Bottlenecks, feedbacks and thresholds in wildfire suppression

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Abstract: Modelling wildfire suppression can help improve the effectiveness, safety, and efficiency of wildfire management, all of which are important for protecting lives, property, and the environment. Suppression models are also important sub-models for strategic risk modelling of wildfires, whereby impact and loss is fundamentally linked with suppression. Weight of attack describes the intensity and magnitude of suppression resources and strategies applied in firefighting. Initial attack is made up of resources from within a response area dispatched with a default with a default weight of attack to. meet the typical landscape risk profile in that area. This response can be supplemented by surge resources which include resources requested from other response areas, along with specialist resources such as aviation. Recent work has focused on the possibilities associated with models that predict the probability of initial attack (IA) success. Other work has sought to model suppression as it occurs through extended attack (EA) explicitly via understanding resource production rates. A conceptual model is under development which considers different categories of fire, and how the weight of attack and type of suppression activities may accelerate or prevent fire progression and impacts. There are limited examples of such conceptual models in the literature, and the model is required to clearly articulate the operations research and modelling challenges most relevant to fire. We propose four categories of fire events, adapted from Keating et al. (2012):

- Sustained ignition self-contained by weather or fuels regardless of local firefighting resources
- IA successful with default resources, without surge resources where access is suitable.
- IA will likely be unsuccessful if only baseline local fire-line production resources are used, but surge ground or aerial resources can augment those resources to achieve successful IA.
- IA will likely be unsuccessful irrespective of surging resources.

While the highest model accuracy can be achieved by examining all four categories, the most useful models should be able to distinguish between the thresholds each. Linked to this are feedback mechanisms that acknowledge the tradeoff between weight of area containment attack (WACA) and weight of asset protection attack (WAPA). These feedbacks include:

- When WAPA is prioritised early, more assets can become exposed as the fire area grows unmoderated, demanding higher WAPA.
- An offensive attack that moderates the growth of the fire area can allow more time for further surge resources to arrive, even if not completely effective.
- The longer fire is able to spread in an area unmoderated, the greater the chance it can encounter fuel, weather or topography that accelerates the spread or increases intensity approaching or exceeding the limits of suppression.

Bottlenecks in the model include response time of resources to arrive, response time, capability and capacity of leaders resource-level production rate limits, and holding rates of containment, both in direct and indirect firefighting. As with the feedback to allow more time for further resources, the ability to “buy time” with suppression can also constitute a bottleneck.These feedbacks and bottlenecks can underpin a conceptual model which more realistically maps the interaction of fire progression and suppression, to guide modelling and operations research into suppression effectiveness.

Keywords: *Wildfire impacts, wildfire suppression, wildfire risk modellings*

1. INTRODUCTION

Wildfires with catastrophic impacts on life and property represent a very small proportion of all fires and by definition are associated with unsuccessful initial attack. However, this unsuccessful initial attack may partially reflect the immediate priorities of suppression where fires where impacts, rates of spread and intensities dictate immediate asset protection. This can come at the cost of fire area containment, as priority is given to immediate life safety of the public and responders. Predicting the risk of these fires is typically done with fire danger or behaviour indices which can distinguish between days of high potential. Recent work has focused on modelling the probability of initial attack (IA) success (Plucinski 2012; Collins et al. 2018; Marshall et al. 2022) by different definitions.

One of the main challenges with these models is that their supporting data can be severely zero-inflated as most IA is successful. Some research has found that response data, such as the number of firefighting resources deployed, is a key predictor of initial attack being unsuccessful (Collins et al. 2018; Marshall et al. 2022). This highlights the importance of resource allocation and effective management in responding to wildfires. Models that leverage information on the weight of attack, however, can only be used descriptively as the weight of attack cannot be known a priori and occurs in response. In this way, any model where firefighting response information is included in training datasets invalidates estimates of performance for any predictive applications. Other work examines suppression as it occurs through extended attack (EA) explicitly by quantifying resource production rates (Plucinski 2019) for containment once IA is unsuccessful. Operationally, these production rate models are leveraged for options analyses manually, but are challenging to implement within simulators due to the data requirements and variety of time and space constraints on the tactics that are ultimately implemented on the fireground.

Beyond response modelling, strategic risk modeling for wildfires often focuses on predicting the probability of house loss. However, existing ‘landscape level’ house loss models may not account for asset protection firefighting strategies (Duff and Penman 2021). Such asset protection can occur on small (isolated point protection) or large (wildland urban interface) scales. This underscores the need for more comprehensive and accurate impact models that incorporate suppression, as well as suppression models that account for the demands of asset protection. Such models ideally would be coupled but with insufficient data to model either, a conceptual model is a logical starting point.

