Considerations on operational wildfire spread modelling

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Abstract

Various issues relating to improving operational prediction of wildfire spread are discussed.
The information content required by fire managers is limited, and can be used to optimise model design. The operational baseline distance (D) for a model implementation reflects the spatial resolution of the database driving the model. Inputs to spread models are scale-dependent - i.e. vary with D. Corrections to their values are needed to match the original design and calibration of the spread model. This may have a significant impact on model results. Passage time generally goes down as D increases. Scaling needs to be done separately for magnitude and direction components of the rate-of-spread vectors. Techniques for geographically representing vectors allow a rethink of how we can display fire spread predictions. It is appears that many fires burn within an "allowed" envelope. Many past fires may not have been extinguished by firefighters - they may have just reached the envelope. A spread model using wind-terrain interaction and the above ideas is presented. Rather than showing how the perimeter would grow over a time increment, it displays all potential spread vectors at once. This also provides new insights into fire hazard and the concept of the "fire corridor". Other fire phenomena may be explained using these ideas.

Paper

My aim with this paper is to show how easy it can be to bring together a host of issues facing wildfire spread modellers. I hope to show that the solutions that need to be sought are not necessarily those that have seemed obvious in the past. I am currently focussing on a short presentation, and aim to write up the details as a paper for the International Journal.
Key issues currently facing us include: (1) the need to tie in atmospheric models; (2) the need to explain step-like acceleration of fires; and (3) the need to explain certain geometric features of fire behaviour that are not evident from current models.
Wildfires are scale-dependent. This was discussed by Simard (1991), in a paper where he defined eight scale-classes for space, time and process. Some of his conclusions were:

- Space, time and process scales are inextricably linked
- Models or systems that have inconsistent scales are likely to be either inefficient or inaccurate.
- One scale class seems to be an acceptable range for fire models and systems. (In this point, Simard was saying that in a continuum of eight categories spanning over 15 orders of magnitude, it was possible to place all wildfire processes in one category.)

Within that framework it is still possible to further subdivide scale into operational classes. From the perspective of the fire manager, it is an inevitable mental tool to think of scales of fire, ranging from the very small to the extremely large. To avoid confusion, I will refer to fire scales in the sense of the operational classes, rather than the elements of Simard's grander scheme.
The basis for what I will now talk about is that **wildfire models are scale-dependent -** that is to say their properties change as their scale changes.
I must start by stating the claim that the **information content of fire models should be loosely constrained**. It is self-evident that too little information is a bad thing - the model output is too broad to be of any use. It is also self-evident, to me, that too much information is also to be avoided - the user of the model should not be distracted by unnecessary detail. Operational decision makers do not want to waste time filtering-out the clutter. As well, processing time and data acquisition and management costs increase with information content.

I will show later that there are critical corollaries to this claim.

In order to describe the effects of information content on fire models, I will use a variable called **D, the operational baseline distance** (in metres). It is analogous to the length of the "measuring stick" used to measure the properties of the real world. It is easiest to describe it as equivalent to the side of a grid-cell in a grid-cell database, but it also has meaning in polygon databases.

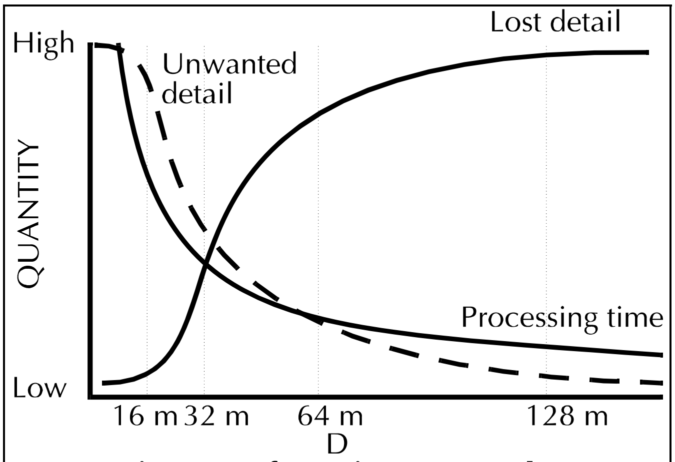

Figure 1. Information versus scale.

