COMPUTER MODELLING OF WILDLAND-URBAN INTERFACE FIRES

William Mell[1], Derek McNamara[2], Alexander Maranghides[1], Randall McDermott[1], Glenn Forney[1], Chad Hoffman[4], Matt Ginder[4]

[1]National Institute of Standards and Technology (NIST) , Gaithersburg, MD 20899-8662 USA
Corresponding Author: ruddy@nist.gov; +1-240-372-5116

[2]McNamara Consulting, Inc., Golden, CO, 80403 USA

[4]College of Natural Resources, University of Idaho, Moscow, ID, 83844 USA

ABSTRACT

Wildland-urban interface (WUI) fires predominantly originate in wildland fuels and subsequently spread through a spatially heterogeneous and non-contiguous fuel system of structures and residential and wildland vegetation. Commonly used wildland fire models were not developed to handle this complex fuel system. Also, there has been very little activity in the research community to develop data collection methods that capture WUI fuel types and their spatial variation over community scales. For example, the spatial variation of vegetative WUI fuels is often below the resolution (~30 m) of satellite based LANDFIRE wildland fuel maps.

In this conference paper, an overview of the use remote sensing data for mapping WUI characteristics will be presented. Specific examples for two WUI communities will be given. The resulting dataset is used to create input files, via a GIS application, for the wildland-urban interface fire dynamics simulator (WFDS). Results from WFDS, applied to a number of settings, are given to illustrate its use in these communities and for exploring risk reduction via wildland fuel treatments.

INTRODUCTION AND BACKGROUND

Fires in the wildland–urban interface (WUI) spread through both vegetative and structural fuels. These fires can originate in either fuel type but usually begin in wildland fuels of natural (e.g. lighting strikes) or manmade (e.g. campfires, runaway prescribed fires, downed or arcing power lines, arson) causes. In the United States, fires in the WUI account for a significant, if not major, portion of wildland fire suppression and wildland fuel treatment costs.[1] Of the top ten fire-loss incidents in the U.S. over the last 100 years, six are WUI fires, all of which occurred within the last 20 years and in the western U.S. (all but one in California).[2]

At its core, the WUI fire problem is a structure ignition problem and the best approach to reducing the severity of the problem is to reduce the potential for structures to ignite.[3,4] The cause of the *initial* structure ignitions in a WUI community is predominately due to exposure to heat flux from flames and/or firebrands generated by a wildfire. Once structures and residential vegetation are burning, they too have the potential to contribute significantly to continued fire spread through the WUI community.[5] The likelihood of a structure's ignition is dependent on both its physical attributes (e.g. roofing material, decks, vents) and its fire exposure conditions (e.g. magnitude and duration of heat flux from flames and firebrands).

Currently, a structure's fire exposure conditions are reduced through treatment of vegetative fuel, both residential and wildland. Wildland and residential fuel treatment actions are not, in general, coordinated and the methodologies used are mostly the result of expert opinion and limited field measurements (e.g., Cohen 2004[6] considered structure ignition via radiant heat). For example, no systematic field studies have been conducted to assess influence of a given wildland fuel treatment method on the resulting heat and firebrand flux exposure to a proximate WUI community. A review of current approaches on reducing the risk of WUI structure ignition and research needs is given in Mell et al. (2010).[3] One important use of suitably evaluated WUI fire behavior models is to provide predictions of fire exposure conditions over a range of representative fuel, weather, and terrain conditions. These would help guide laboratory and field based measurements to study and assess effective vegetative and structural fuel treatments.

Modeling wildland fires is very challenging due to the range of environmental conditions (terrain, weather, and vegetative fuels) and the range of spatial and temporal scales characteristic of the driving physical processes (ignition, transition to established fire spread, fire spread, and smoke transport). Fully addressing the wildland fire problem requires fire behavior models that are faster than real-time (in order to support the operational needs of an incident commander) and are also able to capture the highly detailed fire processes (e.g., heat fluxes and fire plume dynamics) in order to better design wildland fuel treatments to meet the needs of forest restoration and fire fighter safety. A single model with these capabilities would be prohibitively demanding on computer memory and processor speed. For this reason, models appropriate to different applications exist. Operational models for wildland fires include BehavePlus[7], FARSITE[8] in the U.S., Prometheus[9] in Canada, and the McArthur Fire Danger meters[10] in Australia. These operational models are faster than real-time and heavily based on empirical formulas and rules from field observations. Physics-based models of wildland fire, which solve governing equations for fluid flow, heat transfer, and combustion (to varying degrees of approximation, depending on the application) have undergone rapid development over the last 15 years.[11] Physics-based models, which focus more on including the larger scale atmospheric physics and less on the combustion processes, include those of Coen (2005)[12] and Sun et al. (2009)[13]. Models that focus more on including the physics of combustion and the thermal degradation of vegetation include Linn et al. (2010)[14], Mell et al. (2010)[15], Morvan et al. (2009)[16] and Tachajapong et al. (2008)[17]. A recent review of the second group of models is in Morvan (2010)[18]. Of these physics-based approaches, only those focused on atmospheric physics, with sufficiently course computational grids, approach real-time operation.

