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A VISUAL AIRBORNE FOREST FIRE DETECTION PATROL ROUTE PLANNING SYSTEM

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ABSTRACT

The aerial detection planning system that was developed consists of a procedure to forecast an hourly fire occurrence pattern and an algorithm to route air patrols through the occurrence pattern in an efficient manner. Historical weather and fire data from northwestern Ontario were used to illustrate the forecast procedure. To test the system, actual 1972 northwestern Ontario detection results were compared with those that would have been obtained had the computerized system been used during the 1972 season. Results appeared encouraging.

A near-operational computer package, designed for daily detection dispatching, was developed; and experience with it suggested one possible form that an operational field version might take.

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DETECTION PLANNING

In the northern forests of North America the task of forest fire detection is more and more being carried out by aircraft rather than by fixed lookouts. This switch to visual air patrol has usually led to considerable savings in direct detection expenditures with no apparent loss in detection effectiveness. Most of these savings are associated with the ability of an air patrol system to respond, on an hourly basis, to changing fire risk and hazard. However, the magnitude and importance of the daily planning task associated with efficient use of such a "flexible" detection system has rarely been stressed.

Experience of the last decade has indicated that a high degree of flexibility likely can be achieved by centralizing the daily detection planning and control functions for large areas. Under such a centralized system planners should be able to obtain a more complete picture of detection needs and aircraft and budget restrictions.

Associated with a centralized detection dispatching is a large information processing problem. Consider what might be a typical detection planning problem. Several fires are expected to be burning in a 60,000 square mile area. Three aircraft are available for 3-hour detection patrols, but together they can cover at most about 1/3 of the area. Should patrols be sent out at all? If so, at what time and where should they be routed. To answer these questions current and historical weather, fuel state, and fire occurrence pattern data must be quickly assembled, integrated and evaluated.

The daily detection planning process reduces to two tasks -- that of forecasting the expected numbers and locations of new or previously undetected fires and that of determining when and where air patrols should be routed. Historical records give general man-caused and lightning-caused fire occurrence patterns but these can be improved upon by making use of current and recent-past weather, fire occurrence, and fuel moisture content data. For example, the Fine Fuel Moisture Code of the Canadian Fire Weather Index (Anon. 1969) is a good indicator of the expected number of man-caused fires that will occur in a specific area (Cunningham and Martell, 1973). Also, specific thunderstorm paths as obtained from a thunderstorm tracking network provide better information for routing patrols than historical lightning fire occurrence maps. A dispatcher should be aware of the relation between weather, fuel moisture content, storm occurrence, and the number of new fires expected in each locality of the detection area.

The second task - that of determining when and where to patrol given the fire occurrence forecast is as difficult as the first. The frequency of flights depends on how much detection money remains and the nearness to the end of the fire season. Specific takeoff times and routes are determined after considering the fire occurence forecast, the urgency for early detection as indicated by the weather and fuel state, and the values involved where the fires are likely to occur.

Daily detection planning is further complicated by the detection and reporting efforts of the general public. In areas of moderate population density the visual air patrol cannot compete with the high speed of the public in reporting fires. It may not be necessary to conduct patrols in these areas in spite of the high incidence of man-caused fires in high value areas. In general, the efforts of a northern air patrol system should be concentrated in more remote areas in search of lightning and recreation fires.

COMPUTERIZED DETECTION PLANNING SYSTEM

Existing airborne fire detection systems are expensive to operate and their effectiveness in terms of numbers of first detection is not all that impressive. Improved daily planning involving more accurate fire occurrence forecasts and better patrol routing seems to offer the greatest potential for improving the detection system. Such planning, if done properly, will require the daily assembly and analysis of a considerable quantity of weather, fuel, and fire information and will require at least one experienced person and some part-time support staff unless the information processing is computerized. In an attempt to overcome potentially high planning costs, the Forest Fire Research Institute and the Ontario Ministry of Natural Resources began a co-operative study to determine whether or not a computerized procedure could be developed to aid in detection dispatching.

The planning system that was developed consisted of a procedure to forecast an hourly fire occurrence pattern and an algorithm to route air patrols through the occurrence pattern in an efficient manner. Historical weather and fire data from northwestern Ontario were used to illustrate the forecast procedure. To test the system, actual 1972 northwestern Ontario detection results were compared with those that would have been obtained had the computerized system been used during the 1972 season. A near-operational computer package, designed for daily detection dispatching, was developed; and experience with it suggested one possible form that the field version might take.

Fire Occurrence Forecast Procedure

The study area was located in northwestern Ontario between the Ontario-Manitoba boundary and 89^{0} 30' longitude and 48^{0} and 52^{0} latitude. This 72,800 square mile area was divided into 182 cells each 20 miles by 20 miles (Figure1).

An attempt was made to forecast each hour the expected number of undetected fires in each cell. The forecast procedure cumulated to each cell's previous hour's total the number of new man-caused and lightning-caused fires expected to occur that hour. Also, each hour, the expected number of public and air patrol detections were subtracted from each cell's total.

