildups can result and the impact of the fires that eventually occur may be more severe than they would have been had the accumulated fuel been allowed to burn earlier. Fire also plays an important role in the regeneration of some boreal forest species. Jack pine (*Pinus banksiana* Lamb.), for example, is considered to be a fire species. The heat from a fire opens the tree's serotinous cones and the seeds are dropped onto the mineral soil that has been exposed by the fire. Enhanced communications and fire suppression resource mobility enabled fire managers to quickly deploy powerful but costly suppression forces, and thus expend funds much faster than had been the case in the past. Such factors are gradually forcing many North American forest fire management agencies to adopt **Phase III (Fire Impact Management)** policies.

Although numerous agencies still operate under wildfire exclusion policies, there is a growing recognition that this philosophy is neither economically nor ecologically sound, and that it must gradually be replaced by more flexible policies. This phase is best characterized by use of the term "fire management" rather than "fire control". Phase III will eventually be characterized by the selective suppression of fires based on social, economic, and ecological considerations. Considerable research and extensive experience will be required to determine how best to move from a state of fire exclusion to one of fire impact management (Martell 1984). The use of prescribed fire and the selective suppression of wildfires must be discussed with a public who have long had the "Smokey Bear" message imprinted on their minds. Throughout the transition and beyond, fire management agencies must maintain strong suppression capabilities.

Forest Fire Management in Ontario

Ontario's forest fire management program has not been immune to the types of pressure and changes described previously, and the OMNR and its predecessors have gradually evolved from a very small, selective fire exclusion organization to a large agency with a fire management program that is expected to satisfy many diverse objectives and constraints.

Ontario's first fire protection legislation, the Fire Act, was passed in 1878. Its primary objective was to restrict the use of fire for land clearing and other purposes during hazardous periods. Aubrey White of the Crown Lands Department developed fire control plans that were implemented in 1885. Each year, he hired 37 rangers to work on crown land and some timber license areas from 1 May until 1 October. The rangers worked in pairs with two assistants and traveled throughout their area, primarily by canoe. They posted the Fire Act in conspicuous locations, located trees that could serve as good observation platforms for fire detection, and hired local people to help extinguish fires. The total cost of the first season of operation was $7,000. This was shared by the government and timber licensees.

In 1910 the Rainy River fire resulted when three railway locomotive fires and one settler fire joined. The result was 42 deaths in the United States and 300 000 acres burned in northwestern Ontario and Minnesota. In July of the following year the Porcupine fire resulted when drought and high winds enabled many unattended fires to merge and kill more than 73 people as it burned 500 000 acres, including portions of the communities of Timmins, South Porcupine, Porquis Junction, and Cochrane.

The Matheson fire killed more than 224 people and burned 1 329 square miles in July of 1916. It resulted from a prolonged drought, high temperatures, strong winds, and many small unattended fires. Considered by many to have been Canada's worst forest fire, it led to demands for improved fire protection and the passage of the Forest Fires and Protection Act in 1917. The Ontario Forestry Branch was formed and E.J. Zavitz was appointed as the provincial forester. Professor J.H. White of the University of Toronto was appointed as his assistant and the area to be protected was divided into 30 districts. In total, 62 wooden lookout towers were constructed.

By 1922 three HS2L flying boats were being used for fire detection and suppression transport, but a perceived need to economize combined with local pressure led the government to lay off all their fire rangers and withdraw fire permit regulations early in the autumn—before the end of the fire season. Hot dry weather, strong winds, and many settler fires precipitated the Haileybury fire that killed 43 people and burned 18 townships in northeastern Ontario in October of that year. It snowed heavily the day after the fire swept across the area. In 1924 the Provincial Air Service was formed with an initial complement of 14 HS2L flying boats.

Many factors came together to contribute to the major fire losses that were common in Ontario during the first quarter of the twentieth century. Prolonged drought, low relative humidity, high temperatures, and strong winds created the potential for extreme fire behavior. Many fires were left burning unattended and their location and extent were not known and/or were largely ignored. Strong winds whipped these uncontrolled burns into large fires that swept across the countryside, virtually leaped out of the forest without warning, and engulfed the unsuspecting residents of small isolated communities. Modern detection, suppression, surveillance, communication, and transportation capabilities are such that there is very little likelihood that forest fires could cause the loss of life that was experienced in Ontario in the early decades of this century. But small, uncontrolled fires will roam where the wind pushes them and could easily destroy communities and valuable forest resources. Society cannot continue to attempt to exclude fire from Ontario's forest ecosystems nor can "Nature" be totally left to take its course for ecological and economic reasons. The challenge is to find a balance between these social, ecological, and economic concerns.

Recent Changes in Ontario's Forest Fire Management Policy

The OMNR gradually began to move away from traditional fire exclusion practices in 1982 when it adopted a new fire management policy characteristic of Phase III. The new fire management policy was based on the principle that: "Fire has always been a significant factor in the forests of Ontario and will continue to have an impact on people and their environment. Forest fire management is, therefore, an integral part of land and resource management" (Ontario Ministry of Natural Resources 1982).

The policy further defined forest fire management as: "The strategy of fire control and fire use practised in concert with land use objectives and conducted in a manner that considers environmental, social and economic criteria" (Ontario Ministry of Natural Resources 1982).

The OMNR's new forest fire management program objectives were:

- To prevent personal injury, loss of life, and social disruption resulting from a forest fire.
- To minimize the negative impact of fire on public works, private property, and the natural resources of Ontario.
- To utilize the natural benefits of fire in achieving Ministry objectives for land and resource management.

Managers attempted to achieve those objectives through a coordinated approach that included adequate capability, proper preparedness, appropriate deployment, and effective action. Every forest fire in Ontario was to receive a response, and that response was to be governed by the predicted behavior of the fire; the potential impact of the fire on persons, property, and values; and the estimated cost of the response.

In January of 1991 the OMNR revised its fire management program objectives (Ontario Ministry of Natural Resources 1991). The new objectives are:

- To prevent personal injury, value loss, and social disruption resulting from a forest fire.
- To promote understanding of the ecological role of fire and utilize its beneficial effects in resource management.

The policy further states that:

- Fire is a major component of forest ecosystems and its management is essential to be able to derive sustainable benefits from forest resources and to provide safe and secure communities. Forest fire management is, therefore, an integral part of land and resource management.
- Decisions related to fire protection are based on two concepts. The first is that OMNR, as agent of the landowners, is responsible for activities on Crown lands and the potential impacts that these activities may have on other landowners' property. Secondly, public resources must be allocated in a manner that gains the greatest overall public benefit.
- Effective prevention is a key element of forest fire management.

Although the OMNR has modified its forest fire management policy twice in recent years, it still operates very much like a traditional wildfire exclusion organization (except in extensive and measured protection zones). The ministry can be expected to more fully exploit the potential benefits of its recent fire management initiatives as its fire managers and their clients become more adept at living with the many complex challenges posed by the new policy.

Fire Management Zones

The OMNR uses a fire management zoning scheme that is designed to help ensure its fire management activities are consistent with its overall land management objectives. A fire management zone is a parcel or collection of parcels of land that are relatively homogeneous with respect to the potential impact of fire on people and land management objectives. Each administrative region is zoned such that fire management strategies and tactics are applied relatively uniformly within each zone, but differ from zone to zone.

The entire fire region is zoned for either intensive, measured, or extensive protection for fire management purposes. The intensive protection zone involves land where fire has the potential to cause major social disruptions or can have significant detrimental impacts on natural resources. It includes land surrounding communities and land that contains resources that are currently being utilized or are scheduled to be developed in the immediate future. This zone covers 46 percent of the fire region. All fires in the intensive zone are aggressively attacked until they are suppressed.

The measured protection zone covers land where fire may cause significant damage to structures and recreational values, but may have less detrimental impact on natural resources. It contains isolated tourist camps and industrial facilities, timber for potential future industrial expansion, and contingency timber that might be required to replace timber resources burned in the intensive protection zone. It covers 10 percent of the fire region. All fires in the measured protection zone are attacked, but if they escape initial attack, they are subjected to an escaped fire situation analysis. This might call for a limited extended attack action rather than aggressive sustained suppression.

The extensive protection zone involves land where fires may damage isolated, localized values such as tourist facilities, trappers' cabins, and communications facilities, but may have less detrimental impact on natural resources. It also envelops many small northern communities that are classified as part of the intensive protection zone, and covers 44 percent of the fire region. Fires are monitored and suppression action is directed toward public safety[1] and minimizing damage to threatened localized values.

AN OVERVIEW OF ONTARIO FOREST FIRE STATISTICS

Figure 1 shows the high variability of the annual number of fires and area burned in Ontario over time. This variability is largely caused by randomness in fire ignition processes, and variable fuel moisture conditions—mostly determined by weather. Long-term trends can be caused by changes in climate, land use, forest cover or fuel type, protection technology, and protection expenditures. Fire workload also varies significantly over the course of the fire season. Figure 2 shows the number of new fires reported each day for 4 selected years.

Fire losses vary widely among different parts of Ontario. Figure 3 illustrates Ontario districts, before recent reorganizations, and shows the burned proportion of the intensive protection zone. The density of the shading of the map is proportional to the average proportion burned within district boundaries.

Fire losses also vary widely by cover type in different years. Figure 4 shows some of the area burned in Ontario broken down by cover type. Percentages of that area burned are provided in Figure 5. These data indicate that when using area burned (or average area burned), it is important to understand that a wide variation may exist in the specific cover type burned. This also applies to property value lost in fires: two 10-ha fires will have very different impacts if one destroyed a cottage and the other destroyed no structures.

Fire behavior varies widely from one fire to another, largely due to fuel type and fuel moisture conditions. In turn, fuel moisture depends upon the vegetation type and its stage of growth, and on current and previous weather. Fire behavior determines the difficulty of containing fires, and hence their ultimate size. Intensity is one measure of fire behavior: the rate of energy output per unit length of fire line per unit time. Intensity is a function of fuel type, fuel moisture, and rate of spread. Figure 6 illustrates the distribution of the calculated fire intensity at report time in Ontario. For example, 90 percent of fires have an intensity less than 177 BTU/ft per sec, and 50 percent of fires have an intensity less than 14 BTU/ft per sec. Most fires have a low intensity and these can be contained with minimal effort by fire crews. A small number of fires are too intense to suppress with any available technology, and grow freely until burning conditions change. The remaining

[1] Fires that threaten public safety are aggressively attacked regardless of their location.

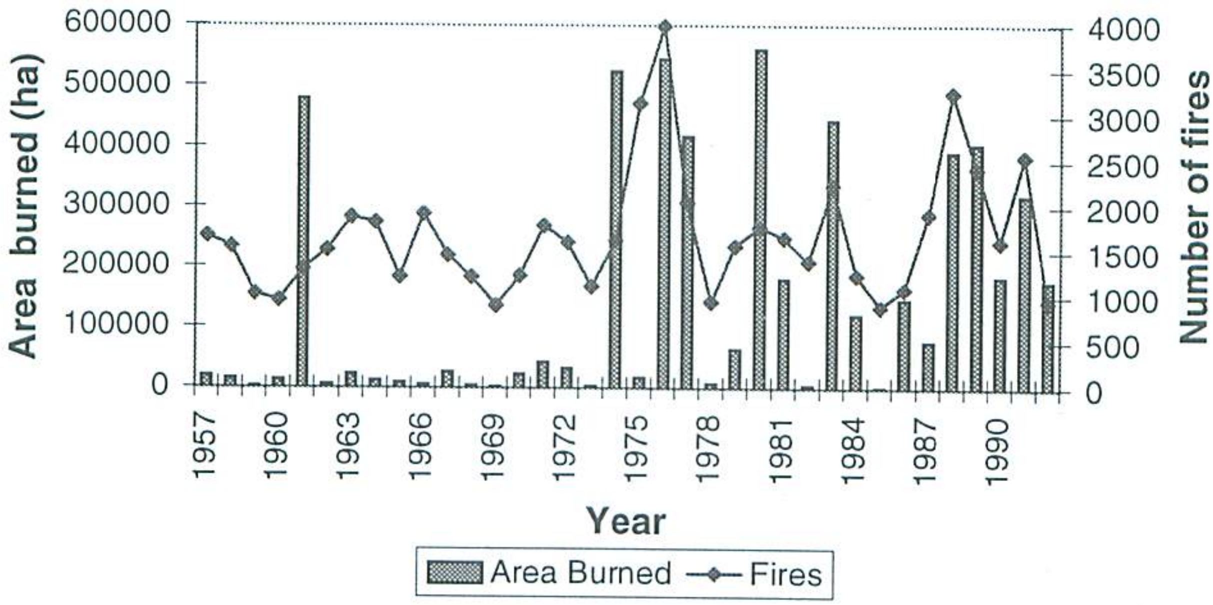

Figure 1. Historical forest fire occurrence and area burned in Ontario.

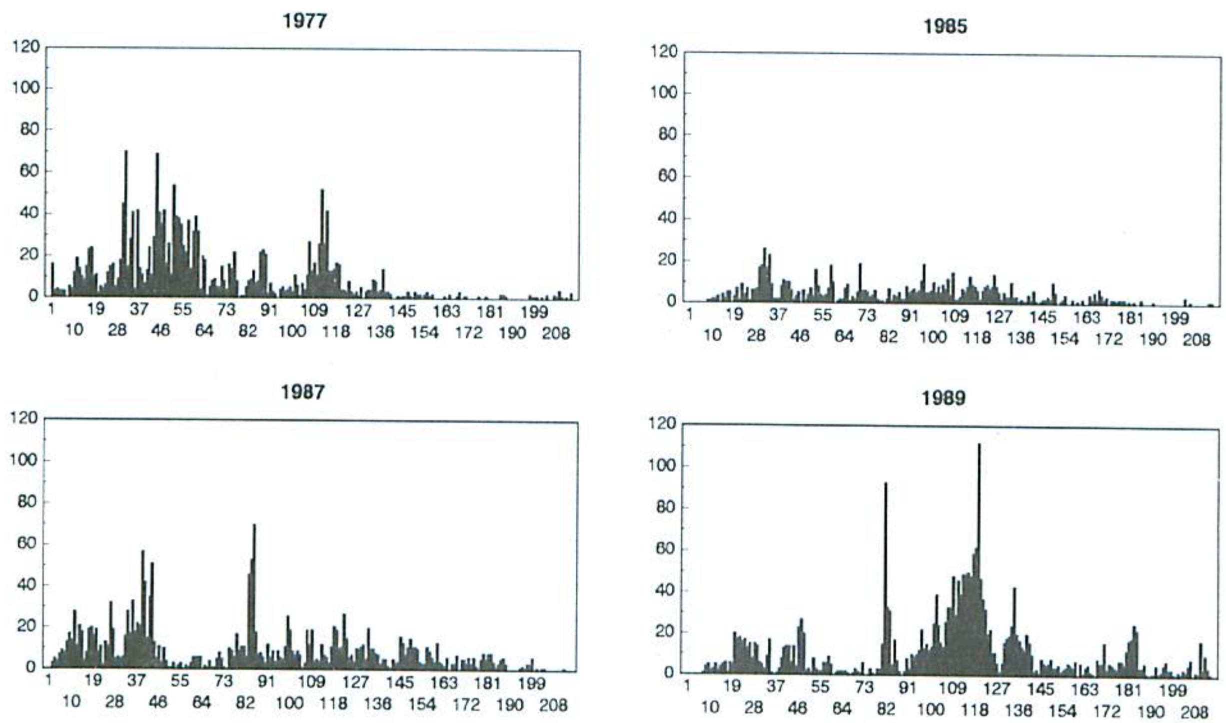

Figure 2. Number of new fires reported each day (Day 1 is April 1).

fires lie within a range or "window" of intermediate intensities and can be controlled by various means, ranging from ground crews with hand tools to heavy air tankers dropping foam. Suppressing these fires with appropriate speed and fire fighting resources can avert a great deal of damage.

