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Wildland fire behavior modeling: perspectives, new approaches and applications

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Abstract
The last 15 years have seen the development of wildland and wildland-urban interface fire behavior models that make use of modern numerical methods in wind and combustion physics. Currently, these approaches are too computationally expensive for operational use and, as for any fire behavior model, require validation through comparison to full-scale measurements. However, these 'physics-based ' models have the potential of providing a more complete understanding of fire behavior over a wider range of environmental conditions than empirically based models. The promise of physics-based models is not to replace the use of simpler and faster models, but to provide a well founded understanding of their limitations and a means of improving them. An example of this is to use the physics-based wildland-urban interface fire dynamics simulator (WFDS) to develop and evaluate a simpler level set model of surface fire spread. A basic implementation of the level set model performs reasonably well but requires further evaluation when applied to scenarios that include heterogeneous fuels and the potential influence of fire induced winds.

Additional Keywords: fire modeling, fire spread, fire behavior, CFD, numerical combustion

Introduction

Wildland fire modeling, considered in its entirety, is a very challenging task. The challenge arises from the range of physical processes and the temporal and spatial scales over which they operate. These processes range from the small-scale (~ 1 mm) ignition event to the large-scale (~100 km) transport of smoke. The focus of this presentation paper will be on the modeling of fire behavior. By this we mean the initiation of fire spread and the subsequent development of a fireline and fire plume as determined by the coupled processes of combustion, buoyancy induced flow, and thermal degradation of vegetation through radiative and convective heat fluxes. Smoke generation and transport, while modeled, is not considered here. Modeling approaches will be discussed and distinguished from each other according to the degree to which the physical processes are explicitly handled. Simple models are those that do not attempt to model the physical processes. Instead, they use formulas for the spread rate, and other quantities, derived from measurements (empirical based) or from observation and experience (rule based). Complex, physics-based, models do attempt to capture the physical processes through the numerical solution of equations governing the physical processes in question. Of special importance is the fact that physics-based models include the interaction and coupling of the driving processes (wind, buoyancy induced flow, combustion, thermal radiation, thermal degradation of vegetation, etc.). As a result, the same model can be used to investigate the relevance of wind, fuel structure, fuel moisture, terrain, etc. on fire behavior over a range of environmental variables. This is not possible with empirical or rule based models of fire behavior. Each environmental scenario requires sufficient, repeatable, measurements (or observations) to form a legitimate basis for developing the model or formula.

Simple models have the advantage that they can provide faster than real-time predictions. However, simple models are derived, when empirically based, from measurements over a limited range of environmental conditions. Strictly speaking, their application to environment conditions outside of those for which they were derived is not justified. Ideally, physics-based models would not have this limitation. The governing equations, upon which they are based, would capture the basic physical processes regardless of the scale of the process (for engineering applications). In reality, however, physics based models are subject to two types of limitations in this regard. The first is a need for empirically derived information, such as the radiation absorption coefficient or the convective heat transfer coefficient, for component physical processes. Because these empirical relations are derived or applicable over a wide range of conditions this is not too severe a limitation. Also, by their nature, physics-based models are constructed such that the importance of component models can be tested in a consistent manner. In particular, targeted experiments in the laboratory and the field can support this testing.

A second limitation of physics-based models is due to limited computational resources. A numerical simulation that attempts to capture, with equal fidelity, the range of processes from ignition to fire plume dynamics would require a computer with prohibitively large memory and processor demands. For example, the physics-based fire simulation tool called the Wildland urban interface Fire Dynamics Simulator (WFDS) (Mell *et al*. 2007; Mell *et al*. 2010) developed by the National Institute of Standards and Technology (NIST) requires approximately 1 kB of memory per grid cell. It is reasonable to assume that resolving the processes of ignition would require a grid cell resolution of approximately 1 mm. At this resolution, a WFDS run with the computational domain that is 1 m on the side would require 1 billion grid cells or 1 TB of computer memory. Present-day supercomputers have on the order of a few hundred terabytes of memory. Thus, it is beyond the capabilities of even today's most powerful computers to capture, with high fidelity, the processes of ignition and larger scale fire dynamics using the same computational grid resolution. The methods of adaptive mesh refinement offer one way to address this problem. In this approach, a sufficiently refined computational grid follows physical processes that require a relatively fine grid. Elsewhere in the computational domain the grid can be less refined. This allows a high fidelity physics-based simulation to occur with much less computational expense. However, these methods are still in the stage of research and development for application to wildfire simulation. Currently, the limitations imposed by insufficient computational resources are addressed through what are called sub-grid scale modeling. In this approach, processes that occur at scales that are not resolved by the grid are handled through separate terms in the conservation equations. An overview of different approaches to sub-grid scale modeling in present-day physics-based wildland fire behavior simulations (including WFDS) is given by Morvan (2010). Details on the sub-grid scale modeling approach used in WFDS are given in Mell *et al*. (2010).

Table 1 lists some general characteristics of complex and simple fire behavior models. The implementation and programming of simple models can be complicated. An example is the extension of a single point fire spread prediction formula used in BehavePlus (Andrews 2007) to predict the spread of a wildland fire over landscapes in FARSITE (Finney 2004). In most applications of FARSITE, the wind field is not calculated and assumed to be uniform in space. Fast turnaround time wind models, that can provide spatially variable winds, have been developed (Forthofer and Buler 2007). Since physics-based models compute three-dimenional fields of wind, temperature, and other variables they can have significantly higher output demands.

Table 1: General characteristics of complex and simple fire behavior models.

Complex Fire Behavior Models (more physics)	**Simple Fire Behavior Models** (less physics)
Physics-based	Heavily empirical or rule based
Potentially high input/output data demand	Usually low input/output data demand
Computationally expensive (usually slower than real time computations)	Computationally cheap (usually faster than real-time computations)
Directly provides heat fluxes, winds, firebrand transport and deposition	Cannot directly provide heat fluxes; winds are usually prescribed; empirical firebrand modeling
Directly handles variable fuels, terrain, weather	Influence of variable fuels and terrain is handled empirically

In the remainder of this write-up, examples of results from a physics-based model and a simple model will be given. The physics-based results will be from the WFDS model (Mell *et al.* 2007; Mell *et al*. 2010). Other physics-based models exist and can be applied to many of the example scenarios shown. These include FIRESTAR (Morvan *et al*. 2009), FIRETEC (Linn *et al*. 2002) and FIRELES (Tachajapong *et al*. 2008). An overview of these models is given in Morvan (2010) and Mell *et al*. (2007). With regard to the range of application of these models, FIRESTAR is limited to two-dimensions, FIRETEC is designed to operate with computational grid cell sizes on the order of 1 m, and FIRELES has, to date, been applied to laboratory scale fire experiments. In reported applications to date, therefore, WFDS appears to have the widest range of applicability. The simple model examples given below will be from a level-set based approach under development at NIST.

