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Comprehensive Open Source Development of Next Generation Wildfire Models for Grid Resiliency (CEC EPC-18-026):

State of Wildfire Science Report: Limitations in Modelling Modern Wildfire Behavior

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Spatial Informatics Group

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Purpose of the Report

This report provides a targeted critique of operational wildfire models. The central thesis is that a gap in wildfire science, namely the absence of a physical theory of wildland fire spread, constrains the ability of existing models to accurately represent fire behavior in many of California's contemporary wooded landscapes. The report briefly describes the modeling framework necessary for assessing fire risk. It concludes by outlining how research objectives and outcomes of Workgroup #2 (project Task 5) will contribute to the development of the next generation of wildfire risk models.

Background

Fire has been an integral part of California ecosystems for thousands of years (Stephens et al. 2007). However, some recent fires have impacted large areas of the wildland-urban interface resulting is the loss of lives, homes, and livelihoods (Edwards 2019). The recent drought (2012-2015) compounded the current fire problem. Drought-induced mortality killed millions of trees in the southern and central Sierra Nevada which could have a large impact on future fire behavior and effects (Stephens et al. 2018). These challenges require an improved fire behavior prediction system that incorporates the potential effects of large-scale tree mortality and deep duff layers.

State of Knowledge

Many aspects of wildfires in California and elsewhere in the western US have changed in the past several decades, including climate patterns, fuel and vegetation conditions, and the development of human infrastructure near wildlands. In particular, wildland fuel conditions have increased the likelihood of fire behaviors that exceed the assumptions of existing fire modeling systems.

Most operational wildland fire models rely on the Rothermel spread equation from 1972 (Rothermel 1972). These include BEHAVE (Andrews 1986), FARSITE (Finney 1998), CAWFE (Coen et al. 2003), and Wildfire Analyst (Cardil et al. 2018). The Rothermel equation predicts steady-state fire spread rates from fuel and weather conditions for an assumed linear flame zone that is independent of the context on a given fire or the size or characteristics of the fire itself. Fuel descriptions mapped across the United States by LANDFIRE (2020) provide only the fuel characteristics intended for existing fire modeling systems (Finney 1998), particularly average properties of fine fuel material described by "fuel models" (Scott and Burgan 2005) and bulk descriptions of live canopy fuel. Fine fuels burn and release heat primarily in the flaming front of the fire, with little residual solid fuel combustion. Yet these components are an increasing fraction of the total fuel load.

As a consequence of fire suppression, large woody fuels and deep duff layers are found in many areas of California (e.g. Cansler et al. 2019). The recent die-off of conifers in the Sierra Nevada from a multi-year drought will only add to the accumulation of solid fuel (Axelson et al. 2019). These fuel components are largely ignored by the Rothermel equation which addresses only the burning characteristics of fine fuel and the advance of the flaming front. The burning rate and heat release rate of fine fuels is assumed fixed by their bulk density, load, and moisture content.

Current wildfire spread models apply only to the flame spread of a line fire, which is a linear segment excised conceptually from the perimeter of a much larger wildfire. Modeled spread rate and intensity of these line segments are assumed to be applicable to fires of any size.

Some wildfire behaviors, however, are exhibited only at the scale of the entire fire and greatly exceed assumptions of the Rothermel equation because they are not a property of an arbitrary segment of the front. Examples include mass fires, pulsating fires, fire whirls and vorticity, fire storms, and atmospheric effects from pyro-cumulus and pyro-cumulonimbus development. Although infrequent, these behaviors likely result when the energy release rate and induced wind velocity become strongly coupled over a large burning area (i.e. produced by a positive feedback cycle). Strong surface winds from large area fires were investigated for decades in relation to the use of fire in warfare, specifically firebombing in WWII (Bond 1946) and the potential for nuclear war (Carrier et al. 1981, 1985). Specifically these fire phenomena are seen where: 1) a high rate of heat release exists over large areas not just the linear flame zones, 2) the heat release rates are greatly increased by ventilation from surface winds induced by the fires themselves (i.e. fire generated in-drafts), and 3) the prolonged release of heat from solid phase combustion is maintained by the presence of long-burning large woody material and deep duff layers (i.e. the fuel components not considered by the Rothermel equation).

