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Expanding the horizons of wildfire risk management

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Abstract
Owing to increased computational capacity and other factors, wildfire simulation methodologies are becoming increasingly sophisticated, and are subsequently seeing increasing use for federal fire management within the United States. State-of-the-art simulation systems account for the occurrence, topological spread, and behaviour of wildfire, all within a spatially-explicit, stochastic framework. Leveraging these advancements in burn probability modelling, researchers and managers alike are better able to assess the hazards and risks associated with wildfires and to identify effective and efficient risk mitigation opportunities. In this paper, we review the role of stochastic simulation modelling in wildfire risk assessment, focusing on how simulation results can be used to support risk-informed decision making across planning contexts. Our principal focus will be describing how novel assessment tools can be brought to bear to analyse risks to the wildland urban interface and to municipal water supplies. We will review how assessment results can inform high-level prioritization and allocation decisions, as well as more in-depth, spatial suppression response and fuel treatment planning.

Keywords*: wildfire management, spatial analysis, simulation analysis, econometric analysis*

The views expressed here are the authors', and do not necessarily represent the views of the USDA

1. Introduction

Wildfire is a global phenomenon with potentially devastating consequences to human life, air quality, water quality, homes, infrastructure, and natural and cultural resources. At the same time, wildfire is an important component of many ecosystems, potentially resulting in substantial ecological benefits. There is a critical need, therefore, to understand where and under what conditions alternative fire management strategies should be employed to balance costs and the impacts of fire, both positive and negative.

Recognizing the inherent uncertainty associated with wildfire processes, federal wildfire management in the United States, the primary focus of this paper, is increasingly adopting risk analysis principles. Principally this entails implementation of a quantitative, integrated wildfire risk assessment framework – the primary components of which are depicted in Figure 1. The likelihood and intensity of wildfire, along with the susceptibility of resources/assets to wildfire, collectively define the three legs of the "wildfire risk triangle." Stochastic wildfire simulation is therefore a foundational component of wildfire risk assessment.

A key aim of this paper is to demonstrate the value of stochastic wildfire simulation to support risk-informed land and fire management decisions. Recent advances in burn probability modelling have enabled the estimation of spatially-resolved fire likelihood and intensity metrics across landscapes, with a growing array of applications. Prominent uncertainties and informational needs vary across planning context, and resultantly a variety of simulation approaches exist, which will be compared and contrasted. In addition to highlighting several real-world planning examples focusing on risks to human life and health, this paper will identify emerging and future applications of stochastic wildfire simulation.

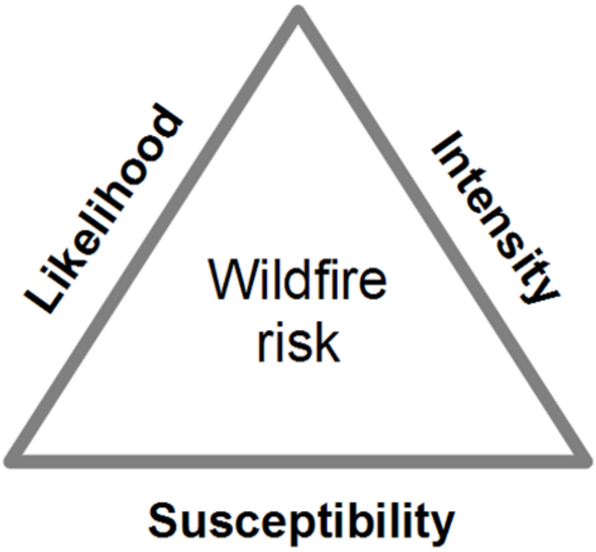

Figure 1. Wildfire likelihood and intensity, along with resource/asset susceptibility comprise the three legs of the "wildfire risk triangle." (Scott et al. 2013)

2. The Role of Simulation and Risk Analysis to Support Planning

Figure 2 identifies the primary sources of variability and their relation to wildfire risk mitigation and planning contexts. In pre-fire environments, the ignition date and location, as well as fire weather conditions influencing fire behaviour are uncertain. The date of the ignition is important because fires earlier in the season may have a longer temporal horizon over which to grow given the right weather conditions, whereas ignitions late in the fire season may be less of a concern as temperatures and dryness levels decrease. The location of an ignition is important relative to fuels and topographic conditions capable of supporting large fire spread, as well as proximity to fire-susceptible resources and assets. By contrast, after a wildfire incident has been detected, the primary source of uncertainty is fire weather, which is generally less uncertain relative to pre-fire contexts due to availability of short-term weather forecasts..

