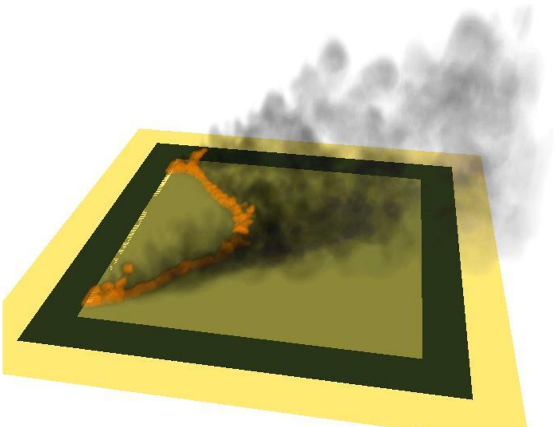
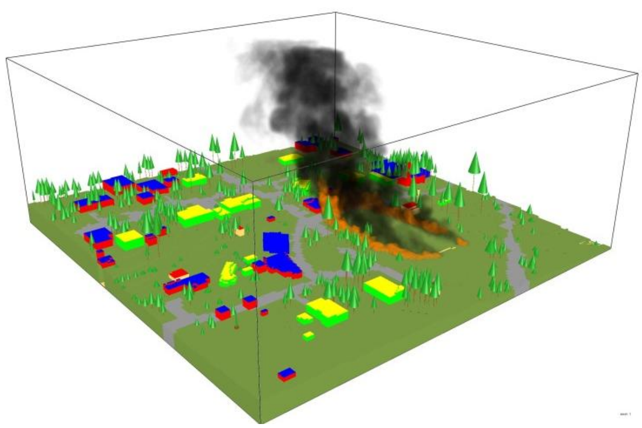
Models for Fire Spread in the Wildland-Urban Interface

Final Report to the Joint Fire Science Program





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I. **ABSTRACT**

The last 15 years have seen the development of wildland and wildland-urban interface (WUI) fire behavior models that make use of modern numerical methods in atmospheric 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 the limitations of simpler models and a means of improving them. In this project the Wildland-Urban interface Fire Dynamics Simulator (WFDS) computer model suite was developed. The WFDS suite includes a physics-based fire model and a simple fire perimeter propagation model based on a level set method. The basic implementation of the level set fire perimeter model is equivalent to FARSITE in that they both provide a method for propagating a fire perimeter based on prescribed spread rates for the head, back, and flank fires.

The WFDS-physics-based model produces a time evolving fireline that agrees well with AU grassland experiments. The WFDS-level set approach produces fire perimeters that are similar to FARSITE's for simple scenarios. These findings support the use of the WFDS-physics-based model to evaluate the performance of the WFDS-level set model and, by surrogate, FARSITE. Fire propagation via the level set approach agrees with the physics-based results for surface fires with uniform grassland fuel on level ground. However, there are significant discrepancies between the physics-based and level set fire perimeters under scenarios of interacting fire lines, fire spread around a single fuel break, fire spread through multiple fuel breaks representing a WUI community, and spread up a slope. These discrepancies are consistent with the limitation of the level set model to fires evolving in a quasi-steady manner with constant head, flank, and back fire spread rates. Non-steady fire-atmosphere interactions, which resulted in non-constant spread rates, are present for cases in which the physics-based and level set models disagree.

Given the growing interest in the development and application of WUI risk assessment methods that use FARSITE-type simple fire perimeter propagation models, it is important to identify the potential shortcomings of these models. Physics-based models are an approach to meet this goal. We do not claim, at this point, that we know how well the physics-based models will work in general. But we do believe that, since they include the driving physical processes, they offer a promising way to investigate and identify "watch-out" scenarios in which the simple fire perimeter propagation models are most likely to be in error. The WFDS model suite developed in this project provides a framework for conducting this investigation.

II. BACKGROUND AND PURPOSE

Over the last several decades, fires in the wildland urban interface (WUI) have become increasingly costly in terms of expenditures for fire suppression and damages to manmade structures and infrastructures, as well as natural environments (e.g., Mell et al., 2010a). In response to the growing wildfire problem and resulting financial strain, Congress passed the FLAME Act **(**2009) to provide a reserve of funds to cover suppression costs beyond those normally appropriated to the Forest Service and the Interior Department.

The FLAME Act also calls for a national cohesive wildland fire management strategy to address a number of issues, including the assessment of risk to WUI communities and prioritization of the treatment of hazardous fuels. A webpage providing an overview of the cohesive strategy is available (CS, 2012). With regard to the WUI, a risk-based approach is attractive since it can provide a framework for prioritizing wildland fuel treatments. The cohesive strategy document, Lee et al. (2011), provides a number of examples, though not all are referenced, in which a measure of risk is obtained using fire perimeter models. For example, Ager et al. (2010) used fire perimeter models to obtain fire risk measures for structures and old growth stands.

The fire perimeter models used in the risk studies that are referenced in the cohesive strategy document employ semi-empirical and empirical formulas for head fire rates of spread in surface fires (Rothermel, 1972). These are linked to rule based and empirical models of crown fire initiation and spread rate (Scott and Reinhardt, 2001; Finney, 2004). The FARSITE model uses these head fire spread rates, along with assumptions on the shape of a fireline spreading from a point, to predict fire perimeter evolution (Finney, 2004). In most applications, wind fields are assumed to be constant in magnitude and direction. The simplicity of FARSITE allows faster than real time predictions of fire perimeter evolution over a landscape. Indeed, in recent in risk assessment applications FARSITE (or a derivative of its fire perimeter propagation method) is run thousands of times, for a given landscape, to obtain predictions of burn probability (e.g., Ager et al. 2010**,** Finney et al., 2011).

However, models with empirical formulas, such as FARSITE, need to be used with care when applied outside the range of the environmental conditions (such as high wind speed and/or heterogeneous fuels and/or topography) for which the empirical correlations were obtained. For example, the application of FARSITE to actual fires often requires extensive calibration and site specific wind fields to better approximate observed fire perimeters (e.g., Stratton, 2006; Arca et al., 2007). In addition, the empirical or semi-empirical formulas employed provide only the head fire spread rate. The flank and backing fire spread rates are obtained from the head fire spread rate and the assumption that the local fire perimeter spreads as an ellipse with an assumed length/width ratio based on the wind speed. Flame lengths depend on predicted fireline intensity according to a chosen correlation. The limitations and assumptions discussed above make interpretations and conclusions based on FARSITE (or any similar simple fire perimeter propagation model) problematic.

The purpose of this project is to develop the capability to assess the limitations of simple fire perimeter models. For the foreseeable future there will be a need for such simple fire perimeter models because of their fast turnaround time. An assessment of fire models could be performed through a well-founded and comprehensive set of fire behavior, wind, fuel, and terrain field measurements, but this is not likely due to prohibitive logistical and financial requirements. Another, more feasible, approach is to use targeted field and laboratory measurements in combination with model inter-comparisons (Mell et al., 2010a). This project focuses on the development of a suite of models of varying complexity to support an investigation into the limitations of simple models (Mell et al. 2010b). This suite is called the Wildland-Urban Interface Fire Dynamics Simulator (WFDS). (Not to be confused with the WFDSS, the Wildland Fire Decision Support System.) It is outside the scope of this project to conduct a comprehensive evaluation of the simple models. However, the building blocks for supporting such an evaluation are developed and initial assessments are made.

It is important to note that we do not know how well WFDS, or any other wildland fire model, physics-based or otherwise, captures the behavior of actual wildland fire over a comprehensive and relevant range of topographical, vegetal and meteorological conditions. What we do know is that the physics-based component of WFDS accurately simulates the head and flank fire behavior of the single Australian (AU) grassland fire case (experiment C064) we have to compare against (see Section IV: Key Findings below). This is, to date, the only reported experiment of a single fire with extended, freely evolving, flank fires. We also know that the physics-based WFDS is able to directly account for the coupling of fire and atmospheric processes, as well as the influence of terrain on wind. Simple, semi-empirical fire perimeter models do not directly account for these processes. Instead, as mentioned, they depend on engineering correlations and measurements from experiments, often performed at only the laboratory scale, and so great care needs to be exercised in applying the results of these models to the range of conditions normally encountered in wildland fires.

Table 1 contains an overview of the differences between complex (more physics) and simple (less or no physics) fire modeling approaches. The more physics-based models take longer to run and explicitly account for the coupled physical processes. In this project, the physics-based component of WFDS is used for the complex fire model. A level set approach was selected, after comparison with a similar model, to represent simple fire perimeter models in tests against the WFDS physics-based model. The level set model is integrated into the WFDS framework. This allows the user to run either the WFDS-physics-based or WFDS-level set model using the same compiled executable, similar input files, and view the results with Smokeview (Forney, 2010). Further details of the WFDS-physics-based and WFDS-level set models are provided in the next section and in the Appendices.

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

Complex Fire Behavior Models (more physics)	**Simple Fire Behavior Models** (less, or no, 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 convective and radiative heat fluxes, winds, firebrand transport and deposition	Cannot directly provide heat fluxes; winds are usually prescribed; empirical firebrand modeling
Directly captures fire-atmosphere interaction	Cannot capture fire-atmosphere interaction
Directly handles variable fuels, terrain, weather	Influence of variable fuels and terrain is handled empirically

Special emphasis is placed on assessing the similarities of the simple level-set fire perimeter model to FARSITE. This is done in order to determine if findings regarding the capabilities and limitations of the level-set fire spread model are also representative of FARSITE. This was not originally part of the proposed work. However, since the proposal for this work was submitted, FARSITE, and similar models, have been increasingly used to provide an assessment of fire risk in WUI areas (e.g., Ager et al., 2010; Finney 2011). Evaluating FARSITE has, therefore, become much more relevant, especially given the potential financial and physical risks embodied in such assessments.

III. STUDY PLAN AND DESCRIPTION OF THE MODELS

Overview of models considered

In general, fire behavior is the result of the coupled interaction of the fire, vegetation, wind, and terrain. The models considered here differ according to how explicitly, or directly, the physical processes present in these interactions are captured. Figure 1 shows a diagram, which was present in the proposal for this project, of eight different modeling approaches.

The left-hand side group of models in Figure 1, "Simple Modeling Approaches", use semi-empirical, empirical, or rule-based spread rate formulas that are functions of the wind, slope, and fuel. The degree to which the net wind (ambient and fire induced) is physics-based distinguishes these models from each other. For example, the simplest model, A1, which assumes a constant wind direction and speed, is compatible with FARSITE. Two simple modeling approaches were considered initially: a Lagrangian based approach (Rehm, 2008; Rehm and Mell, 2009) and an Eulerian approach implemented by the so-called level set method. As stated above, the simple model component of the WFDS model suite uses a level set approach for fire perimeter propagation.

The group of models on the right-hand side of Figure 1 are physics-based and, therefore, directly account for the coupled interaction of the fire, vegetation, wind and terrain. The physics-based component of WFDS (Mell et al. 2007; Mell et al. 2009) is used. This solves the fully three-dimensional, time dependent equations governing mass, momentum, and energy. This includes the three-dimensional radiation heat transfer equation in the gas phase. The endothermic processes of water and fuel vapor creation during thermal degradation of the vegetative fuel are also accounted for.

More detailed descriptions of the simple and complex fire spread models considered and developed in this project are given in the Appendices.

Study Plan

Three fire spread models are developed and put through basic evaluations to ensure they are robust. These three models and a fourth, officially released, fire perimeter model (FARSITE) are also evaluated to determine if, or how, they could be used in a wider model inter-comparison. Again, the purpose of this model inter-comparison is to better understand and quantify the limitations of simple models – thereby paving the way for performance improvements and guidance to users. In order to facilitate this work only grassland fuels are considered. Model comparisons in more complex fuel systems will be undertaken later.

When possible, model predictions are compared to field measurement of fire perimeter evolution. There are, however, very few well characterized measurements of the time evolution of field scale (~100 m or longer) fire perimeters that include the head, flank, and backing fires. (By well characterized we mean that the wind, fuel, and terrain are sufficiently well measured to provide the necessary inputs for physics-based models). The exception to this is the fire perimeter measurements conducted in AU grassland fires. These fire perimeters were compared to the physics-based component of WFDS in Mell et al. (2007) and will also be used here.

For scenarios in which there are no well characterized field measurements (e.g., interaction of multiple fires, spread around fuel breaks, or spread up a drainage) simple models were compared to results from the physics-based WFDS model. These inter-model comparisons provide a first assessment of how well the simple model performs compared to a model that does include coupled physical processes.

The original proposal for this work included the model C1 in Figure 1. This model is not considered here because neglecting the fire induced wind would prohibit the buoyant rise of the fire and smoke plume, leading to an unrealistic distribution of heat and radiant fluxes. Also, the model A3 and B3 have not yet been developed. Instead, this effort was diverted to comparison of FARSITE and the level set model for reasons discussed previously at the end of Section II.

Vegetative Fuels
This first stage in the development of the suite of models in Figure 1 is facilitated by considering only the surface fuel of AU grassland fires. This also has the advantage that measurements of fire perimeter progression exist for this fuel, which supports model validation. It should be noted that the physics-based component of WFDS is capable of simulating raised fuels (e.g., Mell et al., 2009). This capability was developed as part of this project.

Ambient Wind
Overall, two ambient wind speeds are considered: a low and a higher wind speed. This is done in order to run the models in plume dominated and wind dominated regimes. In plume dominated fires, the winds caused by the fire are a significant contribution to the net wind in proximity to the fire. These fire induced winds are not explicitly captured in the simple models.

Terrain
Both level terrain and sloped terrain are considered. Level terrain is consistent with the AU grassland experiments. Two types of sloped terrain are considered: one with a flat slope and one with a drainage imbedded in the flat slope. Fire spread up a slope is particularly important because *fire-induced* winds can have the potential to cause rapid fire spread or life threatening blow ups or "fire eruptions."(Viegas, 2005; Viegas and Simeoni, 2010).

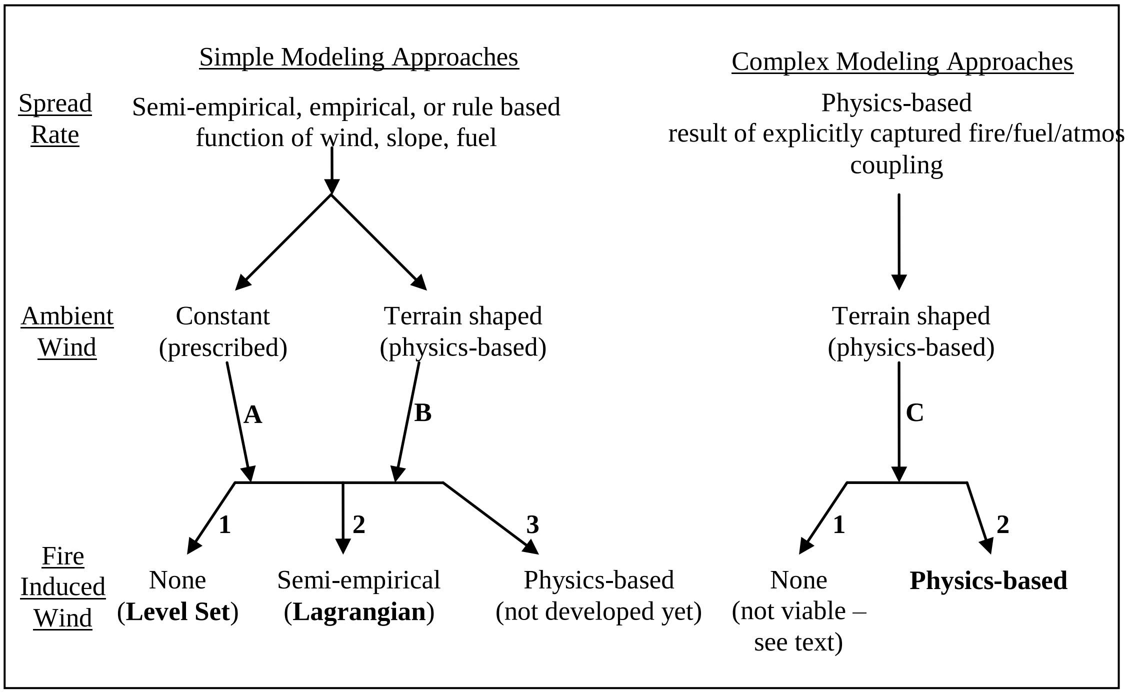

Figure 1: Schematic diagram showing eight different modeling approaches (A1, A2, A3, B1, B2, B3, C1, C2) presented in the original proposal for this work. The left group uses a spread rate that is a simple function of the wind, slope, and fuel or is prescribed to produce a prediction of fire perimeter propagation. The right group explicitly captures the coupled physical processes governing the fire / fuel / atmosphere interaction. Note models A-1 and B-1 are compatible with FARSITE and FARSITE-WindNinja, respectively. Model A-1 developed here is call WFDS-level set. Model C-2 is the physics-based WFDS.

Approach Used for Comparing FARSITE and WFDS-Level Set Models

FARSITE outputs include 'time-of-arrival' (TOA) in raster format, i.e., the time at which the fireline reaches a point in the raster grid that represents the landscape. The level set model was modified to include this output so that the models could be compared by superimposed contour plots of TOA isochrones. The models were compared over a number of scenarios involving flat and sloping terrain, multi-point ignitions and nonflammable patches. Topography and ignition patterns were matched as closely as possible between the two models. Details may be found in Appendix 5.

Approach Used for Comparing WFDS- Level Set to WFDS-Physics-Based Models

Fire perimeter predictions from the two models were compared to perimeter measurements from AU grassland experiments. For other scenarios, for which there are no field measurements, the level set model is compared to the physics-based model after first calibrating the level set so it reproduces the physics-based fire perimeters in base case scenarios. The models were compared over a number of scenarios involving level or sloping terrain, multi-point ignitions and nonflammable patches.

IV. KEY FINDINGS (RESULTS AND DISCUSSION)

1. *Introduction to Findings*

This study is a first step toward a better understanding of the advantages and disadvantage of simple fire spread model. The following discussion was kept to one to two paragraphs for each section, as requested in the final report guidance. Further information and, especially, details on the models can be found in the Appendices.

It's important to note that simple landscape fire spread models are expected perform best under environmental conditions (fuel, wind, terrain) that result in quasi-steady head, flank, and back fire spread rates. In such conditions, the location of the head, flank, and back fires are known from their near constant spread rates. Given these spread rates, the main task for the simple landscape model is to create a realistic fire perimeter that connects the known head, flank, and back fire locations. The head, flank, and back fire spread rates can be obtained from measurements, other models, best guesses, etc. These spread rates can be functions of wind, terrain, and fuel characteristics. They implicitly include the interactions between the fire, fuel, terrain, and wind. But these interactions are such that the resulting spread rate is quasi-steady. While it is possible to account for unsteady fire behavior with simple models, through additional rules and empirical formulas of limited application scope, this runs the risk of over complicating the simple model and confounding an understanding of its error in complex (realistic) settings. On the other hand, physics-based models can directly account for the fire, fuel, terrain, and wind interactions and can be used across a wide range of environmental conditions, whether they result in a quasi-steady spread or a highly transient behavior. While approximations are made in physics-based modeling, they are directly related to the basic physical processes present in *any* relevant environmental setting. Thus, any improvement of physics-based models for specific environmental conditions can result in improvements in model performance for a wide range of environmental conditions with little change in model complexity.

The major challenges for the development and implementation of simple models for landscape fire spread are, therefore, to:

i. Move the fire perimeter in a computationally efficient manner that's generally applicable.
ii. Obtain accurate head, flank, and back fire spread rates
iii. Identify the environmental conditions for which the spread rates will not be quasi-steady and determine a measure of the expected model prediction error for these scenarios.

Three simple fire spread models are considered here. Two were developed as part of this project. They are called the Lagrangian-based and level set approach. The third is FARSITE (Finney 2004) which is has been in use for a number of years and forms the basis for many existing fire prediction tools. We do not consider computational efficiency here, but the simple models considered are all faster than real time.

In the results reported below for the Lagrangian and level set simple models, the spread rates are obtained from an empirical formula (for the head fire) or the WFDS-physics-based model.

The empirical formula used here for the head fire spread rate in AU grassland fires is (Cheney et al., 1998; Mell et al., 2007):

(1) $R = (0.165 + 0.534U_2) \exp([-0.859 - 2.036U_2]/W) \exp(-0.108M)$ (m/s)

Here U_2 (m/s) is the ambient wind speed 2 m above the ground, W (m) is the width of the head fire, and M (%) is the moisture content on a dry mass basis. Comparison of the outputs of simple model to measurements and the predictions of the WFDSphysics-based model is a first step to identifying environmental conditions that result in model error.

In the WFDS-physics-based simulations below, unless otherwise stated, the ambient wind has the following dependence with height:

(2) $u(z) = U_2 (z / z_2)^{1/7}$ where U_2 is the wind speed at the height $z_2 = 2$ m (m/s)

2. Level Set versus Lagrangian-Based approaches to fire spread modeling

Two simple fire perimeter spread modeling approaches are considered in this project. The basis of these models is that the local spread at a point on the fire perimeter is normal to the fire perimeter into unburned fuel. The two approaches are called Eulerian (implemented with a level set method; Rehm and McDermott, 2009) and Lagrangian (Rehm, 2008, Rehm and Mell, 2009; Sethain, 1999; Fendell and Wolff, 2001). Both approaches move the fire perimeter across a surface based on the local rate of spread (ROS), normal to the fireline, which is provided by the user. In the Lagrangian formulation, the advance of each Lagrangian particle on the front is related to the given normal ROS at the locally determined wind speed. The Eulerian method formulates the problem as a time-dependent, convection–diffusion partial differential equation, for which the fire front at any time is a curve representing a constant value of a dependent variable of the problem.