Finally, the fire management workload varies throughout the day. Figure 7 shows the frequency distribution of fire

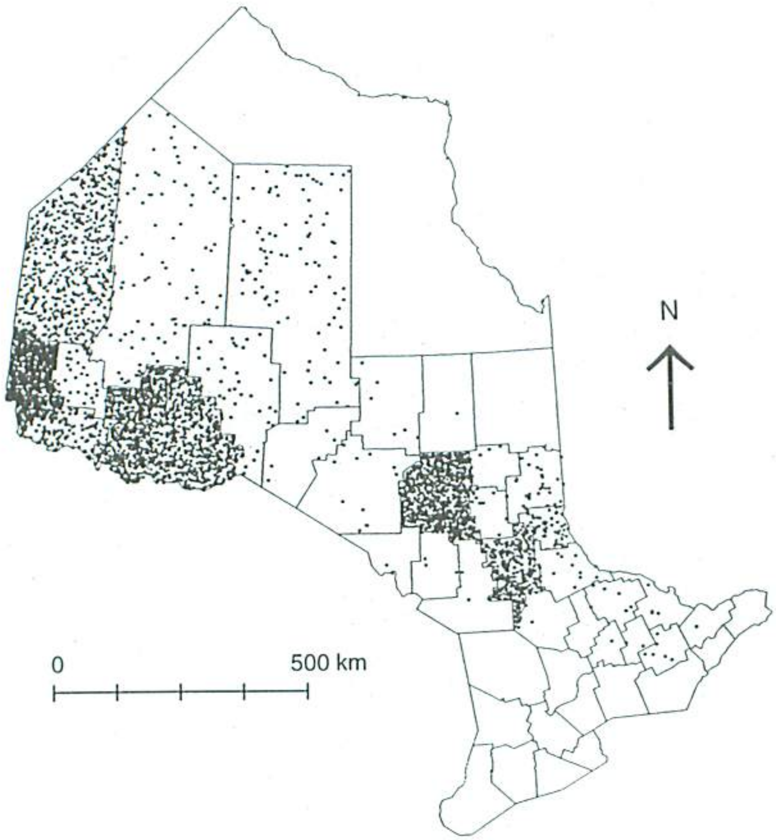

Figure 3. Average proportion burned in the intensive protection zone by district in Ontario, 1976 to 1988. Proportion burned is proportional to the density of dots. Dots are randomly located, and do not represent actual fires or their locations.

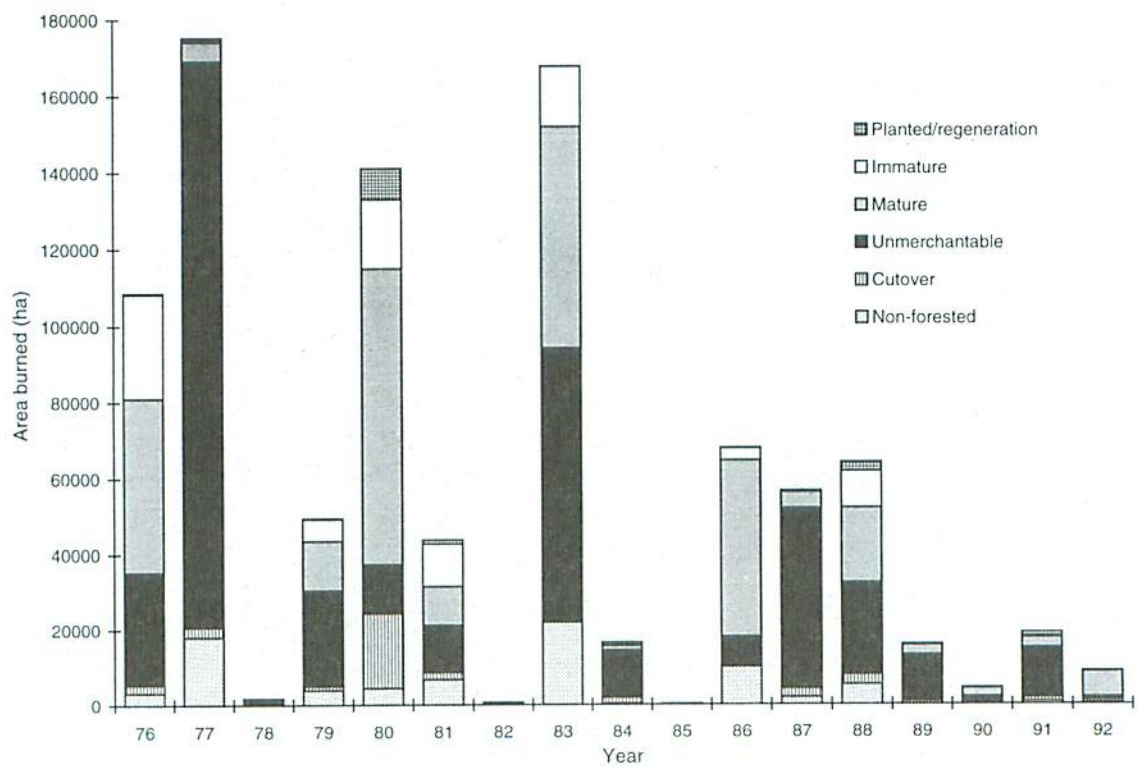

Figure 4. Area burned by a selective sample of fires in Ontario by cover type.

report time. Fire reports tend to cluster in mid to late afternoon, when fire spread rate and intensity are at their worst.

DEFINING LEVEL OF PROTECTION

Some forest fire managers use the term "level of protection" to refer to the measures they use in describing the extent to which their programs reduce the detrimental social, biological, and economic impacts of fire in a designated area. A level of protection measure is an example of what Larson and Odoni (1981) refer to as a "measure of performance", which is used to evaluate the extent to which a system achieves its objectives. It is, in very simple terms, a measure of performance that indicates how well the fire management organization protects the values-at-risk in its jurisdiction. The term clearly indicates that fire can have detrimental impacts on people and the biosphere, and acknowledges that the impact of fire on their protected area is reduced by their actions.

Most Canadian forest fire management agencies were formed in response to a

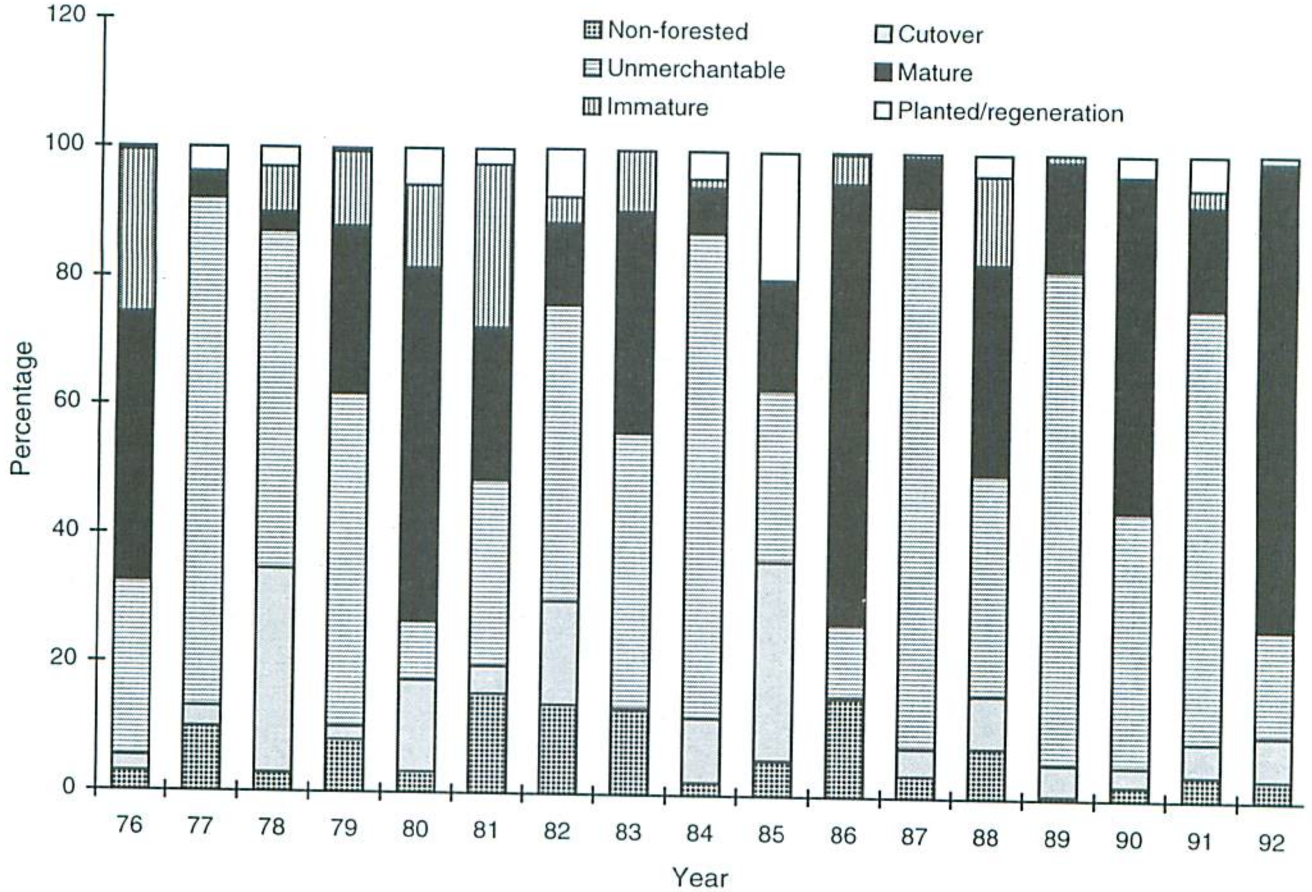

Figure 5. Percent of area burned by a selective sample of fires in Ontario by cover type, 1976–1992.

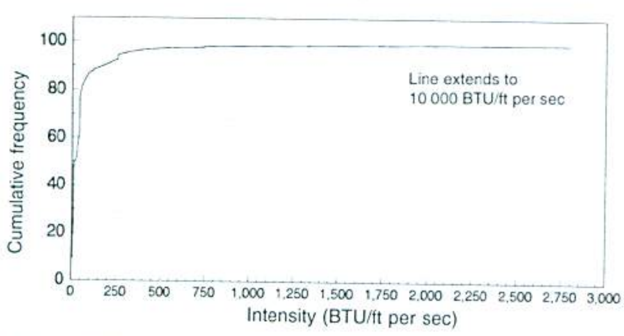

Figure 6. Cumulative percentage of fires vs. intensity of fire at report time.

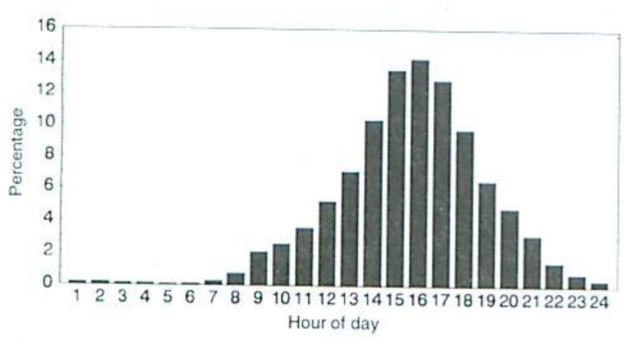

Figure 7. Frequency distribution of fire report time.

need to ensure public safety and to protect timber. Modern communications and transportation technology have all but eliminated the threat to people, other than to those engaged in fire fighting and support operations. Similarly, large communities are seldom burned by forest fires. Forest fire management agencies, like most public service organizations, cannot easily quantify the impact of their programs. They have developed and used many different measures of level of protection—measures that have varied over time and from agency to agency. It is informative to review some of those measures.

Area Burned

The area, fraction, and/or percentage of the protected area burned are often used as level of protection measures. They can also be expressed in terms of a fire return interval or fire cycle, which is an estimate of the average time between fires at some representative point in the forest. Use of such measures is based on the assumption that fire losses, be they timber, property, or threats to public health and safety, increase with the area burned.

Fire management agencies often state their objectives in terms of the percentage of area burned each year. In Ontario, fire managers have been using burned area as a measure of level of protection for many years. The old Northwestern Region, for example, had an annual burned area target of 50 000 ha or less of its intensive and measured protection zones.

Property Damage

The value of property destroyed by fire is also used extensively. Some agencies use depreciated value while others use replacement value. In principle, market value is an appropriate measure if it can be determined and if it represents true economic and social value.

Timber Volume Destroyed

Given the importance of timber production in Canada, it is not surprising that some Canadian fire management agencies gauge their success in terms of the volume of wood burned by fire. Simple measures of volume burned can be misleading, particularly if they ignore the species and location of the volumes consumed. Of even greater significance is the fact that burned volume is specific to the burn site and ignores substitution. Of importance also is the dynamic nature of the forest, which allows flexible forest management responses to fire losses.

The importance of assessing the impact of fire from a forest level rather than from a local burn site perspective will be discussed later. Suffice it to state at this point, that one must look beyond the burn site and assess the impact of a fire in terms of its effect on the potential flow of timber or the allowable cut from the entire forest or management unit.

Comprehensive, Multiattribute Measures

The property damage and timber volume measures described earlier are only two of the many values that can be destroyed by fire. Fire managers and their political masters are ultimately interested in measures that reflect the total cost of the fire management program and the net damage incurred. The widely used "cost plus loss" measure is the total cost of the fire management program plus the net loss due to fire. The United States Department of Agriculture Forest Service (USDA) uses the term "cost plus net value change" to emphasize that fire can have some beneficial impacts. In principle, a fire management agency should, as illustrated later in this discussion paper, be operated at such a level that cost plus loss is minimized. The true impact of fire includes its impact on public safety, property, timber, and other forest values; all of which are very difficult to assess. The theory is sound, but in practice it is virtually impossible to quantify all the values destroyed by fire. Therefore, comprehensive measures like cost plus loss provide valuable insight into fire management planning problems, but they are of little practical value to fire managers and fire management planners at the present time.

Surrogate Measures

Fire managers and fire management planners appreciate the theoretical and practical obstacles to developing and implementing level of protection measures, but are left with the practical problem of overcoming such obstacles and developing suitable multiattribute measures to facilitate their planning and management. They often use surrogate measures, which are relatively easy to understand and measure, in place of more complex measures like cost plus loss. "Area burned" is a good example of a surrogate measure of effectiveness. Its use is based on an assumption that the detrimental impact of fire on public health and safety, property, timber, wildlife, recreation, and aesthetic values increases as the area burned increases.

Surrogate measures are often used to assess the performance of emergency response systems, such as urban fire departments, police departments, and ambulance services, which are designed to protect public health and safety. It is very difficult to determine how many lives would be saved if a specified number of ambulances were added to an existing fleet, and it is even more difficult to quantify the value of the lives saved. Since it is reasonable to assume a reduction in response time will lead to an overall increase in the number of lives saved by an ambulance service, response time is often used as a surrogate measure of the value of an ambulance system.

It is important to note however, that while surrogate measures can be used to help allocate resources, they are of minimal value in helping to determine how much money to spend on an emergency response system. For example, response times can be used to determine how many ambulances are required in major urban centers so that every potential victim of cardiac arrest will have to wait an average of less than 5 minutes for an ambulance. But the 5-minute threshold is very much a subjective criterion. Ultimately, it must be set by the government in consultation with health care specialists who must weigh response times, or public health and safety, with many other demands on public resources.

Fire size at detection, initial attack response time, number of escaped fires, and final fire size are but four of the many surrogate measures used to assess the performance or level of protection provided by forest fire management systems.

Response Time

Initial attack response time is that time from when a fire is first reported to the forest fire management agency until the start of initial attack action. Its use is based on a recognition that area burned usually increases as a nonlinear function of time, and small decreases in response time can lead to significant reductions in another surrogate measure; namely, the area burned. It is important to note that since fuel, weather, and values-at-risk vary by time and place, response times should also vary by time and place. It makes little sense to spend large amounts of money to attain short response times in low value areas when fires are expected to spread slowly, and thereby compromise the ability of the organization to quickly respond to fires in high value areas when the fire hazard is extreme.

Escaped Fires

Some forest fire management agencies use the number of escaped fires as a measure of level of protection, but the procedures that are used to define an escaped fire vary. One of the earliest of such measures was the USFS's "10:00 a.m. rule", which stipulated that a fire that was not controlled by the start of the next burning period was to be classed as an escaped fire. More complex escaped fire criteria have been used in recent years. Some agencies classify fires that cannot be controlled by the initial attack force or fires that exceed some designated size as escaped fires.

