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Using linear programming and GIS for pre-suppression planning of forest fire control resources

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Abstract

The application of geographic information systems (GIS) and linear programming (LP) techniques are presented to optimally pre-position forest fire control resources in anticipation of a fire event. GIS is used to model weather and forest fuels data to output quantitative forest fire behavior potential. Travel times required to reach individual cells within a forest region (attack times) are calculated using forest fire behavior models and initial attack objective sizes. Two LP formulations are presented that 1) determine the number of resources required to minimize the number of fire control resources while maximizing cell coverage, and 2) compute the maximum cell coverage for the forested area given a limited number of resources. GIS is used to display intermediate terrain, fire weather, and fire behavior potential maps, as well as the attack times and coverage assessment maps.

Introduction

The pre-positioning of fire suppression resources to meet the daily fire danger situation in a region is a fundamental problem for forest protection officers. To help officers arrive at this decision, a number of preparedness planning systems have been designed to determine the required manning levels using fire weather models to estimate the relative fire hazard in the forest (Gray and Janz 1983; Lanoville and Mawdsley 1990; De Groot 1991; Hirsch 1991). In more recent years, computer-aided decision support systems have modelled potential fire behavior with available forest inventory, terrain, and weather, thus allowing a more direct method to assess coverage efficiency (Lee and Anderson 1990). This paper extends this work by demonstrating the role of geographic information systems (GIS) and operations research (OR) as complimentary technologies for determination of optimal fire suppression resource positioning in anticipation of a forest fire event.

Operations research is a relatively new science developed during the Second World War. Following its initial military uses, OR was successfully applied to solve various economic and managerial problems. Generally, OR problems take the form of finding the optimal combination of economic factors such as maximizing profits while minimizing costs. Linear programming (LP) is a mathematical technique used to solve a certain class of OR problems that lend themselves to a linear combination of variables. By defining the problem as a matrix, linear algebra techniques such as the simplex method are used to solve the problem.

Methodology

Coverage assessment is an analysis technique used to evaluate the coverage achieved by initial attack resources, such as air tankers and helicopter carried ground crews, over a forest region (Lee and Anderson 1990). Though this paper does not attempt to define spatial coverage requirements, a brief summary of the technique used by Lee and Anderson is presented.

For coverage assessment, the forest region is first divided into an array of cells. Typically, these take the form of squares or grids at a scale of 1 to 10 kilometres per side. The coverage for each cell is calculated as follows. Fuel, topography, and weather for the cell are retrieved from databases and used as inputs for fire growth models. From initial attack policy, the models calculate the time it would take for a fire to freely grow to a critical size . This time is referred to as the attack time and the size as the initial attack size objective. Finally, coverage is defined as the number of resources that can reach the cell within the attack time, given resource get-away times, travel speeds and distances from manned bases to the cell.

Determining attack times is an essential step in the coverage assessment analysis. In the above example, attack time calculations are based on initial attack size objectives. A simpler approach would be to set the attack time to a constant, thus requiring all fires be attacked within a pre-determined time period, for example 30 minutes. Another possible alternative would be to base the attack times on a fire containment model.

LP problems can be formulated to provide an optimal deployment of initial attack resources. These problems are an integer programming class of LP problems where variables must assume non-negative integer valued solutions.

The problems take the following general form. A number of cells require a degree of coverage by fire suppression resources. To achieve this coverage, a number of fire suppression resources can be based at pre-defined initial attack bases. Initial attack bases are numbered 1 to n, with a subscript i, while cells are numbered 1 to m with a subscript j.

