Managing Fire on Populated Landscapes

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Wildfire management poses many challenging interdisciplinary problems with scientific origins in ecology, forestry, and engineering (specifically, operations research). As the science evolves, connections with mathematics and statistics are deepening. Our workshop brought together a diverse group of scientists and fire management agency representatives covering this interdisciplinary spectrum, providing a forum for discussion and collaboration between fire management experts, statisticians, and mathematical modellers.

Although a principal focus of the workshop was on fire management in the Canadian boreal forest, there was a substantial international aspect as well. Scientists from Australia, the U.S. and the U.K. gave insightful presentations and made valuable contributions to the many discussions that took place during the weeklong event.

The primary goal of this workshop was to set a tone that encouraged future collaboration among the participants. Only a few formal presentations were scheduled each day allowing ample time for roundtables, question periods, and informal discussion. About a third of the participants were either students or young researchers, several of whom gave formal presentations on research related to their studies. An enormous benefit for some of the statistics students was the opportunity to interact with and learn directly from wildfire researchers.

1 Overview of the Field

The opening presentation, given by Rob McAlpine, played two important roles in the workshop. It was primarily an overview of wildfire management, from the perspective of one of the leading provincial fire management agencies; it also set an example, followed for the rest of the week, where the speaker initiated lengthy and productive discussions within the framework of the presentation.

The main fire management objective is to balance the impact of wildfire with the cost of responding to it. The negative impacts of wildfire are usually obvious, but there are also positive aspects, mainly ecological, that are often overlooked. Thus, before even contemplating the details, the basic objective itself is difficult to formulate.

The high degree of temporal and spatial variation in fire occurrence, fire behaviour and fire impact make it difficult to meet fire management objectives. Because of limited fire suppression resources, and because of jurisdictional realities, several temporal levels of planning are required. On the immediate temporal scale is the problem faced by the individual firefighter, fire crew or airtanker pilot: what specific tactic should be followed in order to achieve the most effective (and safe) result? At the daily level (during the fire season), relatively immediate decisions regarding resource priorities must be made regarding fire detection, initial attack and continued suppression. On the scale of days (up to a week), decisions must be made as to where suppression resources (crews, airtankers, and so on) will be deployed and whether additional resources need to be borrowed from or loaned to other provinces. These decisions are based on the uncertain status of existing fires as well as forecasts of new fires. One- to three-day-ahead prediction of the location and occurrence of new fires remains an important, unsolved problem. At the seasonal scale, higher-level decisions are required. For example, such decisions relate to buying or contracting equipment as well as which bases will be home to such equipment for the remainder of the fire season. These decisions are based on the most accurate information available, but because of the high degree of inter-annual variation in fire occurrence, it is very difficult to predict resource requirements several months in advance. The coarsest temporal scale is referred to as strategic and is in the order of a decade. At this level, decisions are made as to major investments, such as new aircraft, as well as the level of protection to be applied to various regions of a province; these decisions are influenced by patterns of human migration and industrial development in wildland areas. Assessing costs is very difficult. One participant suggested that an actuarial perspective might be helpful, but this still requires consideration of the value of prevention, for example; what would the effects have been in cases where fires were not actively suppressed. In addition, the costs of the current fire management strategy to First Nations communities is very difficult to assess. A poignant description of the speaker's management of an evacuation event in Northwestern Ontario capped off this presentation, reminding the audience of the human cost of the decisions made at these various levels.

2 Fire Management

2.1 Resource Allocation and Sharing

Among other things, McAlpine's presentation showed that in order to make progress on fire management objectives, mathematical and statistical expertise will need to be brought to bear on the issues of uncertainty which complicate operational planning.

David Martell picked up on McAlpine's central theme, beginning with the 5 R's of Fire Management: "the right amount of right fire at the right place at the right time at the right cost". He then brought the theme into clear focus by addressing specific problems in airtanker deployment. For example, what is the best strategy for an individual airtanker? Is it better to return to its original home base after completing service on a fire, or should it return to the base nearest to that fire? Although progress has been made on this kind of problem using tools from operations research, there is a definite need for predictive fire occurrence models on the order of hours. Work is proceeding on initial attack success prediction, but better service time distribution models are needed. Martell also sounded a call for a methodology aimed at generating good initial attack scenarios, accounting for spatial and temporal dependence. The importance of statistics in fire management was underlined in Martell's presentation where the works by Reed and Errico (1986) and Brillinger et al (2006) were identified as highwater marks in the field.