It can be claimed that the **resolution** of the database is D, and the area covered by the database should, based on experience, be in the order of 20 to 40 times D in both directions to achieve constrained information content. Put the other way, the **geographic area covered by the fire model constrains D**.

A vital realisation is that the values of standard inputs to fire models vary with D. I will concentrate on slope (in degrees) but the principles apply to other terrain attributes, weather attributes and fuel parameters.

Figure 2 shows three values for slope distribution across a study area: (1) an *a priori* expectation based on field experience (and thus an implicit D); (2) output from a tuned digital terrain model (DTM) with an appropriate D; and (3) output from a mistuned DTM, with too large an implicit D.

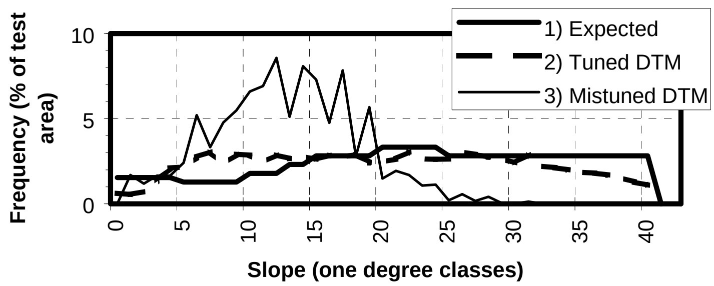

Figure 2. Comparison of slope distributions.

The allowable range of values for slope decreases as D increases. A possible form of the equation is…

$$MV_D = MPV * \left(1 - e^{\left(\frac{-2700*A}{W*MPV*\sqrt{D}}\right)}\right)$$

where

MV_D = maximum allowable value at D

MPV = maximum possible value (e.g. 90^o for slope)

A = amplitude - typical range of local values

W = wavelength - typical distance between repeating cycles

For example, some possible values for slope (^{o}) are given in the table below…

Land unit	A (m)	W (m)	MV_{50}	MV_{200}
Montane	1000	6000	46	27
Plateau	300	3000	31	17
Dunefield	50	5000	4	2
Plain	10	10000	0	0

When a wildfire spread model is developed and calibrated, there is a value of D used, which I will call the native D (or D_N). This has rarely been addressed. It is not necessarily the same for all attributes used in the model. So for a given D, we can correct for not being at D_N by scaling according to the ranges of allowed values, thus…

$$V_{D_N} = V_D * \frac{MV_{D_N}}{MV_D}$$

where V_D is the value of the attribute at scale D. For example, consider a fire model working in montane terrain which uses slope and a D_N of 50 metres. A spread model uses a database of 200m resolution, which includes the output of a DTM. If local slopes in the database are around 20 degrees, then:

A = 1000 m

W = 6000 m

Maximum local slopes at 50m are 46°
Maximum local slopes at 200m are 27°
The 20° slope can be adjusted to a 34° one.

If rate-of-spread is an exponential function of slope, then this would increase predicted ROS by 225%.

The effect of the adjustment is best represented by examining the time taken for the fire to pass between 2 points. A calculated ROS at any point on level ground (ROS_0) can be adjusted to an ROS for slope S (ROS_S):

$$ROS_S = ROS_0 * 2^{(S/10)}$$

And the time taken to travel from A to B is:

$$(D / ROS_S)$$

Assuming an artifically simple undulating terrain of an uphill run and a downhill run, each 200 m long, and ROS_0=1m/min, we get:

	50m resolution	200m resolution
upslope (°)	34	20
downslope (°)	-34	-20
ROS upslope	10.5	4
ROS downslope	0.095	0.25
passage time each upslope run	0.095*50*4= 19 min	0.25*200= 50 min
passage time each downslope run	10.5*50*4= 2112min	4*200= 800 min
total passage time (TPT) for 400 m	2131 min	850 min

There is a clear reduction in TPT as D increases. The inverse of TPT gives a measure of the average ROS, which thus increases as D increases. The degree of this depends on the local range of slope - on a plain the effect would disappear.