Evacuations

Fire has the potential to kill or maim people, but it can also frighten them and disrupt their lives. Residents of small northern communities that are threatened by fire may spend many anxious days worrying and then have their lives severely disrupted when they are evacuated to other communities. Because it is difficult to assess the true cost of evacuations, it becomes reasonable to use the number of evacuations as a level of protection measure.

Selecting Appropriate Performance Measures

There are many different ways of defining and using measures of performance. Care must be taken to ensure the use of measures that induce the system to perform as desired. Consider, for example, area burned. The average annual area burned is a strategic measure of the performance of the overall system and, all things being equal, a reduction in the area burned is desirable. However, if values-at-risk are not uniformly distributed throughout the protected area, a single burned area figure will not encourage fire managers to deploy and use their resources so as to minimize total cost plus loss. Under such circumstances, it would be more appropriate to zone the protected area by values-at-risk and assess system performance by using a given set of burned area figures for each zone. In fact, that is what the OMNR and many other forest fire management agencies do, but it is difficult to make trade-offs between zones.

It is also possible to develop and use measures of performance for subsystems like prevention, detection, and initial attack systems, but it is essential to exercise care and judgement in their selection and use. Consider for example the prevention system. The objective of this system is to minimize the number of fires that occur subject to a constraint on its budget. Given the difficulty in assessing how many fires were prevented, fire managers sometimes use surrogate variables like the number of school visits and roadside signs posted to assess detection programs. Decreasing marginal returns to scale (i.e., the first sign probably prevents more fires than the twentieth sign) and the difficulty in comparing the relative effectiveness of different actions (i.e., how many school visits are equivalent to one roadside sign) make it difficult to aggregate measures of performance.

Fire managers have always found it difficult to assess the performance of detection systems. Consider, for example, some of the surrogate measures of performance that have been used to assess the performance of detection systems. Keep in mind that the public will ultimately find and report all significant fires that are not found by the organized detection system.

Suppose that an attempt is made to maximize the number of fires detected by the organized detection system. That will encourage detection planners to route aircraft along highways and around towns and villages in efforts to "beat" the public. Suppose detection systems are assessed in terms of the detection cost per fire. The agency can minimize that figure by spending little or nothing on organized detection. However, if they are assessed in terms of fire size at detection, that would encourage managers to spend money on low hazard days when fires are not spreading rapidly, and does not reflect that values-at-risk are not spread uniformly throughout the protected area.

The objective of the detection system is to find fires at such a size that they can be extinguished at a reasonable cost plus loss that includes the detection cost, suppression cost, and fire damage. Martell[2] developed a mathematical model that produces a suitable surrogate measure of detection system performance. He compared the predicted area burned with the existing detection system, and a hypothetical "perfect" initial attack system with the area that might have burned with a "perfect" detection system that finds fires as soon as they start. The difference is the loss due to detection delay. This should be minimized, but obviously cannot be eliminated.

[2]Martell, D.L. 1988. An assessment of the effectiveness of Ontario's forest fire detection system. Ontario Ministry of Natural Resources, Aviation, Flood and Fire Management Branch, Sault Ste. Marie, ON. Unpub. Report. 85 p.

In summary, care must be taken when considering the objectives of a forest fire management system or subsystem and in selecting surrogate measures of performance that will encourage people to satisfy the fire management agency's objectives. What is needed are strategic system-level measures of performance or level of protection measures, such as area burned by zone. These could be used by government to determine how much money to devote to forest fire management, and they could assist senior management to decide how to allocate the funds to different activities. Strategic subsystem measures, like average initial attack response time by zone, are required to ensure that initial attack resources are properly deployed and dispatched to fires. Tactical measures, like fire line productivity, are necessary to encourage air attack specialists and fire crews to perform well.[3] One of the objectives of the workshop was to identify and discuss surrogate measures of performance or level of protection that could be used to enhance forest fire management in Ontario, and to ensure that fire management expenditures are compatible with forest management and other values-at-risk.

A HYPOTHETICAL FOREST

A hypothetical, 500 000-ha forest was used to illustrate the basic principles of fire economics and fire management planning, to clarify the meaning of some of the level of protection measures previously described, and to demonstrate how these can be used by fire managers and fire management planners. This hypothetical forest is a highly simplified version of a boreal forest management unit used primarily for timber production. People live and work in communities in the forest and they occasionally ignite wildfires; there are also some shoreline cottages located on the lakes in the forest. There is no lightning fire occurrence. The hypothetical forest has a very simple forest fire management system with a prevention subsystem designed to prevent human-caused fire occurrence. It also has a suppression subsystem responsible for initial attack on all fires and extended attack on fires that escape initial attack.

Values-at-risk

Within this forest there is one small community having 500 single-family homes, a shopping center, a school, a hospital, a municipal office, and a municipal fire station. A total of 1 500 people live in the community and the forest fire management agency's headquarters and fire center are located there. There are 100 cottages uniformly distributed throughout the forest.

The values-at-risk include public health and safety. Given the communications and transportation resources available to the fire management agency, there is no significant threat to people. However, the residents of the community occasionally suffer from smoke produced by fires burning in the area. If there is a fire greater than or equal to 500 ha within 5 km of the community, 1 000 people are evacuated to a town outside the forest for a total of 7 days.

The community is surrounded by good fuel breaks and the buildings within the community cannot be burned by forest fires. However, the cottages, each of which is worth $30,000, can burn. The forest contains numerous timber resources, as described below. In addition, it contains many other forest resources, such as wildlife, that provide both tangible (e.g., fur trapping revenues) and nontangible (e.g., canoe routes and remote campsites) benefits to the residents of the community.

Forest Management

The small area occupied by the town, lakes, roads, and cottages can be ignored. Thus, it is assumed that the hypothetical forest is completely covered with 500 000 ha of 75-year-old stands of Site Class II jack pine at the start of the planning horizon. The forest is fully accessed by roads, and both harvested and burned areas regenerate naturally at no cost with a 5-year delay. A 300-year planning horizon, partitioned into 10-year periods, is to be used. In the timber management plan, the timber harvest flow is constrained to be constant. Similarly, the merchantable volume of growing stock in the forest is constrained to average at least 40.2 cubic meters per hectare at the end of the planning horizon. Wood is sold at a stumpage rate of $30.00 per cubic meter and future revenues are discounted at a rate of 3.0 percent per annum. For this example, salvage, harvest, regeneration, and transportation costs are to be ignored.

To assess the impact of fire and fire management, a model was required that could be used to predict how the hypothetical forest will respond to fire and harvesting. The

[3]In practice, most modern forest fire management organizations perform very well. To improve their performance, fire managers review the specific causes of escaped fires. Many escaped fires can be attributed to: (1) extreme fire behavior that cannot be controlled by any means, (2) multiple fire starts that exceed the capacity of the organization, and (3) a lack of information on fuel moisture conditions due to a lack of sufficient weather stations. Beyond these causes, a large fire might result from a prevention system failure; a detection system failure; inappropriate initial attack resource deployment or dispatch; miscalculation on the part of the air attack officer, the air tanker pilot, or the initial attack fire boss; low productivity on the part of the fire crew; or equipment failure. The final size of a fire is a good surrogate measure of the performance of the overall fire management system, but it cannot be used to assess the performance of its individual subsystems.

authors opted to develop a simple mathematical programing model like the forest level model developed by Reed and Errico (1986) for a hypothetical spruce (*Picea* spp.) forest in British Columbia. The Reed and Errico (1986) model has what is referred to as a Model III network structure, and is based on the assumption that fire losses occur at some average rate with no variance (i.e., some constant average fraction of the forest burns each year, but that fraction is determined in part by the amount of money spent on forest fire management). The fraction of the forest burned each year decreases as the amount of money spent on fire management increases. It constitutes a relatively simple first approximation to assessing the true impact of potential fire losses, and can readily be applied to real forest management planning problems.

Figure 8 provides a graphic representation of the basic network structure of the model. All the stands in the forest are aggregated into one of several age classes (nodes) at the start of the planning horizon. The arcs indicate how the area moves through the network over the planning horizon. Cut area moves from its age class at the time of the cut to the cutover node. It then moves into the lowest age class node at the start of the next period. The area that is not harvested matures into the next age class, but some fixed fraction of it burns enroute and moves down into the burned area node and then into the youngest age class in the next period. This is a mean value model that ignores the variance in annual fire losses. The GAMS modeling language with MINOS[4] was used to describe and solve this forest planning model. The basic mathematical structure of the model is described in detail by Martell (1994).

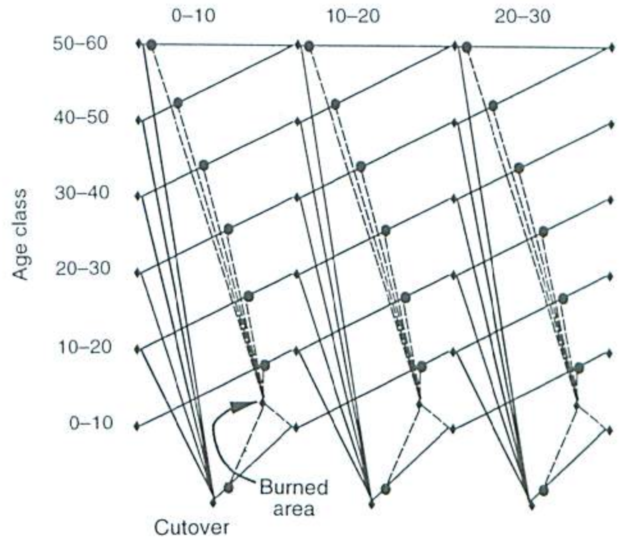

Figure 8. Graphic representation of the area balance network of the timber harvest scheduling model.

Forest Fire Management System

The forest has a small forest fire management organization that is designed to limit the destructive impact of fire on the forest and the residents of the community. In order to simplify analysis it is assumed to carry out only two activities: fire prevention and fire suppression. The prevention subsystem is designed to limit people-caused fire occurrence. The suppression organization carries out initial attack action on all fires that occur in the forest, and is responsible for extended attack on all fires that escape initial attack.

Fire Prevention Subsystem

The fire prevention staff relies on school visits, fire danger roadside signs, radio announcements, and restricted fire zones to prevent fire occurrence. The number of fires that occur varies from year to year due to changes in fire prevention activities, and the random nature of fire occurrence that results from human carelessness.

The uncertainty in annual fire occurrence can be modeled by a Poisson probability distribution that predicts such occurrence in probabilistic terms. The Poisson distribution is defined by a single parameter, the mean or average number of fires per year. If the symbol λ is used to represent the average number of fires per year, then the probability that n fires will occur each year is given by the following formula for the Poisson distribution.

$$P(n) = \lambda^n e^{-\lambda} / n! \qquad for\ n = 0,1,2,\ldots \qquad [1]$$

where: $P(n)$ is the probability that n fires will occur each year;
λ is the average number of fires per year; and
e is the base of the natural logarithm (2.7183...).

For example, if λ equals 50 fires per year, the probabilities that 30, 40, 50, or 60 fires will occur in the forest are shown in Table 1.

Fire occurrence generally decreases as fire prevention expenditures increase. However, the inherent randomness in this process is such that fire occurrence may vary from

[4]GAMS (Generalized Algebraic Modeling System) (Brooke et al. 1988) is a modeling language designed to facilitate the development, description, and solution of mathematical programing models. It can be used to quickly and relatively easily describe large, complex, mathematical programing problems in algebraic formats similar to those that mathematicians and planners often use to describe such problems. GAMS then generates a version of the model that can be interpreted by optimization software or solvers. The authors used a version of GAMS and the MINOS solver (Murtagh and Saunders 1987) to identify optimal solutions to the forest level linear progaming models generated by GAMS.

Table 1. Probabilistic annual fire occurrence with a Poisson distribution and an average of 50 fires per year.

Fires	Probability
30	0.001
40	0.021
50	0.056
60	0.020

year to year (as predicted by the Poisson probability distribution) even if the prevention expenditure remained constant. The following equation is used to approximate the relationship between average annual fire occurrence (λ) and prevention expenditures (E) in the hypothetical forest.

$$\lambda = 110 + 40e^{(-1.5\times10^{-5}E)} \qquad [2]$$

where: E is the annual prevention budget; and
λ is the average number of fires per year.

The annual fire occurrence relationship is portrayed graphically in Figure 9. Note that as is the case with most production processes, there are decreasing marginal returns. The number of fires "prevented" by each successive increase in the prevention budget decreases as the amount of money spent on prevention increases. For example, suppose that \$15,000 is currently being spent on prevention. That would result in an average of 141.9 fires per year. If the prevention program was expanded to \$20,000, the average annual fire occurrence would decrease to 139.6 fires per year. That represents a marginal decrease of 2.3/5 000 or 0.00046 fires per additional dollar spent on prevention. Suppose the prevention program currently operated at a level of \$20,000 per year. An increase of \$5,000 dollars would further reduce λ from 139.6 to 137.5 fires per year. That represents a reduction of an average of 2.1 fires per year divided by \$5,000 or a reduction of 0.00042 fires per increased prevention dollar. Those figures clearly indicate that if nothing is being spent on prevention, a small budget will have a significant impact on fire occurrence. However, if a large amount of money is already being spent on prevention, any increase may have very little impact.

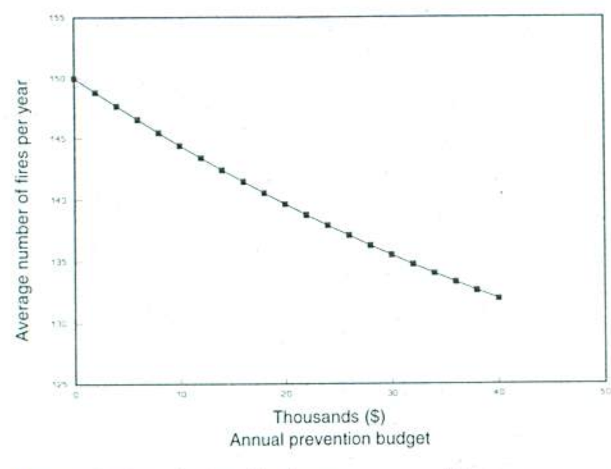

Figure 9. The relationship between annual fire occurrence and fire prevention expenditures in the hypothetical forest.

Note also that although money can be spent on prevention to reduce the average number of fires per year, it cannot be determined how many fires will actually occur each year. Suppose, for example, either \$20,000 or \$25,000 is spent on prevention. The resulting λs and associated probabilities of fire occurrence are shown in Table 2.

Note also that no matter how much money is spent on prevention, there is some non-zero probability that 140 fires will occur during a particular year. Increasing the amount of money spent on prevention will decrease the average or expected number of fires per year and the probability that 140 fires will occur. However, due to the inherent randomness, there is no guarantee that increased expenditures will reduce fire occurrence every year. This is one important aspect of planning under uncertainty that complicates forest fire management and the management of other systems subject to random, or what mathematicians and planners refer to as stochastic, processes. In very simple terms, the manager can spend more and "load the dice" in his or her favor, but Nature or someone other than the manager rolls the dice and determines what will actually happen each year. This important aspect of planning under uncertainty permeates all aspects of forest fire management.

Table 2. The uncertain impact of fire prevention expenditures on fire prevention in the hypothetical forest.

Prevention budget	\$20,000	\$25,000
Average number of fires per year (λ)	139.6	137.5
Probability that 100 fires will occur	0.0001	0.0001
Probability that 110 fires will occur	0.0013	0.0020
Probability that 120 fires will occur	0.0086	0.0114
Probability that 130 fires will occur	0.0249	0.0284
Probability that 140 fires will occur	0.0337	0.0329

Fire Suppression Subsystem

The fire suppression subsystem is designed to carry out initial attack on all fires that occur in the forest. It also has extended attack capabilities that enable it to suppress all fires that are not controlled by the initial attack force. The suppression organization has a presuppression budget *P* that is used to fund the basic cost of the fire management system infrastructure. This includes initial attack operations, but excludes prevention. Initial attack system success increases as the amount of money spent on presuppression increases. The probability that a fire is held by the initial attack force is given by the following logistic relationship between the probability of success and the presuppression budget:

$$PH(P) = e^{(4.392\times10^{-6}P)}/[1+e^{(4.392\times10^{-6}P)}] \quad [3]$$

where: *PH(P)* is the probability that the fire does not escape; and P is the presuppression budget.