Figure 2 also identifies three primary types of wildfire management decisions: pre-fire fuel treatment planning, which entails manipulation of vegetation and fuel conditions to modify fire behaviour; pre-fire response planning, which entails the stratification of objectives and strategies according to possible wildfire scenarios as well as the location of firefighting resources (e.g., crews, dozers, helicopters); and wildfire incident response, which entails the implementation of strategies and tactics to achieve objectives, and the ordering and deployment of firefighting resources. Ideally these three planning processes are linked, so that for instance fuel treatments are designed to enable safe and effective firefighting response. Not included in this figure, although potentially important depending upon context, are efforts aimed at preventing human-caused ignitions.

Expanding upon the sources of variability depicted in Figure 2, Figure 3 displays the primary inputs and outputs feeding stochastic wildfire simulation models. As described above, ignition patterns, fire weather patterns, and the conditions of fuels and vegetation all influence the likelihood and intensity of wildfire across the landscape. The fundamental unit of simulation is a wildfire event and/or a wildfire season, the latter of which may entail multiple wildfire events in a given season. Fire spread modelling is built upon pixel-based, or rasterized, geospatial data, where each pixel represents a composite of topographic and vegetation-related variables, and the continuity of fuels across pixels along with weather patterns drives simulated fire spread. There are two primary sources of outputs: pixel-based outputs that aggregate results across simulated fire events to characterize localized burn probabilities and fire intensity distributions; and event-level or polygon-based outputs that summarize simulation results for individual fires or individual fire seasons.