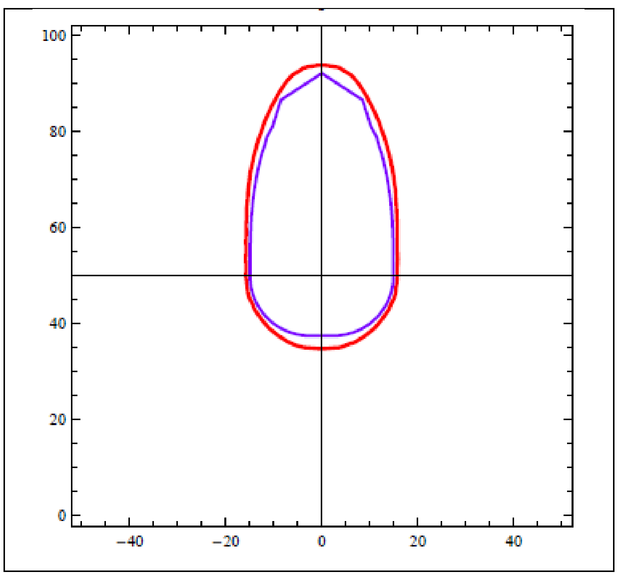

Figure 2: Comparison of two simple methods for propagating a fire perimeter, initiated by a spot fire at coordinates (0,0), across a surface. The domain is 100 m x 100 m. A 3 m/s wind flows from bottom to top. The fire perimeters are plotted 30 s after ignition. Both methods require prescribed values for the head, flank, and back fires. The

smoother red curve is from the level set approach and the purple curve from the Lagrangian approach. Figure is from Rehm and McDermott (2009).

Rehm and McDermott (2009) compare both approaches. For simple scenarios the two methods give very similar predictions of fire perimeter evolution as shown in Figure 2. The Lagrangian approach is the most straightforward description and requires following only a one-dimensional, time-dependent array of the Lagrangian particles. It has the disadvantage that it is less readily implemented for general application. For example, numerically accounting for the merger of fire fronts is a challenging task. Since the level set approach requires the solution of a two dimensional partial differential equation it is potentially more computationally expensive than the Lagrangian method, for simple single fire perimeter cases. However, the level set is straightforward to implement for general application. The merger of fire perimeters is handled naturally, for example. Because of this, we chose to use the level set for most of the simple model testing presented here. Equations and more details on the Lagrangian and level set approaches are given in the appendixes.

3. *Comparison of WFDS-Level Set and FARSITE fire spread models*

A description of the FARSITE model may be found in Appendix 4, with additional comparisons between the WFDS-level set and FARSITE models in Appendix 5. A key assumption of the FARSITE model is that a fireline propagating outward from a point of ignition will assume an elliptical shape. Heading, backing and flank ROS are derived using the elliptical shape factor. In the level set approach, no intrinsic fireline shape needs to be assumed, although a shape may be implicit depending on the model of fireline ROS.

A significant advantage of the level set model as implemented in WFDS is that it may be easily adapted to different empirical and semi-empirical models of fire spread. . For example, Figure 3 shows fire spread patterns in FARSITE compared to two different models of flame spread implemented in WFDS-level set. The first (Figure 3(a)), referred to hereon as the 'primary' model, is a simple spread model based on prescribed head, flank, and back ROS and the direction of the wind. The second, referred to hereon as the 'elliptical' model, is based on the fire perimeter model used in FARSITE. See Appendix 3 for further details.

For a simple point ignition, the time-of-arrival of the fireline from the WFDS-level set matches well with the predictions made by FARSITE, regardless of the level set spread model (Figure 3). The differences between the models are apparent in the fireline shape, which matches more closely when the elliptical constraint of the FARSITE approach is implemented in WFDS-level set (Figure 3(b)). The slight differences between the FARSITE results and the level set model in both figures are trivial compared to the general uncertainty in the prediction of wildland fire spread. Also, the implementation of an elliptical shape constraint is a construct whose validity is unknown.

The predictions of FARSITE and WFDS-level set are also similar for more complicated cases involving more complex terrain (see Appendix 5). The similarity of results suggests that, for a given fuel model, simulations using the level set approach, with either spread model, are suitable proxies for FARSITE simulations of the same configuration. In the implementations of the WFDS-level set model that follow, the elliptical constraint will not be used.

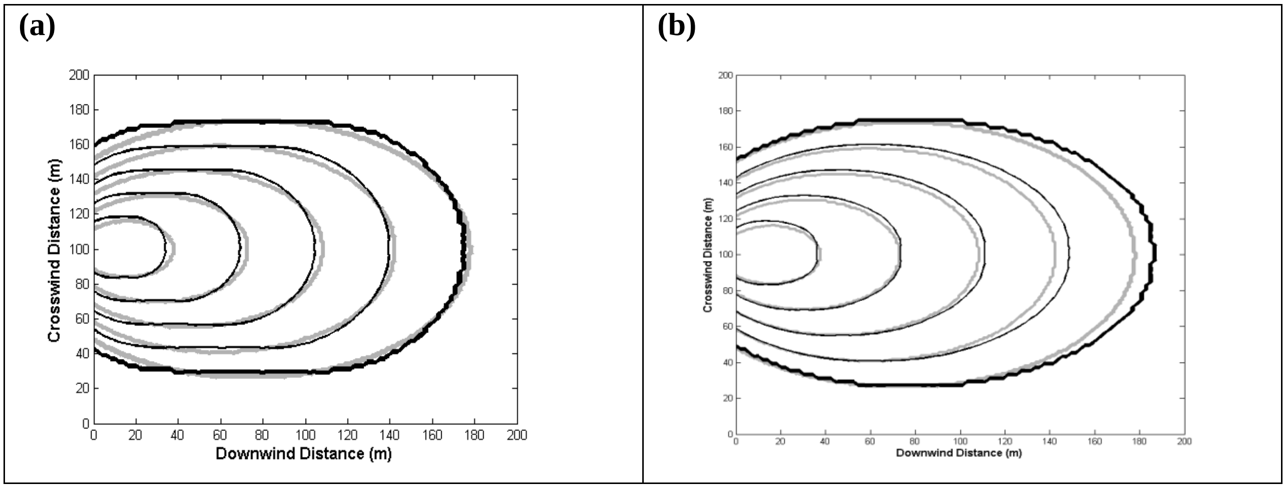

Figure 3: Point ignition modeled using WFDS-level set and FARSITE. (a) FARSITE (gray) and the WFDS-level set model in level set (black). (b) FARSITE (gray) and the WFDS-level set model with the ellipse constraint (black). Fuel properties match the AUF19 case. Wind is 5 m/s from left to right. Isochrones are 60 s apart**.**

4. Model C2: WFDS-Physics-Based simulation of AU grassland fire experiments

Results from an earlier version of the WFDS physics-based model were compared to measurements in AU grassland in Mell et al. (2007). The model performed very well at predicting the head fire rate of spread for a range of wind speeds. The model also well predicted the acceleration of the head fire in the early stages of spread as correlated with the time evolving head width (Mell et al., 2007). However, the flank fire spread rate was over predicted. As part of this project, improvements to both the gas phase and vegetation models in the WFDS physics-based model were made. As a result, the prediction of flank fire spread is significantly improved. The 2007 and current results are shown in Figure 4 for the AU experiment C064. This experiment has extended freely evolving flank fires.

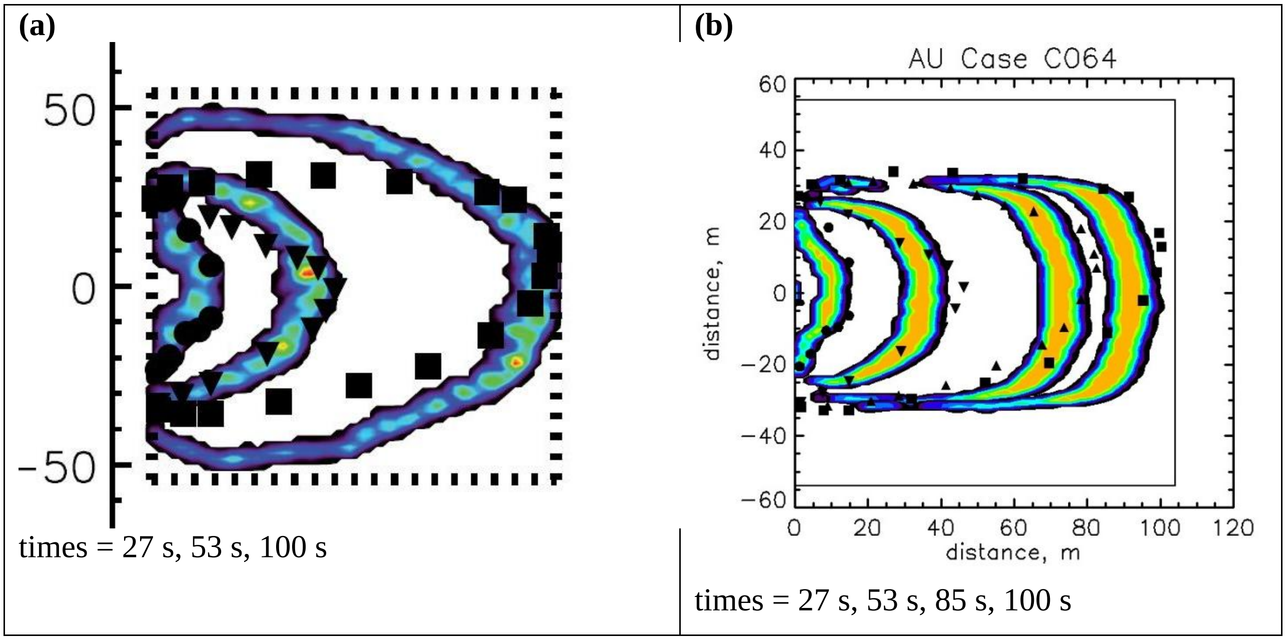

Figure 4: Fire perimeters from the WFDS physics-based model (color contours of burning rate) and the AU grassland experiment C064 (see Mell et al., 2007 for experimental details). Wind speed 2 m above ground is 5 m/s. (a) WFDS results from Mell et al. 2007. (b) WFDS results from the current version of WFDS. Improvements to the model resulted in flank fire rates of spread that better match the experiment.

Figure 5 shows the time history of the location of the head fire, head fire width, and head fire depth as predicted by the WFDS physics-based model for a relatively small ignition source (8 m long [crosswind direction], 2 m wide). The ambient wind speed at 2 m above ground is 5 m/s in Figure 5(a) and 1 m/s in Figure 5(b). Circles on the figures show the head fire location as determined from the empirical head fire spread rate formula, Eq. (1), with the head width determined in two ways. For open circles an infinitely wide head fire is assumed. For filled circles the head fire width predicted by WFDS is used. It is clear, upon comparing Figure 5(a) and Figure 5(b), that it is important to account for fire acceleration in the higher wind case (Figure 5(a)). For the high wind case, if the head width dependence was not included then the empirical model significantly over predicted the spread rate. For example, at 110 s the head fire spread 80% too far if an infinite head width is assumed. Figure 6 is a plot of the same quantities in Figure 5 but a longer ignition line fire of 96 m was used. The ignition line length used in the simulations plotted in Figure 6 is long enough that the assumption of an infinite head fire width is appropriate.

The agreement between WFDS and measurements of the fire perimeter growth in (Figure 4(b) and in the head fire location in Figure 5 and Figure 6 is corroboration that WFDS is handling the fire/atmosphere interaction in a way that's consistent with the measured AU grassland fires. This agreement justifies the use of WFDS to test the simple level set model as applied to AU grassland fires on level ground. To our knowledge, no other fire behavior model has been compared to these AU grassland fires at the level of detail displayed in Figure 4 through Figure 6. These results also show the potential importance of head fire acceleration under conditions of small ignitions (i.e., spot fires) and faster ambient wind speeds. This fire behavior is very difficult to account for in simple models for general application.

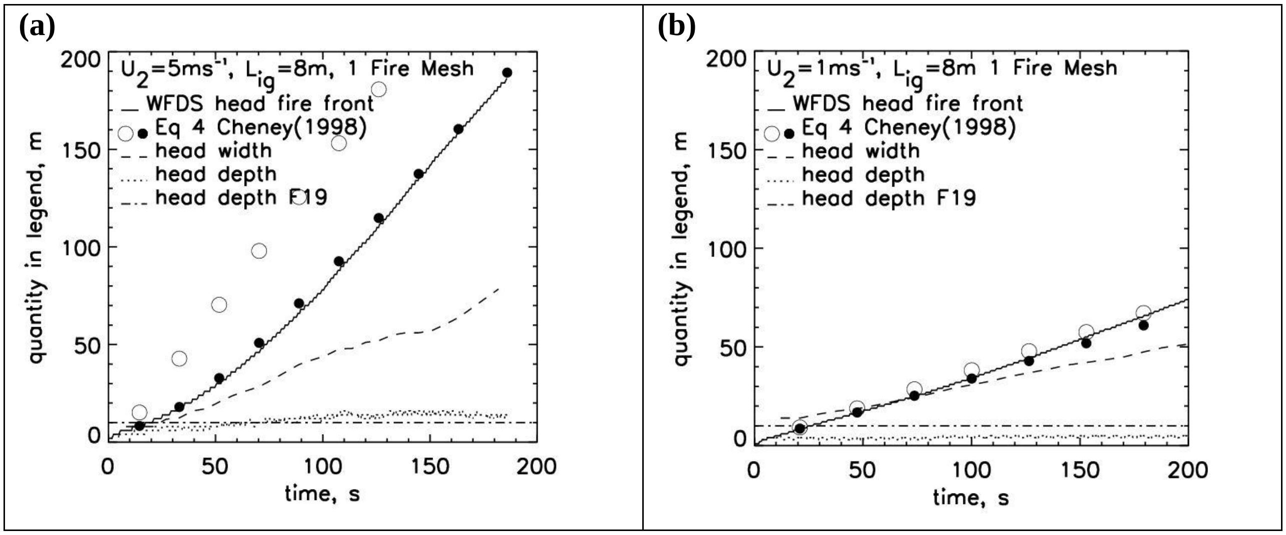

Figure 5: Time evolution of WFDS physics-based model predictions of the head fire location (solid line), head fire width (dashed line), and head fire depth (dotted line) evolving from an 8 m long 2 m wide ignition source. Symbols so the head fire location using the empirical head fire spread rate with infinite head width assumed (open circles) or WDFS predicted head fire width (filled circles). Dash-dot line is the measured fire depth. The properties of the grass are the same as for AU grassland fire experiment F19 (see Mell et al., 2007). Ambient wind at 2m height is 5 m/s in (a) and 1 m/s in (b).

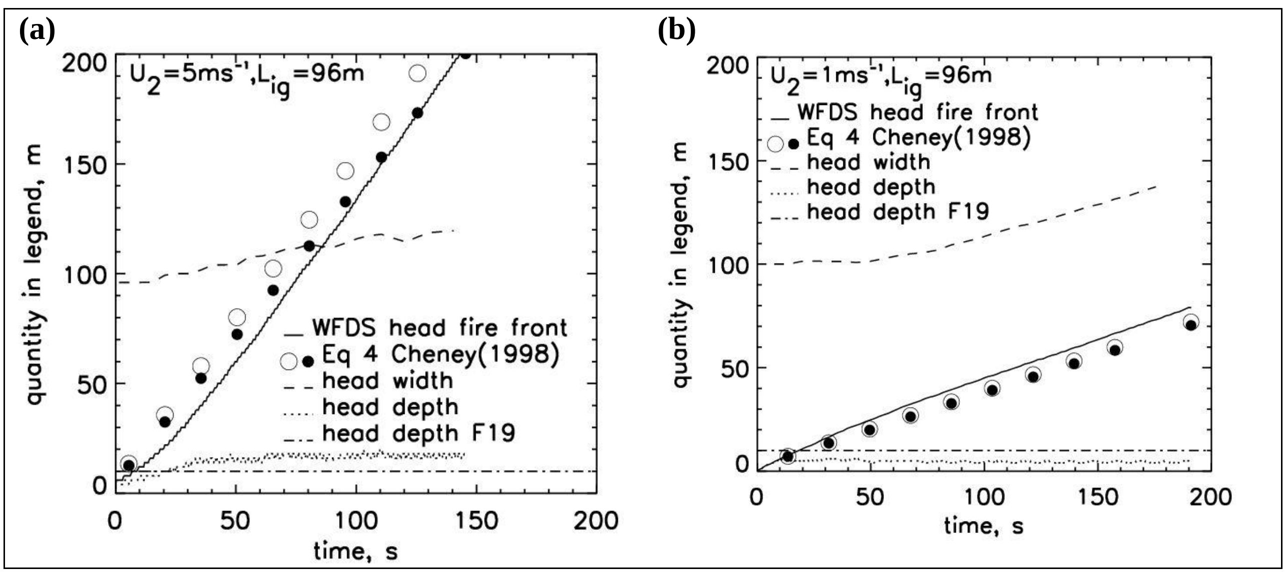

Figure 6: Same quantities and conditions as in Figure 5**Error! Reference source not found.**, but for a longer ignition line fire of 96 m

5. *Model A1: WFDS-Level Set Simulations of AU grassland fire experiments*

A comparison of fire perimeters from the AU experimental case C064, the WFDS-level set, and the WFDS-physics-based model predictions is given in Figure 7. The same comparisons are made for the AU experimental case F19 in Figure 8. The C064 and F19 field experiments differed mostly in the size of the plots and the length of the ignition lines. In both cases, field workers with drip torches started at the center of the upwind edge of the plot and walk in opposite directions. The C064 experiment was on an approximately 100 m x 100 m plot with a 50 m ignition line which took 27 s to ignite. The F19 experiment was on an approximately 200 m x 200 m plot with a 175 m ignition line which took 56 s to ignite. The wind speed 2 m above ground was approximately 5 m/s in both cases.

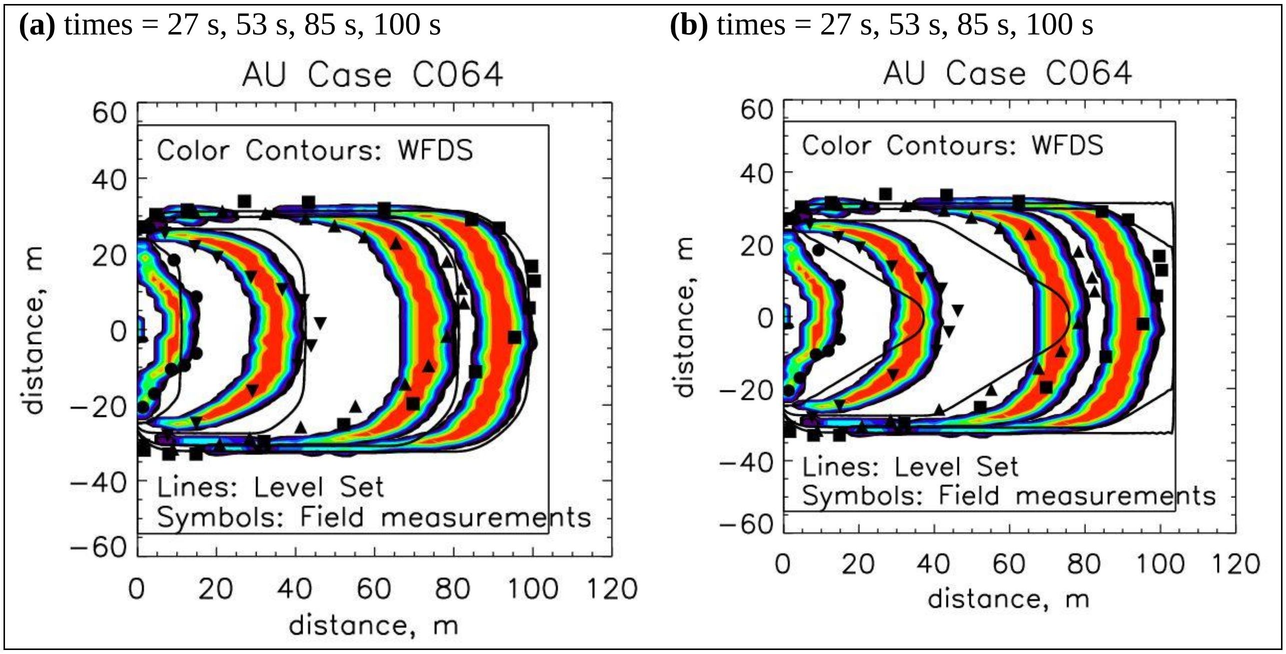

Figure 7: WFDS-Level Set (black lines) and WFDS-Physics-based (color contours of burning rate) compared to measured fire perimeters (symbols) for the AU experimental case C064. **(a)** Level set head fire spread rate is dependent on head fire width by using the empirical head fire spread rate formula. **(b)** Level set assuming infinite head fire width in the empirical head fire spread rate formula.