Each fire that occurs is attacked by an initial attack force that incurs a suppression cost of $2,000. Fires that are controlled by the initial attack force are assumed to burn a total of 0.1 ha. The final size of an escaped fire (*a*) can be modeled as a random variable having an exponential probability distribution with a parameter μ as shown in the following equation.

$$f(a) = \frac{1}{\mu} e^{-\frac{a}{\mu}} \quad [4]$$

where: *f(a)* is the probability density function of the final size of an escaped fire; and

μ is the average size of an escaped fire (assumed to be 750 ha in the hypothetical forest).

The suppression cost for each escaped fire is $2,000 plus a linear function of the square root of the final size of the fire. This reflects that, on large fires, mop-up time is largely a function of the fire perimeter. The suppression cost (SC) for an escaped fire in the hypothetical forest is given by the following expression.

$$SC = 2000 + 1342.6\sqrt{a} \quad [5]$$

where: *SC* is the fire suppression cost; and

a is the final size of the escaped fire in hectares.

Note that the managers of this forest are responsible for determining how much money will be spent on fire prevention and presuppression. The number of fires that occur, the fraction of fires that escape initial attack, and the final sizes of the fires that escape initial attack are all determined by random, or stochastic, processes that are influenced—but not rigidly controlled—by the managers. As was stated earlier, the prevention budget influences the average number of fires per year, but the actual number of fires that occur each year is a realization of a random process that varies about its mean value. The presuppression budget influences the probability that a fire will escape initial attack, but the final fire size is a random variable that is independent of the presuppression budget in the hypothetical forest.

Note that the suppression cost is determined by the fire management policy and the random processes described earlier. The fire management policy for the hypothetical forest stipulates that all fires will be aggressively attacked until they are suppressed. The suppression cost is therefore subject to a policy variable that is set by senior management. It is not a decision variable from the fire manager's standpoint, i.e., under a fire exclusion policy, the manager cannot decide *not* to suppress a fire.

The Uncertain Impact of Fire on the Hypothetical Forest

Random or stochastic processes, such as fire occurrence and fire behavior, contribute to the high degree of variability and uncertainty that are characteristic of forest fire management. One very problematic consequence of that variability is a difficulty in identifying the extent to which changes in the system contribute to improved performance. A fire management agency might hire more fire crews with the hope and expectation that the increased availability of personnel will reduce overall cost plus loss, but find—due perhaps to abnormally dry weather—that fire losses actually increase. Understandably, they are unable to determine the extent to which the additional crews improved the system's performance and the increased fire load decreased its performance. That lack of precision may frustrate managers and make it difficult to evaluate the performance of the organization and rationalize protection expenditures.

The hypothetical forest and its fire management system will be used to illustrate the pervasive importance of uncertainty that is a consequence of the stochastic nature of forest fire management. To begin, it is necessary to explore how prevention and presuppression planning can influence fire occurrence and behavior, with a base case in which the fire manager spends a total of $15,000 on prevention and $500,000 on presuppression, or $1.03/ha each year.

The fire prevention subsystem model described earlier predicts that if $15,000/yr is spent on prevention, an average of 141.9 fires will occur annually in the hypothetical forest. The suppression system model predicts that with a presuppression budget of $500,000, the probability that a fire will escape initial attack is 0.10 or 10 percent. This indicates that an average of 14.2 fires will escape initial attack each year. The exponential escaped fire size distribution indicates the average final size of an escaped fire will be 750 ha. The escaped fire suppression cost model predicts that given this average fire size, the average suppression cost of an escaped fire will be $38,769. These results are summarized in Table 3.[5]

However, the average fire season will seldom if ever occur. Table 4 shows the result of 5 simulated years when $15,000 is spent on prevention and $500,000 on presuppression in the hypothetical forest. The results presented in Table 4 clearly demonstrate the high degree of variability in the outcome.

Suppose the fire manager wanted to increase the prevention budget by $5,000 to $20,000 per year. Table 5 illustrates the result of 5 simulated years when $20,000 is spent on prevention and $500,000 on presuppression. Suppose the fire manager wanted to increase the presuppression budget by $200,000 to $700,000 per year. Table 6 shows the result when $20,000 is spent on prevention and $700,000 on presuppression.

Table 3. Average result if $15,000 is spent on prevention and $500,000 on presuppression in the hypothetical forest.

Prevention cost	$15,000
Presuppression cost	$500,000
Average number of fires	141.9
Number of fires held	127.7
Suppression cost of each fire held	$2,000
Suppression cost for held fires	$255,400
Number of fires not held	14.2
Average size of each escaped fire (ha)	750
Suppression cost of each escaped fire	$38,769
Suppression cost for escaped fires	$550,520

Total cost of prevention, presuppression, and suppression $1,320,920 or $2.64/ha per year.

Fraction of forest burned (ignore held fires) is 10,650/500,000 = 0.0213

Table 4. Five independent simulated annual scenarios with a prevention budget of $15,000 and a presuppression budget of $500,000 in the hypothetical forest.

Year	Number of fires	Number of escaped fires	Total area burned (ha)	Largest fire (ha)	Fire suppression cost ($)	Total cost ($)
1	135	15	24 600	2 810	786,000	1,301,000
2	151	11	17 100	2 140	678,000	1,193,000
3	166	14	17 300	2 770	741,000	1,256,000
4	135	7	18 000	4 570	575,000	1,090,000
5	149	12	24 700	2 580	786,000	1,301,000
Average	147.2	11.8	20 300	2 980	713,200	1,228,000

Table 5. Five independent simulated annual scenarios with a prevention budget of $20,000 and a presuppression budget of $500,000 in the hypothetical forest.

Year	Number of fires	Number of escaped fires	Total area burned (ha)	Largest fire (ha)	Fire suppression cost ($)	Total cost ($)
1	129	10	16 900	2 710	610,000	1,130,000
2	115	8	6 000	1 700	400,000	920,000
3	116	12	25 800	4 480	690,000	1,210,000
4	125	16	23 700	1 600	793,000	1,313,000
5	139	15	23 500	3 170	734,000	1,254,000
Average	124.8	12.2	19 200	2 730	645,400	1,166,000

[5]The authors have considered only fire costs in this example. The assessment of fire losses is much less straightforward, and will be discussed in later sections of this paper.

As indicated, forest fire management is characterized by extreme uncertainty and the simulated results for the hypothetical forest clearly highlight some of the difficulties that uncertainty creates for forest fire managers. Fire managers and planners believe that burned area decreases as fire management expenditures increase, but uncertainty clouds the issue. Fire management planning can be viewed as spending money to build dice that Nature rolls. The more you spend, the more the dice becomes biased in your favor. But it may take many rolls of the dice to identify a clear trend, and that makes it difficult to decide when to stop spending. However, the problem is not as difficult as it superficially appears as there are planning procedures that are designed to deal with such uncertainty.

Although Ontario's forests provide a broad array of benefits that would be threatened by fire, this study concentrates on timber management because timber is a very important forest resource. In recent years, these authors and other researchers have studied and learned a great deal about the impact of fire on timber supply. Other values will be dealt with later.

A FIRE ECONOMICS AND FIRE MANAGEMENT PLANNING PRIMER

Fire Management Objectives

Before dealing with level of protection and resource allocation it is appropriate to review some of the basic principles of fire economics, and to set the stage for a detailed examination of fire management. The implicit objective of most forest fire management agencies is to minimize the net destructive impact of fire subject to constraints on resource availability and utilization. Funds are allocated to fire management on the assumption that the subsequent benefits will exceed the value of the money spent.

Fire management costs are readily expressed in monetary terms. Salaries and equipment costs are easily assessed, as is the cost of supporting fire management personnel in the field. The annual cost of fixed assets is less easily identified, but standard accounting practices should yield reasonably accurate estimates.

The benefits of fire management activities include the reduced losses that result from limiting the number and size of destructive wildfires, the increased productivity that results from the proper use of prescribed fire, and the enhanced environment that would result from successfully monitoring and modifying the suppression of beneficial wildfires. Although fire managers are certain the net benefit of their efforts is positive, they find it difficult—if not impossible—to quantify the monetary consequences of their actions.

Public safety is perhaps the most important benefit of forest fire management. Modern fire management agencies are sufficiently effective that "non-fire personnel" are seldom injured or killed by forest fires. However, it would be virtually impossible to determine how many lives are saved as a consequence of fire management activities.

The reduction of property damage is an obvious benefit of fire management programs. To evaluate this benefit in monetary terms one must first identify the property that was saved as a consequence of fire management efforts. Once the saved items have been identified, replacement cost or other methods could be used to estimate the monetary value of this benefit.

A third major benefit of fire management activities is the protection of timber. Evaluation of this benefit entails a two-step process. The fire manager must first identify the stands of timber that were not burned as a consequence of fire management efforts. Once the saved areas have been delineated it is necessary to assign a monetary value to the timber damage that was averted.

Table 6. Five independent simulated annual scenarios with a prevention budget of $20,000 and a presuppression budget of $700,000 in the hypothetical forest.

Year	Number of fires	Number of escaped fires	Total area burned (ha)	Largest fire (ha)	Fire suppression cost ($)	Total cost ($)
1	150	8	11 000	2 000	547,000	1,267,000
2	155	6	9 000	2 070	504,000	1,224,000
3	146	9	18 000	1 690	641,000	1,361,000
4	127	4	6 500	1 770	385,000	1,105,000
5	117	4	9 900	2 410	408,000	1,128,000
Average	139.0	6.2	10 900	1 990	497,000	1,217,000

The fourth, and possibly the most complex, benefit of fire management is protection of the aesthetic benefits that accrue to people who use the forest or derive satisfaction from the knowledge that certain ecosystems exist. To assess the aesthetic benefits of fire management one must predict the long-term consequences of a fire and place a monetary value on the resulting environment. Aesthetic benefits cannot be convincingly quantified at the present time.

There are of course many indirect benefits that result from fire management. Forest fires often affect wildlife populations; diminish air, soil, and water quality; and disrupt human activities. Although indirect fire management benefits are obviously important, they cannot yet be expressed in monetary terms.

Finally, it is important to recall that fire can have beneficial impacts, such as the preservation of ecosystem "naturalness" and the enhancement of wildlife habitat. In this respect, fire management can have negative effects, and balancing the positive and negative effects is not necessarily straightforward.

What is the Value of Forest Fire Management?

Given the discussion in the preceding section, it becomes clear that it is not easy to measure the value of fire management, decide how much should be spent on fire management, or allocate fire management budget funds to the many subactivities of a fire management program.

In Ontario, forest fire management is a public service that is provided by government on the assumption that accrued benefits exceed the cost of providing the service. In its most abstract form, the benefit of fire management is the net improvement in the quality of life experienced by the people of Ontario. The value of fire management is therefore the quality of life with fire management less the quality of life without fire management. Given the earlier discussion, it is obviously impossible to quantify those benefits and transform them into monetary terms.

A more concrete assessment of the impact of fire management is its effect on the gross national product (GNP) of Canada or Ontario. The value of fire management is the GNP with fire management less the GNP without fire management. That approach ignores many important "quality of life" issues that are not currently included in GNP calculations. It does, however, take into account potential mill closures or increased delivered wood costs that might result from fire.[6] The authors do not currently have an econometric model of Ontario's forest sector that accounts for the structure of the forest products industry, the tourism industry, or the forest itself over long planning horizons. Such an approach awaits the availability of an acceptable version of such a model. As an interim measure it may be possible to use the Regional Economic Impact Model proposed by Kubursi and Spencer (1993).

Some people advocate the use of "value added" figures to assess the value of forest fire management. They point to the retail value of the forest products (e.g., paper) that would have been produced with the wood fiber consumed by a fire, and suggest that figure be used to assess fire impact. The value added approach is fraught with many dangers. These include:

- Not all the retail value in forest production is due to wood. Many resources (e.g., chemicals and energy) contribute to that value.
- The value added approach does not account for the fact that some resources could be shifted away from forestry and invested in other sectors of the economy.
- Employment and community stability have values that are not reflected in simple economic measures.

The value added approach therefore shows little promise for evaluating forest fire management programs in the near future.

Therefore, the authors propose to use stumpage value (the economic value of a tree on the stump) as a surrogate measure of the timber value of forest fire management. In the simplest case a flat stumpage rate that is constant throughout a forest management unit will be used. This approach can, however, readily accommodate harvest, stumpage rates, and transportation costs that vary by location.

It is important to note that this simplification is not necessarily as limiting as it superficially appears. Forest fire management in Ontario is a public service and the government is not in a position to evaluate all of its programs in strict monetary terms. It would be preferable to simply determine the monetary value of fire management, but in the end the government must weigh expenditures on health, education, welfare, and many other services. In an electoral democracy, the government is responsible for allocating funds to forest fire management, and it will use the methods it feels appropriate. Once those funds have been allocated, the task of fire managers and their clients is to ensure they maximize their effectiveness. Relative measures like stumpage might well be satisfactory for that purpose.

[6] It is important to correctly account for all effects of fire. For example, large fire suppression expenditures might increase the current GNP while the fires themselves reduce future GNP.

Selecting Forest Fire Management Budget Levels

The basic principle of fire economics is referred to as the deterministic Least Cost Plus Damage or deterministic LCD model. The term "deterministic" means ignoring uncertainty or the variability that arises from fluctuations in weather and other random processes and considering only long term average outcomes. The simple LCD model cannot be used to specify how much money should be spent on forest fire management, but it can be used to generate valuable insight into the problem.

Consider the very simple case in which a fire manager must decide how much money should be spent on hiring fire fighters in a region for the season. This is what is referred to as the deterministic single resource (fire fighters) LCD model. Common sense and experience suggests that if no fire fighters are hired some large, finite portion of the district will be burned each year; something less than the entire district. If fire fighters are hired, a decrease in fire losses and area burned could be expected. Economic theory suggests there will be decreasing marginal returns to scale so that eventually each additional fire fighter hired produces less and less reduction in fire losses on the area burned.

The deterministic LCD model can be illustrated graphically as shown in Figure 10. The horizontal axis is P, or the amount of presuppression money spent on fire fighters. The vertical axis represents L(P), or suppression cost and fire loss as a function of P. L(P) includes overtime salaries, the cost of bringing on extra fire fighters (EFF) and/or additional fire fighters from other districts, and the cost of fire damage. If one considers the presuppression cost P to be a cost, then T(P) = L(P) + P is the total cost plus loss incurred per year if P dollars are spent on presuppression. The district manager should select a value of P, denoted by P^*, that will minimize T(P) or the total cost plus loss. P^* is the point where the tangent to T(P) is horizontal (*see* Fig. 10).

The deterministic LCD principle is that forest fire management systems should be operated at such a level that the total cost of operation plus fire loss is minimized (i.e., minimize cost plus loss). The basic insight it provides is that total cost plus loss is a bowl shaped or convex function of presuppression expenditures, and the optimal amount of money to spend on presuppression is the amount that corresponds with the point where the total cost plus loss curve has a horizontal tangent. There is only one optimal presuppression value. If either more or less than the optimum is spent, the total cost plus loss will be higher than it need be.

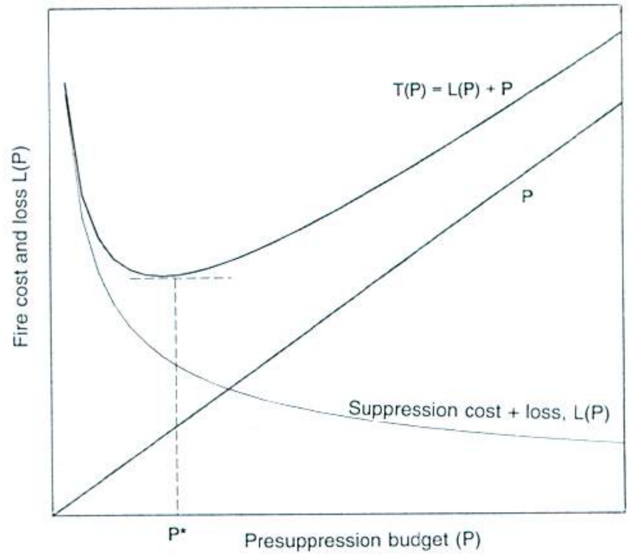

Figure 10. Deterministic least cost plus damage (LCD) model.