The variables that enter the problems are:

b_i = the resource allocation

a_{ij} = a binary coefficient (0 or 1)

R_j = the required coverage for a cell

c_j = the provided coverage for a cell

The resource allocation, b_i, is the number of resources deployed at the ith base; if two crews were deployed at base 12, then b_{12} would equal two. The binary coefficient a_{ij} could be better described as a logical variable set to one if it is true, zero if it is false. The condition it is based on is whether a resource from base b_i can provide coverage for cell j. If at least one resource can reach the cell, a_{ij} equals one, otherwise it is set to zero. The required coverage variable, R_j, indicates the number of resources policy may require to cover a cell. For example, policy may dictate that fires with a head fire intensity of over 2000 kW/m should be attacked by two resources. On the other hand, the provided coverage, c_j, is the coverage actually provided from presently positioned resources, that is the number of resources that can reach a potential fire in the cell before it grows beyond its attack time objective. The provided coverage c_j has an upper limit equal to the required coverage R_j; any coverage provided over that required is ignored in the calculations.

The general problem can be described with two unique LP optimization formulations. The first is to minimize the number of resources required to achieve total coverage over a region. The second formulation is to maximize coverage over a region under the restraint of a predetermined number of resources.

Minimal resources problem

The minimal resource problem can be described as minimizing the number of suppression resources required to provide full coverage (where possible) of all the cells within a forest region. This problem falls into the coverage class of integer programming problems (Schrage 1986).

Formulation

For j cells, the resource problem is:

minimize

subject to

Equation 1 defines the objective of the problem: to minimize the total number of deployed resources, b_i. Equation 2 sets the constraint that, for every cell, a number of resources equal to the required coverage, R_j, must be able to reach the cell within the attack time objective.