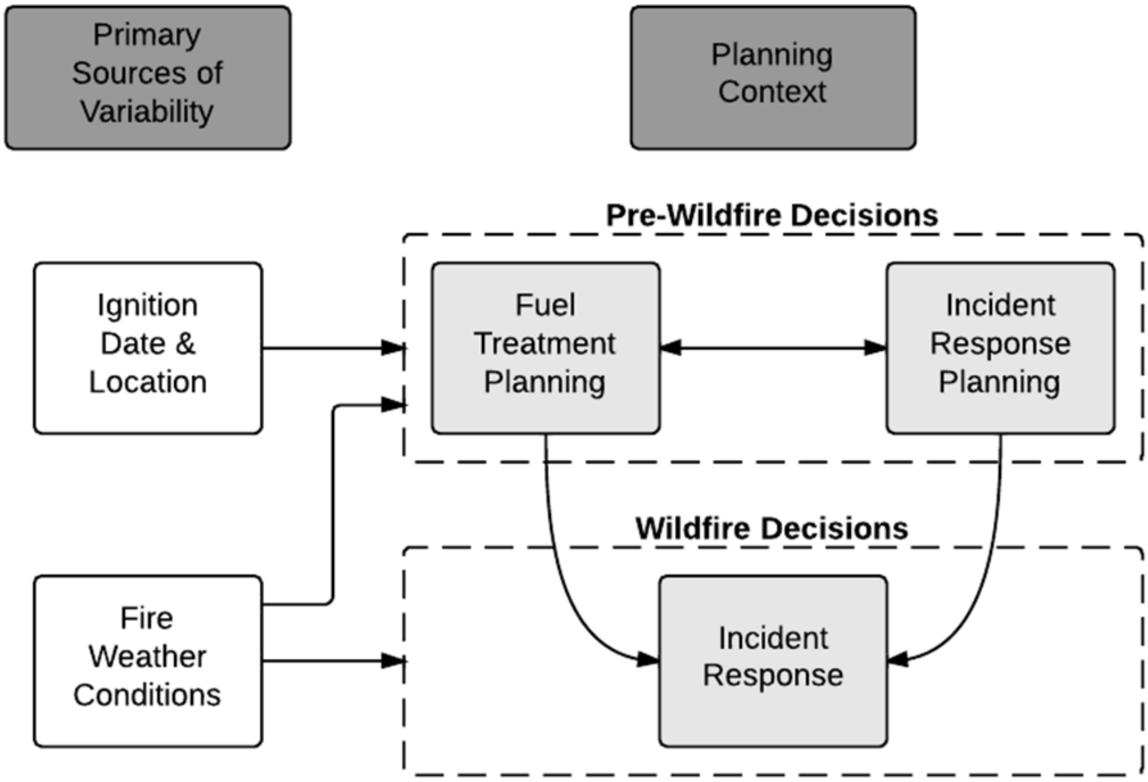

Figure 2. Primary sources of variability concerning wildfire occurrence and behaviour, and their relation to wildfire management planning contexts.

The advent of widespread burn probability modelling for wildfire management in the United States came with the development of the Fire Spread Probability (FSPro) modelling functionality within the Wildland Fire Decision Support System (WFDSS), used for active large wildfire incidents (Calkin *et al*. 2011). Referring to Figure 2, this entails ensemble simulations accounting for thousands of possible realizations of fire weather conditions, given an observed ignition. FSPro simulations depict contours of equal burn probability given fire spread potential over a given time duration, which roughly resemble concentric circles augmented by factors such as topography and forecasted wind direction. Figure 4 displays example FSPro burn probability contours for a large wildfire event in California, USA.