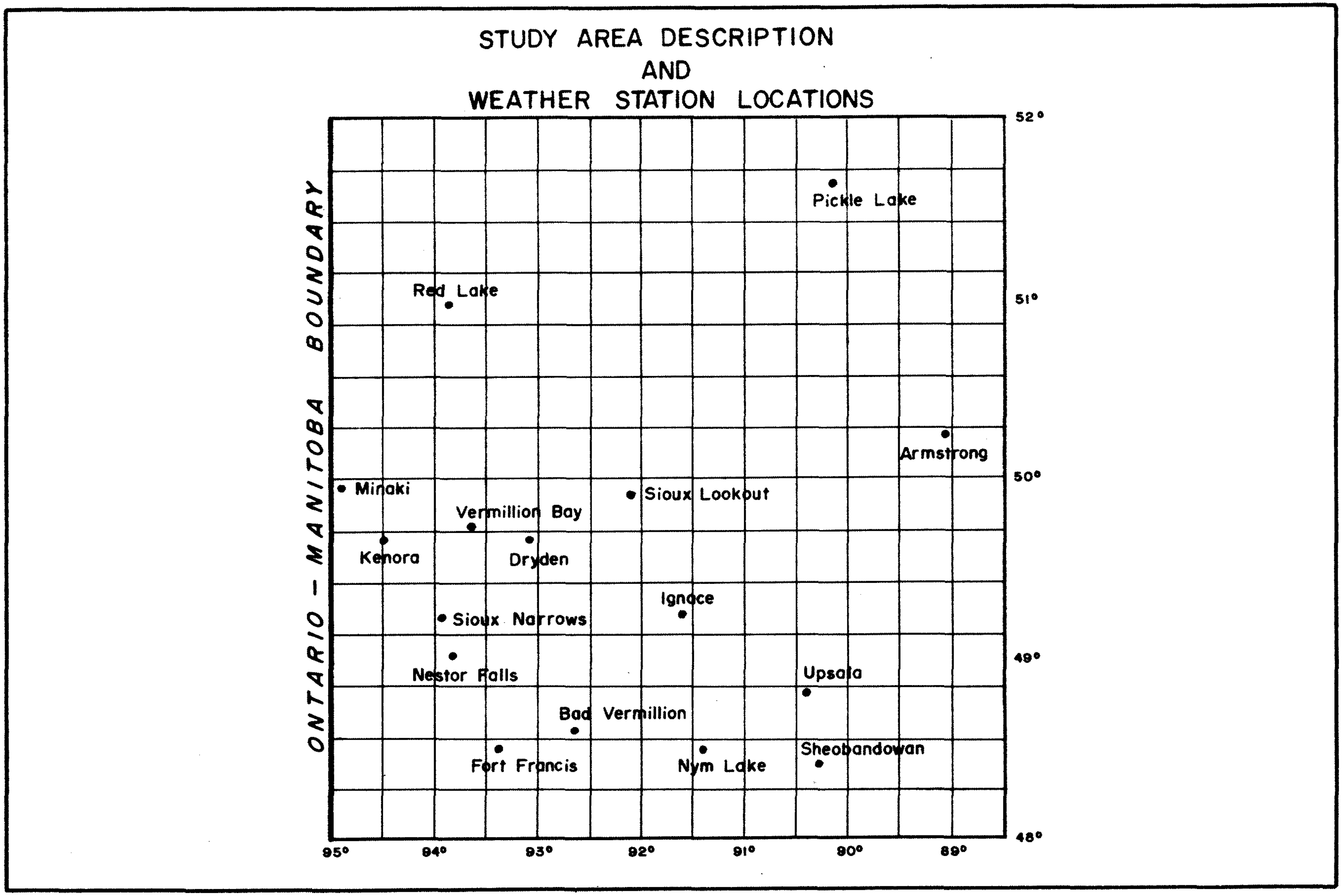
STUDY AREA DESCRIPTION
AND
WEATHER STATION LOCATIONS
ONTARIO - MANITOBA BOUNDARY
Pickle Lake
Red Lake
Armstrong
Minaki
Sioux Lookout
Vermillion Bay
Kenora
Dryden
Ignace
Sioux Narrows
Nestor Falls
Upsala
Bad Vermillion
Sheobandowan
Fort Francis
Nym Lake
52°
51°
50°
49°
48°
95°
94°
93°
92°
91°
90°
89°

FIGURE 1

Thunderstorm occurrence and Fine Fuel Moisture Code (Canadian Fire Weather Index) were obtained for the 1961 through 1971 fire season from 16 weather stations (Figure 1). Coded forest fire reports for the fires that occurred during the same time period were obtained. Also, the nearest weather station to each cell's mid-point was identified (Table 1, Appendix 1).

The thunderstorm and lightning fire occurrence data were used in calculations of the estimate of expected number of lightning fires to be started by a storm over a particular cell. These values were obtained by dividing the total number of lightning fires in each cell by the number of thunderstorms occurring at the station nearest the cell (Table 2 Appendix 1).

Fine Fuel Moisture Code and man-caused fire data were used to obtain an estimate of the expected number of man-caused fires that would occur in each cell during each Fine Fuel Moisture Code class day. Each weather station day was classified into one of four Fine Fuel Moisture Code classes. The number of man-caused fires per cell that occurred on the four Fine Fuel Moisture Code class days were found. These were divided by the appropriate total number of fine fuel moisture class days to give the average number of man-caused fires per fine fuel moisture class day for each cell (Table 3 Appendix 1).

A function in the form of a vector of multiplication factors was devised to distribute over a 24-hour period the daily expected number of man-caused fires per cell. A certain proportion of the day's fires per cell occurred each hour. This function was based on the average diurnal fluctuation of the Fine Fuel Moisture Code as determined by Simard*. (Table 4 Appendix 1).