Part of addressing the inherent links of asset protection and suppression effectiveness is to consider the supply and demand constraints on each of them. Because resources are finite, identification of where, when and why demand exceeds supply for resources (i.e. bottlenecks) is critically important for improving operations. Identifying that these bottlenecks exist and replicating them in models, however, has not been done previously. It is worth considering any feedback that occurs may positively or negatively loop into the supply or demand challenges of wildfire resourcing. Here we conceptually identify these bottlenecks and feedbacks with the intent to outline them as linked with conceptual framework for initial attack in wildfires. In the process, we explain the fundamentals of direct and indirect attack, as well as offensive and defensive strategies with the intent to advocate for further operations research into these topics.

2. BACKGROUND

Firefighting in wildfire can broadly be described as direct or indirect (Plucinski 2019). Direct attack is a method of suppression in which firefighters attack the fire by applying treatments directly to burning fuels. The objective of direct attack is to control the fire's active edge by extinguishing the fire as quickly as possible. Treatments may include wetting the fuels with water or fire retarding chemicals, smothering the fire, or physically separating the burning fuels from unburned fuels using hand tools or heavy plant.

Indirect attack, on the other hand, is a method of suppression in which the control line is located some considerable distance away from the fire's active edge. This method is generally used in the case of a fast-spreading or high-intensity fire. It utilises natural or constructed firebreaks, fuel breaks or favorable breaks in the topography. The intervening fuel between the control line and the fire is usually burned in a controlled manner to remove the fuel and create a barrier. The objective of indirect attack is to create a buffer zone between the fire and unburned fuels, so that the fire can be safely controlled without directly attacking the fire.

These attack operations are executed as tactics, and together make up a strategy. A strategy can be more simply described as offensive or defensive (Australasian Fire and Emergency Services Authorities Council 2016). If the fire can be actively engaged (which may still be indirectly), it can be described as offensive. A defensive strategy prioritizes immediate protection of life and property, including the safety of those responding. As a result, a defensive strategy will rarely incorporate major direct attack tactics with the objective of area containment, and instead focus on the preparation and protection of assets in the path of the fire. The choice of offensive or defensive strategy depends on a variety of factors such as fire behavior, available resources, and the values at risk. Sometimes a combination of both strategies is used to achieve the best possible outcome.

Resource typology (principally firetrucks, heavy plant and aircraft) are oriented around ability to undertake area containment operations, asset protection operations or some blend of the two. An example of these would be a grader (Fig. 1A) resourced to construct mineral earth control lines. Such a resource has high efficacy and reliability in control line construction in grassland, but would be of no direct use in protecting a house from a fire once the fire has arrived at the house. By comparison, pumper appliances (firetrucks with high capacity pumps, structural firefighting tools and equipment but low capacity water tank, Fig. 1B) are highly effective in protecting of a house where a reticulated water supply is available. Cross functional examples include tanker appliances (firetrucks that carry enough water for effective edge containment and asset protection, but typically not as effective as a grader or pumper in each scenario respectively, Fig. 1C). Figure 1 provides examples of each of these resources.

Figure 1. Example of three types of firefighting resources, including heavy plant in the form of a grader (pictured widening mineral earth control lines); a pumper appliance (deployed in the manner it typically would be for non-mobile asset protection); and a tanker appliance with a high capacity water tank being used for mobile 'pump and roll' edge attack

Attack operations can also be described in terms of their weight. Weight of attack in this context simply refers to the number of resources ordered to attend a particular incident, and can be specified further as the Weight of Area Containment Attack (WACA) and Weight of Asset Protection Attack (WAPA). A simplified example of a heavy WACA would be tasking available tankers being used for edge attack, requesting heavy machinery to construct mineral earth control lines, and pumpers being used to increase efficiency of tankers via shortening refill times. By comparison, a heavy WAPA would be tankers being used to protecting houses, and ordering surge resources in the form of pumpers for this purpose.

3. CONCEPTUAL FRAMEWORK IN INITIAL ATTACK

A study conducted by the RAND corporation with the U.S. Forest Service identified three categories of wildfire relevant to the effectiveness of large aircraft in IA firefighting (Keating et al. 2012). It was commissioned to understand the optimal mix of aircraft, but can be adapted for a broader IA application. The three categories they proposed consisted of:

- A "Category A" fire is one that will be contained by local resources, even without aviation support.
- A "Category B" fire will become large if only baseline local fire-line production resources are used, but large aircraft can augment those resources to achieve containment.
- A "Category C" fire will become large irrespective of large aircraft usage

In examination of large numbers of fire records for the purpose of creating improved IA models, analysis in the Victorian fire agencies found that many fires are effectively self-containing considering weather conditions. These include fires such as unattended campfires, haystack fires and other open air 'non-structure' fires that require fire service attendance, but under the majority of conditions are very unlikely to lead to spreading wildfires. Estimates including all non-structure fires equate to up to 85% of records being in this class. Such fires constitute sources of ignition (unlike false alarms), but their self-containing nature is important for the consideration of modelling IA. Many of the decision in fire response relate to allocation of resources, wherein the default resources of one response district make up the surge for another. Considering this potential additional category and for the purposes of this study, we propose four categories of fires:

- "Category Zero" fires – sustained ignition self-contained by weather or continuity of fuels regardless of local firefighting resource attendance.