Results from the physics-based WFDS model can be used to determine head-, flank-, and back- fire spread rates for input into the simple level-set model (in much the same manner as laboratory measurements were used to determine the head fire spread rates used in the FARSITE model). By basing the spread rates used in the level-set model on WFDS results (which account for a wide range of physical processes) it is possible to investigate the importance of various physical processes in fire behavior and, potentially, identify the level of physical modeling required for a given application. For example, if the level-set model is implemented with a constant uniform wind and well matches WFDS results, this implies that, for the scenario simulated, the influence of the terrain and the fire atmosphere interaction were not significant.

Examples from a physics-based model (WFDS)

Fig. 1 shows images from a grass fire simulation using WFDS. Ignition occurs in a localized region (i.e., spot ignition as opposed to line ignition). The top figure shows the fire line and the smoke plume. The middle figure shows the radiant heat flux on the grass fuel and the bottom figure shows the convective heat flux. The region of the head fire can clearly be seen to have larger heat fluxes compared to the flank fires. No backing fire occurs because the grass plot was ignited along a fire break. In the region underneath active flaming the heat fluxes are positive; while in the region of previously flaming fuel the heat fluxes are negative (corresponding to a net heat loss). The actively burning head fire is larger in extent than the flanking fires, as is seen in the field. This figure illustrates the ability of physics-based models to calculate the driving mechanisms in fire behavior.

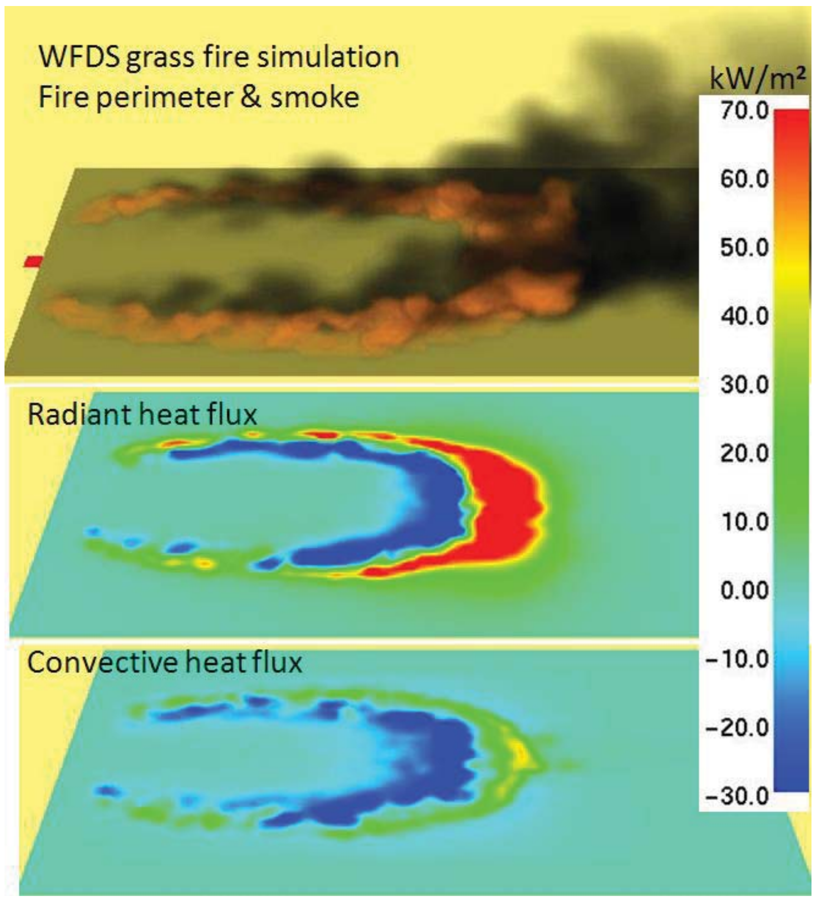
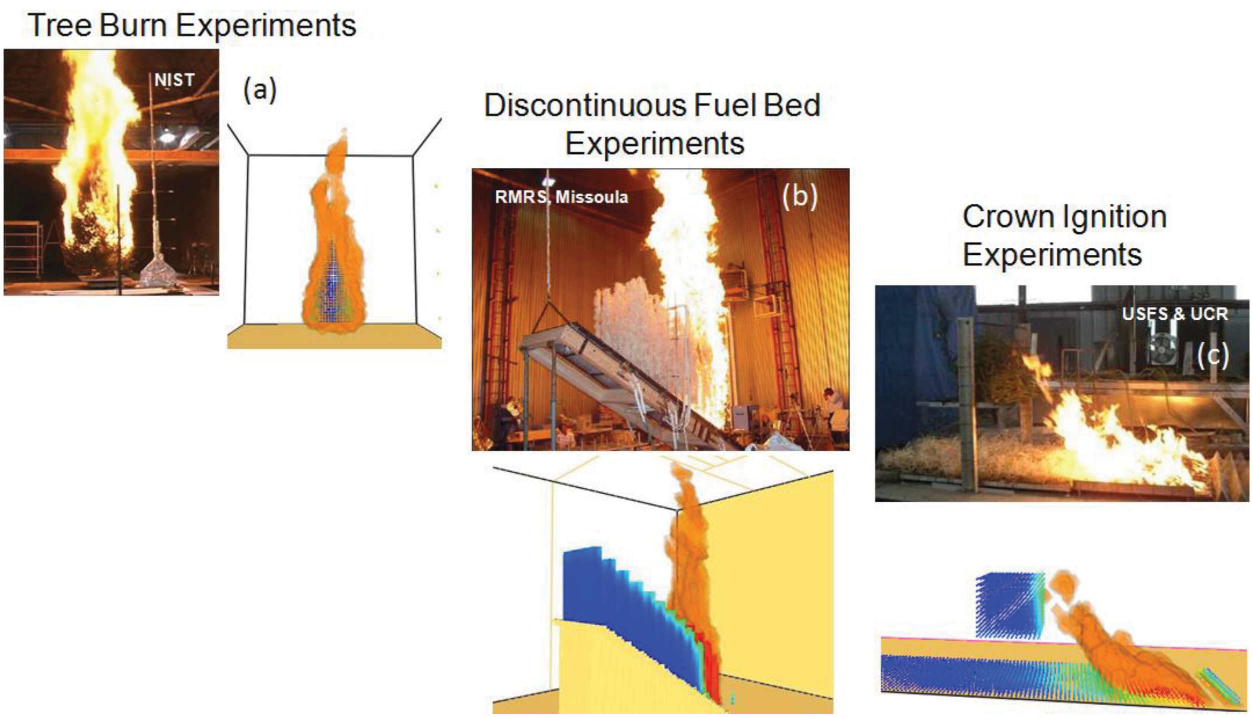