Consider, for example, the fire management system in the hypothetical forest. To simplify the problem to one that can be graphed in two dimensions, assume that nothing is spent on fire prevention. The result, as predicted by the fire prevention subsystem, will be an average of 150 fires per year. The decision, then, is to decide how much to spend on presuppression.

The probability that a fire will be held by initial attack if P dollars are spent each year on presuppression is given by Equation 3. The probability that a fire will escape initial attack if P dollars per year are spent on presuppression is therefore 1 - PH(P).

Ignoring the area burned by fires that do not escape and assuming each escaped fire burns 750 ha, the suppression cost of a fire is given by Equation 5. The cost of a fire that is held is $2,000 and the cost of a 750-ha escaped fire is $38,769.

If fire loss is ignored and only the suppression cost is considered, the average total presuppression plus suppression cost for the fire season is:

$$P + 150[2000\ PH(P) + 38,769(1 - PH(P))] \quad [6]$$

where: P is the presuppression expenditure; and
$PH(P)$ is the probability that a fire will not escape as a function of P.

Figure 11 illustrates the effect of the presuppression expenditure on: (i) the average annual fire suppression cost, and (ii) the average annual total presuppression and suppression cost. It shows that if there is no prevention program in the hypothetical forest and fire losses are ignored, the optimal presuppression budget is about $700,000 per year or $1.40 per hectare.

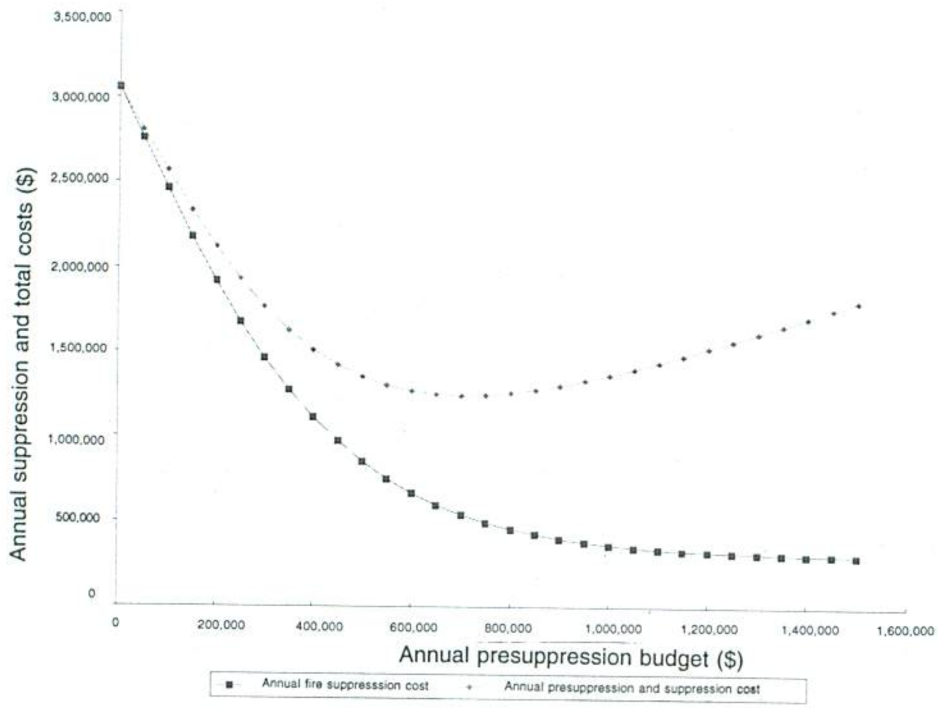

Figure 11. Optimal presuppression budget for the hypothetical forest with no prevention program.

The simple deterministic LCD model does of course have some limitations:

- It is difficult to specify L(P), the production function that relates fire suppression cost plus loss to the presuppression budget.
- Historical data is not necessarily relevant, due to:
  - land use changes;
  - fire environment changes; and
  - technology changes.
- The simple LCD model does not account for more than one type of fire suppression resource.
- The model does not represent the stochastic nature of the problem (i.e., the uncertainty and random processes), which complicates forest fire management.

Multiple Resources and Resource Allocation

Fire managers can, of course, spend their funds on a wide variety of fire management resources. The deterministic, single resource LCD model can be expanded to the deterministic multiple resource LCD model to account for this.

Consider the simplest expansion in which a regional manager can spend S_1 dollars on fire prevention, S_2 dollars on detection, S_3 dollars on fire fighters, S_4 dollars on trucks, S_5 dollars on transport helicopters, and S_6 dollars on air tankers. In theory, it should be possible to express fire loss as a function of those expenditures, $L(S_1,S_2,S_3,S_4,S_5,S_6)$. The total cost plus loss would then be:

$$TL(S_1,S_2,S_3,S_4,S_5,S_6) = L(S_1,S_2,S_3,S_4,S_5,S_6) + S_1 + S_2 + S_3 + S_4 + S_5 + S_6$$

In theory, mathematical optimization techniques could be used to determine how much money to spend on each activity as well as the total amount to spend on fire management to minimize TL. Thereby, one would solve both the level of protection and resource allocation problems simultaneously. In practice, it is not possible to do this.

Resource Allocation with Budget Constraints

As noted previously, the government will not necessarily elect to spend the optimal amount of money on forest fire management. It may decide to spend some lesser amount. In theory, it is also possible to use mathematical optimization techniques to solve the corresponding constrained optimization problem. Suppose the presuppression budget is constrained to be less than or equal to B dollars per year. The presuppression planning problem then becomes:

$$\text{Minimize} \quad TL(S_1,S_2,S_3,S_4,S_5,S_6)$$

$$\text{such that} \quad S_1 + S_2 + S_3 + S_4 + S_5 + S_6 \leq B$$

While it is easy to state the form of these problems, actually specifying TL would be extremely difficult due to the complexity of and uncertainty associated with fire and forest management systems. It is important to note that the solution to the constrained problem can never be better than the solution to the unconstrained problem, and it is quite likely that it will be worse (i.e., total cost plus loss will increase).

FIRE MANAGEMENT PLANNING UNDER UNCERTAINTY

Deterministic LCD models do not account for the high degree of uncertainty that complicates forest fire management. Weather variation, human behavior, and many random processes combine to introduce a great deal of uncertainty into forest fire management. What is required are referred to as stochastic models that explicitly treat uncertainty.

Fire managers presently use simple stochastic models that provide probabilistic predictions of daily human-caused fire occurrence. It is possible to develop stochastic presuppression planning models, and the authors will illustrate the concept by using a very simple numerical example to portray some of the basic principles of planning under uncertainty.

Deciding How Many Fire Crews to Put on Red Alert Each Day

Consider a highly simplified problem in which a duty officer must decide to put zero or one fire crews on red alert for initial attack out of a district headquarters. Since all the crews have used up their regular hours it will cost $1,000 to put a crew on red alert. Suppose zero or one fires will occur and the probability that a fire will occur is 0.1. Obviously if no fire occurs there will be no fire loss. If a fire occurs and there is a crew on red alert, the fire cost plus loss will be $10,000. If a fire occurs and there is no crew on red alert, a crew will have to be brought in and the delay will be such that the fire cost plus loss will be $200,000. Should the crew be put on red alert? What decision analysts refer to as a decision tree (*see* Fig. 12) can be used to illustrate and solve this problem. The square node represents a decision made by the manager. Each branch out of a square node denotes an alternative that can be selected by the manager. The circular nodes represent uncertain, chance, or stochastic processes controlled by Nature. The values at the ends of the terminal branches at the far right represent the total cost plus loss for each combination of an alternative selected by the manager and a chance outcome determined by Nature.

Some managers might be very risk averse and always put a fire crew on red alert. Others might be very risk seeking and almost never put the crew on red alert. Some of the early fire management planning literature suggested managers should plan for average or average worst conditions, but clearly zero or one, not 0.1 or some other intermediate number of fires will occur. The principles of decision theory or planning under uncertainty prescribe that the

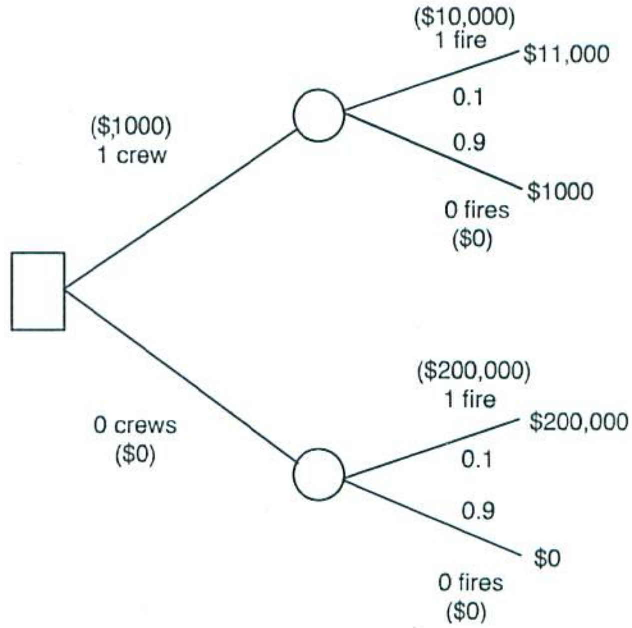

Figure 12. Decision tree for a fire crew alert status problem.

manager could choose that alternative that will minimize the expected or average total cost. This is obtained by adding costs along each decision branch and multiplying by the probability of the branch. The expected cost of putting a crew on red alert is $11,000(0.1) + $1,000(0.9) = $2,000. The expected cost of not having a crew on red alert is $200,000(0.1) + $0(0.9) = $20,000. The optimal solution is therefore to put one crew on red alert.

It is important to note that the manager does not control Nature, but he or she can influence what Nature does. In some respects, Nature rolls the dice, but the manager decides how many crews to put on red alert and thus influences the ultimate outcome. This basic principle of planning under uncertainty can be used to introduce stochastic elements into the single resource LCD model. However, the model is very complex and will not be considered in this discussion paper. Rather, the authors present some interesting results concerning timber management in a hypothetical forest. But first, some previous attempts to resolve level of fire protection decisions will be discussed.

HOW DO FOREST FIRE MANAGEMENT AGENCIES RESOLVE LEVEL OF PROTECTION DECISIONS?

Faced with complex problems like those described above and the lack of suitable decision support models, governments and forest fire managers have been forced to resort to a variety of heuristic (i.e., rule of thumb) procedures for setting fire management budget levels and allocating those funds to program components.

Approaches that have been used include:

1. Tradition
   - slight changes from year to year
2. Best guess
   - intuitive manager uses his or her best judgement
3. Cost-benefit analysis
   - attempt to quantify the costs and benefits of fire management
4. Political necessity
   - need to respond to "calls for action" after fire has threatened communities or destroyed valuable resources

There have been many attempts to develop formal quantitative procedures for evaluating and allocating funds to forest fire management programs. Sparhawk (1925) of the USDA Forest Service appears to have been the first to formally document procedures that drew upon economic factors to rationalize forest fire management expenditures in North America. His study objectives were "to ascertain if some scientific method could be found by means of which it would be possible to determine how much money can justifiably be spent for fire protection on the national forests" and "to provide a basis for the proper distribution of available protection funds between the different units of the organization." He laid the theoretical foundation for the LCD model, but was unable to apply it as he could not develop mathematical models that related area burned and suppression costs to presuppression expenditures, nor could he quantify the values-at-risk.

Nevertheless, he developed a simple liability rating system that could be used to help assess fire management expenditures by fire management unit. The basic structure of Sparhawk's (1925) system was as follows. He began by using climatic data to partition the western half of the United States, excluding Alaska, into 21 subregions. He then classified the forest cover in each subregion into one of several forest types. He used 5 years (1911–1915) of historical data to relate area burned in each cover type and each subregion to the elapsed time between when the fire was discovered and when suppression began, or what now might be referred to as the initial attack response time. He also graphed relationships between fire suppression cost and fire area, and suppression cost and response time for each cover type within each subregion. He discussed the problems associated with evaluating intangible resources and used stumpage rates to assess timber losses. He also developed a general liability index that was the product of the sum of the fire loss and the suppression cost multiplied by the average number of fires per year for each response time category in each cover type in each subregion. His assumption was that planners could subjectively relate response times to presuppression expenditures, and predict the general liability index or average fire loss for each subregion depending upon the presuppression budget and assumed response time for each portion of the forest. Sparhawk (1925) applied the liability rating to a hypothetical forest management unit. The authors did not investigate the extent to which his liability system was subsequently applied, but his ideas clearly shaped attempts to rationalize North American forest fire management planning for many years.

An influential report (United States Department of Agriculture 1977) was written by the USDA Forest Service in response to a request from the Office of Management and Budget for information concerning the escalation of fire management expenditures in the United States during the 1970s. It contained a number of findings: forest values are neither adequately assessed nor properly used in fire management today, and the fire planning process is incomplete. It also contained several recommendations: including, a call for new fire management policies appropriate for the time; the establishment of procedures for estimating forest values; the development of an integrated fire/forest management planning process; the development of improved accounting and budgeting systems; and the development of a comprehensive evaluation system that would include effectiveness as well as efficiency measures, and provide fire and other forest service managers with feedback that could be used to enhance the achievement of the Forest Service's fire and forest management objectives. It appears to have initiated a number of important changes in fire management planning within the USDA Forest Service.

FOCUS is a large computer simulation model developed by the USDA Forest Service to evaluate initial attack systems. Users compile a computerized database that describes the fire environment of the planning unit (e.g., a national forest) and specify alternative initial attack plans (e.g., location of bases, home-base resource allocation, and initial attack dispatch rules). FOCUS simulates the proposed system by fighting historical fires and determines the (cost plus loss) consequences of initial attack. Escaped fires are gamed by a group of local experts who subjectively estimate their cost plus loss.

Warthman (1977) estimated an initial setup cost of from $15,000 to $50,000 to use FOCUS on a planning unit, approximately $500 to $25,000 to evaluate five alternative plans over four fire seasons, and approximately $500 to $25,000 to maintain FOCUS for annual use. Bjornsen and Chase (1971) described FOCUS and how it could be used to help evaluate alternative initial attack plans. Bratten et al. (1981) provide a thorough overview of the FOCUS system and its use. FOCUS provided reasonably accurate predictions of the consequences of the alternative plans, but proved to be too large and costly to use. Some elements of it were incorporated into other models that were subsequently developed and used by United States forest fire management agencies.

In response to congressional requests for improved evaluation of forest fire management expenditures, the USDA Forest Service completed in 1980 what it referred to as a fire management budget analysis of their National Forest System. They focused on a sample of 41 national forests that were thought to be representative of the entire national forest system. Each forest was partitioned into a number of analysis zones, each of which was relatively homogeneous with respect to fire occurrence and behavior. A simulation model was used to evaluate fire management program alternatives in terms of their predicted cost plus loss (which they refer to as cost plus net value change) within each analysis zone. The simulation model used specified fire management resources to fight a set of hypothetical fires that were representative of actual historical fires with respect to their location, intensity, and forward rate of spread. This work, described by the United States Department of Agriculture (1980), was formalized in the Forest Service's standard Fire Management Analysis and Planning Handbook (FSH 5109.19) and is the basis of the US National Fire Management Analysis System (NFMAS). It also appears to have served as the foundation for other fire management planning systems used by a number of forest fire management agencies in the United States.

NFMAS is designed to facilitate a number of fire management planning activities, including evaluation of the efficiency and effectiveness of the USDA Forest Service's fire program at both regional and national levels. It includes an Initial Attack Assessment Model (IAAM), essentially a simulation model used to assess the performance of detection and initial attack systems. It also implicity models the congestion that is characteristic of fire flaps by increasing response time on the assumption that resources are brought in from more distant bases. Several agencies, including the Minnesota Department of Natural Resources, have adapted portions of NFMAS, particularly the IAAM, to their operations (Minnesota Department of Natural Resources 1987).