The general public in relatively populated areas detect a large percentage of the available fires each hour. The ratio of the number of public detections in an area to the total number of undetected fires available in a given hour was selected as the measure of their detection effectiveness. These ratios were calculated for each hour

* *Based on 1960 and 1966 data from A.J. Simard (personal communications).*

for each set of cells associated with the 16 weather stations. Table 5 of Appendix 1 gives these values. Note that most of the public detections occur between 10 a.m. and 8 p.m. and that the ratios are small for remote areas. The decrement in the expected number of undetected fires in a given cell and hour was found by multiplying an appropriate ratio from Table 5 Appendix 1 times the number of fires forecast for the cells.

Detection patrols, in addition to detecting fires, serve a useful information collection function. A revised estimate of expected fire occurrence can be made after every patrol. For example, if an air patrol is capable of detecting 40% of the fires along its route the expected number of fires remaining undetected after the patrol is 60% of the original number. The forecast of the expected number of undetected fires per cell was adjusted for each cell along the route of the patrol in this manner assuming that each patrol detected 1/2 of the fires in the cells that it "visited[1]".

Analysis of daily fire occurrence patterns in the study area indicated that lightning fires frequently occur in clusters of two or more each within a 20-mile diameter circle. Immediately upon detecting the first fire along a patrol route, the original fire occurrence forecast and possibly the corresponding patrol route should be revised so as to reflect the fact that there is a good chance that at least a second fire is nearby. This current version of the fire occurrence forecast scheme does not make use of this clustering effect although it will be built into future versions and is discussed later in this report.

The fire occurrence forecast procedure for a given hour involved the following steps to be carried out for each cell of the study area:

a) Determine if a thunderstorm occurred that hour either from the nearest weather station's thunderstorm historical record or future forecast (depending on whether fire occurrence is to be calculated in the past or future). If a storm occurred, add to last hour's value the number of new fires that are likely to be started in the cell by the storm as determined in Table 2 Appendix 1.

1 *It should be noted that visual detection effectiveness under the many different human, atmospheric, and fire conditions has never been quantified.*

b) From historical or forecasted weather records determine the fine fuel moisture day-class for the nearest weather station. Using this, select the appropriate number of man-caused fires expected to start in the cell that day (Table 3 Appendix 1). Multiply this value times the hourly adjustment factor for that hour (Table 4 Appendix 1) and add the result to the previous hour's expected number of fires for that cell.

c) Determine the percentage of public reduction in undetected fires that hour for the weather station nearest the cell (Table 5 Appendix 1). Adjust the expected number of fires in the cell according to this percentage.

d) Determine if a patrol did or will pass over the cell that hour and reduce the forecast by an amount proportional to the detection capability of the patrol.

Routing of Patrols

The fire occurrence forecasting scheme predicted the number of fires burning undetected in each cell during a given hour. This forecast was used by a dynamic programming algorithm to route the aircraft to the sequence of cell centres with the highest total of undetected fires. A requirement that the aircraft must return to its original base after travelling a certain number of miles was incorporated into this algorithm.

The dynamic programming formulation took the following form:

a) The flight path proceeds from mid-cell point to adjacent mid-cell point and turns are only possible at these points.

b) The airports at which the flight originates and terminates must be mid-cell points (these can be the same points).

c) The initial reward for "visiting" a given cell was set equal to the cell's fire occurrence forecast multiplied by the average detection probability of the aircraft. (Average detection probability is currently set at 0.5).

d) More than one pass over a cell is allowed and the reward structure is such that for each successive repetition of a given cell the reward obtained decreases. Without this decreasing reward structure each patrol route would retrace its original path back to the airport. Currently the reward for second "visits" is set at 0.

e) The dynamic programming stage is the number of cell "visits" made since leaving the airport.

f) The state is the current physical location (mid-cell point).

g) Arrival at a specific cell center can only be made from one of the four adjacent surrounding cell mid-points. Thus there are at most four states in the previous stage to consider for the arrival at a specific state and stage.

h) The duration of a patrol is determined by the number of stages used. For example, a 21-stage patrol would be approximately 420 miles in length if the cells were 20 miles square.

i) For a given stage and state the cumulated return or equivalently the cumulated expected number of fire detections obtained from arriving in an optimal manner is found by:

    (1) Completely decoding the sequence of states that could lead the patrol in an optimal manner in the previous stage to the 4 adjacent states surrounding the state of interest.
    (2) Along each of these routes identify the number of times that the state of interest was repeated.

(3) Add to each of the previous stage's four cumulated returns associated with the adjacent states the appropriate expected number of fires to be detected in the state of interest -- depending upon the number of repetitions already made of this state along the route.

(4) Select the maximum of these four values as the cumulated return for the stage and state of interest.

j) Repeat step (i) for as many stages as desired.

k) The cumulated expected number of fires to be detected after "visiting" N cells and returning to a specific airport is represented by the cumulated return in stage N at the state associated with the airport.

l) The actual route to this point is found by decoding the stage-state network as done in item (i).

m) The algorithm is started by setting the starting dummy stage cumulative returns to $-\infty$ except for the state associated with the originating airport.

It can be shown that this particular formulation does not guarantee that an optimal route will be found. The problem lies in the way repetitions are treated. The reward for a given stage and state is determined only after the route to it is retraced to determine the number of repetitions of that cell. The assumption is made that the earlier decision to include or not to include the cell of interest on the route was correct. This procedure violates dynamic programming's "Principle of Optimality", that states "An optimal policy has the property that whatever the initial state and decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision". (Bellman and Dreyfus, 1962). Here optimality relative to the initial state cannot be guaranteed. The optimal route up to an adjacent state in the previous stage may correctly have included the initial state. However, when forced to the initial state from this same adjacent state, the new optimal route may not necessarily include a repeat of the initial state. The problem lies in the incomplete definition of a state. The current definition does not adequately consider the repetition factor.