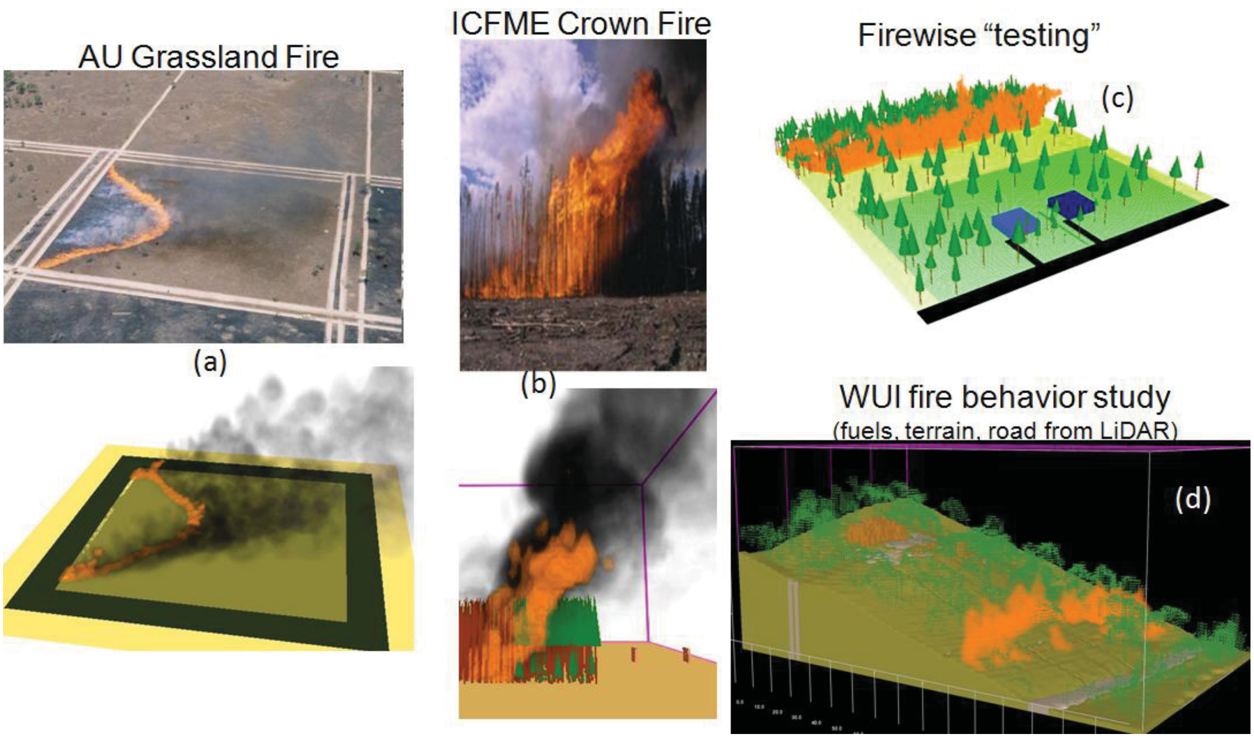
Fig. 1: Three images showing results from a grassfire simulation using WFDS. The grass land plot is 150 m long and 50 m wide. All figures correspond to the same time. From top to bottom: the fire perimeter and smoke plume; radiant heat flux; convective heat flux are shown. The scale for the heat fluxes also shown.

The next two figures illustrate the application of WFDS to laboratory-scale and stand-scale fire scenarios. In Fig. 1 laboratory cases are shown. Fig. 2a shows a snapshot in time from Douglas fir tree burning experiments and simulation. Trees of two different heights and a range of fuel moisture values were burned and simulated (Mell *et al*. 2010). In Fig. 2b a snapshot from the deep fuel bed experiments conducted in the USFS burn chamber in Missoula, Montana, and numerical simulation are shown. In these experiments rows of vertical steel rods, wrapped with excelsior fuel, were mounted on a platform. The spacing and height of the fuel rows was varied, along with the slope of the platform, to determine threshold conditions for fire spread along the entire platform. Experimental results are reported in Finney *et al*. (2010). In Fig. 2c a snapshot from the crown initiation experiments, conducted in the USFS laboratory in Riverside, California (Tachajapong *et al*. 2008 & 2008), is shown along with a result from WFDS numerical simulations of the experiment. These experiments are designed to investigate conditions under which an excelsior surface fire will ignite a raised fuel composed of chaparral branches and foliage. Papers reporting WFDS simulations of the experiments shown in Figs. 2b-c are in preparation. Predictions from WFDS for the cases shown in Fig. 2a-c are in reasonable agreement with measured results. These simulations were slower than real time and conducted using computational grid cells on the order of centimeters. See the Fig. 2 caption for further details on the simulations.