Gilless and Fried (1991) incorporated some aspects of NFMAS into a Fire Protection Planning System (FPPS) developed for the California Division of Forestry. They found that although NFMAS might satisfy the needs of agencies that managed wildland areas where most losses were associated with timber values, the cost plus net value change aspects of NFMAS were not suitable for highly populated wildland–urban interface areas of California. The FPPS includes the California Fire Economics Simulator Initial Attack Module (CFES-IAM) (University of California 1988), which is used to assess initial attack systems. CFES-IAM uses surrogate measures of effectiveness, such as the number of fires contained, rather than standard NFMAS measures like cost plus net value change. The basic structure of CFES-IAM was developed from elements of the NFMAS IAAM. CFES Version 1.11 does not model the congestion that arises due to multiple fire occurrence, but a more recent version that has been developed and is being tested is designed to provide such a model.

HOW HAS ONTARIO HANDLED LEVEL OF PROTECTION ISSUES IN THE PAST?

There have been several attempts to apply the basic LCD theory to forest fire management in Ontario. Quimby Hess, who served the Ontario Department of Lands & Forests in several capacities, including Supervisor of Forest Fire Control, appears to have been one of the first individuals to do so. In a 1958 memo to Mr. A.P. Leslie, then Chief of the Research Branch of the Ontario Department of Lands & Forests, T.W. Dwight, Emeritus Professor of Forestry at the University of Toronto, commented on Hess's attempt to apply what appears to be the Tennessee Valley Authority (TVA) version of the LCD model in Ontario. The memo contains Dwight's comments on the publication of 'A Method for Determining Public Fire Control Expenditures for Private Lands', which had been sent to him by Mr. Hess.

Hess appears to have generated the data presented in Table 7 for all the actively protected part of Ontario described in Dwight's memo. The memo does not indicate if the expenditures were expressed in common dollar units, but his comments suggest they were not. Dwight indicates Hess omitted the 1951–54 data because it was a "blow-up" period that was not representative of normal conditions, and fitted the TVA formula:

$$Burned\ Area = 10^{a} P^{b} \qquad [7]$$

where: P is the fire protection expenditure; and
a and b are parameters that vary from agency to agency.

It appears Hess used a figure of $13.84 per acre for fire damage. Dwight used Hess's annual data for the years 1943–55 to specify an optimal presuppression budget level for Ontario of $0.0212 per acre, presumably in terms of 1958 dollars. The authors have not attempted to document the extent to which Hess's work, and Dwight's extension of it, were implemented.

In 1962 Hess published a paper entitled "Forest Fire Control Planning" (Hess 1962) in which he described in

Table 7. Analysis of the impact of fire protection expenditures on area burned.*

Period	Expenditure (cents/acre)	Percentage of area burned
1943–46	0.97	0.38
1947–50	2.37	0.14
1951–54	2.77	0.38
1955	2.83	0.09

*Based on data contained in an unpublished memorandum from T.W. Dwight to A.P. Leslie.

general terms how potential fire occurrence, fuels, values-at-risk, burning index (an early version of the Canadian Forest Fire Danger Rating System), visibility, and travel times should be used for detection, initial attack deployment, and dispatch purposes. It appears to be based on his 1952 postgraduate degree project, entitled "Forest Fire Control Planning for the Province of Ontario", at the University of Toronto, Faculty of Forestry.

Hess stated:

- Before planning can proceed at any administrative level, the objectives have to be defined in measurable or tangible terms and related to the policy laid down by the executive. For each administrative level, this will permit the evaluation of the degree of effort that must be expended to attain the objectives.
- The comparison of the present efficiency of the fire control effort in a field administrative unit area to the defined objectives will assist in determining the elapsed time standards for each of the major segments of the fire control job, i.e., detection, communication, transportation, and suppression. This will provide the basis for the fire control planning job.
- The translation of the fire control policy, as stated by the executive, into measurable or tangible objectives, which can be used as outlined above, *is not always a simple task* (italics added for emphasis).

His observation continues to ring true today.

The Ontario Department of Lands & Forests hired the firm Stevenson & Kellogg to investigate fire management expenditures and identify optimal expenditure levels. It is instructive to note they observed in their 1963 report that:

> "We understand that Ontario's defence against forest fires lacks performance standards which are capable of specific definition on an area by area basis. We further understand that lack of standards is a true reflection of the lack of any computed need for forest protection on a comparative basis" (Ontario Department of Lands and Forests 1963).

Their study objectives were as follows:

- The prime objective would be to construct a provincewide quantitative base for objectively measuring the comparative needs for forest protection.
- The subsequent objective would be to assess and relate the various states of preparedness to this defined need for protection.
- Having related general preparedness to need on an overall approach, the detailed application would be in establishing an operational "priority" grid for each supervisory area.
- Hence, it will be appreciated that one of the underlying premises of this study is that the apportionment of men and facilities between different areas should be established by the relative values to be protected. Indeed, even "in the pinch" priorities for action and use of facilities should be governed by such considerations.

They studied the system for the period 1950–62 and expressed their costs in terms of 1962 dollars. The province was partitioned into 22 districts, which covered approximately 113 million acres. They, like Hess before them, drew upon the TVA work and developed mathematical formulae and graphs that related the average fraction of the area burned in each district and the entire province to the annual presuppression budget. It is important to note that there was relatively little mobility and sharing of fire suppression resources in those days and that made it possible to assume each district acted as an almost autonomous unit. Because that assumption could not be used today, their analysis would be more complicated.

They assumed that a loss of $73.77 was incurred as a consequence of each acre burned and determined the optimal presuppression budget for each district and the entire province. The provincial optimum was $0.0218/acre (almost identical to Dwight's $0.0212/acre) and they predicted that would result in an average area burned of 56 849 acres or 0.05 percent of the protected area. Table 8 shows results for some of the 22 districts considered. The authors did not attempt to document the extent to which the Stevenson & Kellogg study influenced level of protection decisions in Ontario.

In 1974, G.E. Doan of the Forest Protection Branch of the Ontario Department of Lands & Forests studied the cost effectiveness of Ontario's fire suppression system for the period 1955–74. His basic model is described in Doan (1974a,b). He also had the luxury of assuming the districts operated as relatively autonomous budget and cost centers, and developed what was referred to as a provincial protection possibility curve that related the average fire size to presuppression expenditures. His 1974 work was used to document a fire protection proposal to Ontario's Management Board of Cabinet. He updated his work in 1981 and refined his analysis with additional data. The updated study was also used to document a proposal that was submitted to the board. His work was further used to help set fire protection targets (burned area) that were incorporated into regional fire management strategies in Ontario.

The protection targets in the regional fire management strategies constitute the most recent explicit statement of level of protection in Ontario. In the mid 1980s each of the then five fire regions (Northwestern, North Central, Northeastern, Northern, and Algonquin) embarked upon an area planning exercise that led to the development of a regional fire management strategy. One aspect of the planning process was delineation of the intensive, measured, and extensive protection zones described earlier in this paper. Each region used Doan's protection possibility curve to derive an annual burn target for the intensive and measured protection zone. For example, the old Northwest Region had a target of 50 000 ha. That represents 0.44 percent of the 11.4 million hectares in the intensive and measured protection zones of the current Northwestern Region.

Martell et al. (1984) developed an initial attack system model that was used to help document the OMNR's Management Board proposal to purchase CL-215 air tankers to enhance its fleet in the early 1980s. The initial attack model is a large, computer-simulation model that predicts the performance of alternative sets of fire fighters, transport helicopters, and air tankers when they are used to fight historical fires. The model also has a set of initial attack dispatch rules that describe how many fire crews are required, how they will be transported to each fire, and how many air tankers are required. The model assumes there is an unlimited number of fire fighters available for initial attack, and it explicitly models the growth and suppression of historical fires and the congestion that occurs when the demand for transport helicopters and air tankers exceeds their supply and fires must queue for service. The model has several system performance measures including:

- a cost plus loss figure that accounts for Extra Fire Fighting (EFF) expenditures, stumpage losses, and property losses;
- initial attack dispatch delay (i.e., the elapsed time from the report of a fire until the last air tanker or fighter departs for the fire);
- initial attack interval (i.e., the elapsed time from the report until the first air tanker or fire fighter begins suppression action on the fire); and
- the number of fires that escape initial attack each year.

Table 8. Stevenson & Kellogg optimal presuppression budget recommendations for several Ontario districts.

District	Optimal presuppression budget ($/acre)	Predicted percent of area burned
Chapleau	0.02386	0.0368
Geraldton	0.01775	0.0153
Kenora	0.05435	0.0501
Sault Ste. Marie	0.01395	0.0455
Sudbury	0.02633	0.1598
Swastika	0.01691	0.0403

The Ontario initial attack model has only been used to assess air tanker needs, but it is quite general and could be used to help decide how best to satisfy specific initial attack performance standards (e.g., initial attack response times) in different attack base areas.

From an historical perspective, it is clear that from time to time, roughly every 10 years in recent times, Ontario's fire managers are called upon to "rationalize" their programs. The fire organization then commissions someone to bring the current "state of the art" to bear on the problem and to develop a new and hopefully more accurate assessment of the "optimal" level of fire protection for Ontario's forests. Given that perspective, the present objective is to use modern computer technology and mathematical models to reassess Ontario's level of fire protection needs.

INTEGRATING FIRE AND FOREST MANAGEMENT

Timber is one of Ontario's most important forest resources and timber protection is one of the primary objectives of the OMNR's forest fire management program. Despite the fact that forest managers often communicate their concerns about potential fire losses to fire managers who usually base their plans in part on timber production concerns, there is no formal technical linkage between fire and forest management planning in Ontario. The relative isolation of fire and forest management is, to a large degree, a consequence of the failure of forest management theorists to properly incorporate potential fire losses in forest management planning. Recent years have witnessed a flurry of research activity centered about the impact of fire on timber supply, but those results have yet to influence the practice of forestry. This section describes some of those results, demonstrates how they can be incorporated into forest management planning procedures, and describes how fire and forest managers can develop integrated planning procedures.

In the past, forest management specialists recognized the importance of fire but dealt with it by simply advocating its exclusion from timber production areas. The basic stand level forest regulation theories, such as the Faustmann optimal single stand rotation model, either ignored fire or assumed—incorrectly—that it could be addressed by modifying growth and yield curves downward. Martell (1980) developed a stochastic flammable forest stand rotation model and showed that was not the case. Van Wagner (1978, 1979, 1983, 1986[7]) and Reed and Errico (1986) developed forest level models that demonstrated the importance of looking beyond the burn site to evaluating potential and actual fire losses from a forest rather than a stand level perspective. The result is a much clearer understanding of a concept that foresters have known but have been unable to use formally for many years—that fire protection is an important factor of production. Put simply, foresters who want to maximize their return on investment must use integrated planning models that consider both fire protection and silvicultural treatments as candidates for their limited forest management funds. This section demonstrates how such integrated planning systems can be developed and used in Ontario.

When considering the relationship between fire management and other aspects of forest management, the level of fire protection affects the present and future state and productivity of the forest. Similarly, values and forest management policies should affect the selection of the level of fire protection. One way to look at the system is to put "fire management" into one compartment and "the rest of forest management" into another compartment. While the focus of this project is fire management, its purpose is closely (but not exclusively) linked with other aspects of forest management. It is, therefore, important that the relevant components of those other aspects of forest management be represented.

Assessing the Impact of Fire Regimes on Timber Supply

The forest level timber production planning model for the hypothetical forest accounts for potential fire loss by assuming some constant average annual fraction of the forest burns each year. It is referred to as a mean value model because it ignores the fact that fire loss can vary considerably from year to year due to fluctuations in weather, human behavior, and other random or chance processes. Reed and Errico (1986), who developed the mean value forest level model, suggested that it was reasonable to use the average annual fire loss assumption to estimate the impact of variable fire losses on timber supply on large forest management units. Boychuk (1993) subsequently confirmed the validity of that assumption for forest conditions and fire regimes that are characteristic of the boreal forests of Ontario.

The authors adapted Reed and Errico's (1986) forest level model to the hypothetical forest and used it to assess the impact of fire management on that forest. To begin, individual fires were ignored and the impact of fire was considered over a very long planning horizon (several hundred years). This impact was considered in terms of a fire regime that could be characterized by a single variable, the average annual fraction of the forest burned. It was then possible to incorporate that average fraction into the forest level timber production model and assess the impact of that fire regime on timber supply.

The results are shown in Figure 13. A fire regime can be represented by its corresponding fraction of the forest burned each year. Each point on the graph in Figure 13 represents the impact of a fire regime on timber supply from the hypothetical forest. The portion of the forest burned each year was varied from 0 percent to 4 percent, and the volume harvested each year (the allowable cut) related to the fraction burned as shown in Figure 13. The fraction of each age class burned within the forest was arbitrarily set equal to the fraction of the forest burned.

The volume harvested each year is slightly convex upward for roughly one-half of its range. After this there is a point of inflection and it becomes concave, a consequence of the terminal volume constraint. A 1.5 percent annual burn rate reduces the allowable cut by 36 percent, what superficially appears to be a disproportionate reduction in the harvest. However, an annual burn rate of 1.5 percent means the probability that any small stand will burn is 0.015 during any year. If a stand is established and

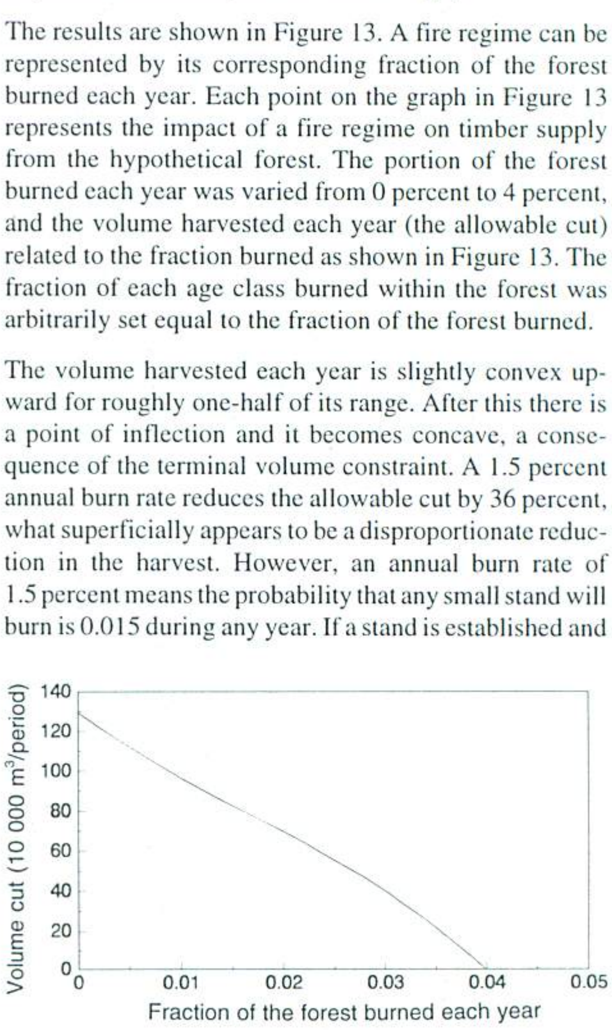

Figure 13. Fire regimes and harvest volumes for the hypothetical forest that is completely covered with 75-year-old jack pine at the start of a 300-year planning horizon.

[7]Van Wagner, C.E. 1986. Catastrophic losses–strategies for recovery. Paper presented at Annual Meeting of Western Forestry and Conservation Association. December 1986. Vancouver, British Columbia. 13 p.

scheduled to be harvested when it is 50 years old, the probability that it will survive until then is 0.47. Since stands regenerate after fire, and the real impact of a fire is to accelerate the harvest of some stands, the overall impact of fire is a large reduction in the allowable cut. However, this reduction is not as great as might be suggested by the simple stand level analogue. The results presented in Figure 13 are, of course, specific to the hypothetical forest and management guidelines outlined. Nonetheless, it is reasonable to conclude that the reduction in the harvest volume will usually be much greater than the average fraction of the forest burned each year.

