fire

Perspective

Advancing the Science of Wildland Fire Dynamics Using Process-Based Models

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Abstract: As scientists and managers seek to understand fire behavior in conditions that extend beyond the limits of our current empirical models and prior experiences, they will need new tools that foster a more mechanistic understanding of the processes driving fire dynamics and effects. Here we suggest that process-based models are powerful research tools that are useful for investigating a large number of emerging questions in wildland fire sciences. These models can play a particularly important role in advancing our understanding, in part, because they allow their users to evaluate the potential mechanisms and interactions driving fire dynamics and effects from a unique perspective not often available through experimentation alone. For example, process-based models can be used to conduct experiments that would be impossible, too risky, or costly to do in the physical world. They can also contribute to the discovery process by inspiring new experiments, informing measurement strategies, and assisting in the interpretation of physical observations. Ultimately, a synergistic approach where simulations are continuously compared to experimental data, and where experiments are guided by the simulations will profoundly impact the quality and rate of progress towards solving emerging problems in wildland fire sciences.

Keywords: physics-based modeling; fire behavior; computational fluid dynamics; model validation

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The behavior of wildland fire and resulting ecological effects are exceedingly complex due to multiple nonlinear interacting processes that occur across a range of spatial and temporal scales [1,2]. For over half a century, the development of wildland fire models has largely been driven by a desire to support operational decisions and has thus emphasized developing tools that provide faster-than-real-time predictions. The most practical path to progress in this regard was through the development of point-functional empirical models based on observed correlations between mean fire behavior (e.g., the forward rate of spread of a head fire) and environmental and fuel parameters (e.g., fuel load, wind velocity, and topographic slope) from laboratory and/or field observations [3,4]. For many operational purposes, such models have played an important role in supporting decision makers and advancing firefighter safety. However, as scientists and managers seek knowledge of fire behavior in conditions that extend beyond the limits of our current empirical models and prior experiences, we will need new tools that foster a more mechanistic understanding of the processes driving fire dynamics (i.e., how fires start, spread and develop) and their ecological effects.

Over the last several decades, processed-based simulation modeling has emerged as an invaluable and effective technique for advancing our understanding of complex systems, across a range of scientific disciplines (e.g., engineering, meteorology, hydrology, oceanography, soil physics, and biology). Process-based models are not simply more complex descriptive or empirical models; they differ in that they are designed to mimic the mechanistic behavior of a complex system by explicitly representing the individual components and the known, or assumed, controlling physical processes and their interactions with each other and the environment. In this way, these types of models represent explicit working hypotheses about how processes and components within a system work causally together to produce a given outcome. Within wildland fire sciences, process-based model development has grown significantly since the 1990s owing to advancements in computing technologies, computational fluid dynamics (CFD), and modeling of turbulent and reactive flows [1]. Examples of these types of models include the Wildland Urban Interface Fire Dynamics Simulator [5,6], FIRETEC [7,8], and FireStar [9,10], among others (Figure 1).

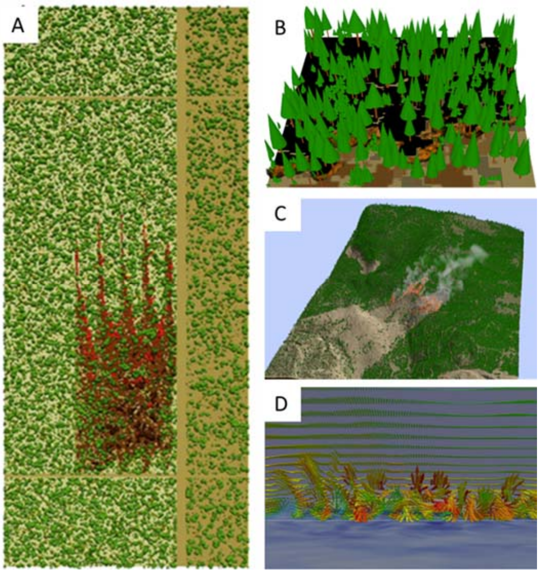

Figure 1. Example process-based model simulations: (**A**) Interacting firelines and crown damage during prescribed fire operations in longleaf pine forests USA; (**B**) Fire behavior and effects in Sierra Nevada forests USA based on 1929 stem maps; (**C**) Landscape scale fire spread in complex topography; (**D**) Investigating of coupled fire/atmosphere interaction on fireline dynamics including the role of buoyancy-induced flow on heat transfer and fire line rate of spread.