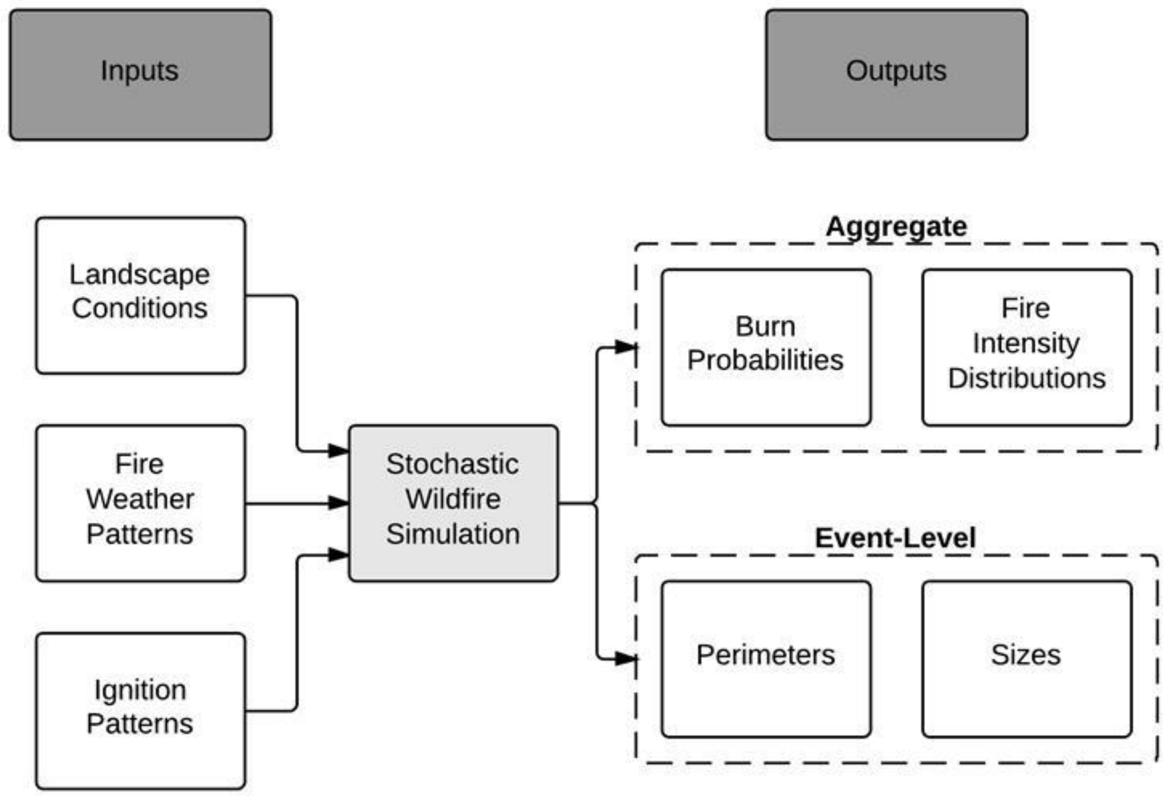

Figure 3. Primary inputs and outputs of stochastic wildfire simulation modelling

As adoption of risk analysis principles has increased, attention has turned to the application of stochastic wildfire simulation to pre-fire planning contexts. Figure 5, for instance, displays spatial burn probability modelling results for a landscape encompassing the Bridger-Teton Nation Forest in Wyoming, USA. Note the stark differences in patterns of probability between Figures 4 and 5, with the results presented in the latter figure capturing multiple ignitions along with variable fire weather conditions. The use of stochastic simulation in pre-fire planning contexts allows for more deliberative, structured decision processes (e.g., Marcot *et al*. 2012), incorporating not just fire modelling results but also information on resource/asset exposure, potential fire effects, and managerial priorities (Thompson *et al*. 2013a). Risk-based assessments built upon pixel-based burn probability results are now being widely used to support land and fire management decisions, in various geographic locations and at various planning scales (Thompson *et al*. 2011; Salis *et al*. 2012). Further, stochastic simulation can be used in comparative analysis frameworks to evaluate the impacts of alternative management strategies and to evaluate how past fuel treatments may have altered fire outcomes (Ager *et al*. 2010; Cochrane *et al*. 2012).

Another major expansion in application of stochastic wildfire simulation has been the transition to utilizing event-level results. That is, instead of focusing on localized burn probabilities and flame length distributions, analyses have focused on aggregating results across simulated events themselves. One prominent example is using simulation outputs to feed economic models predicting suppression costs based upon individual fire sizes, among other variables (Thompson *et al*. 2013b). Use of perimeters is also useful, particularly for capturing the range of variation for possible fire outcomes. For instance, whereas the expected area burned within a given polygon of interest (e.g., municipal watershed) can be captured by summing the product of pixel area and pixel burn probability for all pixels within the area, the use of simulated perimeters can characterize the entire distribution of conditional polygon area burned (Thompson *et al*. 2013c).

One promising application of perimeters is in capturing risk transmission across landscapes and identifying potential fire spread pathways (Ager *et al*. 2012). This type of analysis can estimate the likelihood of ignitions in various locations reaching some resource/asset of interest, for instance isolated patches of wildfire habitat or the wildland-urban interface (Scott *et al*. 2012; Thompson *et al*. 2013c). Spatially identifying the area within which ignitions can reach an area of interest can lead to delineation of a “fireshed” boundary, or the area within with ignitions can transmit risk to the area of interest. As an illustration, Figure 6 displays the location of all simulated ignitions whose perimeters can reach the municipal watershed for Helena, Montana, USA The outer boundary of these ignitions is delineated using a convex hull, with the left panel indicating all ignition locations and right panel further indicating the percentage of watershed burned associated with each ignition.