Kate Larson continued on the theme of resource management, identifying an additional complication: the human psycho-social interactions which affect planning and decision-making. She presented a game-theoretic model for resource sharing among the fire management agencies in Canada. Because wildfire management is largely a provincial matter, there is no enforced national standard for resource sharing. Current practice depends largely on the goodwill of the 13 jurisdictions involved. The Canadian Interagency Forest Fire Centre (CIFFC) in Winnipeg acts as a clearinghouse for the negotiations required to transfer suppression resources across provincial/territorial boundaries in times of need. There is a growing belief that current levels of resource sharing will not be adequate to meet national demand in view of climate change, migration into the wildland-urban interface and government cost-cutting.

Through extensive interviews with fire managers across the country, Larson was able to ascertain some of the characteristics of the negotiation process that goes on when resources are requested and when they are offered. From the point of view of game theory, it appears that the management agencies are being somewhat strategic when deciding what kinds of resources to put on offer. With this understanding, it may be possible to set new parameters on the way resources are shared in order to reduce interagency barriers. Specific approaches remain an important open problem.

2.2 The Banff Connection

BIRS workshops that connect wildfire science and management with mathematics and statistics have a unique opportunity: to facilitate interactions with local scientists (specifically, Parks Canada staff). Jane Park, a fire and vegetation specialist for Banff National Park, gave an insightful presentation on the research carried out in Banff on wildfire management and prescribed fire development, including a history of fire management in the park, dating from the late nineteenth century. Over this period, it has been observed that the fuel composition has changed as a result of fire suppression efforts.

Jonathan Large discussed the operations management tools in use, such as burn severity mapping and smoke mapping and how these relate to wildfire preparedness and response. This presentation pointed out the need to balance ecological, operational and sociological considerations.

2.3 Fire Management Informed by Probability Models

John Hearne, James Minas and Peter Taylor led a session which was a facilitated discussion on how probability models can be incorporated into fire management decision support systems. Various elements of wildfire management were considered including: fire detection, fire suppression, fire prevention, fuel management and community protection. Fire agency participants provided insights into the types of decisions they are required to make and what models and other information sources they currently use to inform these decisions. Research participants shared modelling approaches from their past and current research together with actual or potential management applications.

The focus of the discussion was on how and where all these pieces fit into the fire management decision hierarchy. Themes explored included: difficult decisions that probability models could help with, appropriate models to support decisions at various spatial and temporal scales, desired resolution and format of model outputs, data availability and challenges, and practical implementation issues.

2.4 Fire Smart Programs

Steve Taylor's presentation identified issues confronting fire managers related to the wildland urban interface. Data which would help with modelling the impacts of fire on human activity are difficult to obtain, in part, because of jurisdictional issues; it is difficult to identify the at-risk population.

Models that can be used to assess risk at several spatial scales are needed, and there are still many outstanding open problems. For example, factors affecting the ignition of structures are still not completely understood.

3 Modelling

3.1 Fire Ignition and Rainfall

Mike Wotton outlined the approach taken to modelling fire occurrence and how this is a spatio-temporal process. He noted the importance of clear communication with fire managers in order to maximize insight into observed temporal trends.

Lightning-caused fires ignitions were modelled in stages: ignition, arrival and detection. Factors associated with increased ignition probability have been studied. Wotton has proposed an adjustment to the Duff Moisture Code, long thought to be associated with ignition: the Sheltered Duff Moisture Code. This takes into account the fact that the duff layer at the base of large overstory trees, which are commonly the conduits for lightning ignitions, will be dryer than in other areas of the forest. Fueltype is an important factor.

Lightning detection inaccuracy is a problem. Because of potentially long smouldering times before arrival, it is difficult to pinpoint the time and location of a fire origin.