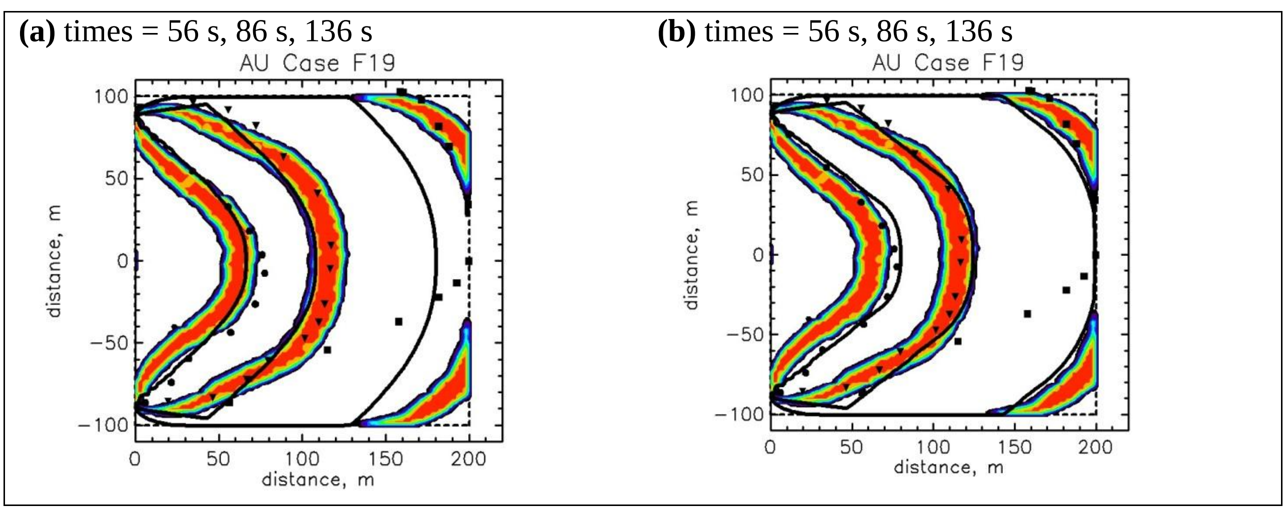

Figure 8: Same quantities as plotted in Figure 7 but for AU experimental case F19. Note difference in scale. **(a)** Level set head fire spread rate is dependent on the width of the head fire. **(b)** Constant head fire spread rate (assumed infinite head fire width).

In the implementation of the level set model, the flank fire spread rate is obtained from the WFDS-physics-based simulations. The head fire spread rate used in the level set model is determined using Equation (1) in two ways. In the first, the head width is time dependent and computed from the physics-based WFDS prediction of the average flank fire spread. In the second, the head fire width is assumed to be infinite, which results in a constant head fire spread rate. There were no back fires in the experiments. Figure 7(a) and Figure 8(a) show results for a head width dependent head fire spread rate. In Figure 7(b) and Figure 8(b) the head fire spread rate is constant. Overall, the level set model does a good job capturing both the head fire and flank fire progression. The largest discrepancy between measured and level set predicted fire perimeters is for the smaller C064 fire when the dependence of the head fire spread rate on the head fire width is not accounted for (Figure 7 (b)).

6. FARSITE simulations of the AU grassland fire experiments

Although it is not an explicit feature, timed line ignitions are possible in FARSITE by using a simulated "crew" to ignite from a containment line (Finney, 2011, private communication). Unfortunately, timed ignition at the linear rate required to simulate the AU burns (>1 m/s) does not seem to be possible. Numerous attempts resulted in odd ignition patterns or program instabilities, even on different computing platforms. Therefore, as an approximation, fire was ignited instantaneously over the total length of the timed fireline (175 m), though this gives an ignition pattern that is not directly comparable to the AU experimental case F19 shown in Figure 8. FARSITE requires the input of a fuel model describing various fuel parameters (loading, bulk density, etc.).

The grass fuel in the AU F19 grassland experiments does not correspond exactly with any of the standard grassy fuel models (see, e.g., Scott and Burgan 2005), so a custom model was created using the measured properties of the fuel. Figure 9**Error! Reference source not found.**(a) below shows the results for the custom fuel model and windspeed corresponding to the measurements (5 m/s). As expected, because of the inability to simulate timed ignition, the shape of the fireline does not correspond well to the field data. The ROS is also significantly slower than in the experiment, despite the customization of the fuel model. However, FARSITE offers the option of adjusting the rate of spread for any fuel model by entering a multiplier ("adjustment factor") customized to the case at hand. In Figure 9(b), the no-wind, no-slope ROS for the custom model (0.04 m/s) was multiplied by a factor of 2.5, which resulted in a better match between the simulated and measured head fire ROS.

Although the fire line shape still does not correspond to the measurements, the similarity between level set and FARSITE spread patterns (Figure 3), and the fact that the level set contours corresponded reasonably well for AUF19 (see section 5), suggests that, if a timed-ignition had been possible, the pattern of fire spread in FARSITE could also be made to match more closely to the experiment. However, even with timed ignition, a good match would be difficult because the dependence of ROS on head width (see section 3 above) is not currently modeled in FARSITE. It is notable that, even with a customized fuel model, *a priori* estimates of fire spread in such cases would most likely be inaccurate using FARSITE or the level set model (Figure 8). Unlike the physics-based model (colored contours in Figure 9), the semi-empirical models often require case-specific adjustments.

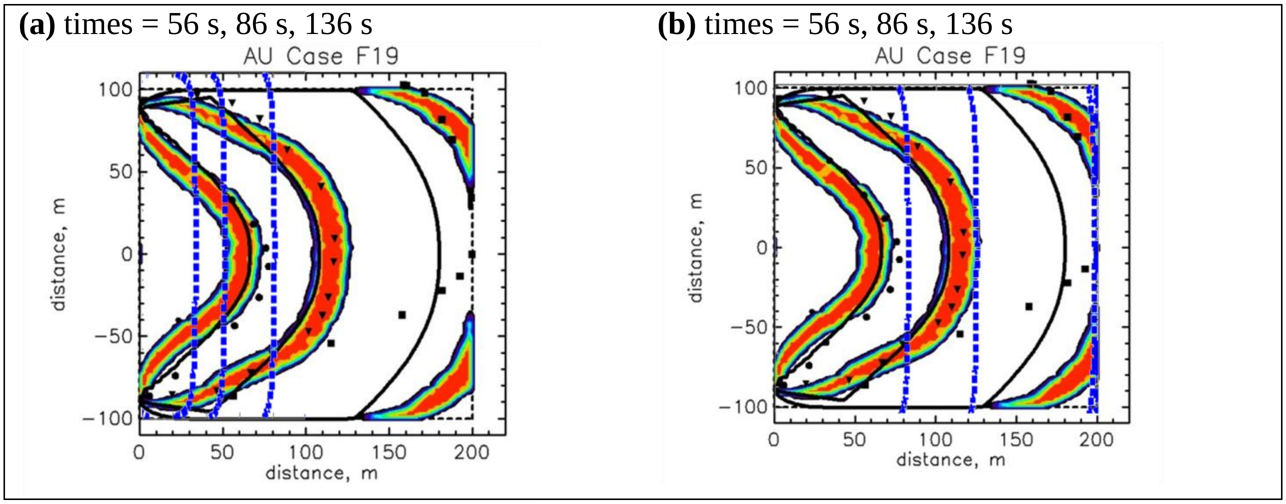

Figure 9: AU experimental case F19. Solid symbols represent field measurements. **(a)** FARSITE (blue dashed line) custom fuel model, windspeed = 5 m/s. **(b)** FARSITE custom model with an adjustment factor of 2.5, wind speed = 5 m/s. Other contours are the WFDS-Level Set (McArthur model) (black lines) and WFDS-Physics-based (color contours of burning rate).

7. *Model A1: WFDS-Level Set, fire spread on level ground*

In this section, results from WFDS-level set fire perimeter predictions are compared to WFDS-physics-based predictions for a number of scenarios of AU grassland fire on level ground. These scenarios are a spot fire(s) with no fuel break and spot fire and instantaneous line fires with fuel breaks. The level set head and flank fire spread rates (there are no back fires) are obtained from fitting the level set fire perimeter to the WFDS-physics-based simulations under the same ignition and wind conditions, but without a fuel break. Unless otherwise stated, the acceleration of the head fire is accounted for using Eq. (1) with the head fire width obtained from the flank fire spread rate. Also, the ambient wind in these cases flows from left to right and is constant with height. The purpose of these fire perimeter comparisons is to assess how the simple level set fire perimeters reproduce the physics-based fire perimeters under more complicated settings than the simple scenarios used to calibrate the level set model. This is relevant because it is impractical to calibrate a simple fire perimeter propagation model for a wide range of specific scenarios.

a. Fire spread from a spot fire

Figure 10 is a plot of the fire perimeters (every 60 s) from WFDS-physics-based and WFDS-level set for a spot fire in AU grassland (case F19) fuels and a 5 m/s ambient wind. In Figure 10(a), the acceleration of the head fire is accounted for in the level set approach (as discussed in the beginning of this section). In Figure 10(b) the head fire spread rate is the constant determined by assuming an infinite head fire width in Eq. (1). The level set model provides very good predictions of fireline progression provided the fire acceleration is accounted for (Figure 10 (a)). The level set implementation with a constant head fire spread rate over predicts the physics-based predictions of the head fire location by roughly a factor of two (within the duration of the simulation). Consistent with the discussion in Section 4 this error decreases for slower wind speeds or longer ignition lines (not shown).

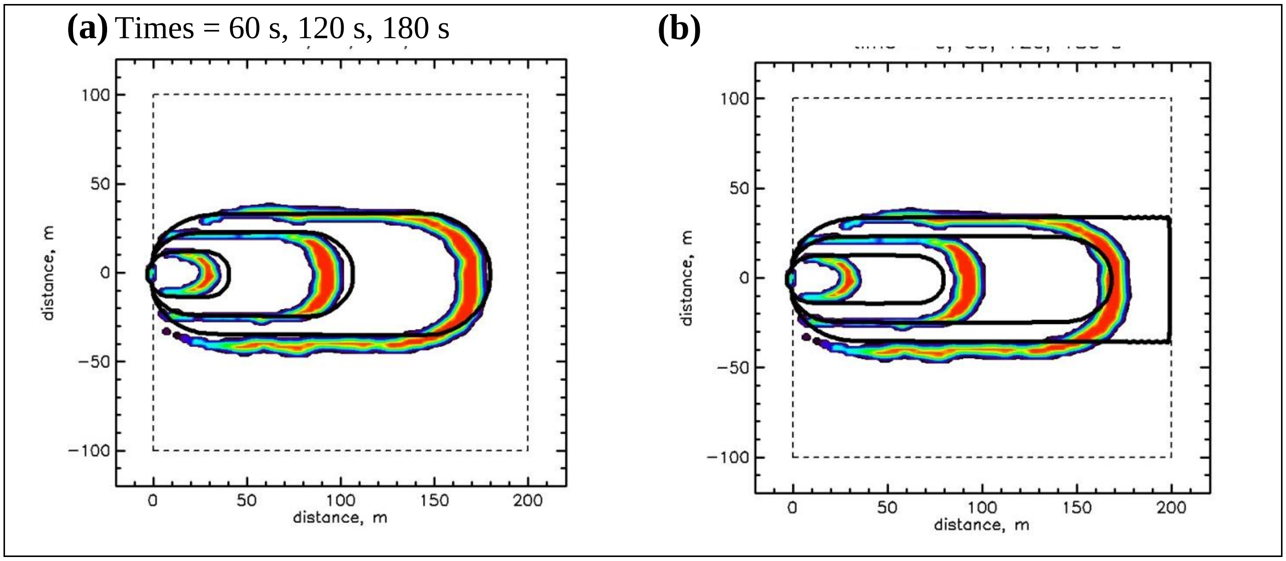

Figure 10: WFDS-physics-based (color contours of burning rate) and level set (lines) results for a spot fire in a 5 m/s wind and AU grassland (consistent with AU experiment F19. Fire perimeters are plotted every 60 s**. (a)** Head fire spread rate in the level set model is dependent on the width of the head fire**. (b)** Head fire spread rate in the level set is set equal to its empirical value for an infinitely wide head fire.

b. Fire spread around 'fuel treatments'

Areas of no vegetation are used to approximate fuel treated grass. These could also be thought of as idealized representations of residential parcels with no burnable fuel and with no accounting of the influence of a structure or vegetation on the wind. In the level-set model this is handled by setting all spread rates to zero in the "treated" areas. In the physics-based model, no vegetation is present.

Figure 11 shows the level set (red lines) and physics-based predictions of fire perimeter in a 5 m/s ambient wind. Figure 11(a) is a spot fire and a 20 m by 20 m fuel break. Figure 11(b) is a 100 m long instantaneous ignition line and a 50 m x 50 m fuel break. The level set model better predicts the larger ignition line case. For the spot fire case the level perimeter spreads too fast, especially initially. This due to its over prediction of the head fire width because the level set model cannot adjust for the occurrence of approximately two head fires, one on each side of the fuel break. The physics-based model accounts for this. The level set model, as implemented, cannot. Instead, the level set, in terms of head fire width, assumes there is one head fire which results in faster head fire spread rate. This fire behavior also occurs in the larger ignition case plotted in Figure 11(b), but the fire width is already sufficiently large by the time the fire reaches the fuel break that it is past the initial fire acceleration stage and, therefore, using an incorrect head width has less of an impact. The case with four 20 m x 20 m fuel breaks in a line shown in Figure 12 behaves similarly to the single 20 m x 20 m fuel break case (Figure 11(a)).

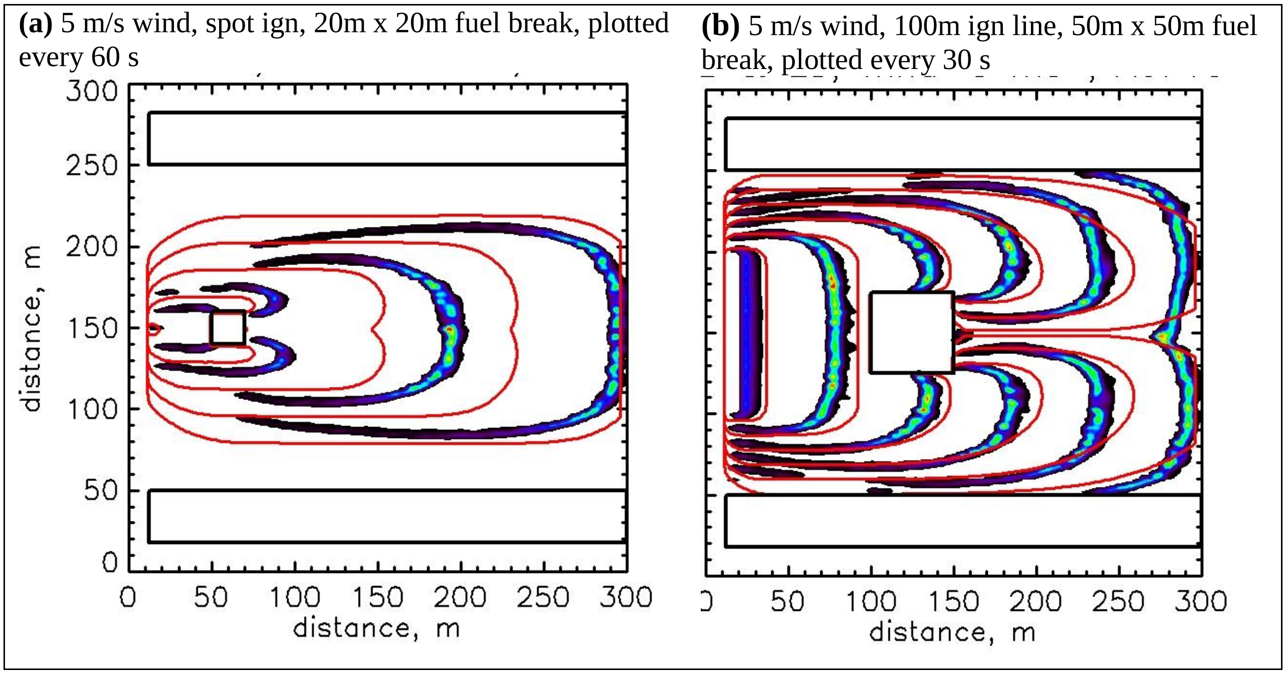

Figure 11: WFDS-physics-based (color contours of heat release rate) and WFDS-level set (red lines) fire perimeters. The terrain is level and the ambient wind speed is 5 m/s flowing from left to right. There are also fuel breaks on the north and south side of the plot. Thick black lines denote the border of grass / no grass. **(a)** Ignition line is 4 m long. Fire perimeters are plotted every 60 s, starting 5 s after ignition. The square fuel break has dimensions 20 m x 20 m. **(b)** Ignition line is 100 m long. Fire perimeters are plotted every 30 s, starting 10 s after ignition. The square fuel break has dimensions 50 m x 50 m. Note that the current plotting method for the level set results gives the impression that the level set head- fire line, at the latest time, is positioned along 300 m. In fact, it has passed the 300 m location in both figures. This occurs in other figures also.

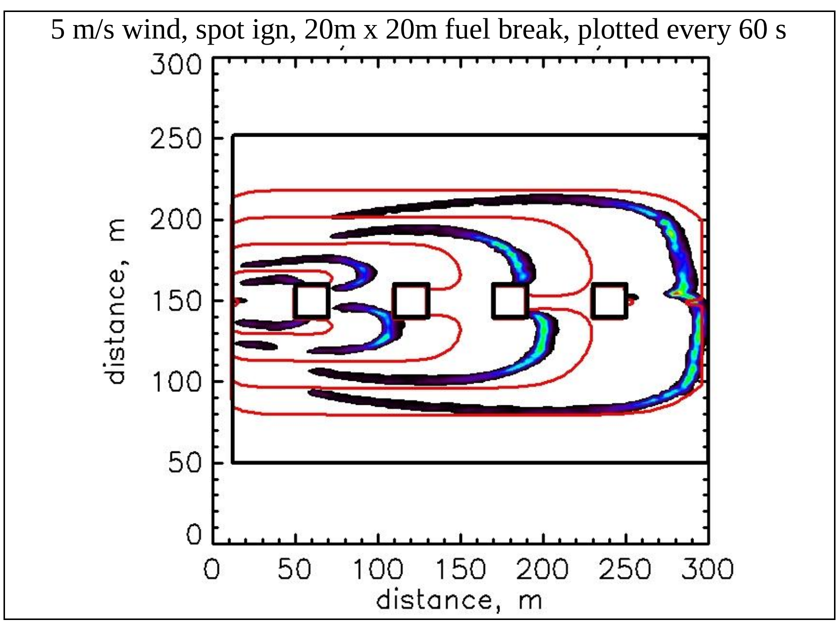

Figure 12: Multiple 20 m x 20 m fuel breaks separated by 40 m. The ambient wind flows from left to right with a speed of 5 m/s.

Twenty-one fuel breaks, each of dimension 40 m x 40 m, and separated by 30 m, are shown in Figure 13. A 5 m/s wind flows from left to right. The physics-based and level set perimeters increasingly separate as they evolve. The fuel breaks create an environment in which the fire atmosphere interaction sets up a pair of counter rotating vortices downwind of the fire line. This causes a flow in the upwind direction along the center of the domain and slows the spread of the fire. The level set model cannot account for this and, therefore, spreads faster. In addition, the fires between the fuel breaks have a smaller effective head width and, therefore, will spread more slowly than a fire freely evolving from the initial 280 m long ignition line (which was simulated to obtain the head fire spread rate used in the level set model). At 360 s the level set fire line is about 170 m ahead of the physics-based fireline (in the central region of the plot).

5 m/s, 21 40 m x 40 m fuel breaks; times = 73 s (ignition), 120 s, 240 s, 360 s, 480 s (only for WFDS-physics-based

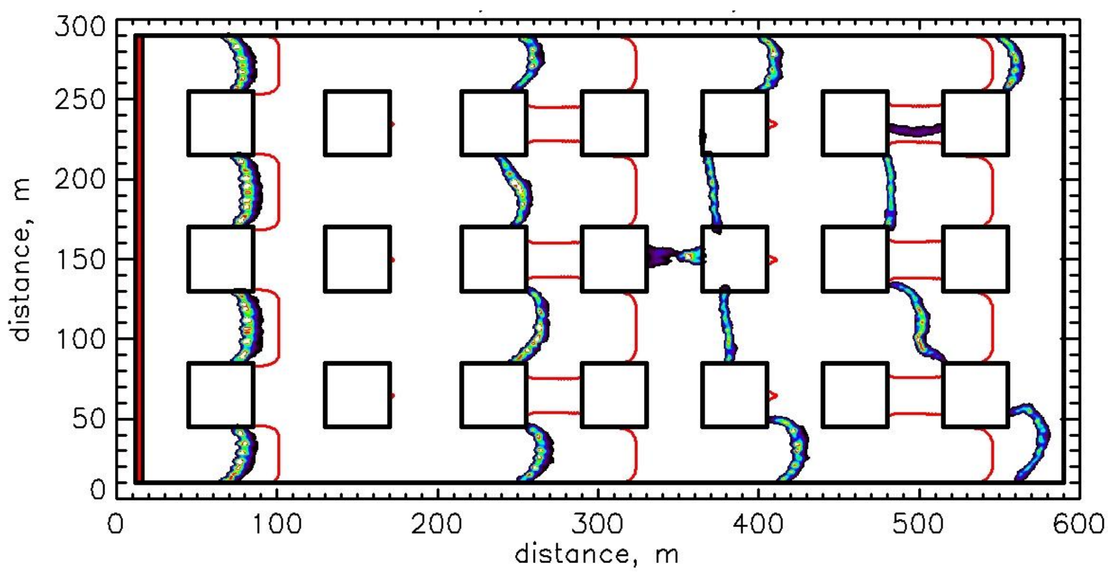

Figure 13: Multiple fuel break case. Twenty one equally space 40 m x 40 m fuel breaks. Ambient wind is 5 m/s. WFDS-physics-based (color contour of heat release rate per unit volume) and WFDS-level set (red lines) are plotted every 120 s. Ignition occurs at 73 s with a 280 m long ignition line.