Here, we suggest that, much like in other scientific disciplines, these process-based wildland fire behavior models are powerful research tools that offer unique capabilities that can help advance our understanding of wildland fire dynamics and effects. However, we submit that, to realize the full value of these models in advancing wildland fire science, it is necessary that they play a more integral role in the discovery process [11,12], acting as a complement to experimentation and theory.

One way that process-based models can contribute to the discovery process is by viewing them as "virtual worlds" that act as a new kind of experimental system [13–15]. The use of simulation modeling as an experimental system has become increasingly important in the study of complex systems in numerous scientific disciplines, including physics, biology, meteorology and engineering [16–18]. Although process-based fire models are idealized simplifications of how wildfires behave in the physical world, they have a unique advantage because the coupled physical processes that drive fire dynamics and effects are explicitly modeled and the evolution of state variables, which are both symptoms and drivers of the numerous feedbacks, can be tracked throughout computational domains. The user has complete control over the inputs, and theoretical basis of the model, which enables manipulation of virtual experiments to a much greater degree than possible in the physical world. In this way, process-based models enable researchers to study aspects of fire dynamics and effects using virtual experiments that would be impossible, too costly, time consuming or risky to study in the real world [15]. Studies that utilize virtual experiments often incorporate many of the same experimental, visualization and statistical techniques that are applied to physical experiments [14]. However, as suggested by Brodland [18], virtual experiments have several advantages over physical experiments including being able to: (1) perform experiments from the same exact starting conditions thus ensuring replication; (2) select any temporal frequency and spatial resolution of observation (at or above the time step and grid resolution used in the simulation) without interfering with the system or it components; and (3) manipulate any variable or process of the system with arbitrary magnitudes, including ones that cannot be modified experimentally in the physical world.

The use of numerical experiments in wildland fire science has become particularly important in situations where physical experimentation would be too risky or costly or, where simple models cannot capture the complexity of these high-dimensional systems. For example, over the last decade there has been considerable interest in improving our understanding of how fire behavior and effects may be altered by bark beetle-caused tree mortality. Researchers hypothesized that the impact of bark beetle-induced tree mortality on fire behavior and effects was due to changes in the fuels complex, which was a function of time since disturbance (e.g., [19–21]). However, empirical studies of wildfires in bark beetle impacted areas were not completely consistent with this hypothesis, leading several researchers to suggest that other factors, including the intensity and severity of the outbreak, fire weather, and host-beetle interactions may be additional important drivers. However, conducting physical experiments that could control for this multitude of factors was not feasible, either in the lab or in the field. Thus, researchers turned to numerical simulation experiments that allowed them to overcome challenges associated with physical experimentation including the ability to hold some factors (e.g., starting conditions and fire weather) constant and manipulate others. For example, Hoffman et al. [22] explored the influence of varying tree mortality levels on fire severity while holding other factors such as stand density and tree spatial arrangement constant. Hoffman et al. [23] examined how fire behavior changed throughout the course of a bark beetle outbreak with different rates and patterns of mortality. Sieg et al. [24] used a process-based model to explore the interaction between time since disturbance, level of tree mortality, and fire weather (wind) on fire severity. Ultimately, the exploitation of process-based models to conduct numerical experiments allowed these researchers to investigate the potential couplings and feedbacks driving fire behavior and effects and develop new insights and theoretical concepts related to fire dynamics and effects that would be difficult if not impossible otherwise.

As researchers increasingly turn to process-based models to help gain insights into wildland fire dynamics, it is important to recognize that the interrelationship between process-based modeling and physical experimentation should be seen not as competitive but as complementary activities that permeate throughout the scientific process. One of the prominent roles that process-based models can play in this relationship is to suggest new experiments, that is, where the motivation for physical experimentation is based on hypotheses and insights gained using process-based models. Examples where findings based on simulations were used to suggest and ultimately carry out new physical experiments are well documented across several other disciplines (e.g., molecular chemistry [25], meteorology [26], physics [27], and biology [18]); yet this approach is still relatively rare (or at least not as well documented) within the wildland fire modeling community. However, one could easily see how hypotheses developed during a numerical experiment could serve as a basis for physical experimentation. For example, Linn and Cunningham [28] and subsequently Canfield et al. [29] used a process-based model to evaluate the dependence of the forward fire rate of spread in grass fuels on wind speed and fireline length. While their results indicated that the forward rate of spread increased with increasing ambient wind speed, as expected, they also found that fire spread rate and shape were dependent upon the length of the fireline due to complex interactions between the ambient and buoyancy-induced flows. Clearly, one could imagine designing new physical experiments whereby the length of fire ignition and wind speeds were varied, and the forward rate of spread and flow fields could be measured along various points of the fire perimeter to provide new understanding of the role of fire-atmospheric interactions in driving fire spread. Such numerical work can also be used to highlight requirements for measurement strategies or critical characteristics of the heterogeneous fire environment that can be used to help add context to physical observations.