Valerie Isham discussed rainfall modelling using point processes. In particular, she described a Poisson cluster process model for storm cells. Here, storms arrive according to a spatio-temporal Poisson process with intensity function λ, and their lifetimes are exponentially distributed with rate γ. Each storm initiates a Poisson process of cell arrivals with intensity β. Each cell has a duration and rainfall intensity.

Specific model details lead to departures from conventional point process assumptions. Storms and cells can overlap in space and time, so many of the usual point process operations which are based on an orderliness assumption are not valid. Furthermore, each storm has a velocity, lifetime, and a shape (somewhat ellipsoidal).

Statistical inference, including parameter estimation, was achieved through a generalized method of moments, since likelihood-based inference is not feasible. Specific inference objectives included occurrence forecasting, and conditional amount forecasting, given occurrence.

Interpolation of rainfall between weather stations, for use in occurrence prediction, was the subject of a roundtable discussion on one of the afternoons. Operations like Kriging are not appropriate, because of the large proportion of 0's in the data. The question was asked whether the indices, such as ISI, should be interpolated directly.

Use of radar data would be helpful in theory, but in practice, there is limited coverage in the northern boreal region. Increased numbers of weather stations was suggested, leading to the question of where they should be located. This kind of network design problem is well studied in the literature in the context of pollution monitoring, but it remains an open problem for rainfall detection.

Francis Zwiers spoke on climate change effects, particularly as they relate to precipitation extremes, both in the historical record and in projections from climate models. His approach to extreme value analysis was the block maximum approach. Here, annual blocks of daily values are summarized by their maxima, which according to the large sample theory follows a generalized extreme value distribution, under fairly general conditions. The application in this context was spatial, but pointwise, ignoring spatial dependence.

One of the goals of the analysis was to look for local trends in precipitation records, which are usually difficult to discern because of the presence of large amounts of noise. The results of the analysis, however, were clear: at 8.5% of the stations studied, positive trends in precipitation were observed over recent decades at a significance level where only 2.5% should be expected. In looking for negative trends, no such surprise was found: 2.2% of stations appeared to exhibit negative trends.

Looking for physical justification for climate change results was also a goal of the research, and it was notable that the changes in precipitation patterns as they relate to temperature, follow the Clausius-Clapeyron relation.

Modelling human attribution, a difficult but important exercise was also described in this presentation. A model for detection and attribution of human influence on climate is

$$y = \sum_i (X_i - \delta_i)\beta_i + \varepsilon$$

where y is a vector of temporal-spatial climate observations, X_i is the expected response from a model due to factor i (of which human influence is one example), δ_i is factor-specific error, and β_i is a scaling factor. Fitting such models to the record revealed significant human attribution.

3.2 Fire Temperature Modelling

David Brillinger presented some work in progress, with Mark Finney, on the analysis of temperature data from a fire burned along a trench in a wind tunnel. The main issue here was the highly transient nature of the phenomenon.

Temperatures were measured with regularly spaced thermocouples. Letting y_i represent the temperature at the ith thermocouple, and motivated by the wave equation model which describes a moving front, Brillinger considered a model of the form

$$y_i(t) = g(vt - x_i) + \varepsilon_i$$

where v is the flow velocity, x_i represents location and ε_i represents random error, not necessarily independent and identically distributed.

A number of estimation techniques were tried, including wavelet analysis, but in the end, $g()$ and v were estimated using projection pursuit regression.

A transfer function model was also considered as an alternative approach. In addition, preliminary harmonic analysis was conducted, searching for periodicities in the temperature data. Nonstationarity created issues here and made it difficult to detect any periodicities using standard tools, such as periodograms.

3.3 Uncertainty Handling and Model Assessment

Haiganoush Preisler discussed fire forecasting and mapping, noting that a strength of probability models is that the errors in the data will come out in error term. Fires can be modelled as marked point processes with fire size being the mark, for example.

An inadequacy in fire mapping is the difficulty in conveying uncertainty to end users of the modelling product. To incorporate variability in such maps, Preisler suggested that some measure of variability be included in the legend (e.g. boxplots).