Figure 14 shows level set (red lines) and physics-based results for a single 50 m x 50 m fuel break and a 1 m/s ambient wind speed. At this low wind speed, the fire induced winds are more relevant than in the 5 m/s ambient wind case of the previous figures. Ignition is via a spot fire in Figure 14(a) and an instantaneous 100 m line in Figure 14(b). As in Figure 11, the fire line interaction with the fuel break causes the level set model to deviate from the physics-based model more significantly in the spot fire ignition case (Figure 14(a)). This is especially true for the flank fires and is due to fire atmosphere interactions not captured in the level set approach. Upon reaching the fuel break, the head fire extinguishes. This results in air that was being drawn over the fuel break, opposite the ambient wind direction, and into the downwind edge of the head fire to be redirected into the flanks. As a result, the flank fire spread rate increases and the physics-based predicted flanks reach the edge of the plot well before the level set flanks. During this redirection of flow, wind vortices are created along the edge of the fuel break (not shown).

(a) 1 m/s wind, spot ign, 50 m x 50 m fuel break, times = 5s, 120s, 240s, 360s, 420s.

(b) 1 m/s wind, 100m ign, 50m x 50m fuel break, times = 5s, 120s, 240s, 300s

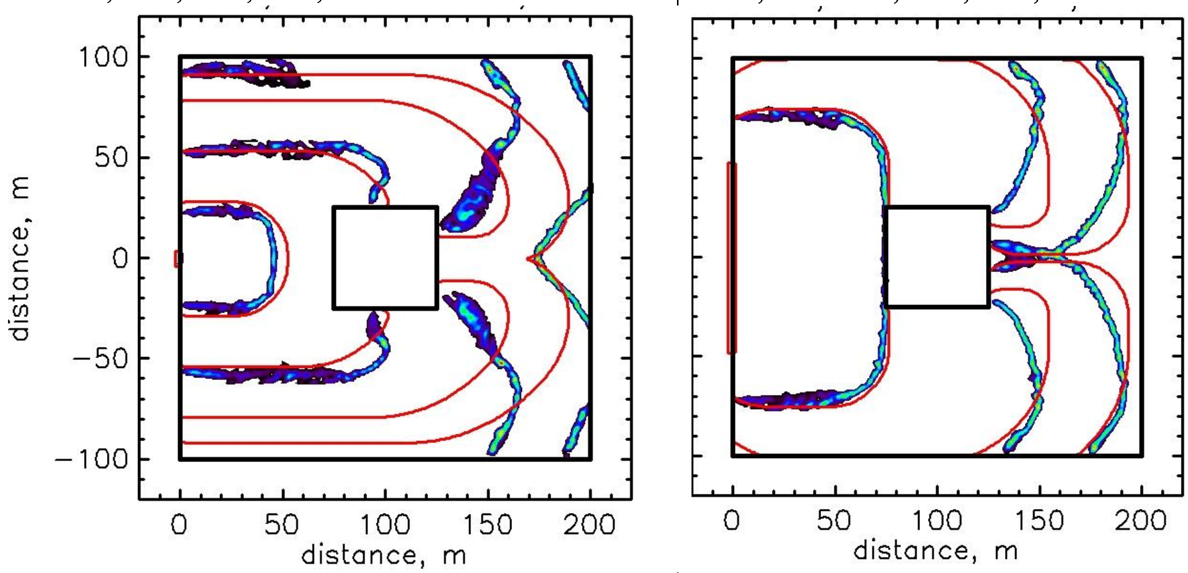

Figure 14: Single fuel break case. WFDS-physics-based (color contours of gas temperature) and WFDS-level set (red lines) fire perimeters. Times of perimeters are given on top of figure. Ambient wind speed is 1 m/s at 2 m above the ground flowing left to right. The fuel break in the center has dimensions of 50 m x 50 m. **(a)** Ignition line is 8 m long. **(b)** Ignition line is 100 m long.

c. Fireline interaction – no fuel treatments

Figure 15 shows fire perimeter evolution from two spot fires, separated by 50 m, in a 5 m/s (Figure 15(a)) and a 1 m/s (Figure 15(b)) ambient wind 2 m above the ground. The level set perimeter matches well with the physics-based up to the point of fire merger; after merger the physics-based fire lines spread faster. This is because the level set head fire spread rate is still based on two spot fires, each with a head width that's smaller than the head width of the single fire that forms after merger.

The evolution of fire lines from two 100 m long ignition lines are shown in Figure 16. The ambient wind flows from right to left with a speed of 5 m/s. The two ignition lines are oriented at right angles to each other causing a head (ignition aligned perpendicular to the wind direction) or flanking fire (ignition aligned parallel to the wind direction). The difference between the physics-based and level set results at early times show how the level set model is unable to account for the entrainment of the flanking fire into the head fire. The continued interaction of the two fires results in a combined fireline whose spread rate the level set model under predicts.

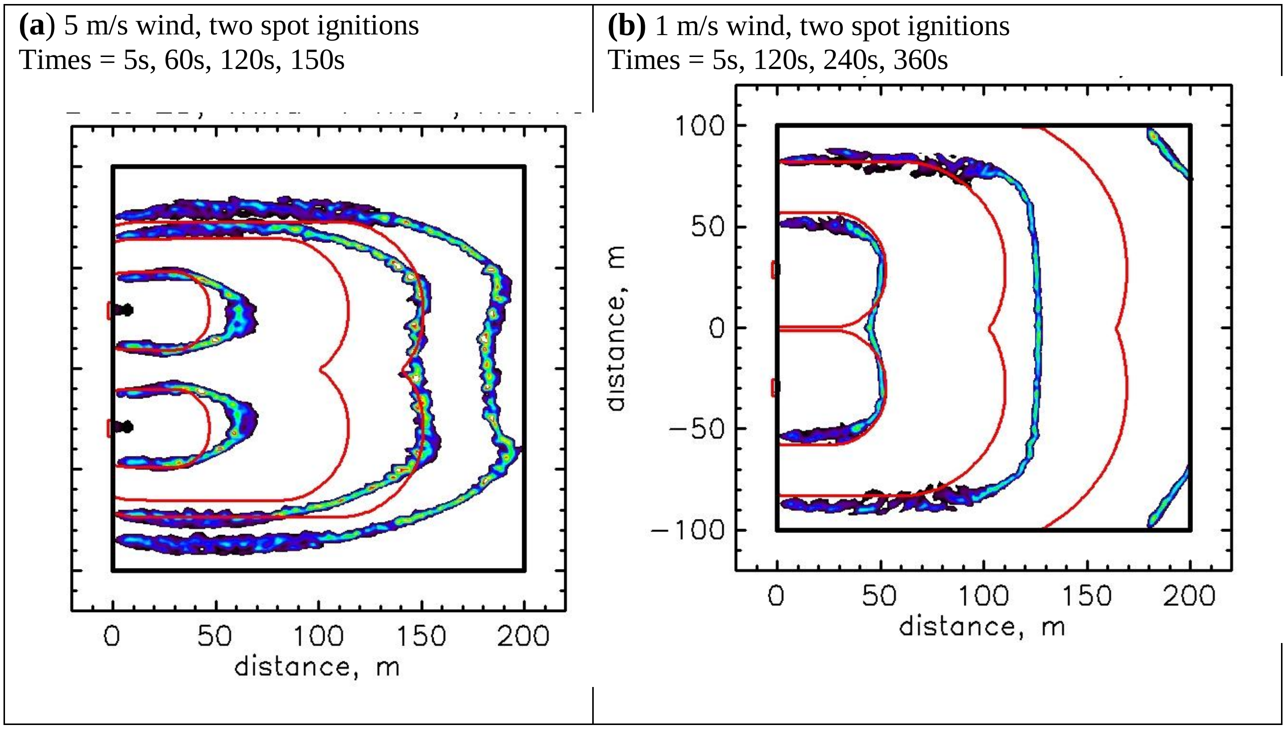

Figure 15: Two spot ignitions separated by 50 m. WFDS-physics-based (color contours of gas temperature) and WFDS-level set (red lines) fire perimeters. Times of perimeters are given on top of figure. Ambient wind speed is 1 m/s.

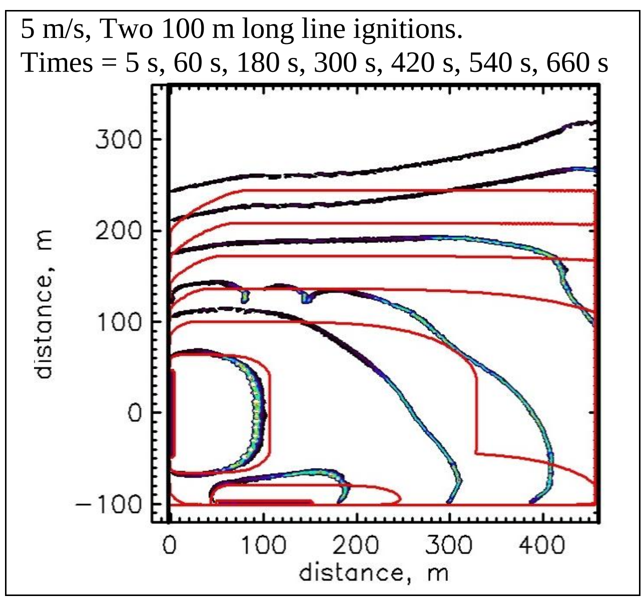

Figure 16: Fire perimeters evolving from two 100 m long ignition lines: along the west side of the plot between -50 m < y < 50 m and along the south side of the plot between 50 m < x < 150 m. The ambient wind flows from left to right with a speed of 5 m/s. WFDS-physics-based model results are color contours of the mass burning rate. Level set predicted fire perimeters are the red lines. The times of the fire perimeters are given above the figure.

8. *Model A1: WFDS-Level Set, fire spread up a flat slope or drainage*

Fire spreading upslope from a 100 m long instantaneously ignited fireline is simulated using the level set and physics-based models for two cases of simple sloped terrain which are shown in Figure 17. They are a flat 27 degree slope case in Figure 17(a) and a drainage embedded in a 27 degree slope in Figure 17(b). The drainage is 54 m deep (other dimensions are given in the caption of Figure 17(b)).

The level set (or FARSITE) approach cannot directly account for physical interactions that result in non-steady spread rates. These simulations are a first look at this limitation for conditions that could lead to the non-steady behavior of a fire accelerating up a slope. It should be noted that the WFDS-physics-based simulations have not yet been validated for this scenario. Also, the dimensions and configurations chosen here are to show the capability of the model suite to investigate the behavior and limitations of the simple fire perimeter models – not to draw conclusions, which is left for future work. However, the fire/atmosphere/terrain interactions are all within the scope of the coupled governing equations so it is reasonable to assume that trends are captured. The level set model uses the same terrain as the physics-based model. For each terrain case, two ambient winds are considered, both flowing in the upslope direction. The level set head and flank fire spread rates are obtained from the WFDS-physics-based simulations on level ground with the same ambient winds and ignition. The influence of slope on the level set spread rates is handled using McArthur's rules (McArthur, 1973).

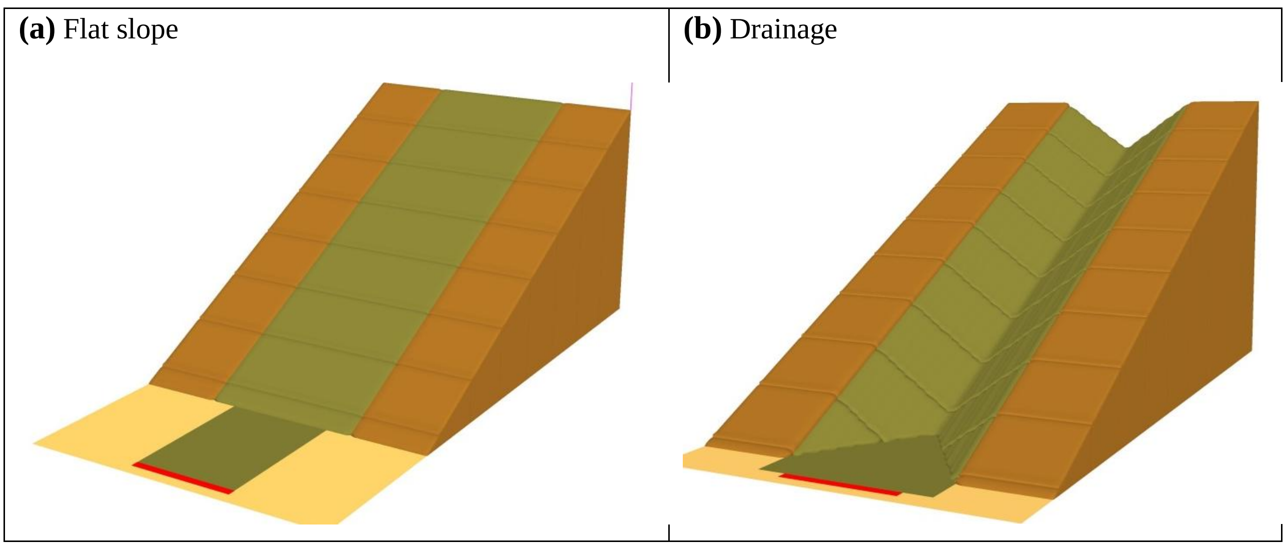

Figure 17: Two slope scenarios. The 100 m long ignition line is shown in red. In each case the total width is 300 m and length is 600 m. Australian grass is present in the green surface. Yellow is bare ground and brown is grass that's prevented from burning. Ambient wind flows from left to right. **(a)** Flat slope of 27 degrees; total distance along slope is 496 m. **(b)** A 160 m wide, 54 m deep, drainage case. Both the waterline and the terrain flanking it (in brown) have slopes of 27 degrees. The slope perpendicular to the waterline is 34 degrees. The total waterline distance is 496 m; the total distance along the slope bordering the waterline (colored in brown) is 616 m. The width-wise . lines are an artifact of the visualization method.

a. 5 m/s ambient wind

Figure 18 and Figure 19 show simulation results for the flat slope and the drainage, respectively. The ambient wind for the physics-based case depends on height above the level ground upwind of the slope according to Equation (2) with $U_2 = 5$ m/s. Results from the WFDS physics-based and level set models are shown for both terrain scenarios. FARSITE results are shown only for the drainage case. Velocity vectors 2 m above the ground are shown in the WFDS-physics-based figures.

The time history of the fireline total heat release rate from the WFDS-physics-based simulation, for both terrain scenarios, is plotted in Figure 20(a). The heat release rate curve for the flat terrain case is constant during the time period when the fire spreads along the level terrain upwind of the slope (see Figure 17(a)). During this period, the fireline evolves in a quasi-steady manner with a near constant length, depth, and spread rate. This results in the constant total fireline heat release rate. In each terrain case, once the fireline reaches the slope, the total heat release rate is no longer constant and rapidly rises. This is due to a fireline that is both lengthening (especially initially) and accelerating. After an initial period of about 60 s, the total heat release rate again develops a more quasi-steady behavior as does the WFDS-physics-based spread rate (not shown).

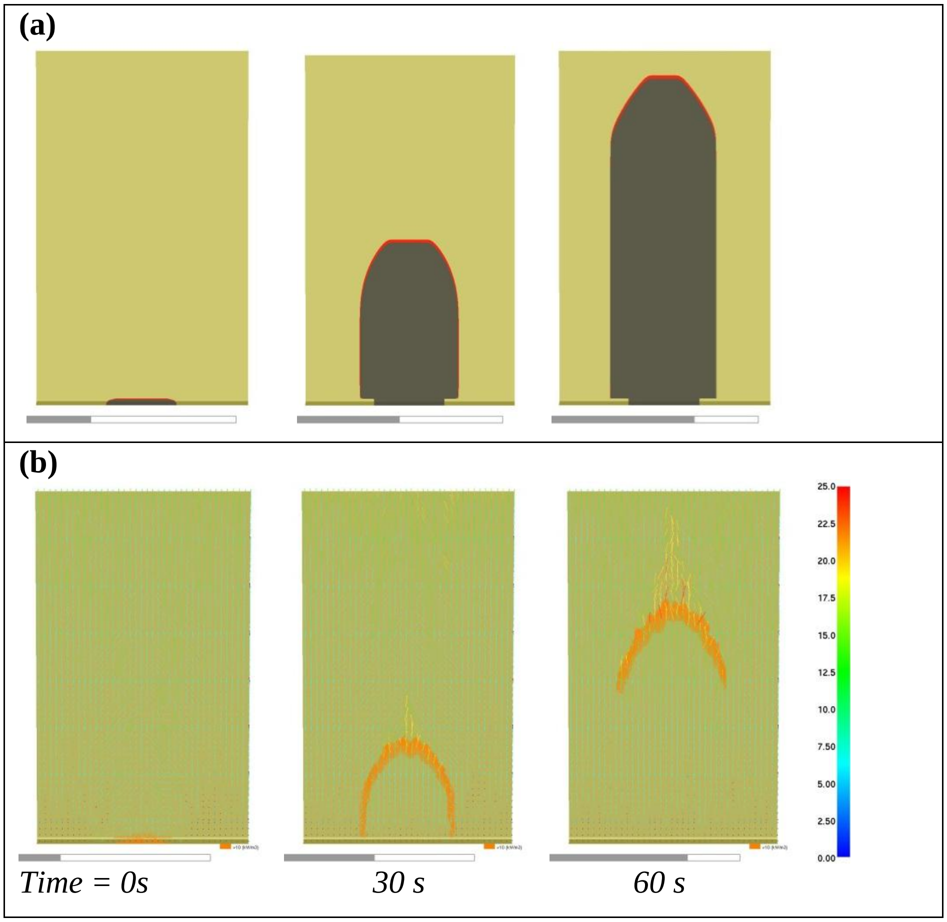

Figure 18: Snapshot from the WFDS-level **(a)** set and WFDS-physics-based **(b)** models for fire spread up the 27 degree flat slope shown in **Figure 17**(a). Time 0 s is when the fire reaches the base of the slope. Ambient wind speed is 5 m/s. The wind velocity vectors 2 m above ground level are shown for the physics-based case. Faster wind speeds are shown by longer arrows and by the color scale at right.

Both the level set and FARSITE were calibrated to match the physics-based head fire spread rate on the level terrain However, neither the level set, nor FARSITE, models are capable of accounting for fire behavior that is not quasi-steady. Both assume instantaneous transition from a constant spread rate on level ground to a constant spread rate up the slope. In the constant slope case, the level set model overpredicts the spread distance. In the drainage case, both the level set and FARSITE models underpredict the spread distance. The difference between FARSITE and WFDS-level set is probably due to the different ways they handle the influence of the slope.

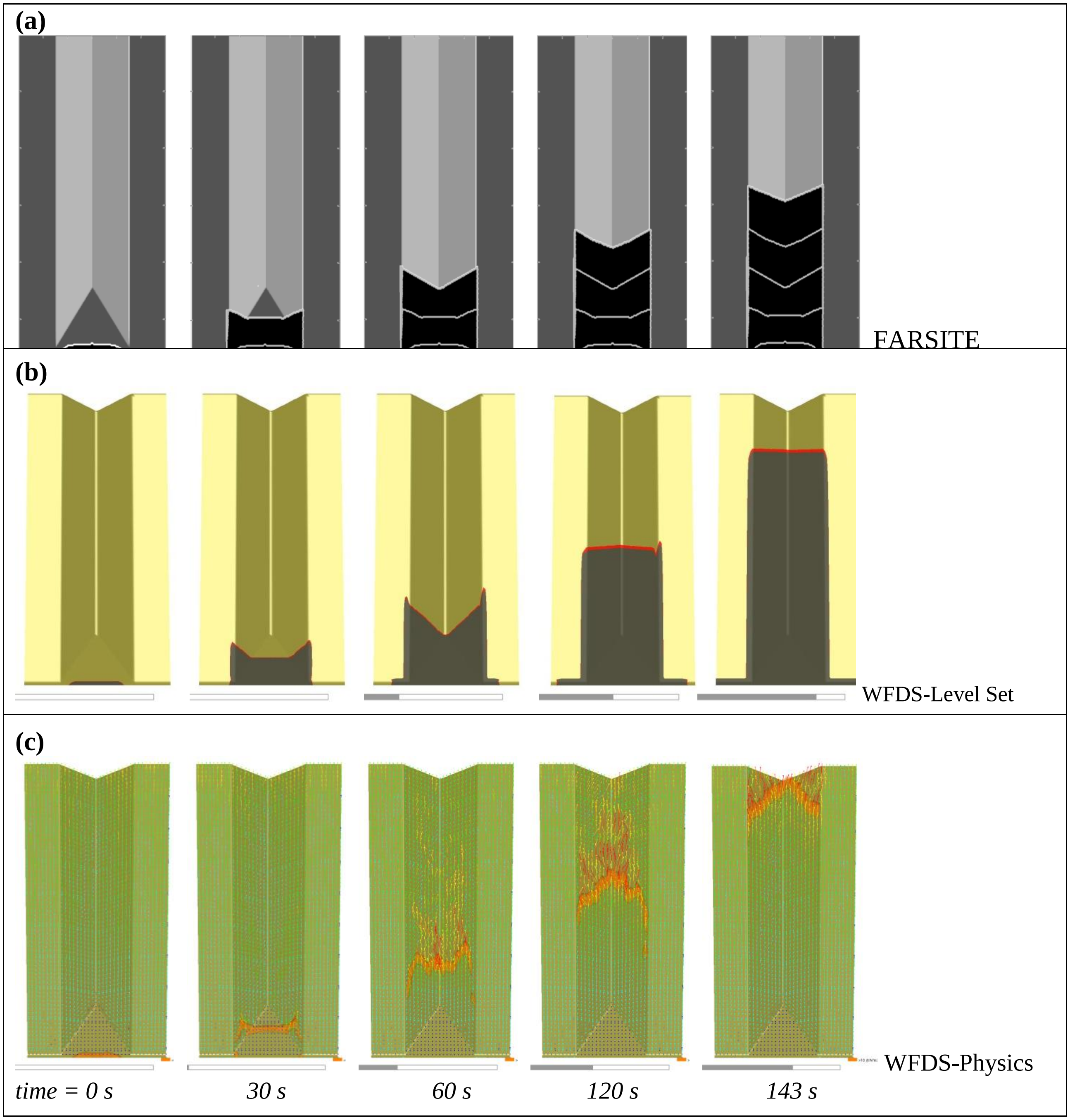

Figure 19: FARSITE, WFDS-level set and WFDS-physics-based simulated fire lines in plan view, for fire spread up the 27 degree drainage are shown in panels **(a)**, **(b)** and **(c)**, respectively. Results are shown every 30 s. Time 0 s is when the fire reaches the location where the flat slopes to each side begin. In (a), dark regions corresponding to burned area, were created using a Matlab script that reads FARSITE output, and overlaid on the original FARSITE image (the dark line in the first figure is an approximation of only fire front position). The color scale for wind velocity magnitude in the WFDS-Physics figures is given in Figure 18(b). The fire induced winds are significantly larger in magnitude than for the flat slope case in Figure 18(b).