Figure 13 describes how timber supply or allowable cut varies as the fire regime varies, and serves as an essential link between fire and forest management. Consider the fraction of the forest burned each year. The model of the fire management system in the hypothetical forest described earlier can be used to transform planned expenditures on fire prevention and presuppression into predictions concerning fire suppression costs and the fraction of the forest burned. Suppose one starts with a specified fire management budget, takes the resulting predicted average annual fraction burned, and inserts it in the forest level timber production model. The result will be a prediction of the optimal amount that can be harvested from the forest each year under that fire regime.

Suppose, on the other hand, that one started with a specified timber production or allowable cut target for the forest. The fraction burned could then be varied until the target harvest volume was achieved. The fire management model could then be used to identify combinations of prevention and presuppression expenditures that would produce that fraction and make that sustainable harvest possible. If a value is assigned to the wood, one can go even further and jointly decide upon an optimum combination of prevention, presuppression, and harvest levels for the forest. Thus a forest level timber supply model, with fire represented in terms of the average annual fraction burned, can be coupled with fire management system models to serve as an integrated planning tool. This tool can then be used to help ensure sound investment of funds in fire management and timber production.

Presented below is a series of fire and forest management planning exercises for the hypothetical forest. They serve to illustrate how one might tackle the problem of developing integrated fire/forest management planning systems.[8]

Exercise 1

Consider the base case fire management system for the hypothetical forest described in Table 3. This case has a fire prevention program and presuppression program that cost \$15,000 and \$500,000 per year, respectively. That program will result in an average annual fire management cost plus loss (i.e., the timber value losses are not included in this figure) of \$1,321,353 per year and an annual burn fraction of 0.0213 or 2.13 percent of the forest. The timber production planning model indicates that when the annual burn fraction is 0.02, the optimal timber harvest schedule is one that will produce an annual harvest flow of 699 404 m^3 of wood (1.4 m^3/ha per yr), and the present net worth of the timber harvested from the forest will be \$707,166,060.

The discount factor α is given by the following formula:

$$\alpha = \frac{1}{1 + \frac{i}{100}} \qquad [8]$$

where: i is the interest rate that is used to discount future costs and revenues.

The present net worth of the forest can be transformed into an equivalent annual net income by multiplying by $1 - \alpha$. Thus a present net worth of \$707,166,060 is equivalent to an annual net timber income of $(1 - \alpha)$(\$707,166,060) or \$20,597,070.

The net value of the forest is therefore the net value of the timber less the cost plus loss of the fire management program (\$20,597,070 – \$1,321,353) or \$19,275,717 per year.

Exercise 2

The burn fraction of 0.0213 is quite high and it is reasonable to explore the extent to which it can be reduced. Consider the possibility of reducing it to 0.002 or 0.2 percent per annum. The analysis will be simplified by initially assuming that the prevention program remains at its base case level of \$15,000 per annum. The question is, how much must be spent on presuppression in order to reduce the burn fraction target from 0.0213 to 0.002? The fire suppression subsystem can be used to model and show that a presuppression expenditure of \$1,059,560 per annum coupled with a \$15,000 prevention program will reduce the annual fraction of the hypothetical forest burned each year to 0.002.

The cost plus loss of the enhanced fire management program will be \$1,407,695 per annum. The timber production planning model indicates that when the annual burn fraction is 0.002, the optimal timber harvest schedule is one that will produce an annual harvest flow of 1,155,330 m^3 of wood (2.3 m^3/ha per yr) and the present net worth of the timber harvested from the forest will be

[8]Note that these exercises are based on an assumption that it is reasonable to ignore the variance in burned area and use the mean value timber harvest scheduling model. The assumption is also made that fire managers are risk neutral.

\$1,236,624,390. A present net worth of \$1,236,624,390 is equivalent to an annual net timber income of $(1-\alpha)$ (\$1,236,624,390) or \$36,018,187.

The net value of the forest with the enhanced fire management program is therefore the net value of the timber less the cost plus loss of the enhanced fire management program (\$36,018,187 – \$1,407,695) or \$34,610,492 per year. Thus, the enhanced fire management program, coupled with a corresponding change in the optimal timber harvest scheduling plan, would increase the net value of the forest by (\$34,610,492 – \$19,275,717) or \$15,334,775 per annum.

Exercise 3

Having enhanced the fire management program by increasing the presuppression program, the next step is to determine if there is some fire management program that would reduce the burn fraction to 0.002 in an optimal fashion. It is possible to vary both fire prevention and presuppression expenditures simultaneously, and achieve a burn fraction of 0.002, by spending \$55,000 on prevention and \$1,037,200 on presuppression. That will reduce the fire management cost plus loss to \$1,396,031. Since the burn fraction remains at 0.002, the timber value of the forest remains at \$36,018,187 per annum. The net value of the forest with an optimum expenditure of fire management funds to achieve a burn fraction of 0.002 per year is therefore \$36,018,187 – \$1,396,031 or \$34,622,156 per annum.

Exercise 4

The optimal fire management system has now been identified for a forest in which the annual burn fraction is 0.002, and an optimal timber harvesting schedule given that burn fraction has been developed. The next task will be to simultaneously consider the optimal solution to the joint decision of what burn fraction, prevention budget, and presuppression budget will maximize the net value of the forest. That task, however, is well beyond the scope of this discussion paper.

It is important to plan simultaneously for both fire and forest management. One can expand the simple timber harvest scheduling model to evaluate richer strategies that include the use of modified harvesting methods and procedures that increase merchantable volume recovery rates. One can also vary silvicultural treatments and adopt more intensive and expensive regeneration techniques to compensate for fire losses. Further in this vein, one could also devote more resources to rehabilitating poorly stocked or not satisfactorily regenerated (NSR) stands. Yields could also be enhanced by implementing thinning and fertilization treatments. In summary, it is important to consider comprehensive integrated fire/forest management strategies that will produce reasonably stable and sustainable harvest flows at an acceptable cost.

Assessing the Impact of Individual Fires

Discussion thus far has focused on long term forest management regimes. Fire and forest management specialists also need to assess the impact of individual fires that have burned, or threaten to burn, designated areas. Not surprisingly, that too must be carried out from a forest level perspective.

The mean value timber harvest scheduling model can be used to assess the impact of an individual fire that has burned some portion of a forest. In the past, people were inclined to focus on the burn itself and assessed fire damage in terms of the apparent value of the timber destroyed by the fire. That approach neglects the fact that a forest is a complex dynamic system that often provides managers with flexibility. This flexibility, in turn, can be used to buffer fire losses.

Consider for example a 150 000-ha fire in the hypothetical forest, all of which was covered by 75-year-old Site Class II jack pine at the start of the planning horizon. A superficial fire loss assessment obtained by multiplying the area burned by the volume of wood per unit area (190 m^3/ha) and the price (\$30/m^3) at which the burned wood was to have been sold would produce an estimated fire loss of \$855,000,000.

The forest level mean value model can also be used to assess the impact of such a fire. The timber supply loss that results from the 150 000-ha fire is the expected return from the forest given the best planned harvest schedule *before* the fire (which is obtained by running the timber supply model with a 500 000-ha 75-year-old flammable forest and a specified average annual fraction burned associated with the appropriate fire regime), less the expected return given the best revised harvest schedule produced *after* the fire (which is obtained by running the timber supply model with the same forest, 150 000 ha of which has been burned). The mean value model indicates that a 150 000-ha fire (or 30 percent of the forest) would reduce the present net worth of the hypothetical forest by about \$2,000,000 or 0.24 percent. This is very much less than the superficial, site-specific estimate described above.

Harvest schedule flexibility and the ability of forests to regenerate after fire help reduce the economic impact of fires that occur in forests that are not being taxed to their limits. The authors stress, however, that results are specific to the particular hypothetical forest. The cost of a fire will increase if the forest is not fully accessed, if the burned area is near established roads, or if there are monetary penalties other than stumpage losses associated with significant reductions in harvest volumes. In very simple terms, one must look beyond the burn and assess the impact of the fire on the value of the forest (however managed) before the fire, less the value of the forest after the fire. This before/after forest level approach is appropriate if one uses an optimizing forest level model like the one used here, or any other formal planning process, to manage the hypothetical forest.

It is important to note that forest level assessment of individual fires can also be used for escaped fire situation analysis purposes. One could specify several possible suppression strategies for an escaped fire, and develop deterministic or probabilistic final fire perimeters for each strategy. A forest level model can then be used to assess the impact of each possible final fire scenario.

Further Insight into Fire and Forest Management Under Uncertainty

Forest managers develop and evaluate forest management plans that prescribe what activities are to be carried out at specific points in time, some of which are more than 100 years in the future. Therefore, it is not surprising that these managers are often very uncertain as to what will happen over their planning horizons.

Many factors contribute to the high degree of uncertainty that is characteristic of forest management planning. There are of course natural processes like fire, insects, and disease that can very quickly change the structure of a forest. The demand for forest products varies over time in response to changes in social and economic factors. Forest products processing technology also influences the demand for forest resources. Climate variation can affect forest growth and revisions in government policy can alter the basic forest land base and bring about changes in regulations that influence how forest resources and forest products are harvested and used.

Forest managers have developed and used a broad array of strategies for dealing with uncertainty. Classical forest regulation techniques, such as the Faustmann procedure for determining an optimal stand rotation, simply ignore uncertainty. Risk averse forest managers sometimes spend large amounts of money in attempts to eliminate or greatly diminish significant sources of uncertainty. They might, for example, establish a large number of permanent sample plots to reduce their uncertainty concerning forest growth and yield projections. Often they simply ignore uncertainty and use deterministic planning procedures to replan every 5 to 10 years over rolling, finite planning horizons.

The province of Ontario was partitioned into 27 districts when the current study was initiated, and although fire burns an average of approximately 0.18 percent of the province's productive forest land per annum, that figure ranges from virtually nothing to as much as 1.46 percent by district. Furthermore, the fraction of a district burned can easily vary by two orders of magnitude from year to year. Depending upon the type of forest regulation strategy employed, such variation can have a significant impact on the stability of harvest volumes.

Boychuk (1993) used a simple simulation model to explore the harvest flow implications of several different forest regulation strategies in a hypothetical spruce forest with a balanced age class structure. He simplified the randomness of the fraction of area burned in his hypothetical forest by assuming that during each 10-year period a small or large fraction of the forest burned. The small fraction was 5.8 percent and occurred with a probability of 0.75; the large fraction was 20.8 percent and occurred with a probability of 0.25. He then used stochastic simulation techniques to generate 18 fire loss scenarios. Each scenario was characterized in terms of the fraction of the forest burned during each period.

He then explored the harvest flow implications of different forest regulation strategies. One strategy was to use age control (i.e., to apply a stand level optimal rotation strategy to the entire forest). Boychuk assumed he would cut all stands that were 50–60 years of age and obtained the results shown in Figure 14. The vertical axis is the volume harvested, and the 18 scenarios are parallel to each other from left to right. Note that after the first few periods, there is considerable variance in the harvest flow.

Figure 14 demonstrates the type of variation that can be realized if classical stand level rotation models that ignore potential fire losses are applied to forests that burn.

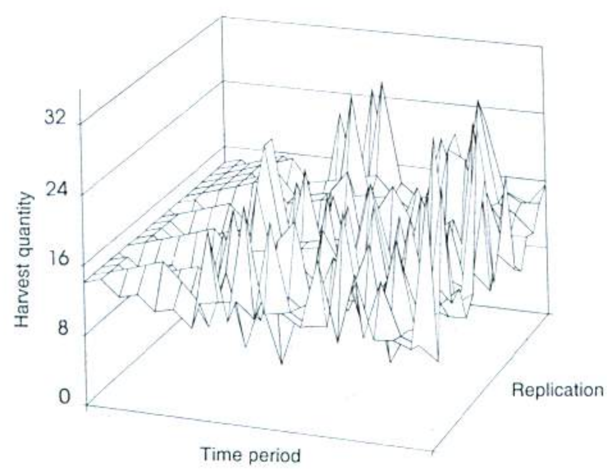

Figure 14. Results of a simulation of the age control harvest rule (18 replications) showing harvest quantity over time (m^3/ha per 10-year period).

Optimal stand rotation models are age dependent and stipulate that each stand should be harvested as soon as it reaches its optimal rotation age. Clearly, such regulation procedures cannot be applied blindly to forests that are subject to significant fire losses.

Forest managers have developed and implemented a broad array of strategies for managing forests that are subject to fire loss. One approach involves reducing the planned harvest level and building up a buffer stock (which of course is also subject to uncertain fire loss) that can be drawn upon after severe fire years.

The basic network presented in Figure 8 can be expanded to include subnetworks that represent different cover types and silvicultural regimes. Stochastic programing models (*see* Wagner 1975) can be formulated and solved to produce robust optimal solutions. Such solutions maximize expected return and are guaranteed to be feasible. But if significant harvest flow constraints are imposed on stochastic timber harvest scheduling models, the need to guarantee feasibility enables highly unlikely but nevertheless possible scenarios (i.e., the possibility of high fire losses every year) to dominate the solution.

An alternative approach is to recognize that harvest flow stability is desirable but not always attainable. Gassmann (1989) suggested that rigid, inviolable harvest flow constraints be replaced with an objective function term which penalizes harvest flow declines. When a harvest decline penalty term is included in the objective function, high values of the penalty will lead to "optimal" solutions that reduce the likelihood that significant harvest flow declines will be experienced. That approach can be used to deal explicitly with the variance in fire losses. One can view the penalty parameter as a harvest volume smoothing parameter and let forest managers see how it stabilizes harvest volume as it increases. The manager can then subjectively select a penalty value that projects a harvest flow variation that is "stable enough". Boychuk (1993) used a stochastic programing model to investigate the impact of random fire losses in a hypothetical forest covered with stands that grow similar to Site Class II black spruce. The forest had four cover types plus NSR land. The four cover types were two regeneration intensity classes, each either enhanced or not enhanced. Some of his findings are described in Boychuk and Martell (1996).

Figures 15 and 16 illustrate the impact of changing penalties on harvest flow in Boychuk's hypothetical forest. Figure 15 shows the probability distribution of harvest quantity over the first six time periods for a low decline penalty. In the first time period, harvest quantity is deterministic in the model, because harvesting takes place before fire losses are incurred. In the third and later periods, the harvest quantity falls below its starting level. There is also significant variance in the sixth period.

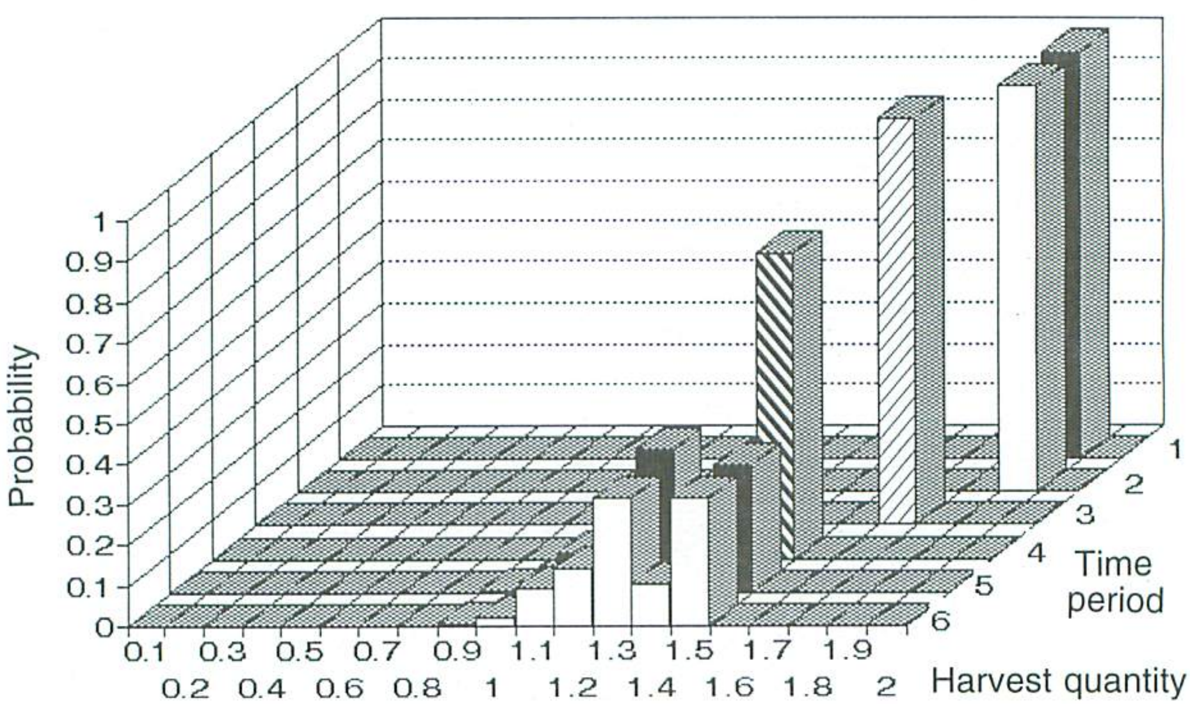

Figure 15. Harvest quantity distribution over time with a low penalty.