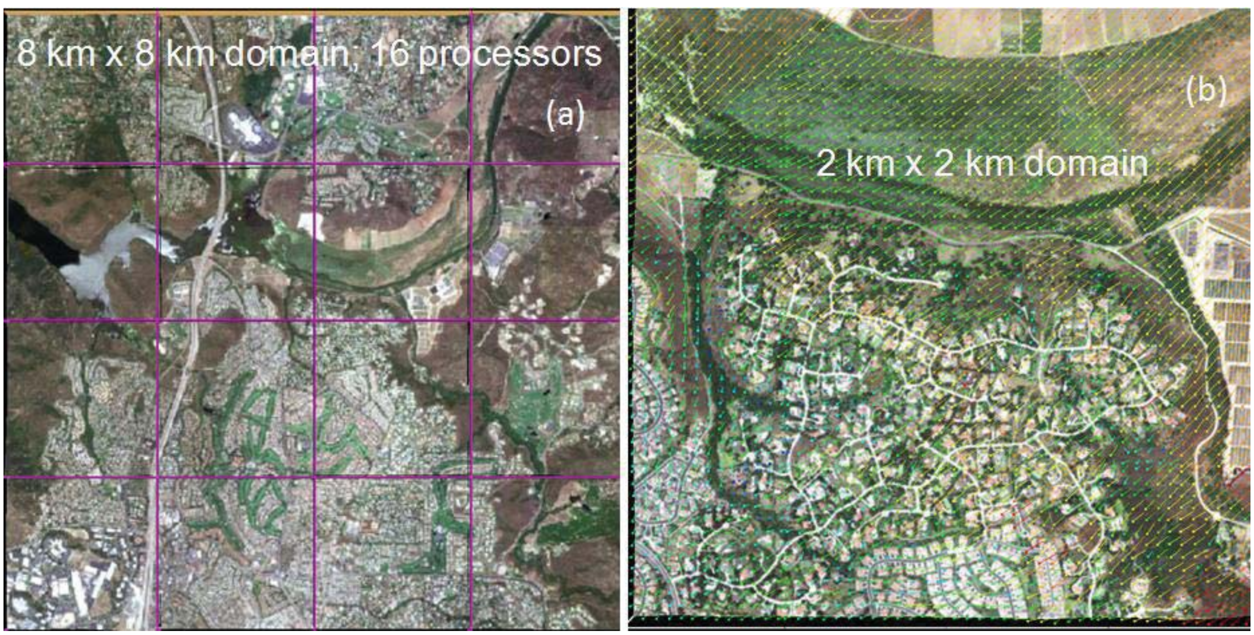
Figs. 2a-c: Examples of WFDS applied to laboratory scale fires: (a) Douglas tree burn experiments conducted at NIST (10 cm grid; 6 m x 6 m x 9 m domain; 300 times slower than real time with 4 processors). (b) Deep fuel bed experiments conducted in the USFS Missoula burn chamber (5 cm grid in fire region; 12 m x 10 m x 6 m domain; 180 times slower than real time with 10 processors). (c) Crown fire initiation experiments conducted in USFS Riverside laboratory (2 cm grid; 1.2 m x 1.2 m x 1.2 m domain; 80 times slower than real time with 6 processors).

Figs. 3a-d display results from WFDS as applied to stand-scale fire behavior scenarios. Fig. 3a is an Australian grassland fire spreading within the plot that is 200 m x 200 m in extent. The parabolic shape is a result of the ignition procedure. Two igniters begin at the middle and walked in opposite directions with drip torches. At the time of the photograph the ignition procedure had just ended. This ignition procedure was reproduced in the simulation. Results from the application of WFDS to this scenario are in Mell *et al*. (2007). In fig. 3b a snapshot from the international crown fire modeling experiments is shown. In the simulation, walls can be seen which reproduce a scenario in which the ignition of walls by the crown fire was studied (Cohen 2004). Fig. 3c is a result of a modeling study to compare the effects of different fuel treatments on fire behavior and heat fluxes on structures (Ginder *et al*. 2010). Results of this study are consistent with findings of the international crown fire modeling experiments (Cohen 2004). Fig. 3d is an example of using WFDS to simulate fires spreading over realistic terrain and vegetative fuels obtained from LiDAR data. The simulation studies shown in Fig. 3b and Fig. 3d are works in progress. The simulations in Fig. 3 used computational grid resolutions of approximately 1 m on 5 to 10 processors; these simulations were slower than real time. It is important to note that the same physics-based model (WFDS, in this case) was used to simulate the fire behavior across all the cases shown in Figs. 2 and 3. This is in contrast to empirical modeling where each scenario requires a different and independently derived empirical model.



Figs. 3a-d show stand scale examples of fire behavior and applications of WFDS: (a) Australian grassland fires (Mell *et al*. 2007) on 200 m by 200 m plots (1.7 m computational grid in fire region; 1500 m x 1500 m x 200 m domain; 125 times slower than real time with 10 processors). (b) Crown fire experiments conducted in the Northwest Territory of Canada (Cohen 2004). (c) Simulation only study of fuel treatment effectiveness in preventing structure ignition (Ginder *et al*. 2010) (0.5 m grid; 150 m x 112 m x 30 m domain; 200 times slower than real time with 8 processors). (d) Example of fire behavior simulation using terrain and vegetation obtained from LiDAR data.

Figs. 4a-b show examples of landscape-scale wind simulations from WFDS. The wind enters the computational domain from the northeast at a speed of 20 m s^{-1}. In Fig. 4a the computational domain is 8 km x 8 km in extent; in Fig. 4b instantaneous wind vectors 5 m above ground level are plotted and the domain is 2 km x 2 km covering a WUI community in the central region of Fig. 4a. The community shown in Fig. 4b was burned in the 2007 Southern California wildfires under Santa Ana wind conditions and is currently the subject of an in-depth study (Maranghides and Mell 2010). Both simulations shown in Fig. 4 used 16 processors. The spatial domains for each processor (2 km x 2 km) for the 8 km x 8 km case are shown as red squares in Fig. 4a. Depending on the grid cell size, wind simulations can be faster than real-time. For example, the 8 km x 8 km simulation with a horizontal grid resolution of 40 m and a vertical grid resolution of 20 m is 10 times faster than real-time. If the grid resolution is increased by a factor of two in each direction the simulation runs three times slower than real-time. The 2 km x 2 km case in Fig. 4b used a 3 m horizontal and 2 m vertical resolution and ran 180 times slower than real-time with 16 processors. The influence of the terrain on the wind can be clearly seen in the valley on the western edge of the community where the wind is redirected to the south.