Rick Schoenberg began his presentation with an extensive review of conventional methods for checking accuracy of deterministic fire spread models. The most common approach is to compare observed burned regions with what is predicted by the simulation, often using a map. Remote sensing techniques have also been used, but the analysis remains relatively crude: an 2×2 matrix comparing burned and unburned pixels from the simulation with the corresponding information on an observed fire. Single-index measures of agreement, such as Cohen's κ statistic (Cohen, 1960) were also described. A more informative approach is Fujioka's (2002) histogram method for assessing over-prediction and under-prediction. Comparing a simulation with an observed fire over a time history has been done by Mell et al (2007), but this technique can lead to results which are difficult to interpret. Instead, Schoenberg advocated likelihood based methods, pointing out that this favours probabilistic models over deterministic models. The likelihood is a natural measure of fit and can be used to assess a single model or, through the likelihood ratio, multiple models can be compared.

Schoenberg also discussed assessment of fire occurrence models, noting initial efforts by Viegas et al (1999) to assess fire danger indices by plotting the percentage of days with wildfires or the area burned per day against a given index, such as the Fire Weather Index. Recognizing that over-prediction of fire occurrence is not captured with such methods, Schoenberg presented methods which accounted for counts of false alarms; Xu and Schoenberg (2011) advocate an error diagram which is effectively an ROC curve. Residual approaches were also considered, but the conventional Pearson residuals that effectively check presence/absence in pixels were rejected for having too skewed a distribution for the kinds of inference that one might wish to make. Deviance residuals, from generalized linear models, are preferred, since comparing the difference in log likelihoods is more effective than comparing the observed counts with the predicted fire counts. Also of note are the superthinned residuals (Clements et al, 2012) and the Voronoi residuals (Bray et al, 2013). In the latter case, the observed ignitions are used to establish a Voronoi tesselation in the region, and the numbers of predicted ignitions are counted in each Voronoi tile, representing the number of predicted occurrences closest to the given observed ignition.

3.4 An Ecological Perspective

Dan Thompson, a hydrologist, has been studying peatland fires in the western boreal forest. Fire behaviour in this region is poorly understood, being of a very different character from the types of fire that commonly occur elsewhere in the boreal region. Although peat fires tend to burn slowly, they burn deep and contribute massive emissions of carbon to the atmosphere; extinguishing such fires is a lengthy process. With increased human activity and as the climate changes, it is unclear what the impacts will be.

Steve Cumming's presentation highlighted the need for methods for simulating seasonal boreal forest fire regimes, comprising frequency, size, and severity, noting that there is a strong need to "backcast" characteristics of past fire regimes if there had not been any fire suppression. Even with a conceptually simple raster-based fire spread model, Cumming was able to gain insight into ecosystem effects.

Meg Krawchuk discussed issues arising in fire occurrence modelling when data come from different sources, such as fire management records, satellite imaging and field-based observations. Because of the zero-heavy nature of the counts, models such as the zero-inflated Poisson distribution find use.

Max Moritz overviewed global-scale modelling of fire occurrence, accounting for moderating factors in the environment and noting the importance and complications of feedback loops as well as limitations in the completeness of the data.

3.5 The Fire Weather Index

The Fire Weather Index (FWI) is an important summary of fire danger used by fire managers across Canada. Martell (1999) studied its behaviour as it related to the Province of Ontario, from the point of view of a

Markov chain. Alisha Albert-Green's presentation started from that premise and suggested simple ways of checking the (homogeneous) Markovian assumption in FWI series. A conventional time series analysis is difficult, because of the excessive numbers of zeros in the data. Ways of visualizing the data were presented, as well as a technique for modelling the runs of zeros and nonzeros with a locally varying beta-geometric distribution.

Neal McLoughlin's presentation highlighted the need for "hot-spot" detection methods when mapping the FWI. He outlined several possible approaches, applied to data in Alberta, noting that certain regions of the province have notoriously high FWI values while in reality not necessarily being areas of high fire danger. John Braun proposed a spatial control chart for the FWI as a way to identify times and locations of (locally) unusual fire danger.

4 Data Issues

Two presentations highlighted an important problem that is not addressed often enough by the general scientific community: data are not always what they appear to be.