Tests of the algorithm indicated that under most circumstances it performs quite adequately and is superior to humans in its ability to quickly identify the best patrol route. It appears that the algorithm fails only when a cell's reward is greater than twenty times that of adjacent cells. Future work in patrol route planning should be aimed at improving this algorithm.

Scheduling of Patrols

A simple "threshold" rule was devised and used to determine the hour at which one or more patrols should be dispatched. Each hour the total number of expected fires in all cells was found and compared to a present threshold value. If this total exceeded the threshold a patrol was dispatched and the expected number of fires was adjusted along the patrol route as previously described. The total was recalculated and the threshold check repeated to see if another patrol was to be dispatched. High threshold values resulted in few patrols but these patrols were carried out when many fires were likely to be detected. Low threshold values resulted in many patrols but the average effectiveness of a patrol was low. In between high and low values would be a value that would utilize the detection budget for an average season. Such a value could be found by trial and error simulation of the planning system for a series of past fire seasons.

This scheduling rule had the shortcoming that it neglected the distribution pattern of the expected fires. Patrols were dispatched whether or not the fires were forecasted to be all located in a small area or evenly distributed over the entire study area. An alternate rule would be to use the routing algorithm to determine a route and the expected number of detections by that patrol. If the expected number of detections exceeded a preset threshold, fly the patrol. This rule was not used in the evaluation simulations because of the excessive amount of computer time that would be required to calculate a potential patrol route each hour of each day.

EVALUATION OF THE PATROL ROUTE PLANNING SYSTEM

One way to determine the worth of the patrol route planning system would be to operate it in the field for at least a season. Another way is to attempt to answer the question -- what would the results have been if we had operated it during one or more past fire seasons. The latter evaluation method was chosen chiefly because it was inexpensive and could be carried out in short order.

Measure of Effectiveness

The patrol route planning system, if it is to be used on an operational basis, should be able to "perform" at least as well as the existing system. But what is a suitable criterion of performance? Sophisticated criteria that involve assessments of suppression costs and forest values either destroyed or saved from fire are far too difficult to evaluate at this time. Instead, a measure of effectiveness involving the ability of the system to schedule and route patrols in the vicinity of undetected fires was chosen.

Specifically, the number and percentage of "available fires that had at least one patrol come within a certain distance class was determined. Here a fire was defined to be available if it was burning undetected at the time when the air patrol passed nearest to it. During the life of a fire, between ignition and actual detection, one or more patrols may have been flown. The nearest distance that such patrols came to the fire was determined and categorized. Note that each fire was counted only once.

This criterion was used to evaluate 1972 actual and simulated patrol routes and was chosen because of its simplicity and ease of calculation. It was reasoned that any good detection planning system must be able to route its patrols near to the "available" fires. The main criticism of this criterion, however, is that it treats all fires alike. Fires differ in their urgency for detection and values at risk.

Effectiveness of actual 1972 Patrols

Actual 1972 patrol route data were available for the study area (previously described) and these data included takeoff dates and times, speeds and patrol routes for each of the 271 patrols flown between May 10 and August 31. Daily Fine Fuel Moisture Codes were available from the same 16 weather stations that were previously used to obtain the fire occurrence forecast data. In addition, location, cause, ignition date and time, detection method, and detection date and time were available for each of the 524 fires that occurred between May 10 and August 31, 1972, in the study area.

Summaries of these data showed that the average patrol length was 445 miles and the 271 patrols detected 14 percent of the total number of fires that occurred between May 10 and August 31. The remaining 86 percent were detected by the public. Fifty-nine percent of all the fires within this period were lightning-caused. It is interesting to note that of the fires that the public detected, 54 percent were lightning-caused and 46 were man-caused. But, of the fires that the air patrol detected, 88 percent were lightning-caused. This indicates that dispatching was chiefly aimed at detecting the troublesome, remote, lightning fires. These statistics also point out the great difficulty in scheduling and routing aircraft. for such a large area.

A computer program was written to evaluate the effectiveness of the actual patrols that were flown between May 10 and August 31, 1972. This program went through the following steps for each patrol that was flown:

a) Using the takeoff time and date and patrol duration, each fire was checked to see if it was burning while the patrol was in progress.

b) For each fire that was burning at that time, the point on the patrol route nearest to the fire was calculated knowing the patrol route and fire location.

c) The time required to reach the nearest point on the route was calculated knowing the takeoff time and the aircraft's speed.

d) If the fire was burning undetected at that time, its nearest distance to the route was calculated and categorized. If the data indicated that the fire had been previously detected by an air patrol sometime near the calculated arrival time it was assumed to be "available" since it likely had been detected by the patrol that was being simulated.

Table 1 presents the results produced by program.

Effectiveness of Simulated 1972 Patrols

If the proposed detection planning system had been operated in parallel with the actual system that was used in 1972 how would the results have compared? An attempt to answer this question was made by simulating the planning system operation using 1972 actual fire and weather data. First, the system was simulated under the condition that 271 patrols would be flown at the takeoff dates and times and patrol durations actually used during the 1972 season. Such a simulation would result in testing the ability of the fire occurrence forecast scheme to predict where fires are most likely to be located. Second, the takeoff time constraint was relaxed and the system itself, using the threshold concept (outlined earlier) selected takeoff times and routes. Here an average patrol length of 440 miles was used for each patrol.