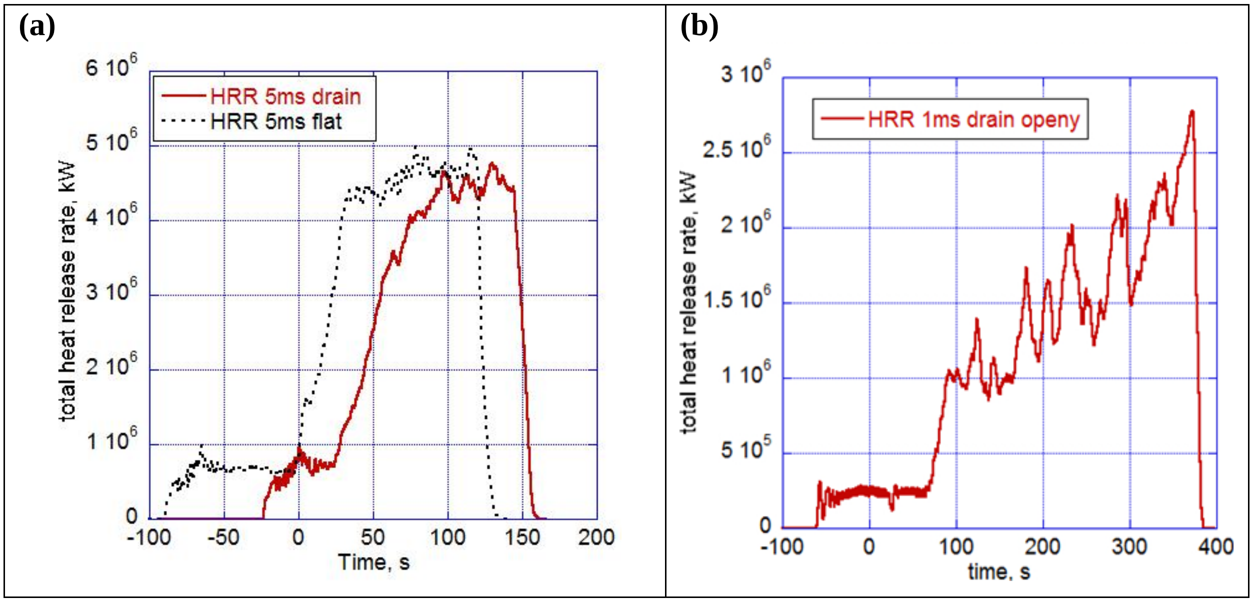

Figure 20: Time history of total heat release rate (kW) of the fireline from WFDS-physics-based simulations. **(a)** Ambient wind speed is 5 m/s. Fire spread up a flat slope (dashed line) and a drainage (solid line). These two cases are shown in **Figure 18** (flat slope) and **Figure 19** (drainage). The time period where the flat slope case is unchanging (t = 100 s to 150 s) corresponds to spread along the level ground upwind of the start of the slope. After a period of time both terrain cases reach a steady state. **(b)** Ambient wind speed of 1 m/s. Fire spread up a flat slope. Note the change in scale from the 5m/s case. The period of spread on level ground is extended. Unlike the 5 m/ s wind case, a steady state is not reached.

b. 1 m/s ambient wind

The drainage terrain scenario in Figure 17(b) was simulated with an ambient wind speed of U_2 = 1 m/s in Equation 2. The time history of the total heat release rate from the physics-based model is shown in Figure 20(b). Unlike the heat release rate in the 5 m/s ambient wind cases, a quasi-steady fire behavior is not reached. The fire line accelerates up the drainage for the duration of the simulation and the level set under predicts the spread rate (not shown).

9. Model A1: Lagrangian Model, fire spread on level ground

Results from the Lagrangian model for the propagation of a fire perimeter over level ground are displayed in Figure 21, which is taken from Rehm (2008). An overview of the model approach is given in Appendix 3: Lagrangian Fire Spread Model. The entrainment wind induced by the burning structure is added to the prescribed ambient wind using a semi-empirical formula (Baum and McCaffrey, 1989). This net wind is used in the AU empirical formula, Eq. (1), to obtain the head fire spread rate. In Figure 21(a) the 40 m long fire line is initiated upwind of the burning structure. In Figure 21(b) the fire line is initiated downwind of the burning structure as would be the case if the passing fireline ignited the structure. The fire perimeters, which are plotted every 25 s, clearly display the influence of the entrainment winds created by the burning structure. This method makes use of analytical expressions for the entrainment wind field which allows faster than real time operation. In general, a structure takes a sufficiently long time to reach the assumed 200 MW heat release rate that the fireline would have spread much further away than this scenario depicts. A potential exception to this would be if the structure was ignited by firebrands generated by a far field fire (whether in vegetation or structures). This approach offers a fast turn-around-time method to investigating the importance of the entrainment winds from burning structures.

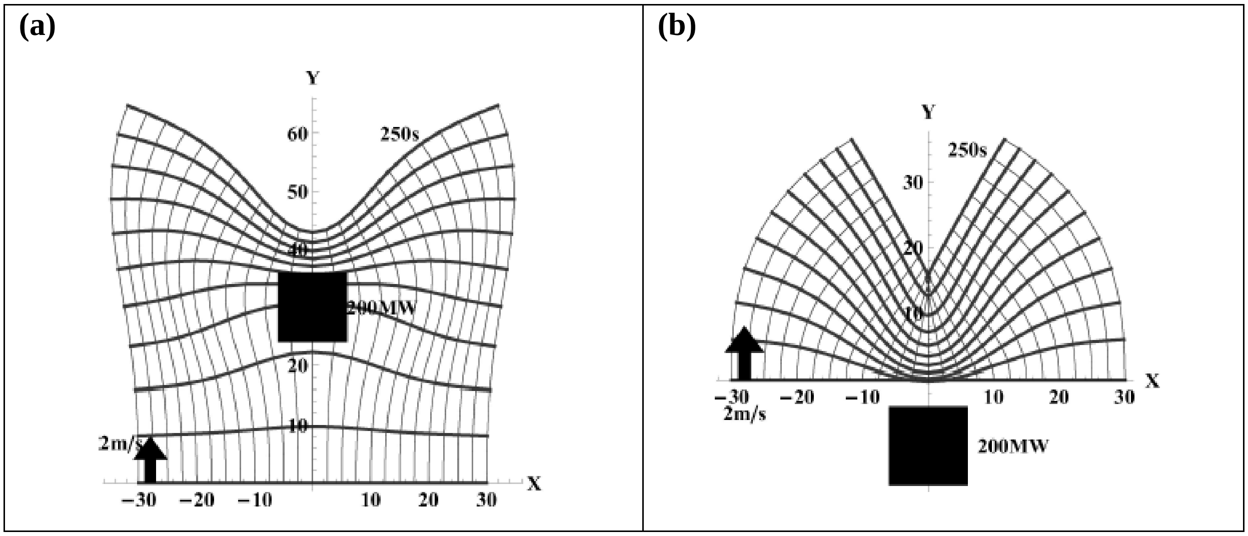

Figure 21: Example results of Lagrangian fire spread model on level ground (from Rehm 2008). Fire perimeters are plotted every 25 s. The black square is the location of a burning structure of constant 200 MW heat release rate which creates an entrainment wind. A 2 m/s ambient wind flows in the positive Y direction. **(a)** The fire line is started upwind of the burning houses. The acceleration of the fire line toward house is evident, as is deceleration downwind of the house. **(b)** Fireline starts downwind of the burning structure.

10. Model B1: WFDS-Level Set, fire spread up slope, CFD wind

While all the components are in place, this model approach has not yet been implemented. It will be equivalent to the FARSITE/WindNinja (Forthofer and Butler, 2007) model combination. However, since it will be implemented within the WFDS suite, a straightforward and consistent testing of this extension can be conducted.

11. Model B2: Lagrangian Model, fire spread up a simple hill

Results from the Lagrangian model for the propagation of a fire perimeter over a simple hill are shown in Figure 22, which is taken from Rehm and Mell (2009). This implementation of the model accounts, in an approximate way, for the contribution of the ambient wind, the entrainment winds induced by the burning structure, and the influence of the slope. Appendix 3: Lagrangian Fire Spread Model provides an overview of the approach. The fire perimeter is plotted at equal time increments. The ambient wind flows left to right, parallel to the *y* axis. The acceleration of the fire perimeter in the region downslope and upwind of the structure can be seen, as can deceleration downwind of the structure. These results are reasonable and this model approach offers one way to assess the influence of slope and entrainment on fire line winds with faster that real time predictions.

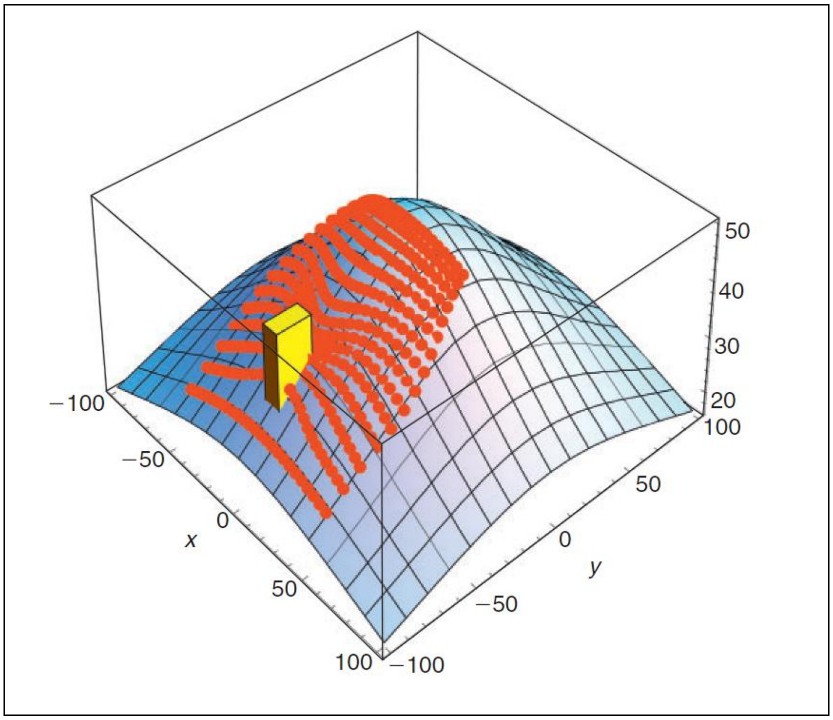

Figure 22: Results of the Lagrangian method for moving a fire perimeter. The fire perimeter is plotted at equal time increments. The axes dimensions are in meters. The yellow block is a burning structure. Three components of wind are accounted for in an approximate manner: ambient, entrainment from the burning structure, and an effective slope generated wind. Ambient wind flows from left to right, parallel to the *y* axis.

12. Summary of Key Findings

- **i.** Simple (no direct modeling of physical processes) fire perimeter models, such as the WFDS-level set or FARSITE, will perform no better than the spread rates they use. There is a significant lack of field-scale measured spread rates.
- **ii.** The level set and Lagrangian based fire perimeter propagation models predict essentially identical fire perimeters for surface fires. Because of its ease of application to general scenarios the level set approach is the model of choice.
- **iii.** The agreement between WFDS-physics-based model predictions and AU grassland measurements justify its use for testing simple fire perimeter models with AU grassland fuel on (strictly speaking) level ground.
- **iv.** The level set approach produces fire perimeters of essentially the same shape as FARSITE perimeters. Thus, the level set approach can be used to evaluate FARSITE for surface fire scenarios.
- **v.** Simple fire perimeter models, commensurate with level set, won't perform better than shown here because the initial phase of fireline acceleration is accounted for using the well founded empirical relation for the head fire spread rate as a function of the head fire width.
- **vi.** In higher wind speeds (equal or greater than approximately 5 m/s – but this needs more investigation) the initial fire acceleration phase is important and will be difficult to account for, in general, with simple models.

vii. Grassfire perimeter propagation predicted from the WFDS-level set model agrees well with WFDS-physics-based results for very simple scenarios: level ground and a single fire.

viii. The agreement between WFDS-physics-based and WFDS-level set fire perimeters breaks down for scenarios with fuel breaks, fireline interactions, or slope. This disagreement is due to the lack of a quasi-steady fire-atmosphere interaction that is the basis of a the simple fire perimeter propagation model. The degree of mismatch would be significant for long duration runs in complex fuel and terrain scenarios (e.g., hours, or greater, of simulated time). Such simulations are routinely performed with FARSITE and similar models.

V. MANAGEMENT IMPLICATIONS

In this project, the simple WFDS-level set fire perimeter propagation model was developed, implemented, and put through preliminary assessments by comparing to fire perimeters from field measurements and the WFDS-physics-based simulation tool. To date, this assessment is for AU grassland fires because field measurements for the entire time-evolving fire perimeter exist. Also, grassfires on level terrain are the simplest full-scale fires to simulate. The WFDS-level set model was also shown to produce fire perimeters that are very similar to the simple fire perimeter propagation model FARSITE. Thus, the systematic comparison of the level set and physics-based models in the WFDS model suite can support a well characterized assessment of FARSITE capabilities over a range of environmental conditions relevant to fire management, fire fighter safety, and fuel treatment effectiveness. In particular, the influence of the lack of fire-atmosphere coupling, terrain shaped winds, and transitions between fuel types can be investigated. The results presented here are the first step of a more complete investigation but imply that significant error can exist in simple models when applied to scenarios that deviate from a single fire spreading in continuous surface fuels on level terrain.

An assessment of the limitation of FARSITE, and other simple fire perimeter models, is more important than ever. With the advent of affordable portable computing devices (e.g., tablets), and internet based terrain and fuels data, simple fire perimeter models can be easily constructed and integrated into a risk assessment framework, whether tactical or strategic in application. An example of this use of simple models is in the Cohesive Strategy documentation (CS, 2012) for WUI risk assessment. As such frameworks are constructed and become more commonly used for management decision support it is imperative that an effort is made to understand the limitations of the simple models employed. The framework and models developed here offer one such avenue for this assessment. In fact, until an appropriate set of field measurements is created the use of physics-based models offers the best available method for assessing simple models.

VI. RELATIONSHIP TO OTHER RECENT FINDINGS AND ONGOING WORK

While other physics-based fire spread models and simple fire perimeter propagation models exist, this appears to be the first study to develop a single software package, including a visualization tool, which contains the two modeling approaches. This supports a consistent investigation into the limitations of the simple models under various slope, wind, and fuel conditions. To date, no such investigation has occurred.

VII. FUTURE WORK NEEDED

Landscape-scale fire modeling and risk assessment

Figure 23 shows a demonstration of the WFDS-physics-based, WFDS-level set, and FARSITE models to a problem relevant to WUI fire risk assessment at the landscape-scale. All models are applied to the simulation of a fire spreading over an actual 2 km x 2 km landscape in southern California. The terrain is obtained from LiDAR data (Mell et al., 2011). Grassland fuel is placed throughout. The results of the fire models overlie a GoogleEarth image of the area. This was provided to aid comparison between the models (i.e., roads and structures are not actually present in the simulations – although they could be in the WFDS-physics-based model). All three models can be applied to this scenario. The WFDS-physics-based model requires 18 hours of cpu time on 16 cores for the 180 s of simulated time. The WFDS-level set model requires 30 s of cpu time on one core. There are clearly differences between the predicted fire perimeters, especially between the FARSITE and WFDS models. Note that the level set flank fire ROS was calibrated to match the physics-based flank ROS. The FARSITE flank fire ROS is the result of its assumption of elliptical fire perimeter (see Appendix 4). The head fire spread rate in FARSITE was calibrated to match the WFDS-physics-based spread rate. (See Section IV.6 above for a discussion regarding the need to calibrate FARSITE). As a result of this calibration, the head fire locations are similar. However, the flank fires are significantly different.

The use of model based WUI risk assessments currently highlighted by the Cohesive Strategy document of Lee et al. (2011) make use of FARSITE-like fire perimeter propagation models over scenarios similar to that shown in Figure 23. However, this application is conducted without consideration of model limitations (e.g., sensitivity to inaccurate spread rates or flank fire spread rate assumptions).

We do not know how close any of the model predictions shown in Figure 23 are to reality. This challenge is especially difficult for simple fire perimeter propagation models because, strictly speaking, they are only as good as the spread rates given them. Unless these spread rates have been shown to be sufficiently accurate for the fuel, weather, and terrain characteristics of the application scenario they should be used with caution guided by knowledge of their limitations. Physics-based fire behavior models can be used to help create a knowledge base to better understand the limitations of simple fire perimeter models. Ideally, such an effort would be supported by targeted field and laboratory measurements. We do not claim, at this point, that we know how well the physics-based models will work in general. But we do believe that, since they include the driving physical processes, they offer a promising way to investigate and identify "watch-out" scenarios in which the simple fire perimeter propagation models are most likely to be in error. In addition, they can provide information about the error (i.e., over or under prediction of the head or flank fire spread rate). This is an important area of future work.

Community and parcel scale fire modeling and risk assessment

The image on the cover page shows a WFDS-physics-based simulation of a fire spreading through a WUI community in Worley, Idaho. NAIP and LIDAR remote sensing data were used to determine the terrain, roads (shown in gray), and location of structures and trees (McNamara et al., 2009). Conifer trees are displayed as cones. Building material vulnerability is colored based on NFPA 1144a (NFPA, 2008) ratings base on field data collection. A surface fire spreading from an arbitrary ignition point, and the associated smoke plume, are shown. The computational domain is 240 m by 240 m in horizontal extent and 100 m tall.

Figure 24 shows a similar application of the WFDS-physics-based model. Figure 24(a) and Figure 24(c) each have different fuel treatments, as described in the figure caption. Figure 24(b) is the time history of the heat flux integral for each structure in case shown in Figure 24(a); the red line the value at which plywood ignition takes place (Tran et al., 1992). For the fuel scenario in Figure 24(a) the house is predicted to ignite, using the ignition integral approach. For the fuel scenario of Figure 24(c), which follows Firewise recommendations, the house is not predicted to ignite.

The last two demonstrations simulations illustrate how physics-based models can account for heterogeneous and noncontiguous fuels and directly provide heat fluxes based on a simulation of the combustion processes. This is not possible with a simple fire perimeter model. However, this level of environmental information and model output allows for scenario specific WUI risk assessments, development and testing of improved Firewise guidelines, fire effects study, and fire fighter training examples. The need for such WUI risk assessments is stated in the Cohesive Strategy documents (see Lee et al., 2011) and in the literature (Mell et al., 2010a provide a review). In order to meet these needs and develop a knowledge base on the limitations of simple models and current Firewise guidelines (Mell et al., 2010a) further development, testing, and validation of the physics-based model is needed.