The magnitude of energy involved is considerable and the dynamics are complex. Consider the analogous process of a charcoal forge. Heat release rates from the solid-phase combustion of charcoal with sufficient impinging air speed is the basis for producing combustion temperatures sufficient to melt metals. The transition from smoldering to flaming fires is commonly experienced when starting a campfire – blowing on the coals increases the temperature of surface combustion of carbon and the rate of energy release and facilitates transition to flaming. Yet none of the operational fire models contain any of these effects. The Burnup model developed by Albini and Reinhardt (1995) simulates combustion of large woody fuels based on their load, sizes, and moisture but without ventilation effects. The Burnup model is included in fire simulation models by Finney et al. 2003, Clark et al. 2004, Coen et al. 2013, but is incapable of generating long-duration heat release behind the flame zone.

There are wildland fire models that can represent the behavior of "the whole fire" but are only applicable to research. These models rely on representations of the physical processes of combustion, heat transfer, and ignition within the framework of computational fluid dynamics (Linn et al. 2002, Mell et al. 2007, Morvan et al. 2007). In theory such models could capture some of the extreme fire behaviors because they have a full 3D gridded domain and account for the energy and momentum transfers between the fire and the surrounding air. However, to resolve the physics of heat transfer, combustion, and ignition, fine resolutions less than a few centimeters are required, meaning that only small fires can be simulated (e.g. 100 m^2). Coarser grids of 1-2m have been used to model fires of several hundred acres (100's of hectares) but the physical processes are not numerically resolved at these cell resolutions and must be parameterized. For all simulations, these models remain far slower than real time (e.g. 100's to 1000's X real time) even with supercomputing. Spatial domains for truly large fires are beyond the ability for these models with existing computing resources.

Modeling for Risk Analysis

The use of wildfire models for risk analysis relies on large numbers of fast-running simulations to characterize probability distributions of behavior across landscape domains up to the size of national scales (Miller and Ager 2013). Expected fire impacts on resources are then estimated by multiplying fire behavior probabilities by vulnerability functions for specific values (Scott et al. 2013). The immense number of possible weather sequences and ignition locations for wildfire scenarios are sampled by Monte Carlo techniques. Weather scenarios are often generated from summaries of historical records, although risk analyses could be conducted for narrow time-windows influenced by prior probabilities, observed weather, or joint distributions of weather factors (e.g. drought, wind). Several uses of wildfire risk analysis have become common. The most frequent analysis is to characterize static risk for large areas (e.g. annual burn probabilities by intensity) by simulating a large number of ignitions and weather scenarios (Finney et al. 2011). Another method is to estimate the probability of impact of fires starting only in specific locations. Other analyses are used to estimate the probability a specific area or resource being burned by fires starting from the surrounding landscape (sometimes called a "fireshed;" Scott et al. 2017).

Because of the vast numbers of fire scenarios used for modeling wildfire risk, fire models must run extremely fast. The speed requirement constrains how quickly advances in fire science can be incorporated into risk models. This constraint is not inherently a modeling or programming problem but rather a science challenge to simplify the essential physics of fire spread.

Gaps in Fire Science

The most critical gap in both basic and applied fire science is the absence of a verified physical theory of wildland fire spread (Finney et al. 2013, Cruz et al. 2018). Without this theory, we do not have the ability to produce models that can reliably address modern or managed fuel conditions or extreme behaviors associated with large fires. Empirical models such as the Rothermel spread equation were not intended to capture physical processes. The existing physical models have introduced a variety of approximations and assumptions to address combustion and energy release, heat transfer, and ignition at space and time resolutions dictated by the intended modeling application. Relatively recent reviews of existing empirical and physical models have been published (Sullivan 2009 a, b, c).

One of the known gaps in fire physics is the varying heat release rates from solid fuel burning. Solid fuel, such as woody biomass, burns both in a flaming phase as gases mix with oxygen and then combust when released from decomposition of heated wood, and in a solid-phase (glowing) which is primarily carbon combustion. The burning rate is defined as the rate of mass loss. The heat release rate is the amount of thermal energy released and may not follow the same trend as mass loss if the mass is not combusted. Incomplete combustion occurs in smoldering, for example, because much of the smoke is fuel gas that remains unburned. Heat release rates are not constant or predicted by existing models for several reasons. First, the fuel burning rate is a function of particle sizes, moisture, and packing. No practical physical models address these behaviors in fire modeling and simplified constant rates are therefore assumed. Second, both the burning and heat release rates are affected by ventilation – wind impinging on the combustion reaction. Ventilation is key to both the burn rate and burn magnitude for woody fuels and deep duff and litter layers. Much of these fuels will not burn in small fires with little ambient wind or it will smolder and release little heat. Alternatively, all the fuel may burn rapidly in large fires with high winds. Once the missing pieces of fire science are better understood, we must have the ability then to measure the vital fuel properties for modeling. Models will have to be developed to include the physics of fire spread in ways suitable for the end use – whether risk modeling or predictive simulation of active fires.

