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FIRE BEHAVIOR MODELLING - HOW TO BLEND ART AND SCIENCE[1]

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ABSTRACT

Every aspect of the control of forest fires depends ultimately on the rate at which a fire will spread, and the question of its frontal intensity is not far behind. Fire management, increasingly more sophisticated, desires quantitative answers in place of the old relative indexes. The true scientific approach is to begin with the basic chemistry and physics of combustion, link these with fire spread in natural fuel complexes, and eventually produce practical estimates of spread rate, energy output, and growth pattern. By contrast, the "artistic" (or, rather, empirical) approach is to observe fires in the forest, record the attendant burning conditions, describe the fuel complex in some distinguishing sense, and then to derive the necessary regressions. An intriguing result is the tendency of these two approaches to converge to similar final practical states. This idea is illustrated by the past and current fire modelling work in both the United States and Canada. Some future possibilities and roadblocks are explored.

INTRODUCTION

There can be few natural physical phenomena with the scope and complexity of a forest fire. The fuel that powers it is found in a huge range of sizes, quantities, and arrangements in space. The weather affects the current condition of this fuel array in a bewildering maze of drying and wetting effects, each fuel component responding to a "different drummer." The combustion process itself, once under way, responds to a complex blend of fuel variation, moisture status, topography, wind speed, and other atmospheric factors. Its frontal intensity varies over an immense range, from tiny flickers easily stepped over, to dense sheets of flame whose fierce radiation keeps the observer at a distance.

Yet, the goal set by the forest fire research community is nothing short of the reasonably accurate explanation and prediction of fire behavior under all possible combinations of fuel, topography, and weather. It is indeed a daunting objective, and it would be easy to doubt that it will ever be accomplished to the fire community's general satisfaction. But, even while retaining a certain humility, one could say that a great deal has been accomplished in six or seven decades of North American fire research. Consider that nearly every move and decision in fire control management depends on decent estimates of ignition potential and fire behavior. It seems as though the better these estimates become, the greater is the pressure for better ones still.

KINDS OF MODELS

What kinds of models can be adapted to fire behavior science? What in fact is a model? Let us simply say that a model is a scheme of some sort that will enable you to predict the outcome of some phenomenon before it happens. If that is agreed, then one can list three basic modelling approaches to the explanation of forest fire behavior.

1) Mathematical models, based solely on the interpretation of the physics and chemistry

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of combustion propagation through mathematics.

2) Laboratory models, based on the observation of small-scale experimental fires in the laboratory, using dimensional analysis to maintain similarity of processes over a wide range in scale.
3) Empirical models, based on the observation of real outdoor fires, either experimental or accidental, analysed statistically.

The interplay of these three approaches over the years has been fascinating to watch. The problem of free spreading fire in the open has intrigued many prominent engineers and physicists. The literature on pure mathematical modelling is hard reading for amateur mathematicians, and the work has not yet led to results of direct practical use in fire control operations. So far, the true benefit of this effort, it seems to me, has been to produce certain basic principles that could be used in the design of the other two model types.

The second approach, in the laboratory, must confront two nearly intractable problems. The first is the impossibility of modelling the spreading combustion process completely with respect to dimensional similarity in all mass and energy flow processes. Examples are the proportional contributions of convection and radiation at various intensity levels, and the interaction of horizontal wind and upward convection. The other problem is simply the immense range in the intensity of the phenomenon; natural fire intensity runs up to 100 000 KW/m or more, whereas anything a few hundred KW/m is too hot to handle indoors. Partial modelling, by controlling a few crucial similarities and letting the rest go, is not so easy to extrapolate with confidence over such a range.

The third approach, the outdoor empirical study, may produce some rough answers fairly quickly, but has its own two particular difficulties. First, a balanced and unbiased sample of fire behavior over the necessary range is difficult to obtain. All outdoor fires, both experimental and accidental, are at the mercy of the weather, and much travel and patience may be needed to be in the right place at the right time. Second, the results of a series of fires in one fuel complex cannot easily be transferred to another.

It seems, as a result of the above brief analysis, that the most powerful approach is most likely a combination of all three: mathematical modelling to produce the basic universal principles, laboratory modelling to yield certain relationships under controlled conditions that cannot be quantified by pure theory, and outdoor empirical studies to confirm these principles at full scale in real-life fuel complexes.