Both phases of the simulation trial required a forecast of fire occurrence each hour of the 1972 fire season. The forecast scheme and 11-year relationships of thunderstorms and Fine Fuel Moisture Code to fire occurrence, outlined previously, were used in conjunction with actual, daily, 1972 thunderstorm and Fine Fuel Moisture Code observations to make these predictions. Here, Fine Fuel Moisture Code data were available each day for each of the 16 weather stations of the study area.

Thunderstorm data was available from the same 16 weather stations. However, it was clear that these data were incomplete. Many lightning fires were reported started on days that the nearest weather station reported no lightning. Consequently, it was assumed that thunderstorms occurred at weather stations nearest to the lightning fires and at the same time that the fires were ignited. This assumption partially corrected the thunderstorm lightning fires relation discrepancy but introduced an unrealistic feature to the simulation. That is, better information was available to the simulation model regarding thunderstorm occurrence than had been available to the 1972 dispatchers.

Recent results from an electronic thunderstorm sensor network in the study area confirm suspicions that fewer than half of the storms are detected by human observers. Based on such evidence and assuming thunderstorm sensor networks will be operated in the future, the thunderstorm-lightning fire relationship based on past data (Table 2, Appendix 1) must be significantly revised.

Despite poor thunderstorm occurrence data and corresponding storm-fire relationship, the evaluation of 1972 simulated patrols that were routed by the proposed detection planning system was carried out. Results are presented in Table 1.

The effectiveness of 271 arbitrarily selected patrol routes, each of 440 miles in length, also was calculated. Nine patrol routes were defined that attempted to systematically cover the complete area. Actual 1972 patrol dates and times were used for their dispatch. At each takeoff time a patrol route was randomly selected from the nine possible. This experiment was repeated four times - each with a different series of randomly selected patrols. The results of these runs are presented in Table 1.

The second phase of the simulation dealt with the ability of the detection planning system to schedule patrols in addition to routing them. The constraint that 1972 takeoff times be matched was dropped. Two such computer runs using 1972 actual weather data and the fire occurrence forecast scheme were made - each with a different threshold value. These threshold values determined the frequency and times of patrol (described previously). Each patrol was assumed to be 440 miles in length. Results of these runs are presented in Table 1.

TABLE 1

Results of Detection System Evaluation

Using 1972 Study Area Data

	No. of Patrols	Threshold Value*	No. of Fires with at Least one Patrol Within Distance Class: 0-10mi	0-15mi	Beyond 15mi	Fires not burning at Patrol Time
Actual 1972 Routes	271	NA	125	173	136	215
Computer Planned Routes	271	NA	176	197	113	214
Arbitrary Selected Routes						
Trial A	271	NA	101	131	180	213
Trial B	271	NA	111	139	171	212
Trial C	271	NA	124	152	163	209
Trial D	271	NA	79	107	199	218
Computer Selected Takeoff Times and Routes						
Trial A	61	6	80	91	80	353
Trial B	107	5	105	121	95	308

* Expected total number of Fires predicted to be burning in study area at takeoff time

DISCUSSION

According to the criterion used, the computer planned patrols were superior to the actual routes flown in 1972. The main reason for this difference likely was the computerized system's ability to more accurately forecast fire occurrence. It is interesting to note that both systems concentrated their efforts in remote areas primarily in search of lightning-caused fires. Here, the two systems both recognized the importance of the public in early reporting of most man-caused fires.

Results varied widely between the four trials that used an arbitrarily chosen set of flight lines. But, results from all four trials were poorer than those of the computer-planned and actual results. This tends to confirm what the field people have suspected for a long time -- that daily fire-occurrence predictions really are possible.

Only one season of actual patrol route data were available therefore the amount of variation in results between seasons of the computer-planned and actual systems could not be determined. However, it appears safe to conclude that the computer-planned system is likely feasible and warrants field testing if it can be run on a daily basis for a reasonable cost.

A "Near Operational Computer Programme

The objective of the planning system is to assist detection dispatchers in determining when and where to dispatch detection patrols. The Fortran computer programs that were used to evaluate season of detection data were modified to approach this objective. This "near operational" program was written for a high-speed, card input, batch computer system and its purpose was to illustrate input and output difficulties associated with a future operational version. It is anticipated that the future version will be run on a slow-speed "teletype" class of remote terminal and the central computer will be at least of medium size.

The "near operational" version has the following characteristics:

a) The starting reference time is assumed to be the previous noon and the program can forecast several days into the future.

b) The input requirements are:

   (1) The fire occurrence pattern that was estimated to exist at the previous noon (determined by an earlier updating of the program).
   (2) The daily fine fuel moisture codes for each weather station in the study area for as many noons as required including those for the previous noon.
   (3) For thunderstorms that occurred since the previous noon and those forecast in the future their times, dates, and nearest weather stations.
   (4) The takeoff times, dates and turning point locations of all patrols flown since the previous noon and the takeoff times, dates, and length of future patrols to be evaluated. Here, not only can detection patrols be entered but also other scheduled forestry and commercial routes.

c) The remaining fire occurrence forecast data are read in separately on cards, or as internally defined constants.

d) The output from this "near operational" version includes:
   (1) A listing of all the input data
   (2) A listing of the fire occurrence forecast constants
   (3) A printout of the fire occurrence forecast every 4 hours since the previous noon.
   (4) The future patrol routes recommended by the system in map form
   (5) The expected number of fires to be detected by each future patrol.