Figs. 4a-b: Examples of landscape scale wind simulations from WFDS. (a) An 8 km x 8 km domain. Computations used 16 processors whose spatial domain is outlined by the red squares. (b) A 2 km x 2 km domain over a community in the center of Fig. 4a. Wind vectors at 6 m above ground level are plotted. The ambient wind enters the domain from the northeast at 20 m s^{-1}. See text for a discussion on simulation specifics.

Figs. 1 - 4b illustrate that physics-based models have developed to the point where they can be used to investigate fire behavior trends and even, to some degree, quantitative measures of fire such as heat fluxes and spread rates. While these models do not operate faster than real-time they can be used to develop and assess simpler fire spread (faster than real-time) models, as will be discussed in the next section. As affordable computers continue to improve in speed and memory capacity, the capabilities and range of applicability of physics-based models will improve. In addition, unlike empirical models, the accuracy of well-designed physics-based models will improve due to increased spatial resolution. As a benchmark, when the Rothermel (1972) surface fire spread model was published, IBM's flagship computer (IBM 370) cost 500 times more, and had one 1/6000 the memory and 1/800 the processing speed of current top-of-the-line laptops.

Example of a simple fire spread model (level set)

The simple fire spread model considered here is based on a level set method (Rehm and McDermott 2009) and is currently under development at NIST. This method is based on solving the equation for the evolution of a scalar field, ϕ, which has values -1 to 1:

$$d\phi/dt + \mathbf{R} \cdot \text{grad}(\phi) = 0 \quad (1)$$

where $d\phi/dt$ denotes the partial derivative of ϕ with respect to time; **R** is the spread rate vector; and grad(ϕ) is the gradient of ϕ. In fluid mechanics Eq. (1) is the material derivative of ϕ, where **R** would be the fluid velocity vector. Thus, an element following the 'streamline' of ϕ which is initially zero (i.e., the fireline location) will remain zero. The spread rate vector **R** is a prescribed function of environmental variables (e.g., wind, slope, vegetative fuel).

In the examples presented here, **R** is a function of the local slope (using rules from the McArthur Forest Fire Danger Meter [McV, 2010]), the angle (θ) between the normal to the fire line and the direction of the wind (see Fig. 5), and prescribed values for the head-, flank-, and back- fire spread rates (here these are obtained from WFDS simulations). **R** is not a function of the fuel type, in the examples below, because only one fuel is considered: grassland. It is also assumed that the spread rate depends on the magnitude and direction of the ambient wind, as opposed to the local wind in proximity to the fire line. This implementation of the level set is commensurate with FARSITE as applied to surface fires. An implementation that includes more environmental information would, for example, use the direction and magnitude of the wind in proximity to the fire line (instead of the ambient wind). This local wind field could be obtained from separate wind simulations such as those shown Fig. 4a-b, above. In this case, the resulting implementation of the level set method would be commensurate to the use of FARSITE and WindNinja (for wind fields) (Forthofer and Butler 2007).

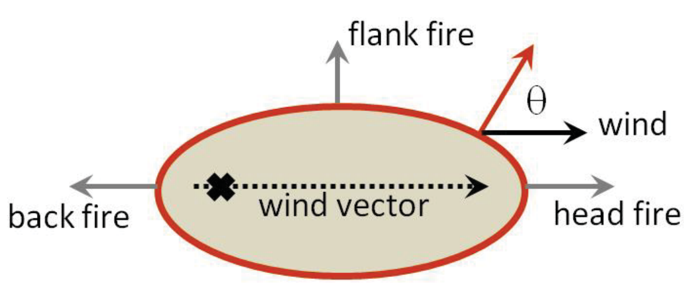


Fig. 5: Schematic illustrating the components of the level set model for fire spread. The red line represents the fireline. The direction (obtained from the model) and magnitude (prescribed) of the head-, flank-, and back- fires are required.

This level set model approach is 'empirically-based' (with the measured data obtained from numerical experiments), faster than real-time, and can predict the spread of the fire line using spread rate 'maps'. These maps would define the spread rates on a landscape for many environmental scenarios (e.g., various fuel, wind, whether, and terrain conditions) and could be based on observations, measurements, or model predictions. The predictions are only as good as the rules and the rules themselves can become complicated, as with any approach that links rule-based or different empirically-based models together. An example would be rules that attempt to capture the complex processes involved in the transition from a surface fire to a crown fire and vice versa.

Fig. 6 plots the fire line location, in an Australian grass fire experiment (Mell *et al*. 2007), at three different times as measured (symbols) and predicted by the level set model (solid lines). For this implementation of the level set model, the head fire spread rate is obtained from the empirical model derived from experimental database and the flank fire spread rate is prescribed. A photograph of the fire line, at the time of 56 seconds, is shown in Fig. 3(a). The level set model does a good job of predicting the spread rate of the head fire (as expected given that the empirical spread rate is used) and a reasonable job of predicting the rest of the fire line. A break in fire line symmetry about the head fire point (in both the measured and simulated fire lines) occurs after 86 s due to a wind shift (which was not measured). The level set simulation was 25 times faster than real time using one processor. Note that the WFDS simulation (not shown, see Mell *et al*. 2007), with the same grid resolution, was 125 times slower than real time with 10 processors.

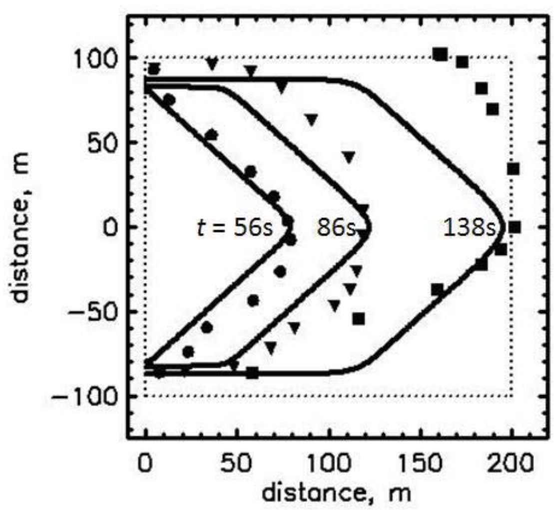


Fig. 6: Level set (solid lines) and experimentally measured (symbols) fire lines at three different times for an Australian grass fire (Mell *et al*. 2007). Grass plot and computational domain is 200 m x 200 m. Level set simulation with a 1.7 m grid resolution was 25 times faster than real time with one processor.