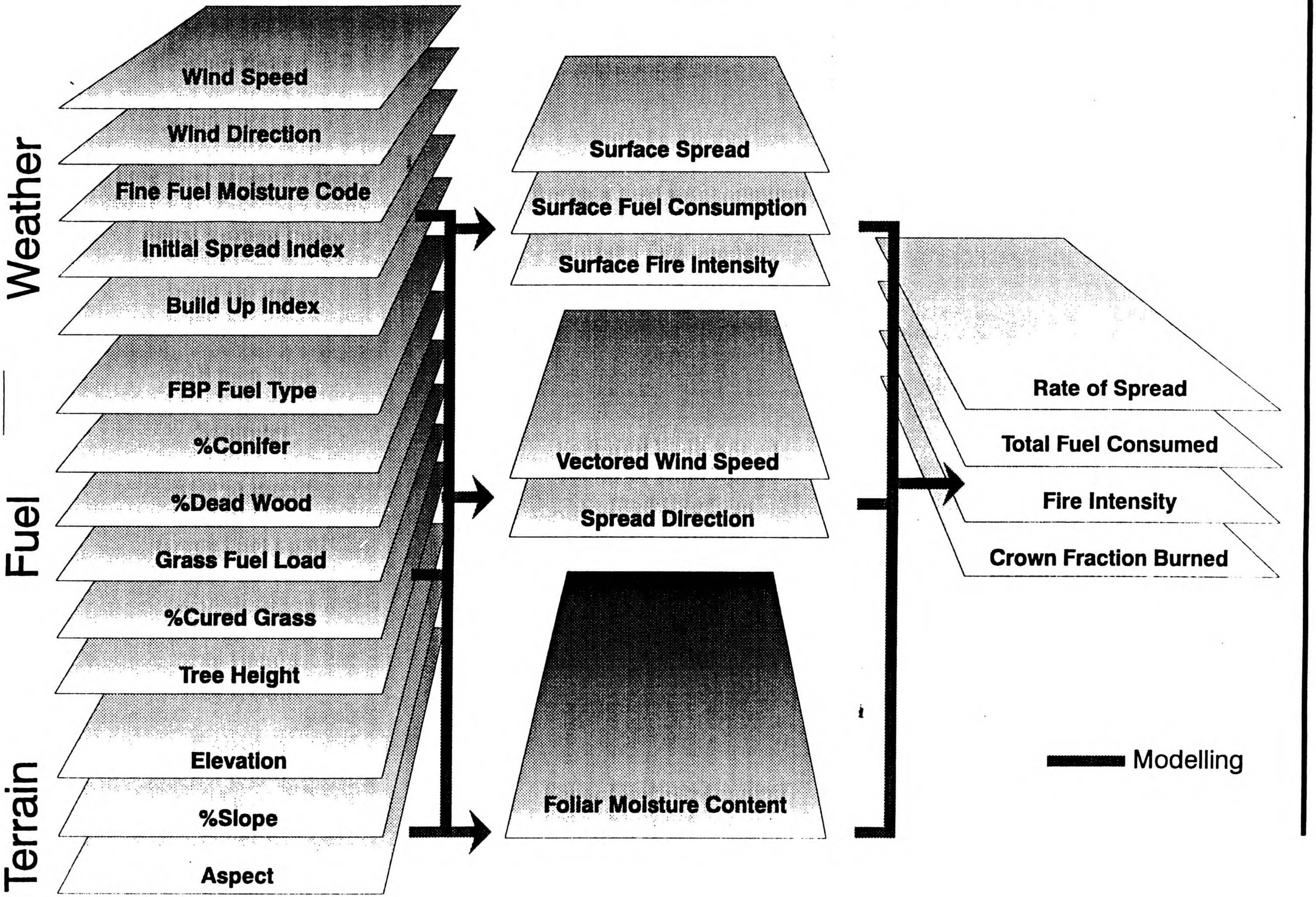
Maximum coverage problem

A variation of the minimal resource problem is to maximize coverage of the forest region while the number of resources is limited. This problem can best be classified as a distribution of effort (Wagner 1969).

Formulation

The maximum coverage problem uses much of the same reasoning as the minimum resource problem but it

FBP System Cartographic Model



is considerably more involved. If we define the resource limit as N, the problem becomes:

maximize
subject to
and
and

Equation 3 states that the objective of the problem is to maximize coverage, c_j. In addition, the objective function minimizes the number of deployed resources, b_i. The intent is to introduce b_i as a variable that must be solved for, otherwise the allocation of resources is unknown. As well, by minimizing the number of resources, the possibility of deploying more resources than are required to reach the optimal deployment described by the minimal resource problem is eliminated.

Admittedly, the units for coverage and resource allocations are not the same and this is a serious concern. Yet, in normal conditions, the sum of the coverage greatly outweighs the number of activated bases and the difference in units can be ignored. The proper method would be to equate the variables to costs, which is discussed later.

Equations 4, 5, and 6 set the constraints. Equation 4 states that the provided coverage for a cell subtracted from the number of resources with travel times less than the cell's attack time must be non-negative. In other words, the provided coverage cannot exceed the number of resources capable of covering the cell. Equation 5 further limits the provided coverage, c_j, to the required coverage, R_j, thus the combination of equations 4 and 5 will set the provided coverage, which is being maximized, to the lesser of $a_{ij}b_i$ or R_j. Equation 6 sets the limit of the number of deployed resources which cannot exceed the constant N.

Linking the LP to GIS

To illustrate the application of coverage assessment, we used data for the Province of British Columbia for July 23, 1990. Vector based fuel type information was imported into ARC/INFO using the GENERATE command. These data were then converted to the GRID data structure using the POLYGRID command. The data was grided at a 10 km by 10 km resolution. This large cell size was necessary due to the small scale of the input data, as well as a physical limit imposed by the LP algorithm on the number of cells possible.

Fire weather station data was brought into INFO as points and attribute data. Using the inverse distance weighting modelling capability of GRID, fire weather data and fire behavior outputs were interpolated across the province at the 10 km level of resolution. The cartographic model used to implement the Canadian Forest Fire Behavior Prediction (FBP) System is presented in Figure 1. Further detail is on the application of this cartographic model to compute fire weather and fire behavior is provided in Lee and Buckley, 1992.