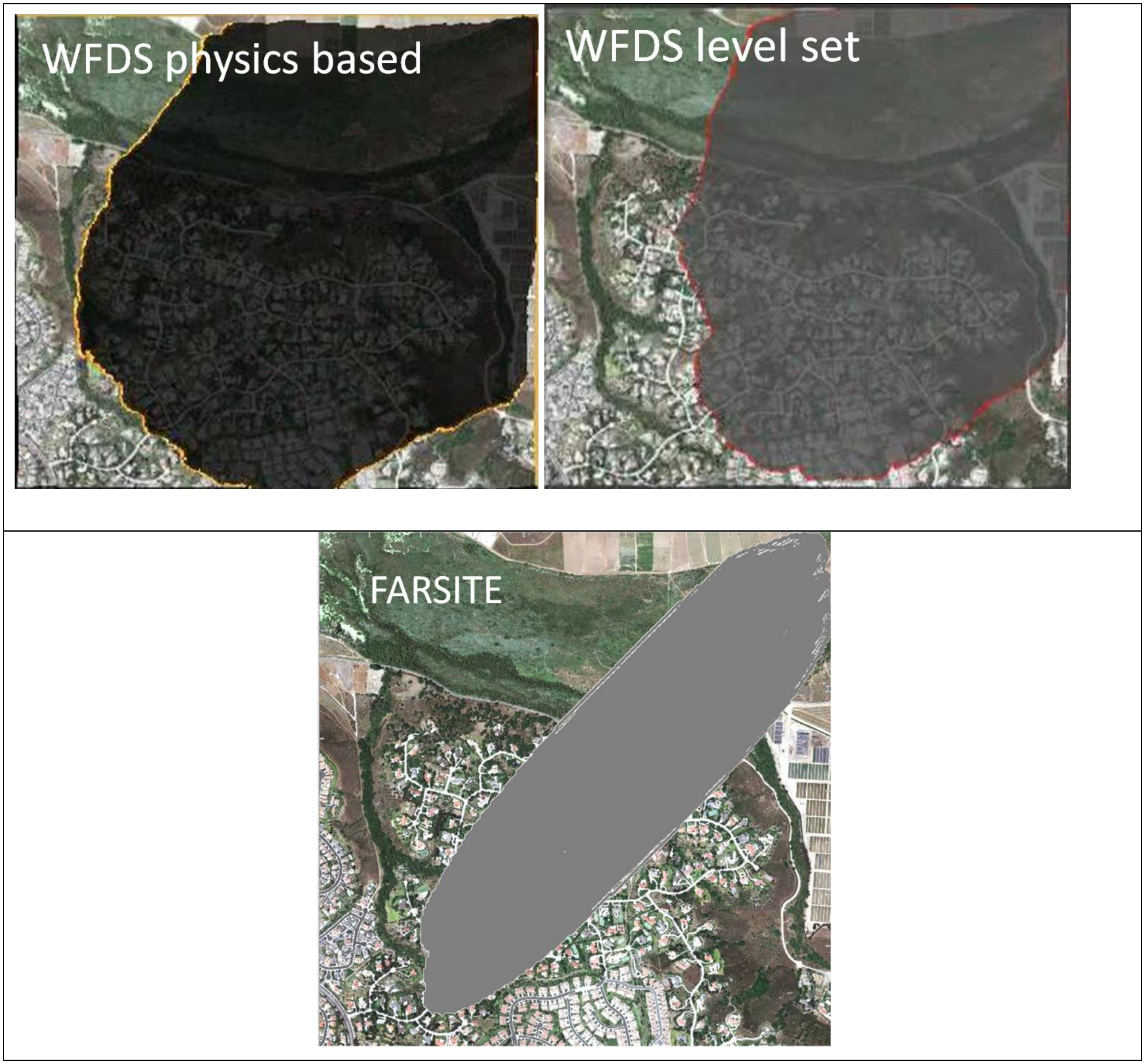

Figure 23: Demonstration simulations of the WFDS physics-based, WFDS primary level set and FARSITE models. All show the position of the simulated fire perimeter overlaid on 2 km x 2 km area image of an existing southern California WUI community burned in 2007 by the Witch Creek and Guejito wildland fires. For the purposes of this demonstration AU grassland fuel completely covers the terrain. Ignition occurred from spot fires in the northeast corner of the domain. The image is from GoogleEarth and is used to facilitate comparison. The terrain was obtained from LiDAR data provided by the USGS. The fuel model in Farsite was customized to match the WFDS physics-based simulation, and an adjustment factor of 1.5 was applied to give a head ROS similar to both WFDS simulations.

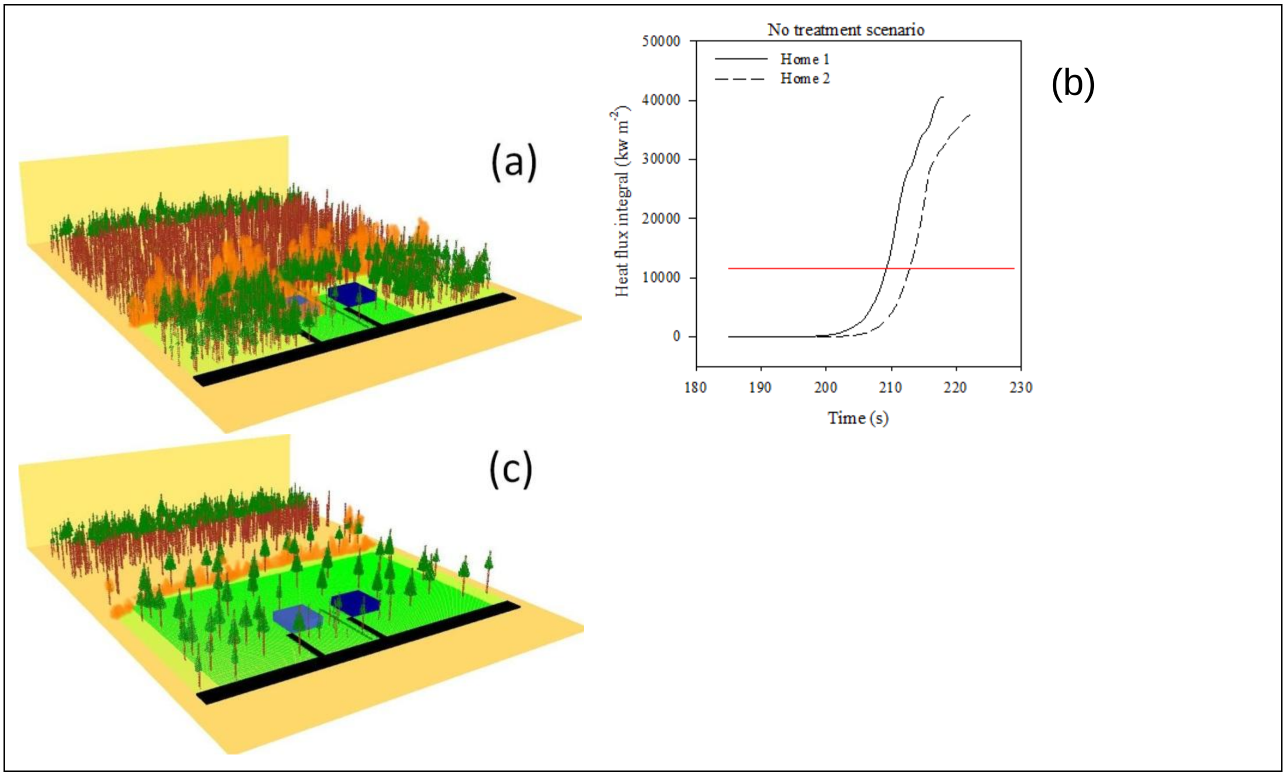

Figure 24: WFDS-physics-based simulations of a wildfire approaching two homes with different fuel treatments. **(a)** Untreated, 700 lodgepole pine trees per acre up to 2 m from homes and TU566 surface fuels. **(b)** Time history of the radiant-heat flux integral for the case in (a). The radiant heat flux on the top of the structures is used. The red line is the value of the head flux integral at which plywood ignition would take place. **(c)** FIREWISE treatment in a 30 m buffer around house: all trees with less than a 22.3 cm diameter at breast height were removed, for the remaining trees the crown base height was raised to at least 3 m and stems were spaced at least 10 m apart, surface fuels were replaced by irrigated lawn; in addition, from 30 m to 60 m TU5 surface fuel was changed to TU166 (low load grass and/or shrub with litter). These simulations required five hours of CPU time using eight processors. The computational domain is 150 m by 100 m in horizontal extent and 30 m high with cubic grid cells 0.5 m on side. Visualization is achieved using Smokeview. Trees are represented by a point cloud of fuel elements, each with its own thermophysical properties of the bulk vegetation (at the resolution of the computational grid).

Field experiments

Field and laboratory scale measurements are needed to support the development and validation of fire models operating at parcel, community, and landscape scales. The Joint Fire Sciences Program is currently funding projects that will expand such a measurement dataset. It is important to note that the Australian grassland measurements used in this project represent the state of the art. They provided fire perimeters at a number of times which allowed testing of the physics-based and level set models' capability to predict the evolution of the entire fireline. Any future field studies that seek to provide data for fire model validation need to place a priority on capturing the time evolution of the location and depth along the entire fire line. For example, the Australian measurement showed that there is an interaction between the flank and head fires leading to a head fire dependence on the distance separating the flank fires. Also, both the depth and spread rate along the fireline determine the total heat release rate and, therefore, the fire-atmosphere interaction. Thus, a physics-based model must well predict both fireline depth and spread rate. Unfortunately, there are very few measurements (field or laboratory scale) of these quantities.

Laboratory experiments have the advantage of a better understanding of experimental error (through replication) and instrumentation error (through onsite calibration). Laboratory measurements are needed to develop and test components of physics-based models: wind through vegetation, thermal radiation, solid phase degradation, convective and radiative heat transfer, etc.

VIII. SCIENCE DELIVERY AND APPLICATION

Table of proposed and actual deliverables

Proposed	Delivered	Status
Final report	Final report. *This is in partial fulfillment of JFSP project # 07-1-5-08*	Complete
Refereed Publications	Eight publications have resulted from this project. Please see a listing in the text following this table.	Completed (Uploaded if in print)
Non-Refereed Publications, Posters, Presentations	Over fifteen presentations over the course of this project were given. A selection is provided in the text following this table.	Completed (two papers uploaded)
Computer Model /Software/Algorithm	The computer models developed here are the result of an ongoing collaboration between the U.S. Forest Service and the National Institute of Standards and Technology (NIST). The WFDS software suite and its companion visualization package, Smokeview, are freely available on the web. The WFDS-physics-based and WFDS-level set models are fully integrated into FDS (Fire Dynamics Simulator) a structure fire model developed and maintained by NIST. Smokeview is also developed and maintained by NIST. The source code for WFDS is also freely available. See the web page item below for html addresses.	Updated as needed
Web Page	The most up to date WFDS suite (with both the physics-based and level set models), user guide, and source code can be obtained through http://www.fs.fed.us/pnw/fera/research/wfds/index.shtml Downloads of the visualization tool Smokeview are available at http://fire.nist.gov/fds/downloads.html	Updated as needed.
Model User guide	Available through http://www.fs.fed.us/pnw/fera/research/wfds/index.shtml	Updated as needed.
Visualization tool	This tool is called Smokeview and is available, along with its user guide, at http://fire.nist.gov/fds/downloads.html	Updated as needed

Table 3. Additional deliverables completed that were not included in the original proposal.

Additional Deliverables Completed But Not Originally Proposed	Status
Comparison of FARSITE fire perimeter propagation model to WFDS-level set	Completed

WEB PAGE

Please refer to the table of deliverables above.

REFEREED PUBLICATIONS (IN REVERSE CHRONOLOGICAL ORDER)

The following publications were the result of model development made possible through funding from this project. It should be noted that this report focused on surface fires because they are the most logical first step in a comparison of physics-based and simple models. However, a significant amount of effort was focused on model development for fires in raised fuels. This is reflected in the published papers. Fires in raised fuels are an important component of WUI fires in general.

<u>Under review</u>

S. Michaletz, E. Johnson, W.E. Mell, Greene "Timing of fire relative to seed development controls availability of non-serotinous aerial seed banks," *American Naturalist*

C. Hoffman, P. Morgan, W.E. Mell, R. Parsons, E. Strand, S. Cook, "Surface fire intensity influences crown fire behavior in forests with recent mountain pine beetle-caused tree mortality in lodgepole forests," *Forest Science*

D. Morvan, S. Meradji, W.E. Mell "Interaction between head fire and backfire in grassland," *Intnl. J. Wildland Fire*

<u>In print</u>

A. Maranghides, W.E. Mell, K. Ridenour, D. McNamara, "Wildland urban interface fires – What is burning and why?," *Fire and Rescue*, May 2012

C. Hoffman, P. Morgan, W.E. Mell, R. Parsons, E. Strand, S. Cook, "Numerical simulation of crown fire hazard following bark beetle caused mortality in lodgepole pine forests," *Forest Science*, to appear

D. Morvan, C. Hoffman, F. Rego, W. Mell, "Numerical simulation of the interaction between two fire fronts in grassland and shrubland," *Fire Safety Journal*, 46, 469-479 (2011)

R. Parsons, W.E. Mell, P. McCauley, "Linking 3D spatial models of fuels and fire: Effects of spatial heterogeneity on fire behaivor," *Ecological Modeling*, 222, 679-691 (2011); http://dx.doi.org/10.1016/j.ecolmodel.2010.10.023

A. Maranghides and W.E. Mell, "A Case Study of a Community Affected by the Witch and Guejito Fires," *Fire Technology* 47(2), 379-420 (2011)

W.E. Mell, S.L. Manzello, A. Maranghides, D. Butry, R.G. Rehm, "The wildland-urban interface fire problem - current approaches and research needs," *International J. Wildland Fire*, 19, 238-251 (2010).

W.E. Mell, A. Maranghides, R. McDermott, S. Manzello, "Numerical simulation and experiments of burning Douglas fir trees," *Combustion and Flame*, 156, 2023-2041 (2009)

R.G. Rehm, W.E. Mell, "A simplified model for wind effects of burning structures and topography on WUI surface-fire propagation," *International J. Wildland Fire*, 18, 290-301 (2009).

SELECTED RECENT PRESENTATIONS RESULTING FROM THE RESEARCH FUNDED BY THIS PROJECT (SELECTED)

"Coupling Wildland-Urban Interface (WUI) Fire Models to a GIS," D McNamara, W Mell, A Maranghides, *2012 ESRI International User Conference*, 23-27 July 2012, San Diego, CA

"Wildland-urban interface fires: Research needs and directions," W Mell, A Bova, A Maranghides, R McDermott, G Forney, Department of Forest & Rangeland Stewardship seminar, Colorado State University, May 2, 2012

"Assessing fire behavior in the WUI with a dynamic fire model," R Parsons, W Mell, *3rd Human Dimensions of Wildland Fire Conference*, 17-19 April 2012, Seattle WA

"Use of WFDS to Model Fire Spread in Chamise Chaparral Fuel Beds", D Weise, W Mell, X Zhou, S Mahalingham, *Western States Section of the Combustion Institute Meeting*, 19-20 March 2012, Tempe, AZ

"Measurements and modeling of wildland fires," W Mell, A Maranghides, *JFSP Workshop Integrated Measurements to Support Improved Fire Behavior and Smoke Models*, 4-6 October 2011, Boise, ID.

"Numerical study of the interaction between a head fire and a backfire propagating in grassland," D Morvan, S Meradji, W Mell, *Internationl Symposium on Fire Safety Science*, 19-24 June 2011, University of Maryland, College Park, MD

"Wildland-urban interface fires," W Mell, A Maranghides, S Manzello, D McNamara, R McDermott, G Forney, *Core Fire Science Caucus*, 19-20 April 2011, Boulder CO

"Wildland urban interface: A coupled problem," A Maranghides, W Mell, *Congressional Fire Services Institute*, 14 April 2011, Washington, D.C.

"Computer modeling of wildland-urban interface (WUI) fires," W Mell, D McNamara, A Maranghides, R McDermott, G Forney, C Hoffman, M Ginder, *Fire and Materials*, 31 January – 2 February 2011, San Francisco, CA

"Fire behavior modeling – Perspectives and new approaches and applications," W Mell, R McDermott, G Forney, *3rd Fire Behavior and Fuels Conference*, 25-29 October 2010, Spokane, WA

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Appendices 1-6--Final Report

JFSP Project # 07-1-5-08

Appendix 1: WFDS–Physics-Based Model

Predictions from the physics-based Wildland-urban interface Fire Dynamics Simulator (WFDS) have been compared to measurements of grassland fires (Mell et al. 2007) and individual Douglas fir tree burns (Mell et al. 2009). Additional validation is ongoing. A web page based user guide is available (WFDS, 2012). Other physics-based models exist and can be applied to similar fire scenarios. 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 (Mell et al., 2010b).

The numerical approach used in the current (April 2012) version of WFDS, is an extension of the capabilities of version 6 the FDS (Fire Dynamics Simulator) to outdoor fire spread and smoke transport problems that include vegetative and structural fuels and complex terrain. This version of FDS is not yet officially released. FDS is a fire behavior model developed by NIST in cooperation with VTT Technical Research Center of Finland, industry, and academics. Until the development of WFDS (which began in 2005), the focus of FDS had been to simulate stationary outdoor fires (e.g., pool fires and tank farm fires) and structural fires. The methods of computational fluid dynamics (CFD) are used to solve the three-dimensional (or two-dimensional) time-dependent equations governing fluid motion, combustion, and heat transfer. Throughout the course of the development of FDS, experiments conducted in NIST's Large Fire Laboratory and elsewhere have been used to evaluate and further refine the modeling approach. The FDS web site (FDS, 2012) has information on FDS validation and verification studies and an FDS user and technical guides.

The numerical model is based on the large-eddy simulation (LES) approach and provides a time-dependent, coarse-grained numerical solution to the governing transport equations for mass, momentum, and energy. The effect of thermal expansion due to chemical reaction and heat and mass transfer enters the computation through an elliptic constraint, derived using the energy equation, on the velocity field. The local mean temperature is then obtained via the ideal gas equation of state. Dissipation of kinetic energy is achieved through a simple closure for the turbulent stress (Deardorff, 1972). The turbulent transport of heat and mass is accounted for by use of constant turbulent Prandtl and Schmidt numbers, respectively. The subgrid heterogeneity of species concentrations and temperature is treated in conjunction with the reaction, heat transfer, and radiation intensity models. Where these effects are important they are included using empirical correlations.

The advective form of the continuity equation is solved together with the Stokes form of the momentum equations on a structured Cartesian staggered grid. The spatial discretizations are second-order accurate for uniform grids. Species mass equations are advanced using a modified version of MacCormack's predictor– corrector scheme and the momentum equations are advanced using a two-stage projection scheme based on the explicit modified Euler method. Combustion heat release rate is modeled based on the Eddy Dissipation Concept (EDC) model of

Magnussen and Hjertager (1976), see the FDS technical and user guides for more details (FDS, 2012).

The solid phase model is similar to models used by previous researchers. In particular, Albini (1985, 1986) presented similar model equations for two-dimensional heat transfer in a medium containing vegetation and air under an assumed heat flux due to an idealize fire shape. Albini's approach provided a fire spread rate but did not model the pyrolysis or char oxidation of the solid fuel. More recently, similar models for the heat transfer within the vegetative fuel bed have been incorporated in CFD models, which include (to differing levels of approximations) thermal degradation (pyrolysis) and char oxidation) and gas-phase combustion, to obtain a more complete approach to predicting the transient behavior of the fire and its buoyant plume (for example Dupuy and Morvan (2005), Linn et al. (2002), Mell et al. 2007). A review of these methods is given in Mell et al. (2007 and Morvan (2010).

The vegetation is assumed to be composed of fixed thermally thin, optically black, fuel elements. Note that an emissivity of 0.9 is characteristic of wildland vegetation (Jarvis et al., 1976) so the assumption that a fuel element is a perfect absorber is reasonable. The thermally thin assumption is commonly used in fire spread models involving fine wildland fuels (grass and foliage of shrubs and trees) (Rothermel, 1972). Vegetation that is thermally thin is sufficiently small in that it is not resolved on the computational grids used here (O (1) m). In the approach used here the thermal, radiative, and drag processes are determined from the bulk vegetative properties (e.g., bulk density). This is similar to other modeling approaches (Dupuy and Morvan, 2005; Larini et al., 1998; Porterie et al., 2005; Zhou et al., 2007)

Both convective and radiative heat transfer between the gas phase and the vegetation is accounted for, as is the drag of the vegetation on the airflow. In general, as the temperature of a vegetative fuel increases, first moisture is removed, followed by pyrolysis (the generation of fuel vapors), and then char oxidation (also known as smoldering combustion). In the modeling approach used here, the temperature equation for the fuel bed is solved assuming a two stage endothermic decomposition process of water evaporation followed by solid fuel pyrolysis. Char oxidation requires sufficiently high solid temperatures and gas-phase oxygen concentrations. As a first approximation to the prediction of flame spread through vegetation, char oxidation is not modeled here.

An example of a WFDS physics-based prediction of the three-dimensional fire and smoke plume and radiative and convective heat fluxes on the AU grassland fuel is shown in Figure 25. This is a relatively small fuel plot compared to the simulations conducted in this study. Examples of other applications of the WFDS physics-based model, for a range of scales, are given in Figure 26 and Figure 27 . These results are discussed in Mell et al. (2010b).

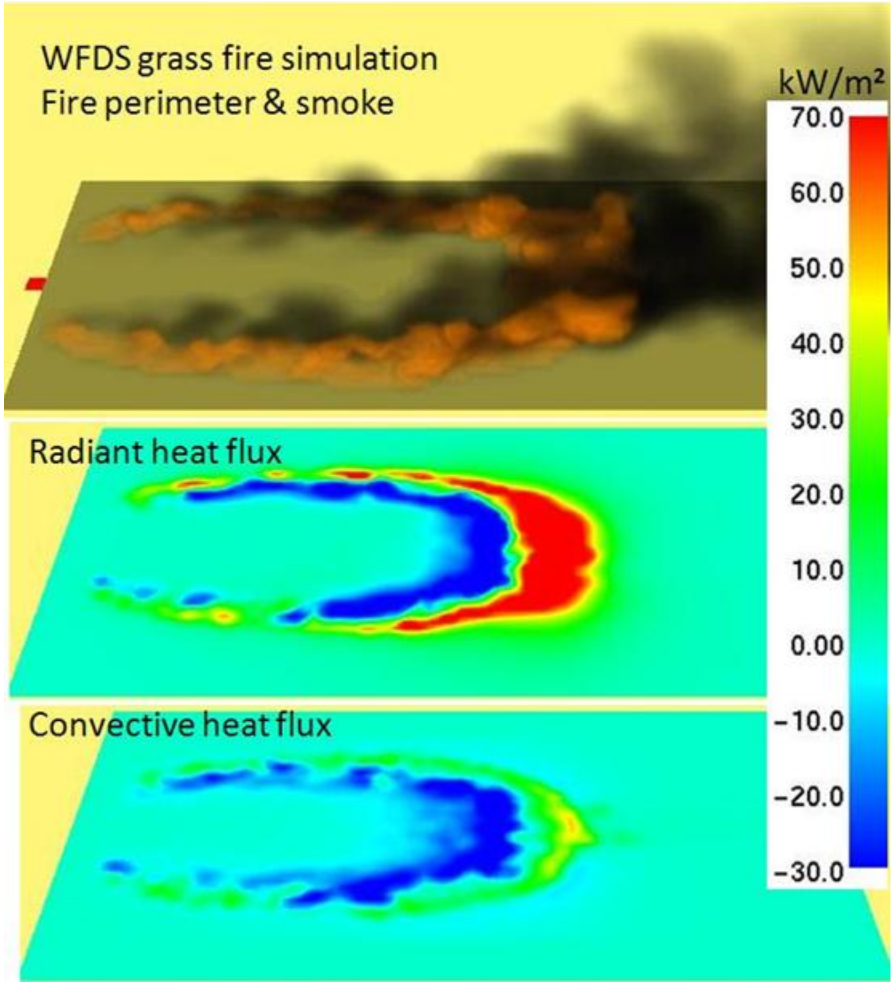


Figure 25: Three images showing results from a grassfire simulation using the physics-based WFDS. The grass land plot is 150 m long and 50 m wide. All figures correspond to the same time the ambient wind flow from left to right. From top to bottom: the three dimensional fire perimeter and smoke plume; radiant heat flux; convective heat flux are shown. The scale for the heat fluxes also shown**.** Note that region upwind of the fire is in a state of net heat loss (i.e., cooling) as shown in blue.