Developing and testing the level set model using the physics based model (WFDS)

This section presents some preliminary results from an approach which uses the physics-based model, WFDS, to determine the head- and flank- fire spread rates for use in the level set model. The level set model was then tested for transition scenarios in which the fire spread from natural to treated grasslands and vice versa. No backing fire was present because ignition took place along a firebreak. The ambient wind speed was 10 m s^{-1}. The WFDS simulations for determining spread rates were made in a computational domain of dimensions 300 m x 150 m x 25 m and a grass plot of dimension 100 m x 50 m (the computational domain must be sufficiently large to ensure that the boundary conditions do not influence the fire behavior). WFDS simulations on much larger domains (2700 m x 2700 m domain and 900 m x 900 m grass plot) were also conducted and compared to level set predictions to determine if spread rates obtained from simulations on small domains would be applicable (this is discussed in the following section). Fuel characteristics for natural grass were based on field measurements: 0.3 kg/m² loading, 0.5 m height; 120 cm^{-1} surface area to volume ratio; 6% moisture (Cheney *et al*. 1998; Mell *et al*. 2007). Treated (cut) grass had a fuel loading and height reduced by cutting the grass to 1/5 its height (0.1 m) and removing the clippings (0.06 kg m^{-2} fuel loading).

Fig. 7 shows results from WFDS and level set model predictions of a fire spreading through natural (untreated) Australian grass from a point ignition. Color contours show WFDS burning rates and the red lines show the fire line position as predicted from the level set model. The head- and flank- fire spread rates from WFDS were used in the level set model. It is known from field measurements (Cheney *et al*. 1998) and reproduced in physics-based models (e.g., Mell *et al*. 2007) that the head fire spread rate increases until the width of the head fire is sufficiently large (~50 m). For this reason, this WFDS simulation will be used to obtain the flank fire spread rates for the level set model.

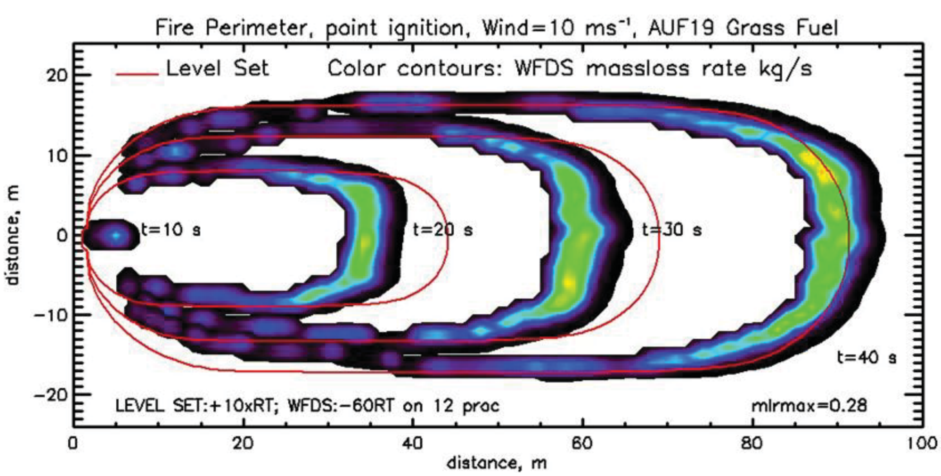
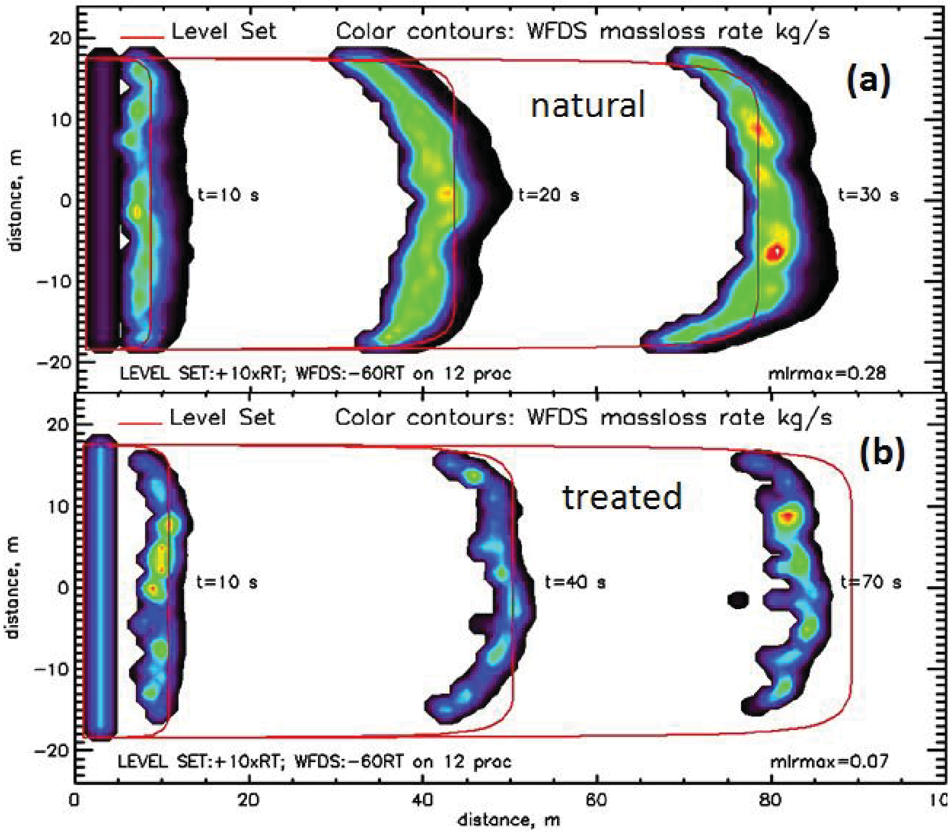


Fig. 7: Results from a WFDS and level set model simulations of fire spread through Australian grass (fuel properties are listed in the text). Color contours are mass loss rate from WFDS; red line is the fire line from level set. Ambient wind in 10 m s^{-1} and a point ignition was used. Level set was 10 times faster (one processor) and WFDS was 60 times slower (12 processors) than real time. The head and flank fire spread rates from WFDS were used in the level set model.