Using the rate of spread GRID layer, an attack time map was produced for an initial attack size objective of 1.2 ha (Fig. 2). This map was then exported to the LP model using the GRIDASCII command in ARC. In addition to this ASCII file, the LP needed to know the effective range and cruise speeds of the helicopters used to transport the fire crews from the heliports to potential fire starts (cells). Briefly, the LP program computes the travel times to every cell from all initial attack bases and keeps count of the number of bases that are capable of reaching the cell within the initial attack size objective.

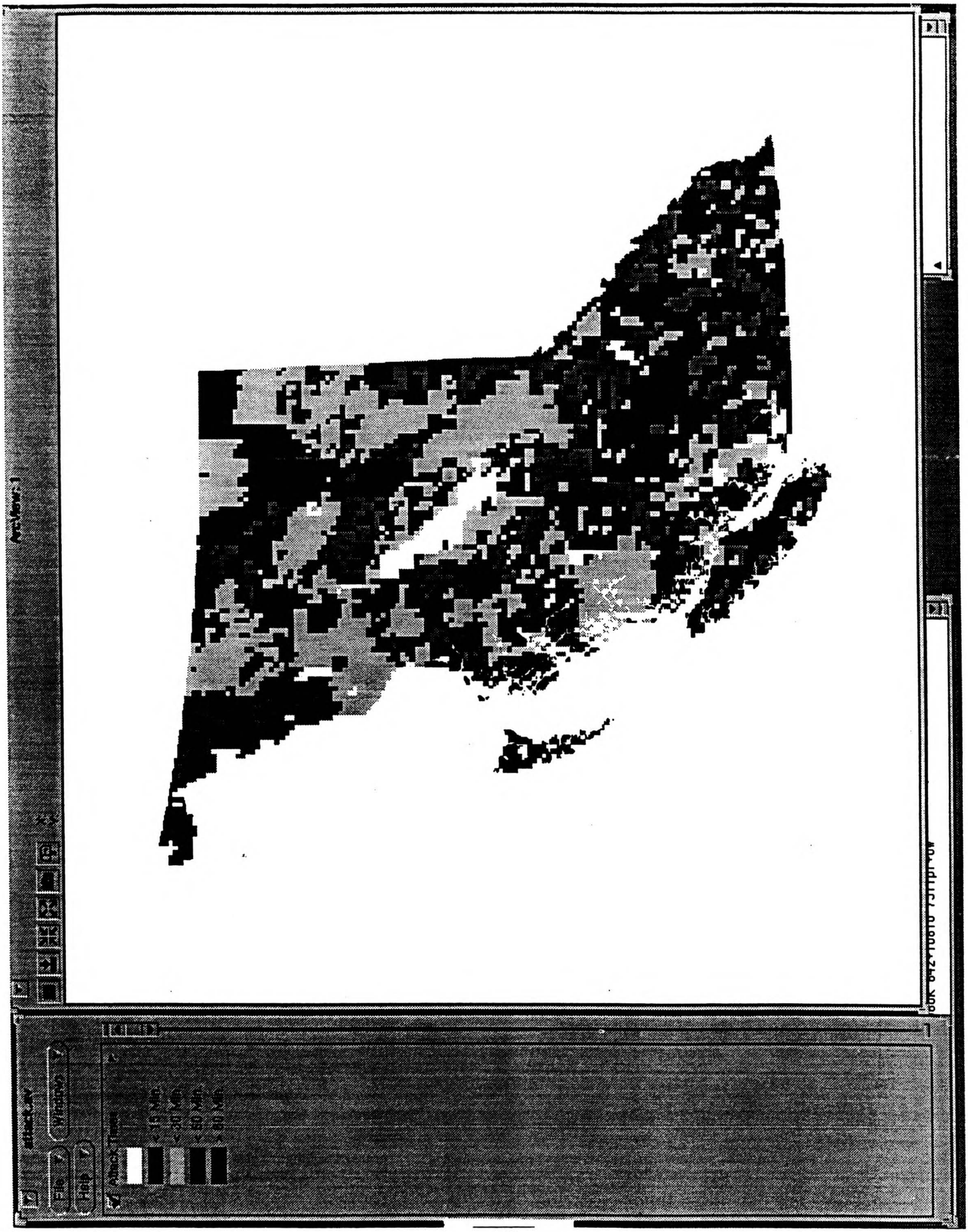
Figure 3 demonstrates the type of cartographic product that can be produced using the GIS and the maximum coverage LP model. Using the actual weather and fuels data for July 23, 1990 the hypothetical question of which 10 of a potential 143 airports and heliports should be activated for use as initial attack bases. The map shows the location of all heliports and optimal positioning of initial fire crews for the 10 fire crews. The map also shows the portions of the province that can be reached by one, two, or more crews. Areas of the province that cannot be reached before the fire grows to 1.2 ha in size are also indicated.