As process-based models are increasingly used in wildland fire science, it is important to continually evaluate how well such models approximate wildland fire dynamics and effects, and assess their limitations and uncertainties through verification, validation and uncertainty quantification (VVUQ). Although model validation has a long and often debated history, it generally involves the comparison of modeling results with experimental or empirical results. However, as described by Rykiel [30], validation can take many forms, ranging from qualitative assessments like "face validity" and "visual comparisons" to quantitative assessments such as "predictive" and "statistical" validation. Although historical empirical data sets have been, and will continue to be, useful for process-based model validation (e.g., [2,6,28]), their use for quantitative assessments is often constrained due to missing or incomplete information on critical input parameters or boundary conditions, few measurements of the variable of interest and/or little or no estimation of measurement or experimental error. We therefore suggest that new "validation" experiments that are co-designed by modelers and experimentalists provide an opportunity to foster new capabilities, improvements and understanding for both the modeling and experimental communities.

We suggest that the benefits of such validation experiments will be most effectively realized if some guidelines are met. First, we propose that such experiments should be developed and conducted within a hierarchical validation framework [17,31,32] that provides model assessment across the full range of complexity contained within a process-based model. These assessments will likely range from comparisons of the full model with large-scale field experiments (e.g., [2]) to comparisons of sub models (e.g., convective and radiative heat transfer or drag) with highly controlled laboratory experiments (e.g., [33]). Second, they should seek to estimate both measurement and experimental uncertainty for all information required by the process-based model to simulate the experiment, including initial and boundary conditions, material properties, and the fire behavior or physical metrics of interest. Finally, these experiments should include a range of fire behavior and effects metrics that are relevant or of interest to scientists and managers [30]. Such experiments should go beyond providing estimates of the mean fire behavior characteristics, but also include estimates of spatial and temporal variability as well as overall fire pattern. Ideally, all the information needed for VVUQ activities, including description of the physical experimental setup, instrumentation, measurements and processing, boundary and initial conditions and uncertainty estimates would be well documented and made available in a database to the broad community for model evaluation. New validation experiments such as those described here would not only lead to improved model evaluation, but often will, as Wimsatt [34] (p. 56) suggested, "shade into the discovery process." For example, the VVUQ process can help identify model inputs with large uncertainties and inspire the development of new measurement and experimental methods to reduce these uncertainties (e.g., new sensors or new sampling protocols). As user confidence grows due to VVUQ efforts, these models can begin to take on expanded roles such as helping researchers identify the potential parameter space and fine-tune measurements for proposed experiments, and assist in the interpretation of physical experiments.

To advance wildland fire science, we must continue to seek an understanding of the complex processes and feedbacks that drive wildfire dynamics and effects by leveraging all the tools and resources at our disposal. We are now entering an era where our increased computational capacity and massive data acquisition capabilities (e.g., LiDAR) have unlocked new opportunities to utilize models within the discovery process in ways that were impossible only a decade ago. Process-based models can play a particularly important role in advancing our understanding, in part because they allow their users to evaluate the potential mechanisms and interactions driving fire dynamics and effects from a unique perspective not often available through experimentation alone. For example, such models could play a crucial role in helping advance our understanding of fire behavior in increasingly novel and dynamic environments [35] including those with a mixture of live and dead fuels [36], and the mechanisms responsible for the spatial distribution of fire effects and mortality [37]. This is not to say that process-based modeling is the answer to all scientific questions. Rather, the perspectives, insights and knowledge gained with process-based models should be used with new experimental work, field observations, and data collection networks to advance our understanding of wildland fire dynamics and effects and to develop predictive models that provide meaningful answers to current questions in fire dynamics and effects for the right reasons. Ultimately, we believe that a synergistic approach where simulations are continuously and carefully compared to experimental data, and where experimental designs can be guided by the results of simulations, will have a profound impact on the quality and the rate of progress towards solving emerging problems in wildland fire sciences.

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