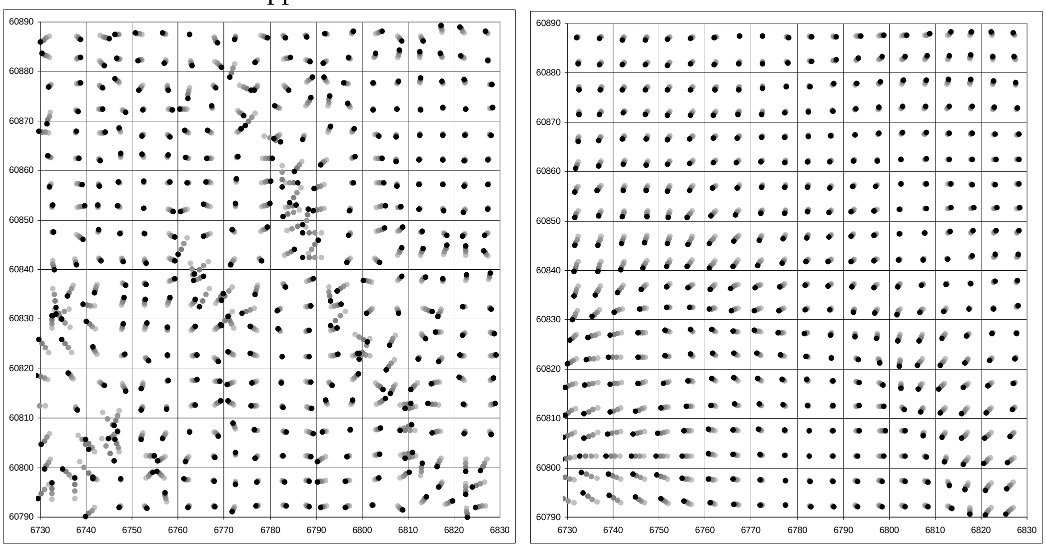

Figure 3. Effects of changing D on slope field over a fixed area.

It is important now to remember that fire spread is a vector, and as such has both magnitude and direction components. We have seen how the former varies with D. Does the latter as well?

To an observer on the ground using a fixed personal D, the fire model would seem to be using ever smoother representations of the terrain as D increases (see Figure 3). However to the fire the change is nowhere near as great. As D increases, the effect is equivalent to spatially filtering the terrain, and the result is scale-independence (self-similarity). However because the Z range is limited and the X and Y range is not, there is an asymptotic limit beyond which the filtered terrain becomes bland, and thus can have little impact on steering the fire. Most fires, however, do not approach this limit.

We have now reached a situation that ties into the work on meso-scale atmospheric models for wildfire spread. It is imperative that we now include wind-terrain interaction into wildfire spread models. *In lieu* of the ultimate model, I am using a simple model that does the job well enough (see Figure 4). It uses look-up tables for corrections to wind speed and direction based on the difference between aspect and wind direction, and the meso-scale elevation residual (McRae, 1992). The wind vectors are calculated and can be plotted in Excel. I feel that the use of vector plots, which are so familiar to meteorologists, should be used more by fire modellers.

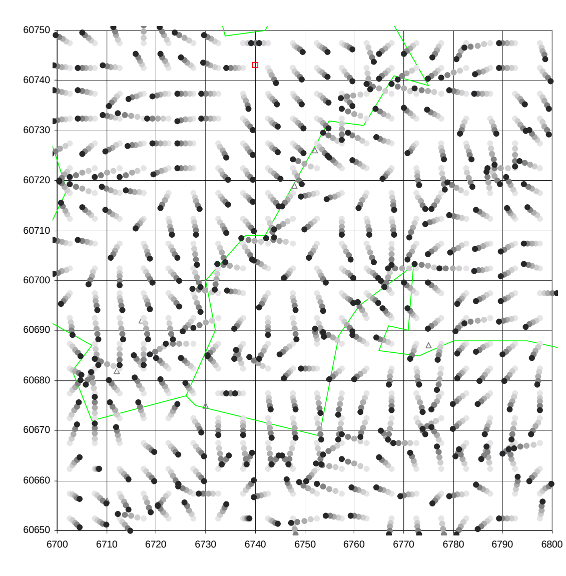

Figure 4. Wind-terrain interaction model output showing wind vectors.