Discussion

Solving these problems for a real situation requires considerable computing resources. Forest inventory databases, weather interpolation schemes, and fire behavior models all must be integrated to formulate the attack time requirements for each rasterized cell. The application of GIS is considered to be a viable platform for conducting coverage assessment analysis at a provincial level. Linking external LP engines such as the LINDO software used in this paper (Schrage 1986) is also considered to be viable.

There are limitations to the approach presented in this paper, however. Cells in which no resources can meet the attack time are excluded from the analysis. Future investigations will look for a formulation that ensures at least one initial attack base meets the initial attack objective time for each cell. Also, the calculations assume a constant travel speed and get-away time for all resources. To include a variety of aircraft with different cruising speeds requires a more complex problem with an insurmountable number of calculations.

Perhaps the most serious shortcoming of this approach is that this is an answer for a static world; however, in reality, it must be applied to a dynamic world. Often initial attack resources are mobilized and sent on patrols over potentially troublesome areas. When resources are dispatched to fires, holes are also created in the coverage network. This may be serious in the case of multiple fire starts.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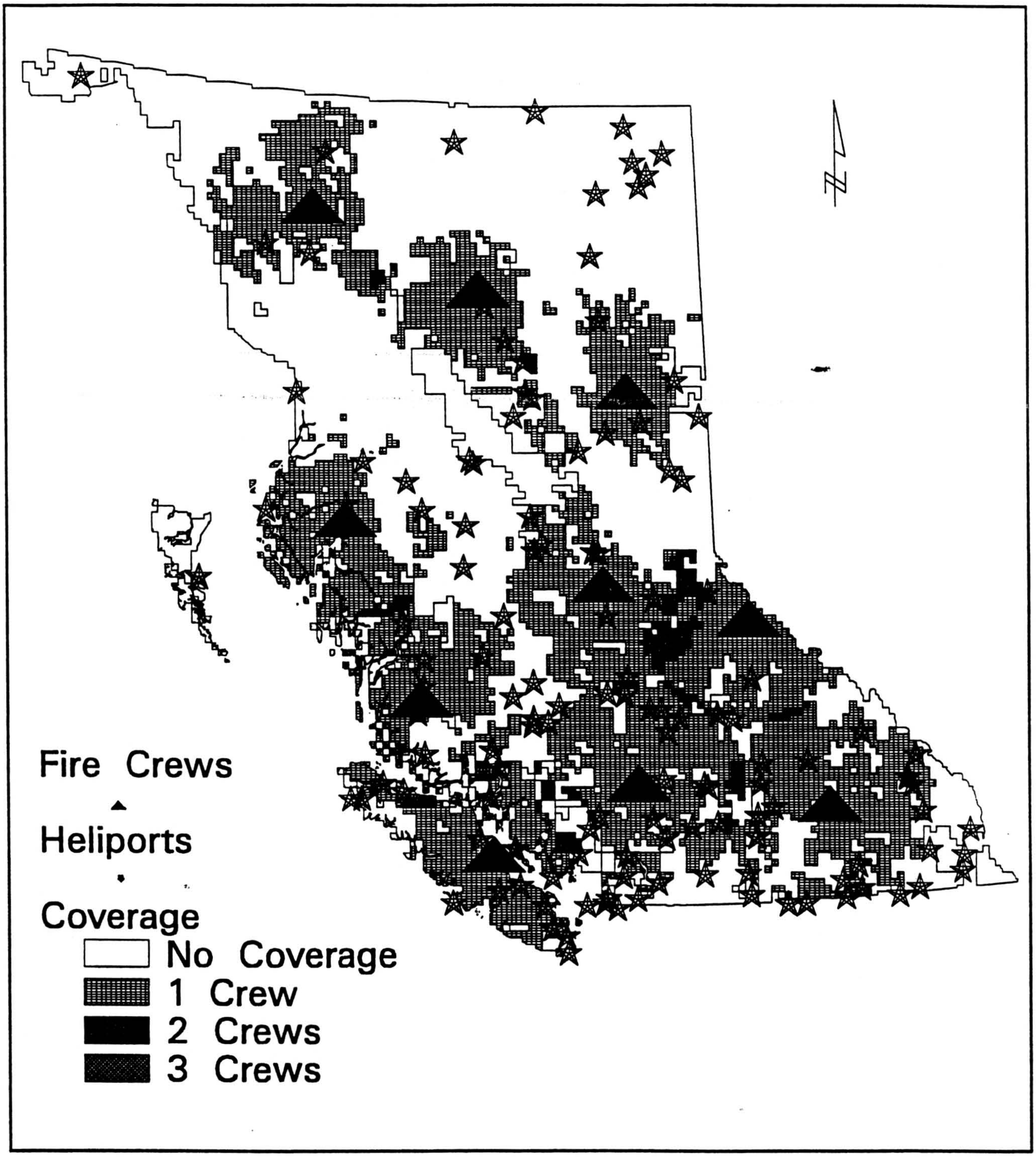
Fire Crews
Heliports
Coverage
No Coverage
1 Crew
2 Crews
3 Crews