- "Category One" fires – IA successful with default resources, without surge ground or aerial resources where access is suitable for the resource type.
- "Category Two" fires – IA will be unsuccessful if only baseline local fire-line production resources are used, but surge ground or aerial resources can augment those resources to achieve successful IA.
- "Category Three" fires – IA will be unsuccessful irrespective of surging resources.

An important distinction between Category One and Category Two fires is that IA may still be unsuccessful where accessibility conditions do not permit a given resource to effectively suppress the fire. These four categories and the related threshold effects between them are represented by Figure 2.

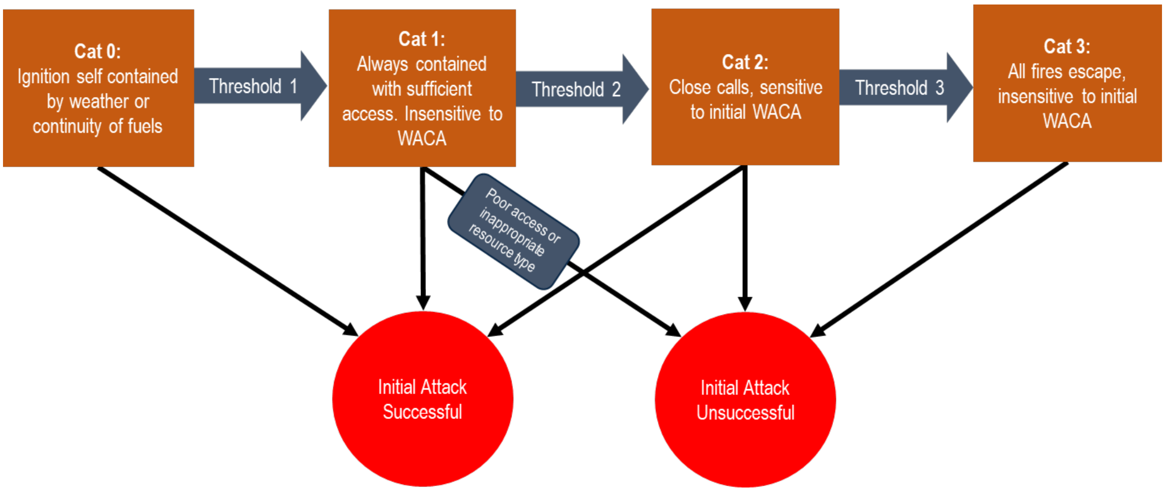

Figure 2. Four proposed categories of IA wildfires, adapted from Keating et al. (2012)

Reflecting on existing descriptive and predictive models for IA, the separation of Category Zero fires greatly assists with the zero-inflated nature of unsuccessful IA data. In other words, IA models that include Category Zero fires may have high skill by most metrics, but have limited usefulness as most fires are contained 'by default'. Additionally, an IA model that focusses on skill between Category Two and Category Three fires may represent a much smaller sample of fires, but should be far more useful for identifying when and where outcomes can be changed and informing triage. An assumption about Threshold Two (which constitutes worsening conditions between Category One and Category Two) should help with the design of training datasets for multiclass classification models such as with a naïve bayes or multinomial logistic regression approach. In general, studying the tails of the distribution of Category Two fires (effectively Thresholds Two and Three) through statistical and case study approaches will be critical to understanding the margins of effectiveness of suppression.

4. BOTTLENECKS IN SUPPRESSION

The spatial and temporal dimensions of where resources can successfully intervene but demand is not met will always be a priority for fire agencies. The below five bottlenecks are likely universal in terms of firefighter operations in a wildfire context, across both initial and extended attack scenarios.

- **Response time of resources to arrive.** Response time is well profiled for various resources types around the world, as is the underpinning principle behind emergency response driving and the prearranged default weight of attack, typically tuned to daily or hourly risk levels. The bottleneck applies to both the default responding resources for an incident (usually local) and surge resources ordered from further away as demand grows in both WACA and WAPA.
- **Mobility on the fireground.** Once on the fireground (the area where the firefighting operations are broadly undertaken), there is still the requirement to move where a particular operation can be undertaken. This can be studied through travel cost models, and is one of the principal advantages of firefighting aviation in addition to intelligence. It includes, however, basic factors such the ease of transport of heavy machinery around the fireground and safe passage through areas with trees structurally compromised by fire.