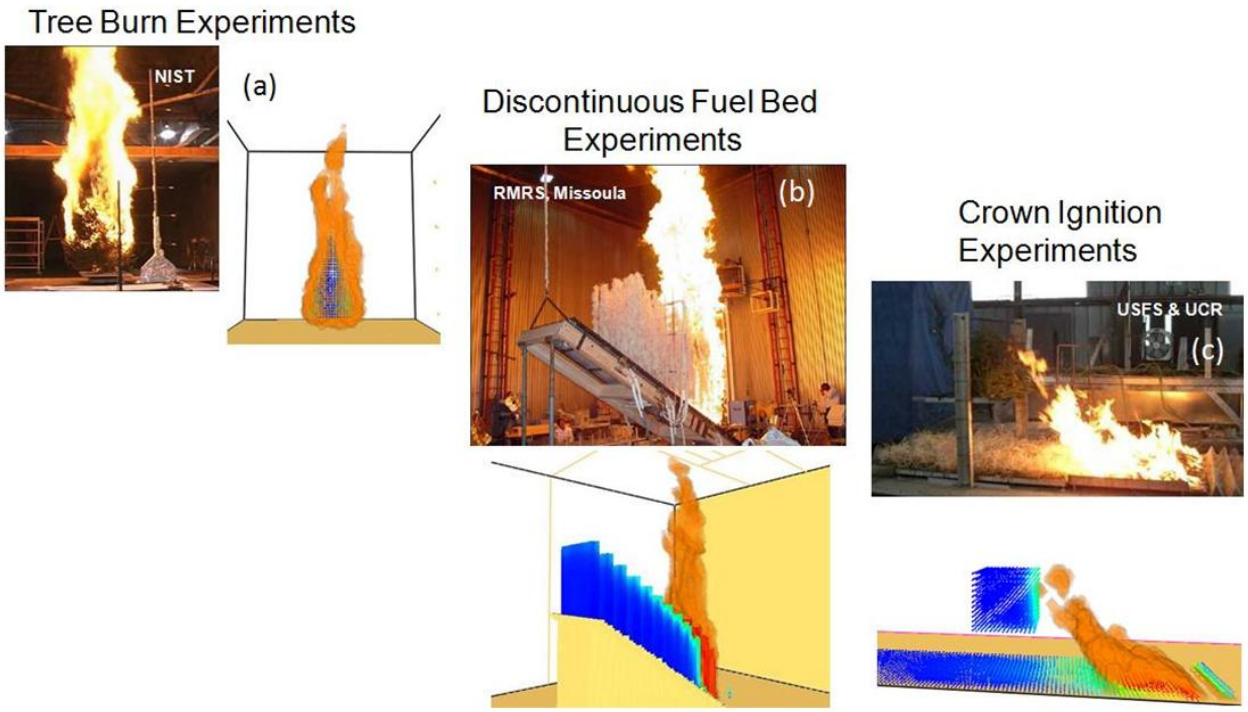


Figure 26: Examples of WFDS applied to laboratory scale fires. (a) Douglas tree burn experiments conducted at NIST (10 cm grid; 6 m x 6 m x 9 m domain; 300 times slower than real time with 4 processors). (b) Deep fuel bed experiments conducted in the USFS Missoula burn chamber (5 cm grid in fire region; 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).

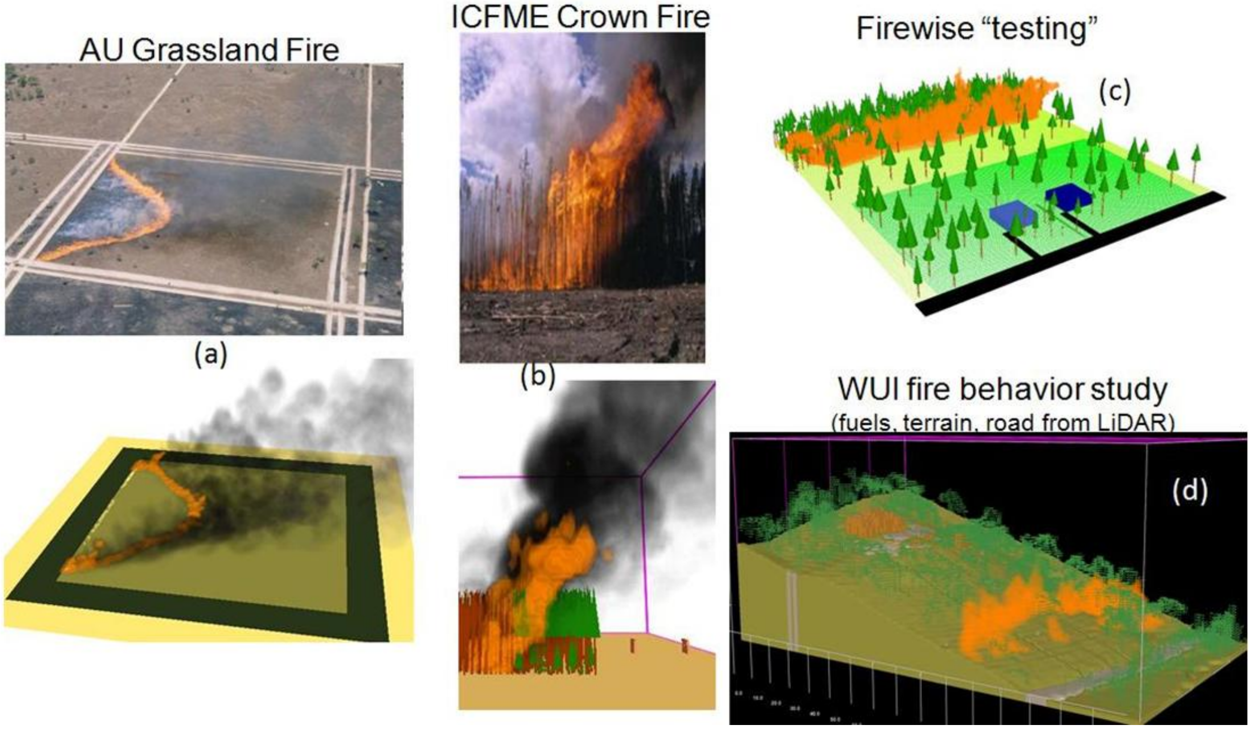


Figure 27: Stand scale examples of fire behavior and applications of WFDS. (a) Australian grassland fires (Mell et al., 2007) on 200 m by 200 m plots (1.7 m computational grid in fire region; 1500 m x 1500 m x 200 m domain; 125 times slower than real time with 10 processors). (b) Crown fire experiments conducted in the Northwest Territory of Canada. (c) Simulation only study of fuel treatment effectiveness in preventing structure ignition (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 over a southern California community.

Appendix 2: WFDS–Level Set Model

Theory

The principles of the level set method, as it is used for modeling the evolution of a boundary or interface, are outlined in Sethian (1997), and described in greater detail in Sethian (1999). The level set method is a geometric concept, in which the movement of, for instance, a two-dimensional closed curve is visualized as a changing intersection of a plane and the surface of a three dimensional object. As an example, a circle expanding over time on a level plane may be visualized as the intersection of the plane and the surface of a cone moving perpendicularly through the plane. A three-dimensional system is the easiest to visualize, but the method is generalizable to higher dimensions. Despite the extra complexity added by including an extra dimension, the level set method has several advantages, described below, over other methods of tracking a moving interface.

Finding the set of points that intersect a higher-dimensional shape turns out to be rather simple mathematically. In a Cartesian coordinate system, a level set function, $\phi(x,y,t)$, gives a distance normal to the plane at point (x,y) at a time, t, and so describes the volume of a shape in three dimensions over a period of time. In essence, the method exchanges a Lagrangian description of the motion, i.e., from the perspective of the moving points on the curve of the interface, to an Eulerian formulation in which each point on the plane changes value according to the level set function (Rehm and McDermott 2009, Sethian 1997). Accordingly, the evolution of the function is given by its material derivative. Thinking again of a three dimensional shape moving through an intersecting two-dimensional plane, the location of the moving curve at a given time is the set of all points in the plane of vertical distance zero from the intersecting shape, i.e., where $\varphi(x,y,t) = 0$. Equivalently, changes in the level set function over time are found by setting the material derivative of the function to zero and solving the resulting partial differential equation (the variables of the level set function, φ, have been omitted for clarity):

(2-1) $\partial\varphi/\partial t + U_x\, \partial\varphi/\partial x + U_y\, \partial\varphi/\partial y = 0$

where U_x and U_y are the velocities of the interface along the respective plane axes. Clearly, a key factor in the evolution of the level set function is the velocity vector, U, of each point at the moving interface. Formulas that define the velocity can be physical or empirical, and depend on the problem at hand. Bose (2008) gives a form of the above equation in which the velocity of the front is based on Richards' equations (1990), and so will give the same fire spread patterns as FARSITE. In WFDS-level set fire simulations, the solution of the level set at a given time, *t*, (i.e., where $\varphi(x,y,t) = 0$) defines the location of the fireline.

Numerical Methods

The numerical methods used to solve the equation are given in full in Rehm and McDermott (2009). The domain of the level set model is a two-dimensional grid with spacings Δx and Δy. The values of φ and U are node-centered (i.e., defined at the grid intersections).

The gradients of φ (shown below with arguments omitted), are approximated at each time step, n, and each grid location (i, j), by central-difference formulas,

$$(\partial\varphi/\partial x)_{i,j}^{n} \approx (\varphi_{i+1,j}^{n} - \varphi_{i-1,j}^{n}) / 2\Delta x, \text{ and}$$

$$(\partial\varphi/\partial y)_{i,j}^{n} \approx (\varphi_{i,j+1}^{n} - \varphi_{i,j-1}^{n}) / 2\Delta x.$$

These gradients are in turn used to calculate the unit normal vector, $\underline{n}$, to the fireline at the grid location (i, j):

$$\underline{n} = \{1 / |\text{grad}(\varphi)|\} \{(\partial\varphi / \partial x)\, \underline{i}_x + (\partial\varphi / \partial y)\, \underline{i}_y \},$$

where $\underline{i}_x$, $\underline{j}_y$ are unit vectors in the x- and y-directions and

$$|\text{grad}(\varphi)| = \sqrt{ (\partial\varphi / \partial x)^2 + (\partial\varphi / \partial y)^2 }.$$

Fireline speed (ROS), calculated according to an arbitrary fire spread model, is then computed for the direction of the normal vector. Equation 2-1 is solved using a second-order Runge-Kutta scheme (Rehm and McDermott 2009).

Wind and Terrain

In WFDS-level set, the wind vector is derived from user-prescribed wind speeds along the x- and y-axis, although the physical modeling capabilities of WFDS allow for the implementation of time-varying, terrain-altered winds in future versions. Terrain in WFDS is currently modeled by the filling of mesh cells with solid, rectilinear obstructions (see Appendix 1). Local slope at a grid point is calculated as the central difference of heights, z, at neighboring points in the x- and y-directions:

$$(\partial z/\partial x)_{i,j} \approx (G_{East} - G_{West}) / \Delta x, \text{ and}$$

$$(\partial z/\partial y)_{i,j} \approx (G_{North} - G_{South}) / \Delta y,$$

where

$$G_{East} = ½ [(z(i, j) + z(i+1, j)],$$

$$G_{West} = ½ [(z(i, j) + z(i-1, j)]$$

$$G_{North} = ½ [(z(i, j) + z(i, j+1)]$$

$$G_{South} = ½ [(z(i, j) + z(i, j-1)].$$

The surface over which eq. (2-1) is solved is visualized as a plane conforming to the surface topography, i.e., the grid point (i, j) implicitly maps to the point (i, j, k), where $k\, \Delta z = z$.

Fire spread models in WFDS-level set

The level set method has been used to model the propagation of wildland fire fronts on simple, plane surfaces (e.g., Rehm and McDermott 2009, Mallet et al. 2009, Mell et al 2010b). Currently in WFDS, the velocity of the interface, referred to as ROS hereon, may be calculated by two different methods. In the first (or 'primary') method, head, back and flank ROS are prescribed, therefore wind, regardless of speed, affects heading direction only. The effect of slope is calculated according to the McArthur (1973), with the option of invoking an ROS dependence proportional to the square of the tangent of the slope angle. This option gives a slower uphill ROS similar to that calculated by Farsite. This method is used for comparison with FARSITE in Appendix 5.

In the second, or 'ellipse-constrained,' method, model inputs include a no-wind, no-slope ROS (nominally 2 cm/s), and fuel bed parameters such as surface-to-volume ratio, packing ratio and depth. Head, back and flank ROS and direction are then calculated according the surface fire spread model used in FARSITE (see Appendix 4), including the assumption of elliptical propagation and the dependence of the length-to-breadth ratio of the ellipse on 'effective' wind speed. Prescribed wind direction and speed affect the direction of fire spread.

Appendix 3: Lagrangian Fire Spread Model

This discussion follows Rehm (2008) and Rehm and McDermott (2009). In the Lagrangian formulation, the locations of a number of nodes, distributed along the initial prescribed fire perimeter are advanced with time. The overall fire perimeter is the curve passing through these nodes. The time evolution is determined as the solution of a set of ordinary differential equations by the method-of-lines. Results for the behavior of the front were reported for wind-blown fires in the presence of single or multiple burning structures on level or uneven terrain, Rehm (2008) and Rehm and Mell (2009).

For simplicity, in this section we consider only fire-front propagation in the presence of burning structures over level ground (no terrain). The extension of the approach to uneven terrain is given in Rehm and Mell (2009). The governing equations describing the propagation of a node on the fire perimeter in the horizontal plane are:

(1) $d\underline{R} / dt = (\underline{U} * \underline{n})\ \underline{n}$

The equation is given in vector form: $\underline{R} = x\ \underline{i}_x + y\ \underline{i}_y$, where $\underline{i}_x$, $\underline{i}_y$ are unit vectors in the x and y directions and the symbol * denotes the vector dot product. $\underline{U} = U_x\ \underline{i}_x + U_y\ \underline{i}_y$ is the spread rate (or the rate of spread (ROS) vector in m/s) of the fire front at the location (x,y), and $\underline{n}_x$, $\underline{n}_y$ are the components of the unit normal to the fire front directed toward the unburnt fuel.

At each point, the fire front is advanced in the direction normal to the front at a speed determined by the local ROS for the fire. This ROS, in turn, can depend on several variables including the total wind speed at that location. The method of lines (MOL) and a centered difference scheme for the spatial discretization of the interior nodes of the fire-line was used. Discretization at the end nodes, was performed with a one-sided difference scheme with the neighboring interior node.

Let $\underline{V} = V_x\ i_x + V_y\ i_y$ be the total wind velocity at a specified height. Assume that the linear relation for Australian grass (Cheney et al., 1998) is valid for the normal ROS and the local wind velocity normal to the fireline:

(2) $U_n = r_o\ (1 + c_f V_n)$

Here $U_n = \underline{U} * \underline{n}$ and $V_n = \underline{V} * \underline{n}$ with constants r_o and c_f. This equation can be derived from Eq. (1) in the main text through grouping of terms and assuming a very low moisture and very large head width. Using Eq. (2) in Eq. (1) gives

(2) $d\underline{R} / dt = r_o\ (1 + c_f\ \underline{V} * \underline{n})\ \underline{n}$

If the fire front curve at any specified time t is described by the vector function ($x(s, t)$,$y(s, t)$), where s is a parameter specifying the curve, then, the unit tangent vector can be written as

$$\underline{\tau} = 1 / |\mathrm{grad}(\phi)|\ \{ (\partial x / \partial s)\ \underline{i}_x + (\partial y / \partial s)\ \underline{i}_y \}$$

Where $|\mathrm{grad}(\phi)| = \mathrm{sqrt}\{ (\partial x / \partial s)^2 + (\partial y / \partial s)^2 \}$. The unit normal is

$$\underline{n} = \{1 / |\mathrm{grad}(\phi)|\} \{-(\partial y / \partial s)\, \underline{i}_x + (\partial x / \partial s)\, \underline{i}_y \}.$$

In component form, the equations can be written

$$dx/dt = U_n n_x , \quad dy/dt = U_n n_y$$

Where

$$U_n = \underline{r}_o \{ 1 + c_f [-(\partial y / \partial s) V_x + (\partial x / \partial s) V_y] / |\mathrm{grad}(\phi)|.$$

More general model equations were reported in Rehm and Mell (2009) and include the influence of the ambient wind (as shown in the equations above), the entrainment wind generated by a burning structure or structures, and the effective slope-generated wind. To obtain the entrainment wind generated by a burning structure, an approximation to the analytical formulas developed by Baum and McCaffrey (1989) was used. The wind generated by multiple burning structures was obtained by summation (Rehm, 2006). It is assumed that the entrainment wind from each burning structure is dependent only on the vector distance, in a horizontal plane, between the location on the fire perimeter and the location of the center of the structure. For consistency with the derivation of the entrainment velocity equations, the ambient wind must not be strong enough to significantly tilt the fire/smoke plume off vertical. To account for the influence of slope on the wind, a proportionality constant based on the on the slope is applied following Rothermel (1972). This approach for including the in influence of the slope is consistent with the approach used in FARSITE and in WFDS-level set.

Appendix 4: Summary of the FARSITE Surface Fire Spread Model

The Fire Area Simulator (FARSITE) is a wildland fire growth model developed by the U.S. Forest Service. It is freely available at http://www.farsite.org. The discussion below focuses on factors affecting the modeling of surface fire spread, although Farsite also contains parameterizations for crown fire spread.

The key feature of FARSITE is its treatment of a fireline as an expanding wavefront in accordance with Huygens' principle (Finney 2004). In this model, fire lines are advanced as connected sets of vertices, forming fire polygons. At a given time step, each vertex in the set is assumed to act as the upwind (or 'rear') focus of an elliptically-shaped wavelet. The assumption of an elliptical shape is mathematically convenient, although other simple fire shapes have been reported. For example, Richards (1995) lists four different shapes (ellipse, double ellipse, lemniscate and tear drop) observed during the equilibrium (constant spread rate) phase of surface fires. Over a given time step, the furthest points reached by these wavelets, in the direction of propagation, define the new fireline and serve as rear vertices for the next time step. The space along the fireline between vertices is rediscretized to maintain the user-prescribed resolution of the fire line.

To estimate the rate of spread (ROS) of surface fires, FARSITE employs the Rothermel spread formula (Rothermel 1972), in which ROS (min-1) is calculated as the ratio of estimated reaction intensity (kJ min-1 m-2) to the fuel's volumetric "heat of pre-ignition" (kJ m-3). The effects of wind and slope on ROS are accounted for by multiplying the no-wind, no-slope, steady-state ROS by empirically derived wind and slope factors:

$$\mathrm{ROS} = I_R\, \xi (1+\varphi_w+\varphi_s) / (\rho_b \varepsilon Q_{ig}) ,$$

where,
I_R is "reaction intensity" (kJ min^{-1} m^{-2}), ξ is the propagating flux ratio (itself a function of fuel surface area-to-volume ratio, σ, and packing ratio, β) (dimensionless), φ_w is the wind factor (dimensionless), φ_s is the slope factor (dimensionless), ρ_b is the bulk density of ovendry fuel (kg m^{-3}), ε is the dimensionless "effective heating number" [= exp(-4.528/surface-to-volume ratio of fuel)] in metric units, and Q_{ig} is heat of preignition (kJ kg^{-1}).

It is assumed that ROS and intensity do not depend on interactions of the fire and environment. For example, the dependence of ROS on the width of the head fire found by Cheney and Gould (1995) in Australian grassland fires cannot currently be modeled in FARSITE. However, fire acceleration, i.e., increase in ROS over time as fire propagates from an ignition point, can be modeled, though it is assumed that fire behavior does not affect acceleration, which depends only on fuel type and whether the ignition source is a point or a line.

An empirically derived length-to-breadth ratio (LTBR) (Anderson 1983) is used to define the ratio of heading to backing ROS at a given vertex. This ratio, and the heading ROS, are in turn used to calculate the corresponding lengths of the semi-major and semi-minor axes, and the rear vertex-to-center dimension, of an ellipse propagating from an ignition point. The length-to-breadth ratio, LB, of the elliptical wave front expanding from a vertex at the rear focus of the ellipse is determined by the midflame windspeed, U (m s^{-1}), by the formula,

$$LB = 0.936 \exp(0.2566\, U) + 0.461 \exp(-0.1548\, U) - 0.397,$$

which approaches unity as U goes to zero (Finney 2004, citing Anderson 1983).

The head to back ratio, HB, is then calculated as

$$HB = (LB+(LB^2-1)^{0.5})/(LB-(LB^2 - 1)^{0.5})$$

and the semi-major axis, b, semi-minor axis, a, and the ignition-point-to-center distance, c, are calculated using (Finney 2004):

$$a = 0.5\ (R + R/HB) / LB$$

$$b = (R + R/HB) / 2$$

$$c = b - R/HB.$$

These relations are a consequence of defining the heading rate of spread as b+c, the flank rate as a and the backing rate as b-c. For sloping terrain, coordinate transformations are used to translate the planar rates of spread to the slope coordinates according to the method of Richards (1990).