An example of this output is provided in Appendix 3.

Trials with the current version of the programme indicated that the cost of an individual run is moderately high and required about three Univac 1108 computer-seconds per forecasted patrol route and about three to five seconds for the necessary "bookkeeping" functions associated with input, output and fire occurrence forecasting. The average cost per run on the batch 1108 system is about three dollars assuming a 5 or 6 hour forecast from a current time of 8 a.m. and three future patrols. This cost can be expected to increase when a slow-speed "conversational batch" computer system is used with the current version of the programme. A significant number of simplifications and improved programming features are required in order to reduce this cost.

Improvements Required in the Planning System

Thunderstorm-Lightning Fire Relation

Recent electronic sensor data from the study area indicated that thunderstorms occur far more frequently than the visual reporting system data indicated. It is now clear that the historical data on which the thunderstorm-lightning fire relationship was based is in error.

This relationship, if used in conjunction with the existing thunderstorm tracking network, would forecast far too many lightning fires. It is assumed also that each storm over a given cell will start the same number of fires. However, experienced field personnel are aware that the number of lightning fires burning in a particular area is closely related to the previous and accompanying precipitation pattern over the area. It appears that few lightning fires will be burning in an area regardless of the severity of the storm if a uniform, moderate to heavy rainfall preceeded or accompanies the lightning. Severe lightning activity without rain or with great variation between rain guages in areas with dry fuels (before the storm) can be expected to start many fires. It should be possible to construct a procedure to estimate the expected number of lightning fires given the lightning sensor network results, lightning fire history, the precipitation measurements and possibly fuel moisture contents. Such a scheme should completely replace the existing lightning fire occurrence forecast procedure.

Diurnal Variation in Detection Capability

The existing detection planning system assumes that a patrol is equally effective in detecting fires at all times throughout the day. Once again, experienced field personnel are aware that this is not true. Diurnal fluctuations in fuel moisture, and temperature inversions within timber canopies and valleys make it much more likely that detectable smoke will be produced by fires in the late morning and afternoon rather than in the early morning or late evening. This relation is further complicated by daily and hourly variations in visibility. Such considerations must be incorporated into the planning system before operational trials begin. Otherwise many patrols will be dispatched too early in the morning in search of lightning fires and still others will be dispatched under extremely poor visibility conditions.

Updating Fire Occurrence Estimates

Revised estimates of the number of fires in each cell along the flight path were made after every real world patrol was flown based on an assumed detection capability. But updates should have been made for all cells -- not just those along the route and these updates should be based on the actual number of fires detected as well as the expected hourly detection capability. In a similar fashion, updates of expected fire occurrence should be made based on actual public reports compared to the forecasted number of public reports.

The value of update information is so high at certain times that special patrols will be dispatched with the primary goal of determining the correctness of fire occurrence forecasts. For example, after a nighttime "dry lightning storm" the forecast may be for a large number of lightning fires. Early morning patrols likely should be dispatched in spite of poor detection capability in an attempt to confirm or disprove this forecast so that the fire control organization can be built up in time to cope with the increased job load if necessary. The importance of update information implies that under normal conditions rarely will two or more patrols be dispatched simultaneously and that the takeoff time and route for the next patrol will be determined only after the results of the previous patrol have been used to update the fire occurrence forecast. Based on this reasoning there is little need for the operational planning system to forecast beyond the time of the next future patrol. Therefore, the long-term forecast feature and multiple patrol aspects of the existing computer program do not appear to be necessary.

Configuration for Operation Use

Experience with the "near operational" program plus the previous discussion of improvements required indicate that a complete revision is in order. An improved lightning fire forecast procedure, diurnal detection capability and an improved fire occurrence updating procedure should be incorporated into the next version. In addition, the input storage structure and event processing sequences of the computer programme should be changed in the following manner:

a) A separate computer program is required to receive Fine Fuel Moisture Code, thunderstorm, past patrol route, and detected fire update data and to store these in a device that is accessible to the patrol routing programme. This input program would allow these data to be entered in at any convenient time before use of the main program. Also, this input program should update and store in a separate location the latest fire occurrence forecast. This avoids the need to recalculate the forecast from the previous noon with each rerun of the patrol route programme.

b) The patrol route programme must be restructured to read the current time's updated fire occurrence and Fine Fuel

Moisture Code forecasts from an auxiliary storage device. It also must be further modified to forecast only a few hours into the future and handle at most three patrols. Terminal input requirements at the patrol planning time will be negligible.

c) Terminal output will be reduced to include only the estimated number of detections and the routes for the proposed patrols. Routes will be defined in terms of coordinates of turning points.

d) A large cell size will be defined for the fire occurrence forecast procedure. This not only will shorten the calculation time required for forecasts, but also will result in patrol routes with fewer turns. The new sizes likely will be about forty miles square. It may be possible to easily modify the patrol routing algorithm to allow cross-diagonal patrols in an effort to compensate for the larger cell size.

It has been estimated that the cost of operating the above mentioned system should be less than $2,000 per season.

CONCLUSIONS

The patrol route planning system, if it had been operated during the 1972 season would have routed the patrols nearer to a significant number of undetected fires than the routes actually flown. Based on this comparison it appears that the planning system offers the potential for significantly improving the efficiency of the detection system in the study area. The next step in evaluating this system should be an operational field trial.