- **Resource-level production rates**. Second to response time modelling, production rates are likely the best studied and modelled of these bottlenecks to date (Plucinski 2019). In Victoria, production rates are subject to the previously studied constraints of fuel load, slope, aspect, intensity, road proximity and flame height. Vehicles (including firefighting aviation) that require water or chemical suppressant/retardant reloading are subject to turnaround times.
- **Response time, capability and capacity of leaders with enabling communication technology.** Span of control requires that one leader function should not have more than five reports. For example, a crew leader on a truck should not have more than five firefighters reporting to them, and a strike or task force leader should not have more than five trucks in their reporting line. From a workforce perspective, these field command positions can be hard to fill with experienced leaders. Additionally, due to the low probability nature of high consequence events, it is unlikely that the field leader has previously experienced one of these events in their early stages. This challenge is assisted by the scaling of theatre command with various levels of pre-established command and control centers, but this is not without information bottlenecks or transition of control challenges (Andrew 2011).
- **Holding rates are limited by rates of patrolling reinforcing established lines.** While there can be reasons to suppress fire faster than it can be held (e.g. a balance between WACA and WAPA), ultimately the holding rate is more important than the construction rate of any resources individually or combined. The demand cost for resources of a breakout minutes, hours, days or even weeks after a control line or feature can be very high. Holding rates are highly weather dependent, and can undermine even the most productive containment of a fire.

The nature of emergency response can introduce many other bottlenecks, and incident management functions and leaders exist primarily in a problem-solving capacity to enable resources to complete their taskings efficiently and safely. It is not expected that these five bottlenecks exhaustively describe the supply and demand space for resources during the response phase of wildfires. However, they are consistently identified within fire agencies as common issues, and worthwhile of further study and potential optimisation.

5. FEEDBACKS IN SUPPRESSION

Beyond the basic supply and demand bottlenecks that apply to wildfire response, it is worth considering basic scenarios wherein unmet resource demand can theoretically beget more demand (positive feedbacks), as well as where tradeoffs in WACA and WAPA can result in easing demand. The feedbacks identified are:

- The surge demand of resources for an incident can deplete the default local supply of resources in other areas, affecting the weight of attack for new incidents that may start. This feedback is subject to a threshold distance wherein resources already active within some radius of a fire can quickly response to new fires nearby. However, fires that start outside this radius from the first incident are subject to reduced turn out times. It most apparent at a national scale, with the most in demand resources having longer travel times. A common use case for IA models is to assist with triage related to this, and this triage is commonly required for aerial firefighting resources as per Keating et al. (2012).
- When WAPA is prioritized early, more assets can become exposed as the fire area grows unmoderated, demanding higher WAPA. At a critical rate of spread (as in Category Three fires), this feedback may be irrelevant as fires are beyond the range of any practical WACA regardless. This may be combined with the safety implications of firefighting in such conditions, which essentially dictate a defensive strategy.
- The longer fire is able to spread in area unmoderated, the greater the chance it can encounter fuel, weather or topography to accelerate spread or intensity that approaches or exceeds the limits of suppression. This is environmentally conditional, as these factors could also ameliorate. For example, a fireground receives rainfall, reducing its intensity.
- An offensive attack that moderates the growth of the fire area can allow more time for further surge resources to arrive, even if not completely effective. This constitutes the principal negative feedback identified, and is potentially the most challenging to study. Modelling the effect of “buying time” requires specific knowledge of the efficacy and reliability of the operations which can be highly sensitive to fire behaviour or accessibility conditions.

6. DISCUSSION AND CONCLUSIONS

The initial attack fire categories, bottlenecks and feedbacks presented here illustrate an alternative approach to modelling the effectiveness of suppression. There has been insufficient work studying suppression at a case study level in modelling or post event analysis to show if all of these occur. Further work is also required to understand the frequency and extent to which these mechanisms occur within and between events. Understanding these mechanisms is likely to have significant implications for the way risk is modelled for bushfire, and how operational models explain and predict likelihood of initial attack outcome.

Work is currently underway with the Country Fire Authority and Forest Fire Management Victoria to evaluate the suitability of the four categories of fires for modelling application. Additionally, case studies and modelling experiments are underway to examine sensitivity in existing risk models to understand the likelihood and prevalence of the feedback and bottlenecks. Focus is being put on studying Category Two fires in detailed reconstructions, where marginal resourcing makes a difference. Understanding each threshold in the four categories IA framework is relevant to preparedness and response decision making within fire agencies.

Examining wildfire suppression in terms of supply and demand is not in itself novel. However, framing the problem in terms of what can and cannot be changed in terms of suppression outcomes can assist the focus and prioritisation of suppression modelling problems. By understanding where efficacy and reliability matters most and least, an operations research agenda for suppression modelling in wildfires can be set to assist fire agencies in investment, readiness and response decision making.

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