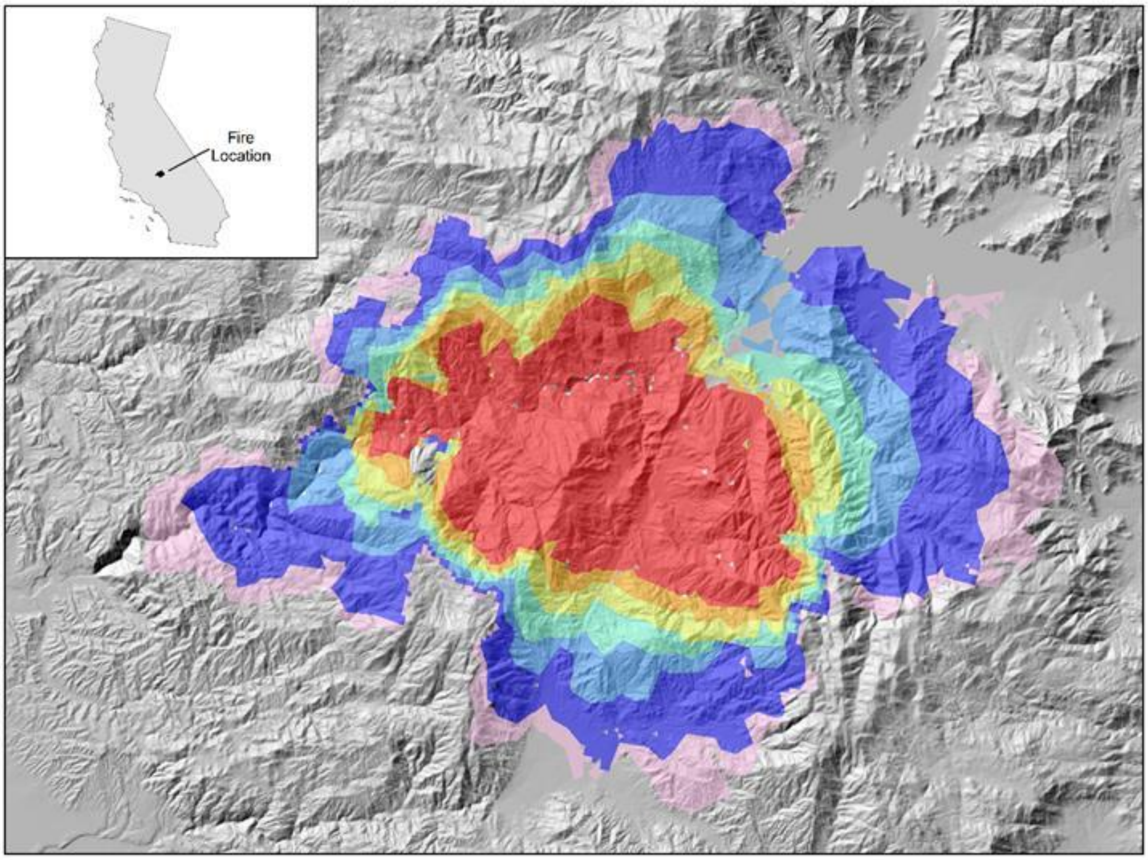

Figure 4. Simulated burn probability contours for a large wildfire event, given an ignition and fire weather forecasts. (Thompson et al. 2012)

The attribution of fire-level impacts to ignition locations has great potential to identify and differentiate areas of high risk transmission, and further to inform pre-fire strategies for mitigating risk. One prominent question in wildfire management, for instance, is which landowners comprise the greatest share of contributed risk and therefore bear the greatest burden for investing in risk mitigation. Figure 7 presents results from an analysis in the Front Range of Colorado, USA, examining the potential amount of human population affected within each simulated perimeter. The figure presents probabilities of exceeding a given amount of population impacted, charts which are commonplace in other arenas such as flood modelling but are only now being integrated into fire modelling. In this case, the impacts of ignitions are partitioned according to whether the fire ignited on federal or non-federal land, with results indicating non-federal ignitions have a greater potential to impact populated areas, due to geographic patterns of land ownership and human development in this region.