Experience with a "near operational" version of the planning system has pointed out that improvements are required aimed at simplification and cost reduction. In addition to these, the historical thunderstorm-lightning fire relationship that was used to forecast lightning fire occurrence for the 1972 evaluation must be replaced. Also, the current version assumes erroneously that fires are equally detectable at all hours. This assumption must be replaced by a diurnal detection effectiveness function that possibly is conditional on hourly visibility. A new procedure for updating fire occurrence forecasts must be made and this procedure should include the use of actual fire detections by the patrols and by the general public.

Participation by all levels of field personnel in determining the system's structure and operating constraints is essential if the next stage - that of implementing a trial version - is to be successfully carried out. Indeed, it can be said that more field input should have been present throughout all phases of this study. Also, considerable thought should be given to a training programme to accompany the system and to the method of evaluating the trial results.

Interesting sociological problems associated with technological innovation likely will arise. Some individuals may feel threatened not only by the machine but by the people who control the machine. The seriousness of such conflicts and the manner in which they are handled could determine the success or failure of the system.

An operational field trial of the system will identify many short-comings that will require correction. Certainly a period of several years will be required to evolve a satisfactory operational version.

References

1. Anon. 1970. Canadian Forest Fire Weather Index. Canadian Forestry Service

2. Bellman, R.E., and S.E. Dreyfus, 1962. Applied Dynamic Programming. Princeton University Press

3. Cunningham, A.A., and D.L. Martell, 1973. A stochastic Model for the Occurrence of Man-Caused Forest Fires. Canadian Journal of Forest Research, Vol. 3, No. 2

APPENDIX 1

Data used for Hourly Fire Occurrence Forecasting

TABLE 1

Grid cell - Nearest Weather Station Relation

12	12	12	12	12	12	13	13	13	13	13	13	13
12	12	12	12	12	12	13	13	13	13	13	13	13
12	12	12	12	12	12	13	13	13	13	13	13	13
12	12	12	12	12	12	10	13	13	13	13	13	13
12	12	12	12	12	10	10	10	10	13	13	1	1
9	9	12	8	8	10	10	10	10	10	1	1	1
9	9	8	8	5	10	10	10	10	10	1	1	1
9	4	8	8	5	5	10	10	10	11	1	1	1
4	4	7	8	5	5	11	11	11	2	2	2	1
4	7	7	6	5	5	11	11	11	2	2	2	2
7	6	6	6	15	15	15	16	16	2	2	2	3
6	6	6	14	15	15	15	16	16	2	3	3	3
6	14	14	14	14	15	15	16	16	16	3	3	3
14	14	14	14	14	15	15	16	16	16	3	3	3

WEATHER STATION CODE NUMBERS

Code No.	Weather Station Name*
1	Armstrong
2	Upsala
3	Sheobandowan
4	Kenora
5	Dryden
6	Nestor Falls
7	Sioux Narrows
8	Vermillion Bay
9	Minaki
10	Sioux Lookout
11	Ignace
12	Red Lake
13	Pickle Lake
14	Ft. Francis
15	Bad Vermillion
16	Nym Lake

* See Figure 1 for station locations

TABLE 2

Average Number of Lightning Fires (multiplied by 1000) Per Storm for each Grid Cell

GRID COLUMN

GRID ROW	1	2	3	4	5	6	7	8	9	10	11	12	13
1	4	4	4	0	0	0	0	4	0	0	0	0	9
2	22	18	13	4	4	9	9	14	0	0	9	9	9
3	31	45	13	13	40	13	19	19	4	19	14	29	19
4	54	58	59	18	22	36	10	19	24	14	29	19	14
5	59	49	36	27	27	16	5	26	10	14	9	26	62
6	60	54	68	124	12	37	80	21	10	5	35	53	80
7	148	27	124	105	78	37	59	37	59	10	71	35	17
8	40	66	74	49	32	39	96	59	64	9	80	35	35
9	90	123	75	99	98	78	13	36	27	5	43	91	98
10	18	58	100	78	92	32	18	18	36	5	27	97	54
11	0	0	219	96	99	6	24	61	23	0	32	27	108
12	0	0	8	48	124	6	24	23	30	54	34	19	34
13	0	0	0	0	0	49	111	153	130	84	73	9	9
14	0	0	0	0	0	0	18	176	76	15	4	9	4

TABLE 3

Average Number of Man-Caused Fires Per Fine Fuel Moisture Class Day for Each Grid Cell (times 1000)

Class 1 Fine Fuel Moisture Class Days

GRID COLUMN

GRID ROW	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	4	0	0	0	3	0	0	0	0	0	0	0	0
7	4	0	0	0	0	0	0	0	0	0	12	0	0
8	0	3	0	7	0	0	0	0	0	0	0	0	0
9	0	3	0	0	0	0	4	0	0	0	0	0	3
10	0	0	0	0	0	0	0	0	0	0	0	0	4
11	0	0	0	0	0	0	4	0	0	4	0	0	0
12	0	0	0	0	0	0	0	13	0	0	0	0	3
13	0	0	0	0	0	0	0	0	0	0	0	0	6
14	0	0	0	0	0	0	0	6	0	0	0	0	0

TABLE 3 (Continued)

Average Number of Man-Caused Fires Per Cell (times 1000)