Research Objectives

The research topics addressed by Task 5 in this project include: 1) solid phase burning rates, 2) fuels measurements, and 3) future fire modeling. The research objectives for each topic are discussed in detail below.

Solid Phase Burning Rates. Burning rates of most natural fuels vary widely with moisture and wind, and exhibit transition from smoldering to flaming (and back), dramatically changing the heat release from fuel combustion. Smoldering combustion consumes fuels slowly and converts only a small fraction of the fuel mass to heat because the volatile gasses are released without combusting. Transition to flaming is poorly understood, as are the ventilated burning rates, and neither are included in any wildland fire model. As indicated above, high loads of woody fuels and duff found in many California forests store chemical energy that can be released for long periods either slowly or quickly depending upon the fire or burning conditions. The objectives of this research are threefold. First, we will develop repeatable and controlled fuel materials and mixtures that can be burned at laboratory scales, similar to previous laboratory work on burning rates. Second, we will devise experimental apparatus to determine the dependency of burning rate, transition from smoldering to flaming, and heat release rate on the range of moisture and wind experienced under field conditions. Finally, we will test predicted heat release rates across the range of fuel structures and environmental conditions found in wildland areas.

Fuel Measurements. At present, the range and variability of fuel conditions across California are poorly characterized. Fuel measurements and mapping schemes follow standards devised to support existing operational models (i.e. Scott and Burgan 2005), do not represent fuel components outside operational modeling systems, and do not capture spatial variability that strongly affects fire spread and behavior. A new fuel measurement and mapping system will be devised to resolve the essential fuel components and spatial heterogeneity occurring at multiple scales. At the broad scale, remote sensing will be used to classify and describe fuel strata as a set of distributions that specify cover, patch size, departure from randomness, and overlap among strata. Properties of the "patches" will be determined from stratified field sampling based on categories identified in broad scale remote sensing data. Patch properties include the load, particle size distributions, vegetation type, and depths as well as barren areas. This approach contrasts with the use of fuel models for the Rothermel spread equation in that the distributions of properties are explicitly characterized (not average bulk properties) and can be used to generate numerous realizations of the fuel properties that occur within a given type. Individual realizations of fuel characteristics can feed advanced fire models, and multiple realizations then used for developing ensemble predictions of fire behaviors. The nonlinear wildfire behavior response to fuel conditions means that anticipated responses are not produced by average fuel and weather conditions. Only ensembles of fire behavior outputs can produce accurate characterizations of fire behavior variability.

Future Fire Modeling. Several discoveries of fire physics by the Missoula Fire Sciences Laboratory in the past 5 years make it possible to develop accurate, scalable, fast, and simple models of the non-steady spread and behavior. The first, is the *proof of the decisive role of convective heating of fine particles to ignition*. The second is *the characterization of convective heating from rectangular flame zones*. The third is *characterization of burning rates of fine fuel beds*. Unrealistic assumptions of fuel particle convective heat transfer have required models to assume excessive radiant heating. Models that attempted to incorporate convective heating were forced to assume the gas temperature distribution ahead of the flame zone or rely on numerical computational fluid dynamics simulations for fluid dynamics of the flame zone. In the first case, the dependencies of convective heating on topography, wind, and flame zone geometry were not known. With numerical approaches, the fine grid resolutions required to resolve flame behaviors near the hard boundary of the ground surface are computationally prohibitive. A solution to these deficiencies comes from recent findings that the gas temperature profile along the ground ahead of a flame zone follows a power-law function of distance, with the curve modified by wind speed, slope inclination, energy release rate, and flame zone geometry. The burning rates of regular fuel configurations (i.e. cribs) have been characterized from laboratory studies using different wind speeds and moisture contents. Scaling relations for these burning rates indicate the heat release and flame residence time only across a limited range of relatively fine fuels. More research will be required to develop general-use sub-models for burning rate that would address both fine fuel beds as well as large woody material and deep duff layers and their flaming and glowing responses to ventilation. A prototype one-dimensional fire spread model is under development that responds dynamically to time- and space-varying environmental conditions. The model works well for uniformly fine fuels but will require characterization of the time-dependent burning rates of larger or denser fuels and the representation of fuel variability under natural conditions and this will be undertaken in this project.

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