Figure 16 illustrates the corresponding results for a high decline penalty. When the penalty increases, the harvest flow in the first two periods decreases, as does the variance in the sixth period.

The best way to deal with potentially large fire losses is to establish a "buffer stock" by reducing the short term harvest quantity, and increasing harvest age. The superficially paradoxical result is a more stable harvest flow and the production of more wood spread out over the entire planning horizon, but less profit. This finding will be of particular interest to policy analysts and others who must ultimately trade off corporate and community stability, the amount of land devoted to industrial fiber production, and profits. The degree of short term harvest reduction, however, is sensitive to assumptions about the way timber management decisions will be regulated in the future.

LEVELS OF FIRE PROTECTION FOR SUSTAINABLE FORESTRY IN ONTARIO

Having explored fire economics and fire management planning, it is time to return to the study's primary objective, the development of level of protection measures appropriate for Ontario. The workshop participants were asked to consider some of the measures discussed earlier in this paper, to identify others they feel might be appropriate, and to suggest what measures should be used.

The specification of level of protection targets (e.g., initial attack response time targets by fire hazard and fire management zone) was beyond the scope of the workshop itself. However, workshop participants were encouraged to suggest how fire and forest management objectives should influence the specification of such targets and who should decide on the actual level of protection targets for the OMNR.

Larson and Odoni (1981) suggest that performance measures should be designed such that they can be easily understood by the agency personnel and the citizens they protect. They should also be readily measurable and depend on policy and procedures that can be controlled. Finally, it is essential to ensure that they are real measures of system performance, reflect the agencies true objectives, and do not subvert those objectives (e.g., encourage detection planners to search for fires that can readily be detected by the public). These characteristics apply to both direct measures (cost plus loss) and surrogate performance measures (response time).

The following level of protection measures appear to merit consideration for forest fire management in Ontario:

- annual area burned;
- property damage;
- timber volume destroyed;
- community evacuations; and
- initial attack response time.

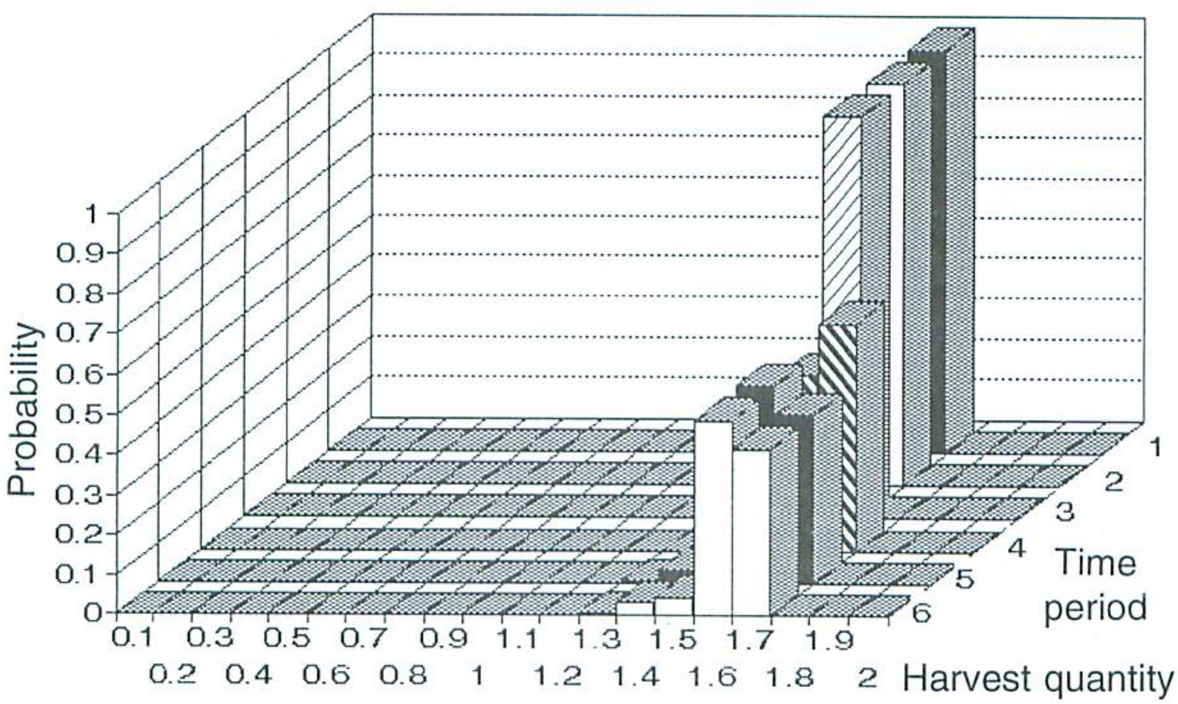

Figure 16. Harvest quantity distribution over time with a high penalty.

It is important to explore these and other measures and to identify potential benefits and problems associated with their use. Consider, for example, initial attack response time. It is clear that the response time should decrease as the fire hazard increases, but at what rate? Should the response time decrease as the expected number of fires increases? How should public health and safety, property, and timber values influence response time guidelines? Should Ontario be partitioned into zones and response time targets be specified according to zone? Response time guidelines and other performance measures can and no doubt will be used to help resolve decisions concerning the allocation of fire suppression resources to home bases and their daily deployment to initial attack bases. Who will resolve the conflicts that are sure to arise when one area manager, district manager, or regional director demands that the response times in his or her jurisdiction be smaller than those in neighboring areas?

Workshop participants were asked to consider these and other issues related to the development and implementation of level of protection measures for forest fire management in Ontario.

ISSUES THAT MAY INFLUENCE THE DEVELOPMENT AND USE OF LEVEL OF PROTECTION MEASURES IN ONTARIO

Forest fire management is a public service; thus, it is essential to look beyond the fire organization and the OMNR and address some of the broader public issues that may have a bearing on forest fire management in Ontario. At the risk of appearing to exert undue influence, the authors developed a preliminary list of issues that the workshop participants were asked to consider and discuss. Of first consideration were some contentious questions and issues characteristic of the types of problems that fire and forest managers, and the government of Ontario, will have to address in the near future.

Some Contentious Questions

1. How should funds be split between the different components of the fire management program (e.g., fuel management, prevention, detection, initial attack, large fire suppression, prescribed fire)?
2. How should the available funds be spread across the province by management area?
3. Given that fire is a natural component of many of Ontario's forest ecosystems, how can one trade off traditional public safety, resource and property protection, and ecosystem management objectives?
4. Can fire be used to enhance the effectiveness of the OMNR's wildlife management programs?
5. How should fire be managed in wildland/urban interface areas?

Values Subject to Impact by Fire

Past studies have focused on the impact of fire on timber supply. The following is a preliminary, partial list of values that may be of concern to fire and forest managers in Ontario.

- aquatic and terrestrial wildlife habitat;
- biodiversity (intraspecific, interspecific, and landscape);
- carbon sequestration;
- cultural and social activities;
- ecosystem health and naturalness;
- hydrological functioning;
- property;
- public health and safety;
- recreation and tourism activities;
- representative ecosystem preservation;
- soil conservation;
- systems infrastructure;
- timber production and other economic activities; and
- transportation and communications.

Are there important values-at-risk that are not included on this list? What is the relative importance of these many different values? How can one assess the extent to which fire has positive and negative impacts on them?

Timber Production

Timber production is an important aspect of forest management in Ontario. To what extent should public funds be used to protect industrial timber supplies against fire and insect losses?

Fire Impact Assessment

Fire management objectives include the protection of public safety; property; and ecological, economic, and resource values. Numerous authors have explored the effect of fire on timber supply, which has been treated as the dominant quantifiable value in the past. However, forest managers in Ontario are now committed to integrating multiple values in decision making. As such, how can one assess the impact of fire regimes on such values?

Aboriginal Communities

Many small communities in the far north are surrounded by forests that have not been significantly affected by fire suppression. In many respects these constitute natural fire regime forests. Although people can be evacuated (at some cost to the government and with considerable hardship to the people involved) in advance of large uncontrolled wildfires, smoke from large but distant fires has the potential for a significant detrimental impact on the health and well-being of people in such communities. Furthermore, although fire is a natural component of the forest ecosystem in this area, it can disrupt trapping and other aboriginal land use activities. How should one establish the level of protection in those areas?

Biodiversity and Disturbance

The measures of biodiversity that appear in the literature are fundamentally static. While they measure the state of a system at one point in time, there is, of course, recognition that the state evolves over time and numerical measures change.

Few would argue that biodiversity should be maximized; most recognize that some natural systems have lower biodiversity than anthropogenically disturbed systems. For example, a natural boreal forest with large fires can have a lower biodiversity than a boreal forest with fire protection and selection harvesting or patchy clear-cuts.

It has been recognized that:

- Fire is a natural part of the boreal ecosystem.
- Despite the frequent natural disturbance by fire in any one place, the larger scale boreal forest ecosystem is stable and resilient (assuming climate stability, etc.).
- Fire and fire protection affect the state of the forest, measures of biodiversity, and their evolution over time.
- Fire protection has greatly reduced the frequency of major disturbance by fire.
- There is a relationship between fire frequency and a measure of biodiversity (Suffling et al. 1988).
- Harvesting is a major disturbance in boreal forest stands. In some ways it is similar to fire, but in many ways it is very different.

Concern with biodiversity is now embedded in thinking about forest management. As such, quantitative measures of biodiversity will be generated and used in forest management decision making. But it does not appear, however, that measures of the frequency of disturbance are similarly considered. While the frequency of major disturbances by fire or harvesting affects future biodiversity, explicit measures of frequency of disturbance are appropriate in forest management decision making. This is particularly necessary when jointly evaluating timber production, fire protection, and other losses. To the extent that these disturbances are similar with respect to stand renewal, measures of individual and collective disturbance rates have a role in decision making.

Forest Landscape Ecology

Concern with patterns of the spatial distribution biota and ecosystem types in landscapes over a wide range of scales has lead to a need to address the effect of harvest methods and their location over time and space. Geographical information systems are now being used to project patterns of forest cover type, habitat distribution, and other values over time and space. While it is difficult and perhaps impossible to objectively evaluate alternative spatial patterns for overlapping multiple values, they are nonetheless an important concern in forest management. Fire and fire suppression have a major impact on the landscape. The number, sizes, and locations of fires are largely random, but heavily influenced by suppression efforts. How should such impacts be assessed?

Further Notes on Area Burned

To be more meaningful, area burned as a measure of effectiveness would have to be related to the total area protected, i.e., specified as a percentage or proportion burned. Further, burned area should be classified according to whether its impact is detrimental, beneficial, or neutral. An example follows of a framework that might be used to classify burned area by impact.

1. Detrimental (primarily economic impact)
   - area burned
   - percent of total protected area burned
   - based on fire load, estimated losses that would have been incurred without intensive fire suppression
   - percent of estimated potential losses actually incurred
   - impact on timber supply, by working group
   - impact on wildlife habitat
2. Beneficial (primarily ecological impact)
   - area regenerated by nonprescribed fire
   - area regenerated by prescribed fire
   - percentage of area burned objective achieved for vegetation/ecosystem/landscape management purposes
   - percent of objective for natural fire in managed area
   - impact on wildlife habitat
3. Neutral (negligible impact)
   - e.g., grass fires, 0.1-hectare fires, low-intensity fires in hardwood stands

Further Notes on Response Times

Response times should probably vary by:

- attack weight, i.e., the capabilities of the resources dispatched

- expected fire behavior
- values-at-risk
- cost of protection

Response time can be the principal measure for translating overall level of protection analysis to operational guidelines. In some cases, the response time objectives might be derived from other objectives, e.g., area burned. In other cases, where the other measures are less important, response time can be the main level of protection measure.

Equal vs. Fair or Cost-effective Protection

Consider the following consequence of the least cost plus damage principle. For simplicity, assume all values can be measured in dollar terms. Under *equal* protection, each unit of value in Ontario would get the same level of protection, e.g., the same response time and weight. This might not be a *cost-effective* use of public funds if it costs far more to protect distant or isolated values-at-risk. Under cost-effective protection (e.g., a policy that minimizes the total cost plus loss to society), every property of the same value might not get the same level of protection (e.g., response time and weight) since the protection costs (e.g., travel, service) are higher for distant or isolated values-at-risk. For such cases, a given protection expenditure buys less response time and/or initial attack weight. Another way to think of the problem is as follows. To minimize the total cost plus loss in the province, more protection resources should be located near areas with high concentrations of values-at-risk.

Value Lost vs. Value Saved

Fire impacts are typically losses (e.g., property destroyed, area burned, timber destroyed, rare ecosystem area destroyed, etc.) and the effect of fire protection is to reduce losses.[9] However, while measures of performance are often stated in terms of losses, they could also be considered in terms of what was saved (e.g., property saved from destruction, area saved from burning, timber saved from destruction, fragile ecosystem area saved from destruction) as was suggested by Martell (1978).

Thus, it is necessary to consider whether to state the performance of the fire management system in terms of value *lost*, or value *saved*. The advantage of using value lost is that losses are generally readily observable. The difficulty with using value saved is in estimating the value that might have been lost in the absence of protection. Usually this is highly uncertain.

In principle, the ideal measure is the *marginal* value saved or lost per dollar spent. That is, how much more value would be saved by spending an additional dollar on fire management? Or, how much more value would be lost by spending one dollar less? The least cost plus damage principle leads one to keep spending an additional dollar on protection as long as more than a dollar of value is saved from destruction. Protection expenditure stops increasing at the point where an additional dollar spent saves less than a dollar of value. Note that as presuppression expenditure increases, fire loss typically decreases, but at a diminishing rate. The optimal protection level corresponds to the minimum point on the total cost plus loss curve. The optimal point is not determined by the value saved (lost). That is, it does not matter if the value saved (lost) is greater or lesser than the cost of protection. The optimal protection level is determined by the *marginal* value saved (lost).

Decision makers should consider the marginal value saved or lost even though every individual value cannot be measured in dollars. Suppose decision makers are comparing a set of alternatives with different presuppression expenditure levels. Suppose also that each alternative has an estimate of value lost (saved). As the budget increases, the value lost decreases (the value saved increases). However, due to diminishing returns, the value lost decreases at a diminishing rate (value saved increases at a diminishing rate). The decision makers select a budget beyond which they consider that the further reduction in value lost (increase in value saved) is not worth the additional expenditure. In this process, they are considering only the marginal value saved or lost.

While decisions should be made on the basis of marginal value saved or lost, it is still interesting to know the total value involved. For example, the total value saved might greatly exceed the total cost of protection, and yet too much is being spent on protection. That would happen if the last dollar spent is saving far less than one dollar of value.

CONCLUSIONS

Ontario's forest fire managers and their many clients are currently poised on the brink of a new era during which they will be forced to resolve many important decisions about fire management needs; fire management budget levels; and the allocation, deployment, and dispatching of fire suppression resources.

The issues are challenging, interesting, and most importantly, have the potential to significantly influence forest management and the quality of life of the people that live and work in and near the northern forest regions of Ontario. It is possible to draw upon the expertise of the fire and forest managers and to use management science and

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[9] In this section, it is assumed for simplicity that all fire impacts are detrimental and can be measured in dollars.

computer technology to develop and implement new level of protection measures that can be used to help resolve some of those crucial issues.

It is the authors' hope that this discussion paper will stimulate fire and forest managers and other interested readers to explore and discuss the potential rewards and pitfalls of the level of protection approach, and to suggest level of protection measures that may be appropriate for Ontario.

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