It should be noted that the formula for LB was derived for the effects of wind only (Anderson 1983). To account for the effect of slope on LTBR, the increase in ROS due to slope (φ_s in the Rothermel model) is calculated as a vector, and the components are added to the corresponding components of the wind factor (φ_w). The formula for the wind factor,

$$\varphi_w = C(0.3048U)^B(\beta/\beta_{Optimum})^{-E}$$

where C, B and E are values calculated from empirically derived formulas and β is the fuel packing ratio, is then solved for the wind speed, U, giving an 'effective wind speed' that is then used in the formula for LB. Finney (2004) notes that that this assumption, i.e., that slope and wind have similar effects on fire shape, is unverified.

The differentials of spread rate, $X_t = \partial x/\partial t$ and $Y_t = \partial y/\partial t$, are calculated from:

$$X_t = a^2\cos\theta(x_s \sin\theta + y_s\cos\theta) - b^2\sin\theta(x_s \cos\theta - y_s\sin\theta) / D + c \sin\theta$$
$$Y_t = -a^2\sin\theta(x_s \sin\theta + y_s\cos\theta) - b^2\cos\theta(x_s \cos\theta - y_s\sin\theta) / D + c \cos\theta$$

where , $D = [b^2 (x_s \cos\theta + y_s\sin\theta)^2 - a^2(x_s \sin\theta - y_s\cos\theta)^2]^{1/2}$ and the coordinates $x_s = x(s,t)$ and $y_s = y(s,t)$ are functions of a closed-curve parameter, s, where $0 <= s <= 2\pi$. The values a, b and c are from the elliptical axis formulas described above.

Domains in Farsite are defined via selection of fuel, weather, wind and topographic files by means of a graphical user interface (GUI). The topography and fuel files are assumed to be in GIS raster format (e.g., gridded ASCII), while wind and weather information are contained in simple data files. Weather data include precipitation, and temperature and humidity extremes that are used to build diurnal weather profiles. These, along with cloud cover, are incorporated into the BEHAVE fuel moisture model (for 1- and 10-hour fuels), and the NFDRS model (100-hour fuels), to adjust fuel moisture over the course of the simulation. Wind data are given as the wind speed and direction at various times covering the span of the simulation. It is assumed that the given wind speed is at a height of 10 m above the surface (or 20 feet, if British units are used). For surface fires, wind speed is then adjusted to the speed at the mid-flame height, assumed to be twice the fuel bed depth, using the formula given by Albini and Baughman (1979). The wind is also assumed to be parallel to the terrain.

Ignition points, which can be connected as lines, are manually placed in the domain. After ignition, fire front lines are displayed by the GUI at intervals equal to or greater than 1 simulated minute. The simulation continues until the end of a preset duration, or until the fire leaves the domain. Data files containing ROS, fire line intensity, time-of-arrival at a point, and other measurements can be output to separate files.

Appendix 5: Comparison of WFDS-Level Set and FARSITE Fire Spread Models

The same model of fire spread may be employed by the level set method and FARSITE in order to give similar behavior, but there are underlying differences between the two methods. The level set method requires only a model for the velocity (U) at a point. The assumption of an intrinsic fire shape is not necessary, although a shape may be implicit in the model of fireline ROS. A great advantage of the level set model as implemented in WFDS is that it may be used with a variety of different empirical and semi-empirical spread models, as in the implementation of both the Rothermel/FARSITE model (Figure 3) and the relatively simply McArthur model. In future work, WFDS's fluid dynamics capabilities may be used to modify the level set method so that the fire spread model is influenced by the local environment. For example, the local movement of the fire line could be influenced by wind speed and direction as they are actively altered by the topography around the fire line. Simple models of heat release from the level set fire line could also be used to couple the interaction of wind and fire.

A disadvantage of the level set method is that, as explained above, it requires three dimensions to model a two-dimensional interface. However, there are numerical tricks, such as the so-called 'narrow-band' method, that decrease the dimension of the problem and reduce the time to solution (Mallet et al. 2009).

The disadvantage of an extra dimension is also offset by a mathematical benefit of the level set approach. The method of advancing and connected vertices, as used in FARSITE, is a variation of the 'buoy' method described in Sethian (1997) with a more technical discussion in Sethian (1985). Although simple in concept, it leads to computational difficulties when, for example, fire lines merge or cross, forming loops or knots that must be adjusted so that they make physical sense. As noted by Finney (2004), the process of removing crossovers and keeping only physically sensible vertices consumes considerable cpu-time. However, this issue is neatly sidestepped in the level-set method, which responds automatically to merging and crossing interfaces (Mallet et al. 2009), eliminating the cpu-expensive process of tracking and removing overlapping points and lines. If, for example, two expanding circular flame fronts meet, the level-set solution gives a single closed curve rather than two overlapping curves (Sethian 1994).

The elliptical spread equations developed by Richards (1990) apply to flat terrain only (Finney 2004). In FARSITE, the vertices that form fire polygons are stored in a horizontal plane, and must therefore be transformed to represent the local sloping plane before the differentials of spread components and direction are used in Richards equations. Resulting components of spread rate must then be projected back to the horizontal plane. In WFDS, slopes are formed by stair-stepped obstructions, the surfaces of which are regarded as the plane in which the solution of the level set function is found, obviating the need for coordinate transformations.

Cases

A comparison of Farsite and the WFDS-level set model for a simple point ignition is shown in Figure 3. In that figure, both the primary and ellipse-constrained (FARSITE-like) level set results were compared, but we use only the primary model for the qualitative comparisons shown below. Currently, fireline acceleration in the WFDS-level set model is limited to dependence on head width, whereas in FARSITE it is a function of fuel type (Appendix 4). To facilitate direct comparison, acceleration was turned off in both models for all comparisons shown below. Spatial resolution was also equivalent at 10 m in the x- and y-directions.

Figure 28 illustrates the simple case of a fireline moving up a 15° slope. The differences between the primary level set model and FARSITE are minor and due partially to differences in the parameterization of the effect of slope. For this and all cases below, note that there may also be slight differences (about +/- 1 grid cell) between the display of isochrones because of the differences between FARSITE's method for estimating fireline location and the separate numerical script for estimating fireline 'time-of-arrival' for the WFDS-level set routine.

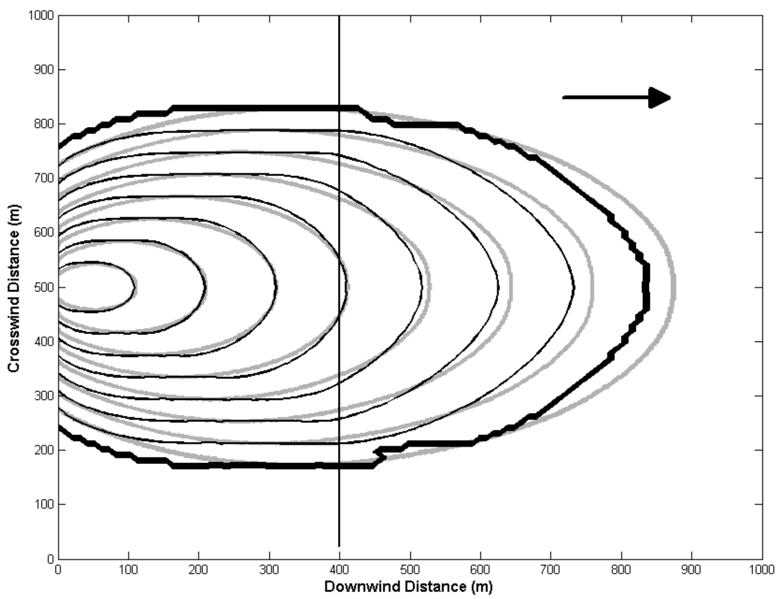


Figure 28. FARSITE (gray) and WFDS Level Set primary model (black) on a 1 km x 1 km domain for the case of a 15° slope, beginning at x=400 m (vertical line) and increasing toward the right (spanning the y-direction). The isochrones represent time-of-arrival and are 180 s apart. The direction of fireline propagation is shown by the arrow. Wind speed is 5 m/s from left to right.

The progress of a fireline 'wrapping' around a large, noncombustible patch is shown in Figure 29. Again, the match is close between FARSITE (gray) and the level set model (black), though slight differences are apparent in the flanking behavior near the front and rear of the fire lines.

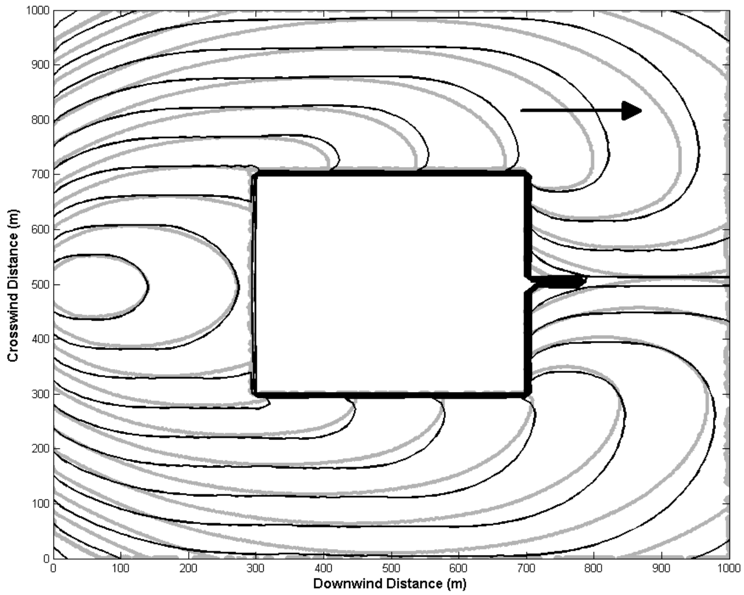


Figure 29. Fire spread around a noncombustible fuel block. FARSITE (gray) and WFDS Level Set primary model (black) on a 1 km x 1 km domain. The isochrones represent time-of-arrival and are 240 s apart. Direction of propagation is shown by the arrow. Wind speed is 5 m/s from left to right.

A slightly more complicated case is given in Figure 30. Here, we see two separate ignition points, ignited at the same time, merging into a single fireline perimeter. As in the cases above, the match between isochrones is good, with differences arising mostly in the front and rear flanks. As mentioned above, the FARSITE model has routines to test for the crossing of the vertices that are connected to represent a fireline, while, in the level set model, merging happens as a natural consequence of the solution of the level set equation (2-1).

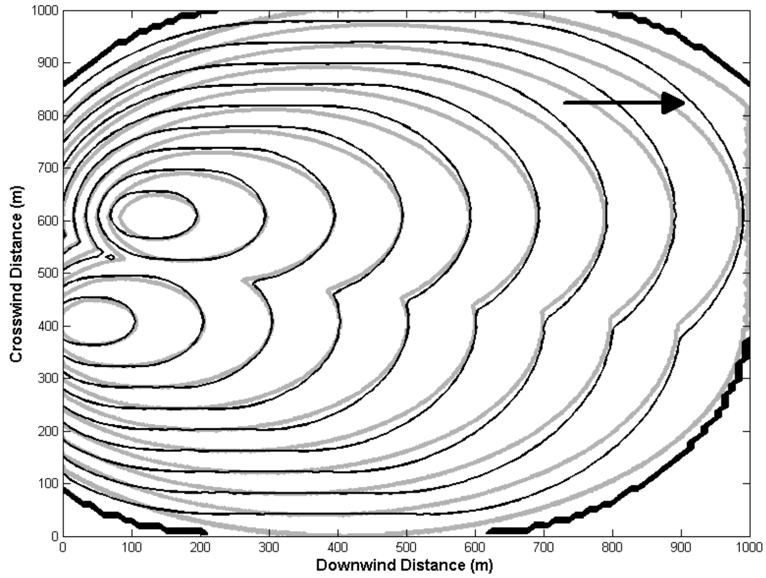
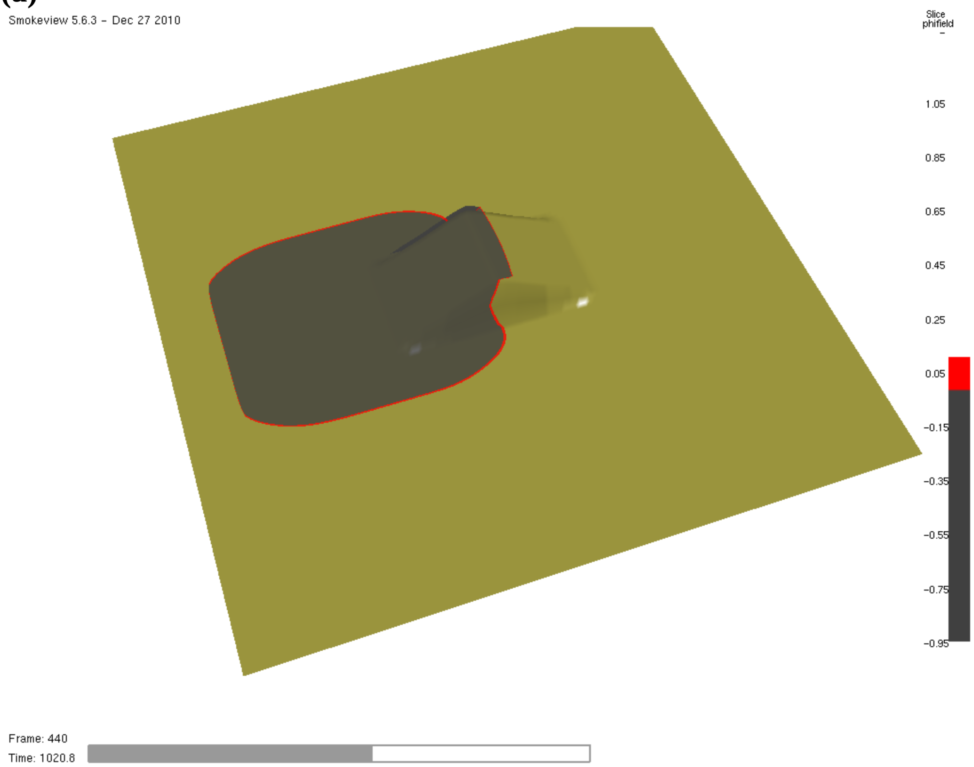


Figure 30. Merging of fire lines from two separate ignition points. FARSITE (gray) and WFDS Level Set primary model (black) on a 1 km x 1 km domain. The isochrones represent time-of-arrival and are 180 s apart. Direction of propagation is shown by the arrow. Wind speed is 5 m/s from left to right.

Differences between the fireline parameterizations are more apparent in Figure 31, though, again, the isochrone patterns are qualitatively similar. A screen shot of the WFDS-level set model (a) is provided to clarify the scenario illustrated in the isochrone plot (b). Fire lines in the primary level set model tend to be somewhat slower uphill and somewhat faster downhill than in FARSITE. Interestingly, small differences in flanking behavior near the head are magnified as the fireline moves past the hill.

(a)



(b)

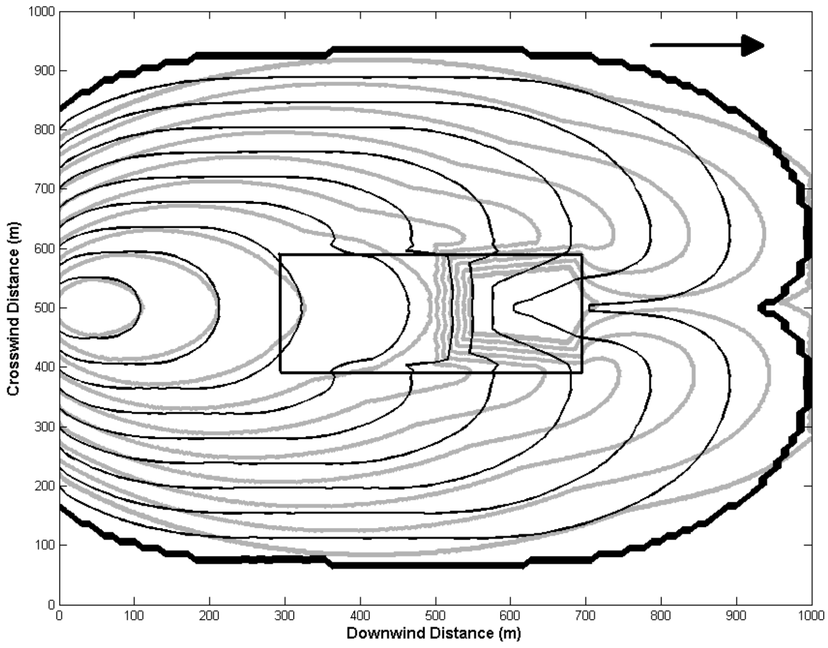


Figure 31. Fire spread up and down a 30° hill. (a) Screen shot of the WFDS primary level set model as the fireline crests the hill. (b) Isochrone (180 s) plot of FARSITE (gray) and WFDS Level Set primary model (black). The box in the center represents the hill boundary. Direction of propagation is left to right (arrow). Wind speed is 5 m/s from left to right.

Finally, the simulation of fire spread over a complex landscape is compared between the two models in Figure 32. The landscape was randomly generated and contains slopes of up to 30 ° over a total elevation change of about 70 m. To illustrate the landscape, the upper panel (a) shows a screen shot of the WFDS-level set simulation. Panel (b) illustrates large difference in fire coverage between the models, despite having the same ROS for level ground. The level set model produces, for this scenario, fire lines with greater spread in the rear flanks, while the FARSITE model cover a larger area in the forward direction. Overall, however, the pattern of fire propagation is the same, and, on a landscape of this size and complexity, differences between the models would likely be within the range of error of either model.

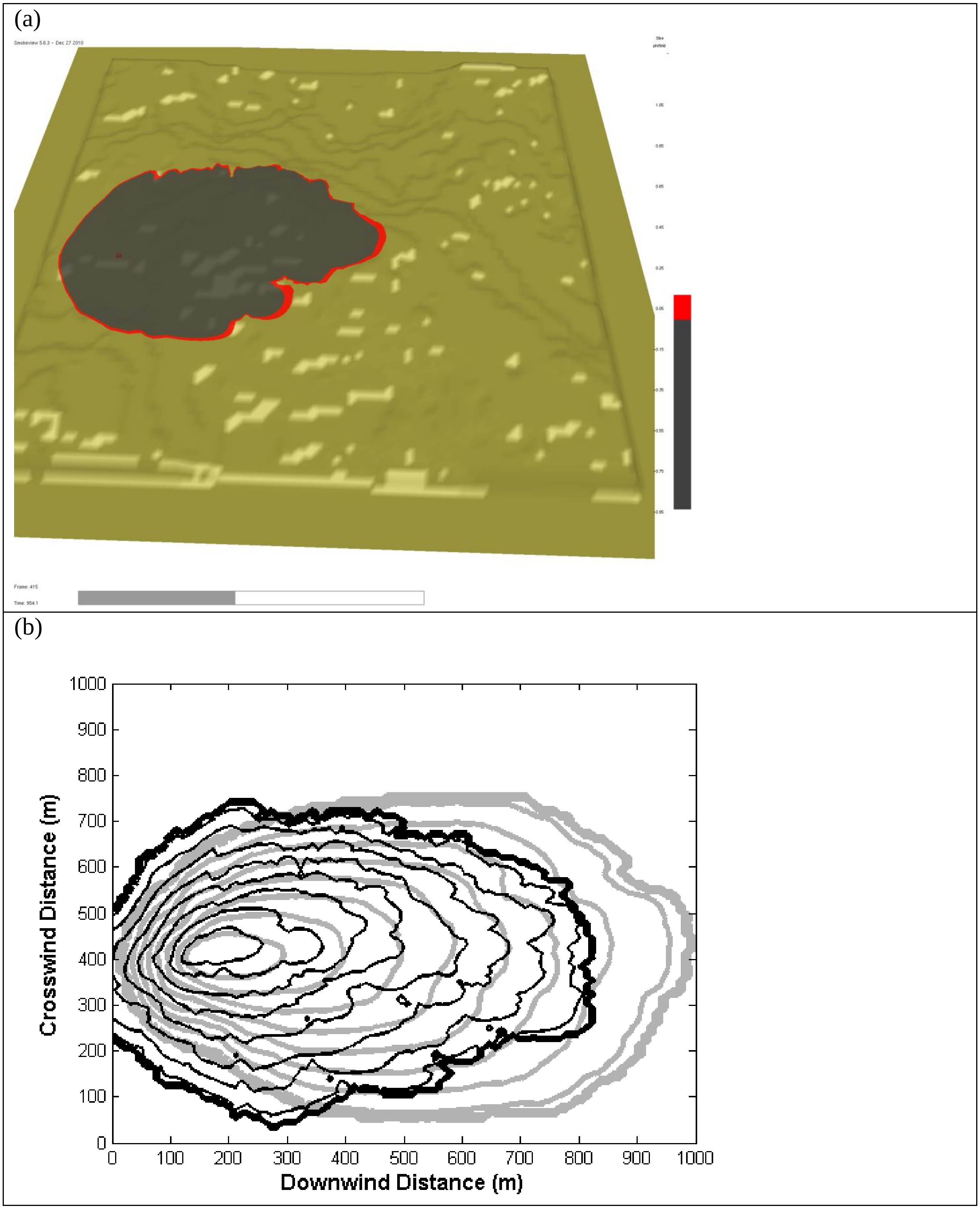


Figure 32. Fire spread over a complex landscape. (a) Screen shot of the WFDS primary level set model on a complex landscape in a 1 km x 1 km domain as visualized using Smokeview. (b) Isochrone (240 s) plot of FARSITE (gray) and WFDS Level Set primary model (black).