MODEL CONVERGENCE

With such a maze of possible approaches to fire behavior prediction, it is no wonder that the subject has been tackled differently in different places, even in the United States and Canada which are right next door to each other, so to speak. The American approach has been primarily a blend of laboratory and mathematical modelling with a touch of the empirical as well. In Canada, on the other hand, the main approach has been empirical, bolstered as needed by mathematical principles and some lab work. Now that both schools have produced practical working schemes (the United States sooner and in greater quantity than Canada), an intriguing tendency can be observed, namely that both approaches tend to converge to similar practical states. So, each has classified the forest into a number of distinct fuel types or models, each type with its specific equations for rate of spread, intensity, and so on. How come this final similarity? The reasons are two, it seems to me. First, no matter how the researcher first described a fuel complex, whether in simple qualitative terms or quantitatively by load, size class, and density, real-time identification for the practitioner must be quick and simple. A picture or a verbal description must do. Second, no matter what the approach and route, the final result must be a set of equations in terms of the weather and topographic variables measured in the fire danger rating system. Once in place, empirical tuning may proceed continuously, and the practitioner may eventually be hard put to choose between the original approaches. All this seems to me a strength rather than a weakness of fire modelling in general.

FUTURE CHALLENGES

Everyone who has spent some time in fire behavior research has his own list of worthwhile unsolved challenges. Here are two particular ones of mine.

I. The "fuel-type" problem. Take, for example, a typical northern conifer stand, with a fuel complex somewhat as follows, working upward from the mineral soil

- a layer of dense, decomposing organic matter,
- a cover of live moss, herbs, and surface litter,
- shrubs and small conifers in varying density,
- flaky bark and dead tree branches,
- a tree foliage layer of varying density.

The whole would be about 20 m in depth, and weigh in all perhaps 20 kg/m². Such a fuel complex is distinguished by two things especially: 1) vertical gradients in moisture content and bulk density, and 2) spaces between some layers, mainly between crown layer and surface fuels. And, yet, the great majority of modelling efforts, both mathematical and laboratory, have concentrated solely on a single layer of uniform density and moisture content, if not piece size as well. Actually the problem of such a simple fuel is difficult enough, and there is not yet general agreement on its solution. The fire world would beat a path to the door of the modeller who could account for vertical gradients and interruptions in moisture content and fuel density as well. Crowning fire is the most obvious application for such a comprehensive model.

II. The "blow-up fire" problem. When a fire becomes very intense, there is no wonder that its principal manifestation is a huge convection column. Consider that every kilogram of fuel requires 5 m^3 of air to supply its basic oxygen need, and produces upwards of 0.5 kg of water vapor in the process. Furthermore, several times this amount of air may be entrained by the time the combustion products leave the flame zone. All this gas is then heated to flame temperature and thereby endowed with tremendous buoyancy. But is this immense superstructure to be dealt with as cause or effect? Does the main control of fire behavior still reside in the high temperature region of fuel and flame, or has some distinct discontinuity of process taken over? Can a forest fire become a true mass fire so that all air inflow is centripetal? If so, how does it spread? Does it matter whether the convection column breaks through to a towering mushroom, or blows out at a pronounced angle (except for spotting potential)? If certain features of the atmosphere-in-depth have been identified as associated with extreme fire behavior, are these features also well correlated with weather near the ground? This last question sums up the problem as it relates to everyday fire danger rating systems. Do we or do we not need an additional atmospheric variable, as well as the standard surface weather observations, to account for the extreme end of the intensity range? It seems to me that the definitive answers to all these questions are still waiting in the wings.

The great current advances in the technology of remote sensing and computing raise their own peculiar new problems. Can fuel types be identified as distinctively from satellites as by aerial photography or, in turn, as by the observer on the ground? If not, what becomes of the carefully ordered lists of fuel models and types when the computer builds its maps and grows its fires based on what the satellite can see and no more? Fire modelling of all kinds will, no doubt, be increasingly challenged by both the limitations and the new horizons of high technology.

CONCLUSION

If one could boil down the whole science of fire behavior to its practical essence, it might just be to put in the hands of the fire boss a decent estimate of how fast his newly-reported fire will advance. Fire behavior predictions may not be infinitely valuable; but as long as the forest fire people continue to want better ones, and there are researchers to work on them, it is safe to say that next year's predictions will be better than last year's. And because, in a subject as complex as fire science, pure scientific logic just doesn't seem to be enough, the researcher had better be something of an artist as well as a scientist.