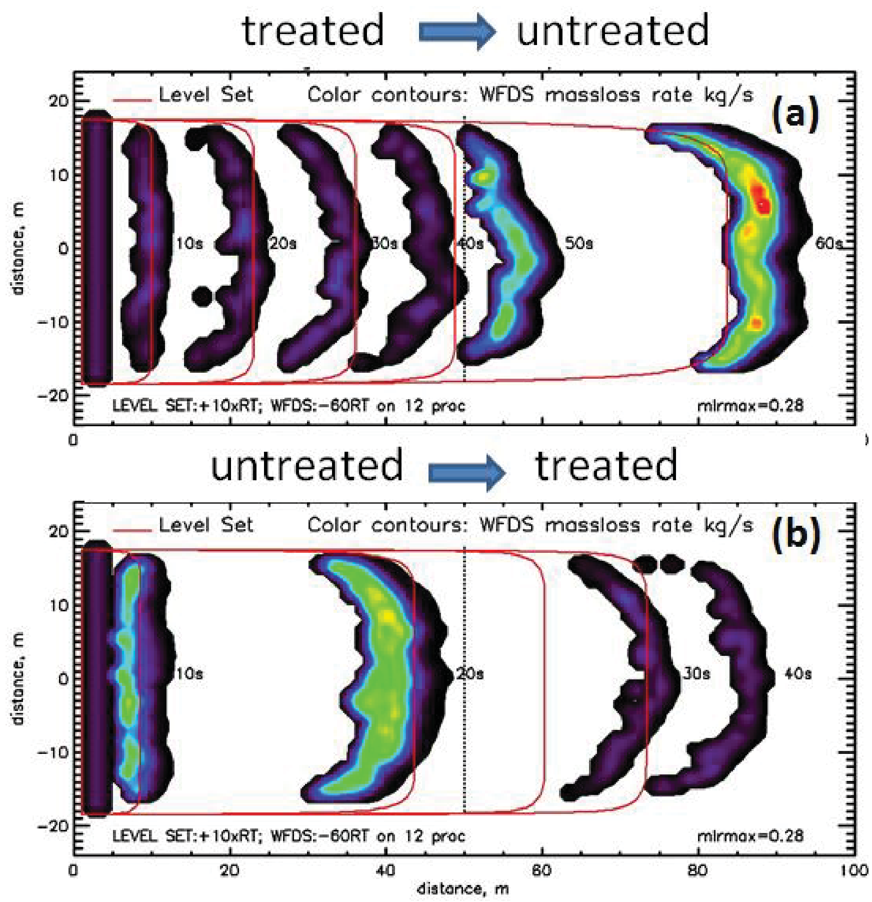
Head fire spread rates for the level set model were obtained from WFDS simulations of grassland fires using a line ignition (no flank fires were present). Figs. 8a-b show the results of these simulations for natural (Fig. 8a) and treated or cut (Fig. 8b) grass. As in Fig. 6, color contours show the burning rate (kg s^{-1}) from WFDS and red lines show the location of the fire line from the level set model. Fire spread and mass loss rate in the treated grass was significantly lower than in the natural grass. Spread rate in the treated grass is about half its value in the natural grass. The maximum burning rate in the untreated case is 0.28 kg s^{-1} and 0.07 kg s^{-1} in the treated grass. The area of active burning is also significantly larger in the natural grass case. The level set model head fire spread rate was obtained from WFDS after a quasi-steady spread rate was established, well past any period of time required for ramp-up from ignition.
Predictions from both models for the case when the fire spreads through a change in fuel loading are shown in Figs. 9a-b. The location of the fire line is plotted every 10 s; time labels are positioned next to the WFDS fire locations. A vertical dotted line gives the location of the fuel loading change. Prior to the transition in fuel loading, the level set and WFDS models are in good agreement. In Fig. 9(a), the fire spreads from treated to untreated grass. The WFDS mass loss rate contours clearly show the increase in fire intensity when spreading from treated to untreated grass. The level set significantly over-predicts the spread rate after the transition because it is based on the quasi-steady spread rate in WFDS and so does not account for the ramp up from ignition to established spread rate. This fire acceleration period is a known fire behavior phenomenon and FARSITE (Finney 2004) has an adjustable parameter to account for it with default values based on field observations of fires in different fuels, etc.



Figs. 8a-b: WFDS (color contours of mass loss rate) and level set (red lines) model results for fire spread in Australian grass. (a) natural grass, (b) treated grass (natural grass cut to 1/5 its height, clippings removed). Note that the maximum mass loss rate was 0.28 kg s^{-1} for the natural grass and 0.07 kg s^{-1} in the treated grass; the color contours are scaled to show red for the maximum mass loss rate in each case.

In Fig. 9(b) the fire spreads from untreated, natural, grass to treated grass. In this case, the level set location of the fire line lags the WFDS location (opposite of Fig. 9(a)) even though the quasi-steady spread rate from WFDS is used in the level set model. This occurs because, in WFDS, the treated fuel is pre-heated by the approaching, high intensity, fire in the untreated fuel. This causes the fire in the untreated fuel to accelerate rapidly and outpace (note the separation distance between WFDS fire locations in the 10 s interval between 20 s and 30 s) the level set predictions. However, by 30 s the WFDS fire has decelerated and, although it leads the level set fire, is spreading at a rate equal to the level set (as can be seen by comparing the separation distance between the fire locations at 30 s and 40 s in both models). In FARSITE it is assumed that the fire will decelerate instantaneously (Finney 2004).

The results shown in Figs. 8a-b and 9a-b are meant to be illustrative of one type of fire transition that cannot be captured by simple models without additional ‘tuning ‘ or calibration. How important these particular fire behaviors, and others, are requires further study. This type of study is especially important if simple models are to be applied to complex, realistic, landscapes with heterogeneous fuels (such as fuel treatments).