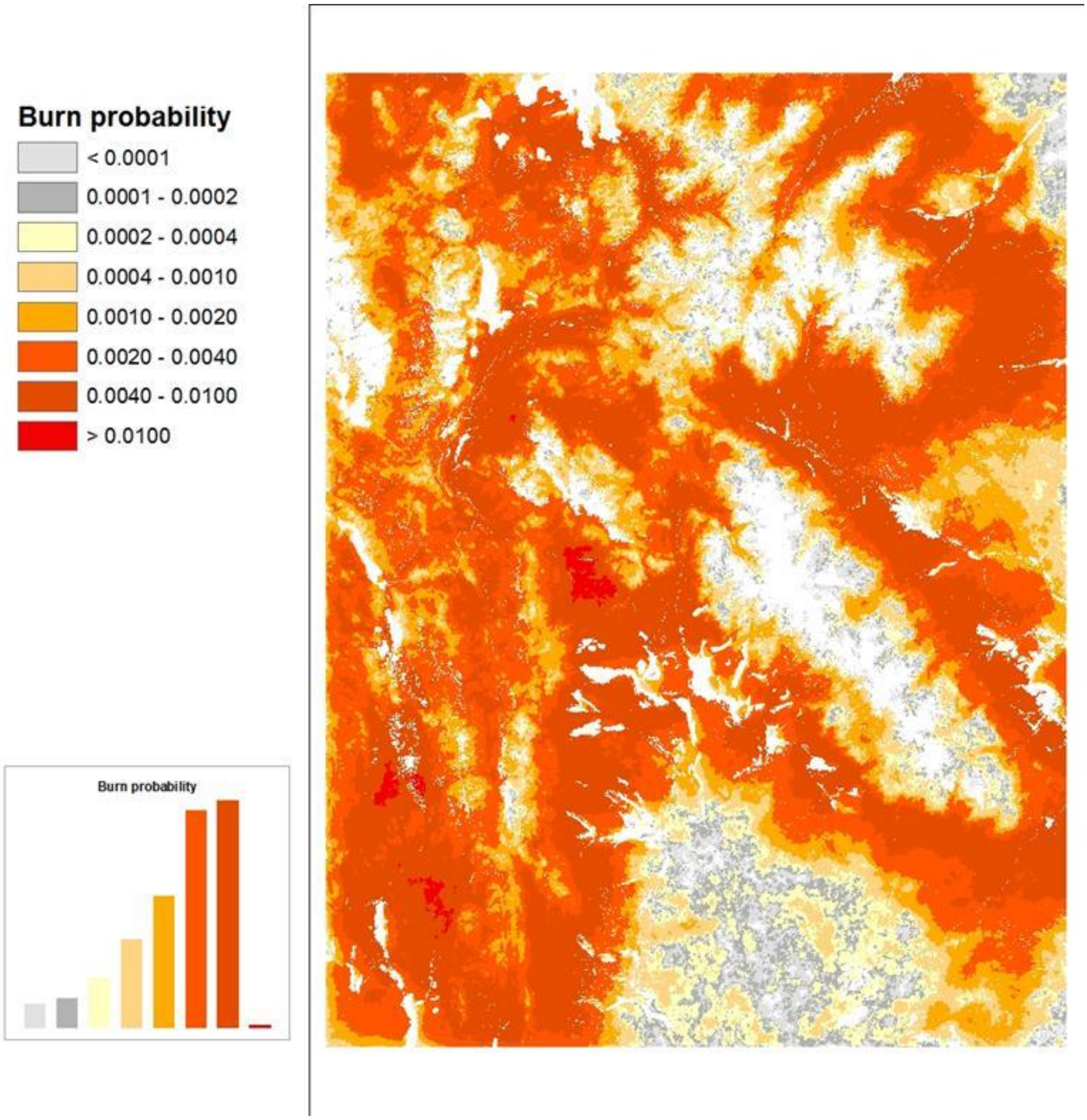

Figure 5. Annual burn probability results for thousands of simulated large wildfire events, with variable ignitions and fire weather conditions. (Scott et al. 2013)