Using vector outputs to show wildfire spread (see Figure 5) can give key insights that are not available from perimeter-versus-time plots: (1) rapid identification of property at risk; (2) estimation of zone at risk from spot fires; and (3) prioritising resource deployment. It also allows a neat way to side-step the contentious geometric issues that have bedevilled traditional output products.

The surprising thing about vector outputs is that they make clear that fires driven by radiation or convection want to burn within an envelope. For wind driven fires, convection dominates, and the fire spreads along the wind vectors. **It may be that, for clearly wind-driven fires, slope corrections should not be made as the terrain has already been considered in deriving the wind vectors**.

For no-wind fires in steep terrain, radiative heat transfer dominates, and drives the fires upslope. It is only slow backing fires that want to escape the envelope. The role of fire suppression then becomes one of enforcing the envelope, protection of property within the envelope and anticipating events that alter the envelope (e.g. wind changes). This claim that large fires burn where they want to awaits widespread use of wind-terrain models for verification.

We are also allowed new insights into wildfire hazard analysis. The fire problem is that fires start, spread and, upon reaching property, cause damage. Traditional measures of fire spread for hazard assessment have simply measured proximity to life and property using Cartesian distance. It is claimed that distances should be measured along the vectored paths described above.

To illustrate, take a point along an urban interface. Sort 10-degree increment wind direction classes in descending order of importance for wildfires. Include in this list a “calm” option. Work through the top 3 or 4, doing spread prediction with wind-terrain interactions. If the vectors would indicate that fire would be driven towards the interface, then there is clearly a threat. However, it may be found that all vectors point away from the interface, in which case the threat is low. It must be remembered that the further out from the interface the fire starts, the “smoother” its path to reach the interface would be. (Algorithmically, working in reverse, away from the interface, would be easier.) It is critically important to understand the effects of distance from the interface on ignition frequencies.

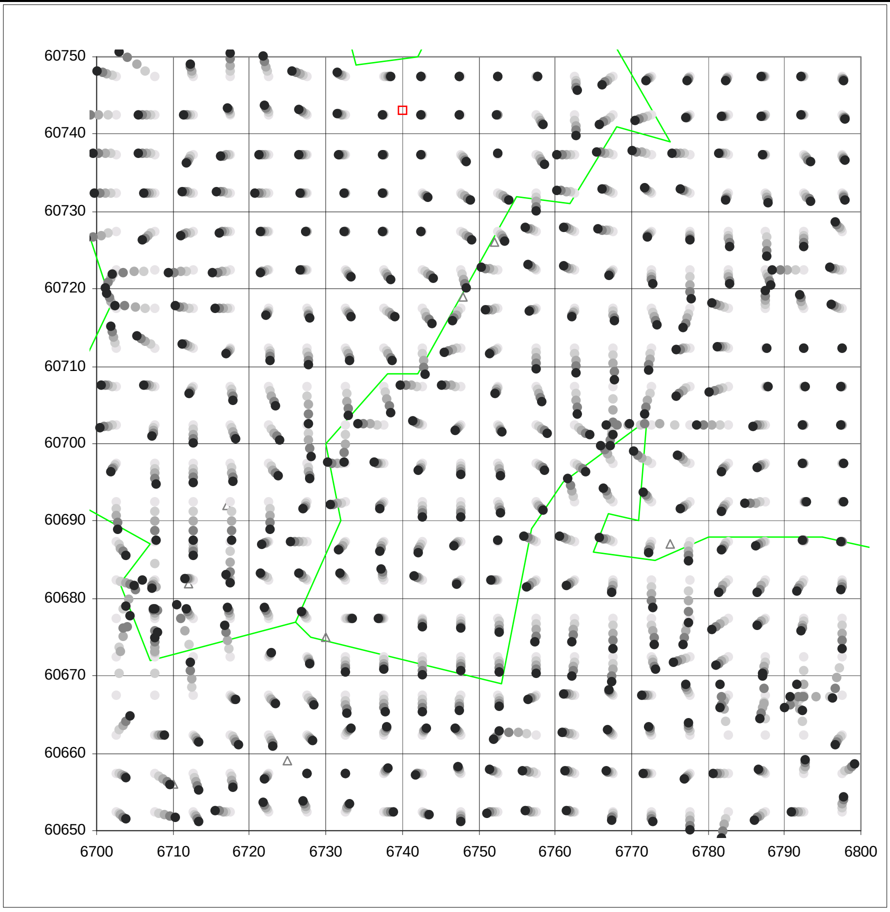

Figure 5. Wildfire spread model output showing ROS vectors.