Neal McLoughlin gave an engaging presentation highlighting 10 difficulties that he saw in the Alberta fire and weather data. Many of the observations that he made are generalizable to data arising in other fields and are important for the data analyst to remember, before making firm conclusions:

1. Fire management data come from diverse, inconsistent sources. In Neal's case, he has weather data from Environment Canada stations as well as from Alberta Government stations, for example. Protocols are not exactly the same.
2. When assessing fire progression, it should be noted that the published areas at the time of attack are estimates. Re-mapping, which is often done when the fire is held or under control, provides more accuracy but sometimes leads to an anomalous fire size history. The term "Under Control" is not synonymous with cessation of fire spread.
3. The ignition location of most fires is unknown and decisions must be made as to which location to designate as the fire origin. Protocols and mapping have not been consistent over time.
4. When assessing area burned, care must be taken with fires burning near management area boundaries. In most cases, the fire record will only contain the area burned with the management area.
5. Maps of fuel types are often constructed from different sources, leading to inconsistencies and errors. In some cases, error rates up to 60% have been observed.
6. Wind speed measurements are supposed to be taken at a height of 10m. Not all weather stations are set up for this. In addition, wind direction measurements can be highly granular. In some cases, only four compass directions are used, or perhaps eight.
7. The location of a weather station can lead to substantial biases. Ridge top stations can exhibit very different readings of wind speed, precipitation and temperature from what is actually happening in the surrounding area.
8. In many cases, weather data are reported without flags indicating station malfunctions or location changes.
9. Data dictionaries do not highlight inconsistencies in data collection over time.
10. Policy changes can lead to inconsistencies in fire and weather records.

A long-term historical view of fire data collection was taken in Mary Grunstra's presentation. Additional observations on data inaccuracy were made, from the perspective of Ontario's fire management records. By going back to original hardcopy fire reports, progress has been made on improving accuracy in the Ontario fire and weather record.

5 Lingering Fire Management Questions

The final roundtable session featured a wide-ranging discussion of general fire management issues and research needs. In recent years, and during the meeting itself, probabilistic models were advocated repeatedly as being more appropriate than the widely used and (in many cases) trusted deterministic models. A natural question to ask then is, “How will a fire manager deal with or react to a probabilistic answer to a fire management question?”

A decision must be made, and deterministic models (even if wrong) will provide a manager with a certain answer. Probabilistic models are “fuzzier”, providing the manager with the reality that the decision is really being made with uncertain information and that ultimately, the manager will be responsible for how the probabilistic information is used. This sounds difficult, but it is entirely appropriate. The models we produce, through mathematical, statistical and operations research methods, can be viewed as decision support tools; they aid the manager who must still exercise expert judgement.

The question then becomes one of seeking the best response to the uncertain information provided. This is not easy either. The costs and benefits of each decision must be weighed carefully; of course, in the fire management setting, the impact of a decision in one location may have consequences for other locations.

Studying the expected losses, by simulation for example, is a possibility. Studying the success rates resulting from various management decisions could be useful in assessing various decision-making strategies. Unfortunately, good decisions, under uncertainty, do not always lead to favourable outcomes, for a variety of reasons, including the transient nature of uncertain information.

Other problems with the above proposal are that it is limited to situations where good models exist and also limited to a single characteristic of a potentially much richer set of distributional information. Maximizing (or more generally, optimizing) the expected value is not the only useful goal.

6 Summary and Outcomes of the Meeting

The scientific aspects of fire management were the focus of this workshop, stemming from the general goal of improved operations management. Mathematical and statistical methodological developments discussed and proposed were in wide spectrum of areas, including game theory, zero-inflated count modelling, point process modelling, projection pursuit modelling, simulation, and control charting.

The goal of the meeting was to bring forest fire scientists and modellers together to discuss open problems and forge future collaborations. By focussing on input from the fire scientists and managers as well as modellers from Canada, the U.S., the U.K. and Australia, the statistical methodologists in the audience were provided with a large number of open problems and data analysis difficulties.

It was evident during the roundtable discussions, coffee breaks, and breakfast, lunch and evening discussions, that several collaborations were being initiated. Pockets of researchers at locations such as Laval and Simon Fraser University discovered the possibilities of interaction, not only across the country, but also, in some cases, simply across campus.

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