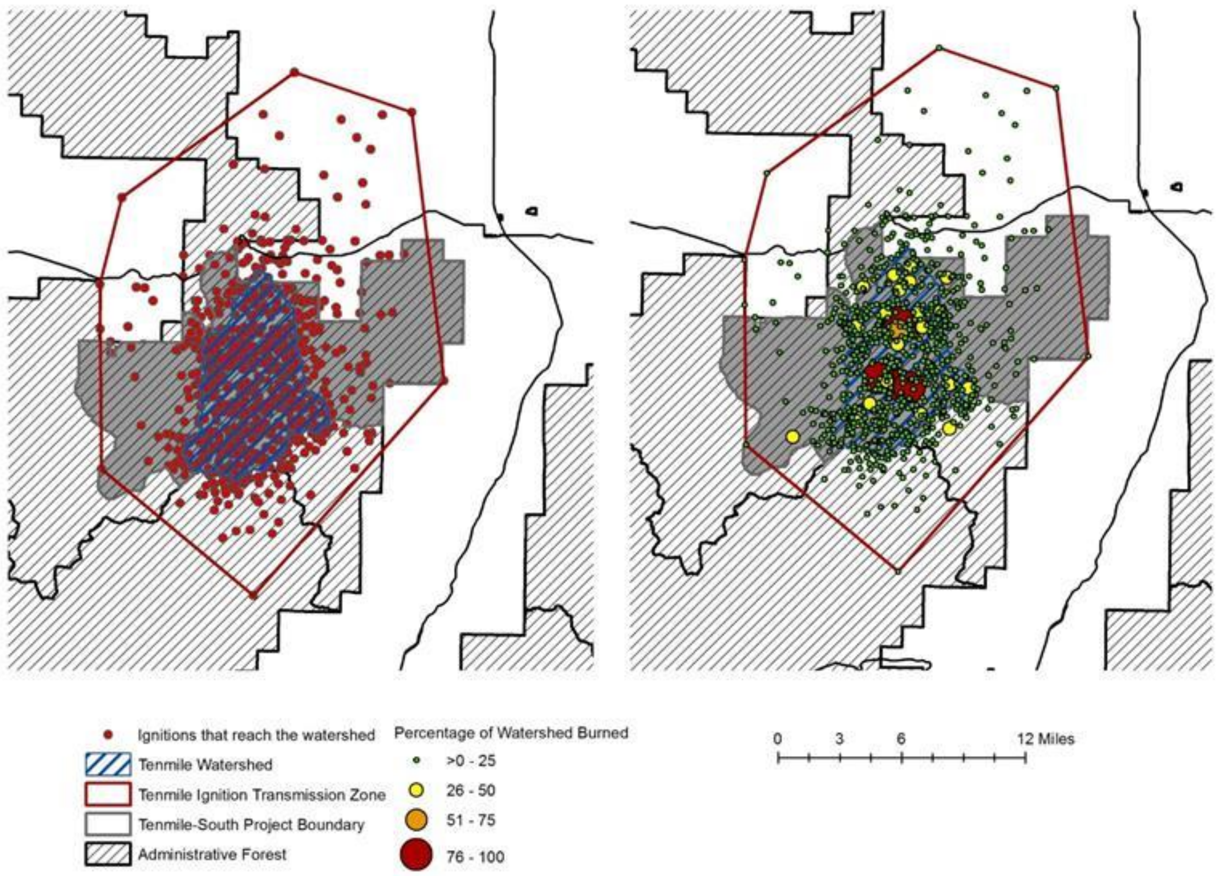

Figure 6. Fireshed (ignition transmission zone) delineation for all ignitions reaching the municipal watershed, along with area burned attributed to ignition.

3. Future Research Directions

Practically speaking, one key future direction of stochastic simulation is expanded application to other geographic regions throughout federally managed lands in the United States and elsewhere. Early adopters have largely reported beneficial outcomes, setting the stage for broader-scale adoption in a variety of contexts and planning scales. Notably, many of the assessments performed to date have occurred within collaborative planning environments, which in the ideal scenario will lead to less conflict and more streamlined implementation of risk mitigation activities. The availability of fire and fuel modellers, geospatial analysts, and process experts may largely determine the application rate of stochastic wildfire simulation and geospatial risk assessment frameworks, an area ripe for science delivery and technology transfer from the research world to land and fire managers.