Class 2 Fine Fuel Moisture Class Days

GRID COLUMN

GRID ROW	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	2	4	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	2	0	0	0	0	4	0	0	0	0	0
4	0	0	4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	2	0	0	0	0	0	0	0	0	0
6	2	0	0	2	9	0	0	0	0	0	0	0	4
7	8	0	2	0	0	4	24	0	0	0	2	0	0
8	0	2	4	16	4	4	2	0	0	0	0	0	2
9	9	2	13	0	2	4	2	0	0	2	2	0	0
10	2	4	4	0	0	0	0	2	0	0	0	0	2
11	0	0	2	0	0	2	0	0	3	13	5	0	0
12	0	0	2	0	18	0	0	3	3	8	18	11	4
13	0	0	0	0	0	8	8	7	3	0	0	0	30
14	0	0	0	0	0	0	0	14	0	7	5	0	0

Class 3 Fine Fuel Moisture Class Days

GRID COLUMN

GRID ROW	1	2	3	4	5	6	7	8	9	10	11	12	13
2	0	4	6	0	0	0	0	0	0	0	0	0	0
2	0	0	4	0	0	0	0	0	0	0	0	0	0
3	0	0	4	0	2	2	0	0	0	0	2	0	0
4	0	4	20	0	4	2	0	0	0	0	2	0	0
5	0	0	2	9	4	0	0	0	0	0	0	0	0
6	0	0	4	2	10	0	0	0	0	0	0	0	9
7	20	2	6	15	2	16	27	16	2	0	0	3	0
8	43	15	17	34	22	0	2	0	2	0	3	0	0
9	15	23	14	8	17	7	75	29	4	0	7	0	6
10	5	23	16	2	4	0	0	17	9	0	0	0	0
11	0	5	26	2	0	2	5	3	3	7	28	2	6
12	0	2	5	17	11	5	0	21	7	13	20	25	4
13	0	0	0	0	0	2	13	10	7	7	6	9	99
14	0	0	0	0	0	0	0	7	3	7	6	0	0

TABLE 3 (Continued)

Average Number of Man-Caused Fires Per Cell (times 1000)

Class 4 Fine Fuel Moisture Class Days

GRID COLUMN

GRID ROW	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	14	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	5	0	0
3	0	0	3	3	3	10	2	2	0	0	2	0	0
4	0	14	74	10	0	0	0	0	0	2	2	0	0
5	0	0	0	17	17	0	0	0	0	2	5	0	0
6	25	5	0	11	28	0	0	3	0	6	0	0	31
7	45	11	7	11	11	24	134	3	3	6	0	0	3
8	94	84	54	100	74	11	6	3	13	0	0	0	6
9	52	64	23	19	26	40	19	30	7	3	9	0	6
10	7	25	53	3	9	0	7	19	34	6	13	9	13
11	2	9	23	11	10	2	10	11	3	42	13	0	13
12	5	11	31	21	25	12	12	59	36	22	57	51	19
13	0	0	0	0	0	10	25	29	18	33	16	38	135
14	0	0	0	0	0	0	0	81	29	3	13	27	5

TABLE 4

Function to Distribute Daily Numbers of

Man-caused fires throughout a 24-hour period

Hour of Day	Proportion of Man-Caused fires
1	.03690
2	.02952
3	.01845
4	.01107
5	.00369
6	.00000
7	.00369
8	.01187
9	.01845
10	.02952
11	.04059
12	.04797
13	.05804
14	.06273
15	.07011
16	.07380
17	.07380
18	.07011
19	.06642
20	.06273
21	.05904
22	.05535
23	.05166
24	.04428

TABLE 5

Effectiveness of Public Detection (times 1000)*

Weather Station Code No. (See Table 1, Appendix 1)

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	10	0	0	0	0	7	15	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0
3	0	0	10	0	9	0	0	7	0	0	0	0	0	0	0	0
4	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	24	0	0	12	0	0	0	0	0	0	0	0	0
6	0	11	0	16	18	0	0	14	10	0	28	0	0	0	20	0
7	12	11	60	8	54	40	32	21	20	0	7	0	0	0	10	20
8	0	33	60	80	27	40	88	0	40	0	21	30	0	0	40	20
9	0	22	40	48	18	40	36	49	40	19	7	0	29	0	50	10
10	0	33	130	16	117	88	80	28	50	36	77	0	29	0	30	50
11	0	55	120	52	81	48	44	42	60	18	189	30	0	0	40	20
12	0	22	150	115	72	72	92	28	45	18	77	60	0	210	60	30
13	12	33	200	84	117	72	88	56	95	0	77	30	29	190	60	40
14	36	33	220	60	162	160	96	70	65	54	63	90	29	350	80	50
15	24	99	200	84	108	56	68	84	115	72	42	60	87	90	90	60
16	48	33	290	124	153	96	124	77	130	54	140	60	87	90	50	90
17	36	55	220	56	189	56	32	49	110	54	84	60	0	90	70	50
18	60	66	250	56	153	56	68	21	60	72	84	60	29	160	30	50
19	36	22	180	44	117	40	60	14	105	54	56	0	0	110	40	20
20	12	44	130	3	81	0	64	28	55	0	14	0	0	0	30	20
21	0	0	110	0	18	24	16	7	40	0	0	0	0	0	0	0
22	0	0	60	9	0	8	0	7	0	0	28	0	0	0	0	0
23	0	0	50	16	0	0	0	0	0	0	0	0	0	120	0	10
24	0	0	10	0	0	0	0	7	0	0	0	0	0	0	0	0

*Ratio of the number of public detections in a weather station area to the total number of undetected fires in the same area.