Figs. 9a-b: Results showing the model predictions when the grassland fuel loading changes: (a) from treated to untreated treated (1/5 fuel height and loading) and (b) from untreated to treated. A vertical dotted line denotes the boundary between fuel loadings. The location of the WFDS fire line is shown every 10 s. WFDS results are color contours of mass loss rate (scale of contours is the same for both figures) and level set model results are the red lines showing fire line location. See text for discussion.

Application of the level set model to landscape scale fires

The last section presented preliminary results from the application of the level set and the WFDS models to relatively small domains (200 m x 150 m computational domain). A question relevant to the development of empirical models of landscape fire spread is: Can spread rate formulas based on measured data sets from relatively small-scale field experiments be legitimately applied to large landscape scale fires? (The same question is even more pressing when laboratory measurements form the basis for the empirical model – but that issue is not considered here.) This question also holds for the modeling approach used here: Can WFDS simulations over relatively small domains be used to develop a level set model for application to landscape scales? A first step to investigating this was performed by simulating a much larger grassland fire.

The landscape-scale grassland plot is 900 m x 900 m and the fire was ignited along a 400 m ignition line (this should be viewed as an approximation to a fire that developed from a much smaller ignition). The head and flank fire spread rates from the smaller scale WFDS simulations in untreated grass fuel (discussed in the previous section) were used in the level set model. A comparison of the WFDS and level set models is shown in Fig. 10. The level set predictions, although based on smaller scale WFDS simulation, well predicted the large-scale fire perimeters. In as much as WFDS is capturing the physical processes driving fire behavior for this larger scale fire these results imply that smaller scale simulations, and field experiments, can be used to develop simple fire spread models applicable to landscape scales. It should be kept in mind that the scenario considered here is about as simple as you can get: flat terrain, a single thermally thin fuel type, and a constant wind. There is a great need for a well conceived, coordinated, and comprehensive field measurement effort to test these conclusions.

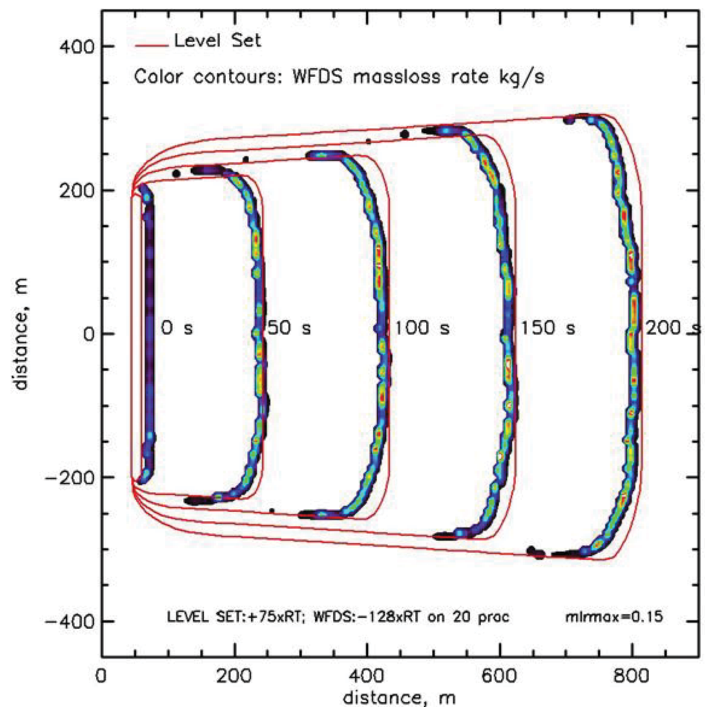


Fig. 10: Comparison of the WFDS and level set model predictions of grassland fire perimeters. The computational domain is 2700 m x 2700 m x 200 m with a grassland plot of 900 m x 900 m (area of figure). Fire perimeters are shown every 50 s. Level set head and flank fire spread rates were obtained from smaller scale (100 m x 50 m grass plot) WFDS simulations.

Fig. 11 provides a final illustrative example of the use of the level set model and its development and testing via a physics-based model such as WFDS. This figure shows the result of applying WFDS and the level set models to an area occupied by a community in southern California. This community was burned in the 2007 southern California wildfires and, as mentioned above, is the subject of an ongoing case study (Maranghides and Mell 2010). As a first step in assessing the performance of the simple level set model to this situation of interest, the entire landscape (2 km x 2 km) was covered in grass. Note that the community is on a hill, with a large valley to the north and two smaller drainages on the west and east (see Fig. 4b for wind vectors without a fire present). Santa Ana wind conditions (20 m/s from the northeast) were simulated. Both the head- and flank- fire spread rates used for input to the level set model were obtained from the WFDS simulation. The level set model assumes a constant wind direction from the northeast and used rules from the McArthur Forest Fire Danger Meter (MkV 2010) for the spread rate dependence on slope. Overall, the leading head and southeastern flank locations were well predicted by the level set method. The western flank was not as well predicted. While more testing and evaluation is needed, the most likely cause of this, based on examination of the WFDS results, is the lack of fire induced winds in the level set model. The western flank fire, in WFDS, significantly redirected the ambient winds toward the fireline, resulting in a faster spread rate.

Fig. 11: Simulation of firespread over a 2 km x 2 km region with complex terrain encompassing a southern California community. The terrain was obtained from LiDAR data. For simplicity, and as a first step in model testing, the entire domain is covered in grass (image showing the roads, structures, and vegetation is used for ease of reference when comparing the figures). The WFDS (level set) simulations required 41 million (2000) grid cells; 16 (1) processors; and were 400 times slower (5 times faster) than real time.

Summary and conclusions

An approach for using a complex, physics-based WFDS model to develop and assess a simple model level set model was presented. For simple scenarios with flat ground, constant wind speed and direction and simple fuel (grass), the level set model shows promise. Simulation results on relatively small domains were used to build simple models applicable to larger scale simulations. This has implications on field studies also: measurements from smaller stand-scale fires, which are more logistically and fiscally feasible, can potentially be used to develop models for, and improve our understanding of, landscape-scale fire behavior. The simple level set model can be easily and efficiently applied to more complex scenarios. Further testing of the simple model, over a range of environmental conditions (varying fuels, terrain, and winds) is underway.

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