Three arenas of active research are worth mentioning. First, decision makers would benefit from increased application of stochastic wildfire simulation and associated modelling efforts to better understand the impacts of fire management policies. Such efforts are by necessity interdisciplinary, for instance combining risk analysis, fire ecology, and economics, to better understand the likely costs and benefits of alternative strategies. Second, stochastic wildfire simulation outputs can help better characterize the range of potential post-fire consequences, and in particular can help with probabilistic characterization of nested disturbance processes such as post-fire debris flows. Third, stochastic wildfire simulation, in combination with other modelling efforts, can help better capture spatiotemporal dynamics of ecosystems and wildfire impacts. These questions are far more complex and uncertain, and require consideration of vegetation succession, disturbance processes, the impacts of current decisions on future conditions, and climate change. There are clear roles for expanded application of sensitivity analysis, scenario analysis, and uncertainty analysis, among other approaches.

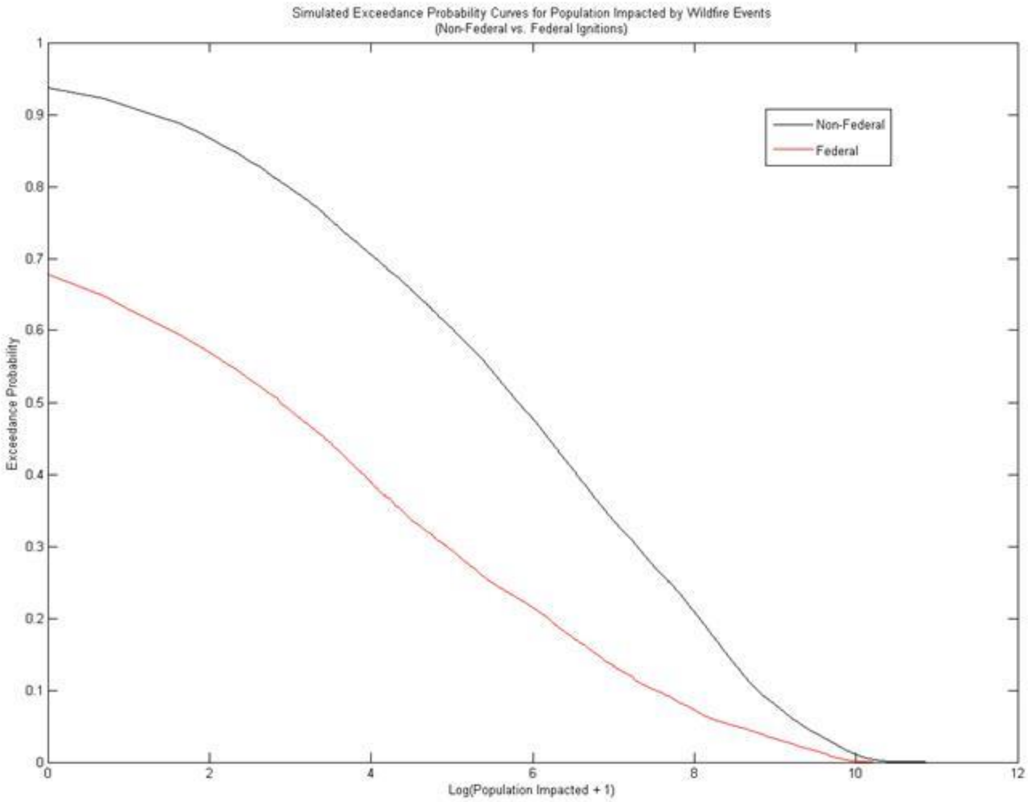

Figure 7. Exceedance probability charts for human population affected per simulated fire event, partitioned according to ownership at ignition location

4. Acknowledgements

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