Following the same lines of argument, we can gain insights into the concepts of fire corridors. In rugged terrain, prominent landform features may well deflect the majority of significant wind directions in similar ways. If this happens, the implication is that wind driven fires would also be steered in the same way. Practical experience in such areas would have labelled them as "fire corridors". In these areas a wide range of ignition locations and a range of wind directions would, given continuing opportunity to spread, shepherd the fire through the corridor. Any areas that were identified as potential corridors would require careful analysis before being opened for any visitor use or development.

It is possible to use the notion of constrained information content to develop measures for validating the success of wildfire spread predictions. This is an area that has suffered from a lack of formal criteria for deciding whether or not a prediction was successful, and as a result has led to public claims of success based on subjective techniques that have been difficult to assess.

For any given fire we could measure the prediction efficiency (PE) afterwards by the ratio of "area burnt ***and*** predicted to be burnt" and "area either burnt ***or*** predicted to be burnt". This has the feature of being symmetric for under- and over-prediction.

This can be quantified by allocating areas to one of the cells in the following matrix…

	Predicted to burn	Not predicted to burn
Burnt	**i**	**ii**
Not burnt	**iii**	**iv**

PE can thus be calculated as:

$$\boxed{PE = \frac{i}{(i + ii + iii)}}$$

It is suggested that a successful prediction could be defined by PE > 0.9 (i.e. a 10% error)

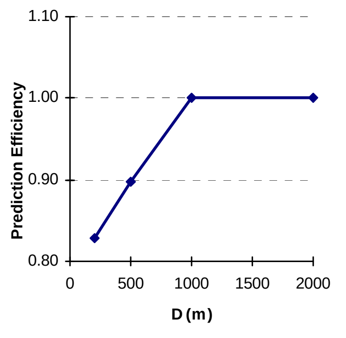

Figure 7. PE versus D.

Figure 6. Fire resolved at D = 1000m, 500m & 250m; black = i, dk grey = ii; lt grey = iii

This can be illustrated by examining the fire shown in Figure 6, which shows a possible prediction for this fire which has been resampled at three different values for D (for the purposes of illustration). The results are shown in Figure 7.

It can be seen that the prediction would have failed at D < 200 m. As the fire scale was c.3 km we would have operationally set 150 m < D < 300 m to optimise information content, and thus a prediction such as this may well have been called successful.

Another interesting insight concerns step-wise fire acceleration. The notion of scale-dependence accounts for findings of rapid, pulsed acceleration after 2 fires merge to form a larger fire: (1) fire size and constrained information content act to set a value for D for each of the initial fires; (2) D determines the results of calculating their behaviour; (3) as D goes up with fire growth, then TPT goes down, and the fires' mean ROS goes up; (4) when the 2 fires merge, D jumps to higher value; and (5) when this happens, TPT goes down sharply, and the mean ROS of the combined fire goes up.

Thus a larger fire can be said to "see" the physical factors that drive it with lower resolution. We must account for this lower resolution before running fire spread models.

We can also ask "what is the size of a fire lit from a line?" Here we lack the clarity that arises from a continuous fire perimeter. If we include actively smouldering areas as part of the fire, and those that have cooled off as not part of the fire then we can distinguish between: (1) line ignitions that curve as they spread due to a large width and depth, that increase D and thus smooth out the way the fire "sees" the world, and (2) linear sedge fires that have a negligible smouldering zone and thus never increase their active size, and therefore see the world at a constant resolution.

Hopefully I have given a convincing argument for scale-dependence in fire models. The magnitude of its effects on rate-of-spread and the range of observed phenomena that it can explain mean that, at the least, it must be considered carefully, and at best that it is a clear endorsement of the need for the next generation of fire models that view fuels, terrain and weather as complex components of complex systems.

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Simard, A.J. (1991). Fire severity, changing scales, and how things hang together. *Int. J. Wildland Fire* **1(1)**:23-24.