While the current formulation could incorporate a cost of activating each man-up base, this has not been attempted. To factor this in, weight the number of deployed resources, b_i, with a cost. This could be further developed to show economics of the impact of fire. This can be done by weighting the required coverage variable, R_j, with the value of the timber.

Conclusions

Using linear programming techniques to optimally place fire suppression resources is a practical option available to GIS based fire management information systems. It has been shown that linear programming can be used to solve two problems: that of minimizing the number of resources required to provide total coverage of a forest region, and to maximize coverage of a province by a limited number of resources. Undoubtedly, there are more applications that can be designed.

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Erratum: Volume 1, pages 102 and 103.

Paper by Lee *et al*: Section headed "Minimal resources problem" should read:

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Formulation

For j cells, the resource problem is:

minimize

$$(1) \quad \sum_{i=1}^{n} b_i$$

subject to

$$(2) \quad \sum_{i=1}^{n} a_{ij} b_i \geq R_j$$

Equation 1 defines the objective of the problem: to minimize the total number of deployed resources, b_i. Equation 2 sets the constraint that, for every cell, a number of resources equal to the required coverage, R_j, must be able to reach the cell within the attack time objective.

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Formulation

The maximum coverage problem uses much of the same reasoning as the minimum resource problem but it is considerably more involved. If we define the resource limit as N, the problem becomes:

maximize

$$(3) \quad \sum_{j=1}^{m} c_j - \sum_{i=1}^{n} b_i$$

subject to

$$(4) \quad \sum_{i=1}^{n} a_{ij} b_i - c_j \geq 0$$

and

$$(5) \quad c_j \leq R_j$$

and

$$(6) \quad \sum_{i=1}^{n} b_i \leq N$$

Equation 3 states . . . (*continues as per printed text*)