Modeling WUI fires has all the challenges associated with wildland fire modeling with additional challenges due to the relatively more complex fuels environment. The WUI landscape contains wildland and residential vegetative fuels, a variety of fuel break types (e.g., roads, sidewalks, and lawns), as well as a range of structural fuels (e.g., siding, roofing, and decking materials) and building assemblies (eaves, decks, and various roofs). Current operational wildland fire models were developed for fire spread through solely vegetative fuels that are contiguous. As a result they have limited application to fires in the heterogeneous, non-contiguous, WUI fuel system, as do the atmospheric weighted physics-based models mentioned above because they rely on the operational wildland fire spread formulas. In addition, the operational models cannot directly provide heat and firebrand flux predictions. These are critical to an assessment of the fire exposure conditions experienced by structures in WUI fires. Physics-based models that simulate fluid flow, combustion, and the thermal degradation of the vegetation are more capable of providing heat and fire brand fluxes.

The application of physics-based models to WUI fires is in the initial stages of development. As with the development of any model, measurements of the key physical variables are needed from experiments in which the processes of interest evolve over relevant scales and environmental conditions. This is extremely challenging for both laboratory and field measurements because many destructive WUI fires occur in high winds and are fast spreading (e.g., 10 m s^{-1} mean winds with 17 m s^{-1} gusts and 2.2 m s^{-1} fire spread rates have been observed[19]), can have large actively burning fire line widths (e.g., grass fires can have fire widths of 10 m[20]), and have high heat release rates (e.g., heat release rates for 5 m tall trees can reach 30 MW[15]). Only a limited number of field measurements that capture the behavior of extended portions of a freely evolving fire line have been conducted.[20] However, such measurements are planned in the spring of 2011 at Fort Eglin, Florida, as a follow of an earlier campaign.[21] It should be noted that laboratory measurements on components of the problem can be undertaken (e.g., the firebrand, flame, and radiant exposure testing on wall and eaves reported in this conference). However, when interpreting and applying results from these measurements it is important to place the laboratory conditions in the context of the actual environmental conditions during a WUI fire event.

WUI fire models, operating over community scales (1000s of meters), can provide guidance for the interpretation of field observations of fire behaviour, the development of wildland fuel treatments to reduce WUI community exposure conditions, and a reference point for laboratory experiments that attempt to represent the salient fire exposure conditions. Such fire models require a sufficient representation of the WUI environment. This includes the location and extent of vegetative and structural fuels, terrain, and fuel breaks. Because of the spatial extent and complexity of these WUI characteristics, remote-sensing offers a promising potential alternative to ground sampling or oversimplification. A brief review of the use of remote sensing for this application is considered next, followed by specific examples of the Wildland urban interface Fire Dynamics Simulator (WFDS) currently under development at NIST.

USING REMOTE SENSING DATA FOR MAPPING WUI COMMUNITY CHARACTERISTICS

Remote sensors employed in the mapping of WUI fuels and topography fall into two general categories: passive and active sensors.[22] Passive remote sensors record the reflection of solar radiation or emitted energy from the Earth's surface or objects on that surface.[22] Active remote sensors record energy emitted from the sensor and reflected or scattered back from objects on the Earth's surface.[22] Different sensors provide variations in spatial, radiometric, spectral and temporal resolutions; information that can be extracted; data processing procedures and costs; and accuracy.

Vegetation inputs to operational wildland fire models have typically come from passive remote sensors to either directly or indirectly derive fuel models. As described in Keane et al. (2001)[23], passive remote sensing technology with spatial resolutions between 5 m to 5 km has historically been used to create spatially explicit two-dimensional (2-D) fuel maps. National fuel model maps for the U.S. from satellite imagery (30 m resolution) and biophysical modeling have been constructed.[24] The use of very high resolution (VHR) multispectral imagery (spatial resolution less than 5 m) for deriving inputs to operational fuel models has been more limited.[25] A possible reason for this is the spectral mixing of adjacent reflected targets that might occur in VHR imagery, resulting in poor results for traditional pixel-based classification methods.[26] However, objected-oriented classifications of high resolution multispectral imagery, when employed, have shown greater than 80% accuracy in certain fuel types[25] and a higher accuracy in mapping built area environments compared to pixel-based classification approaches[26]. Hyperspectral imagery has also shown potential for the direct and indirect measurement of fuel types**.**[25]

VHR imagery has also been used in the discrimination of structures, structure roof type, and fire barriers. The use of remote sensing data for structure extraction has been occurring for sometime from high-resolution aerial imagery[27] and more recently from satellite imagery.[28,29] The use of hyperspectral imagery with object-oriented classification techniques has shown promise for discrimination of roof materials.[30] The use of VHR imagery has also been extensively studied for the extraction of roads, which are typically fire barriers.[31] Very few studies examine the extraction of structures, structure materials and fire barriers in the context of inputs to fire models, however, McNamara et al. (2009)[32] examined the extraction of fire barriers using object-oriented classification procedures to derive inputs to WFDS.

The use of passive remote sensing technologies in the derivation of wildland vegetation fuel maps has several limitations. Many methods to derive forest biophysical measurements from passive sensors have been shown to be non-linear where above ground biomass saturates at approximately 100 Mg/ha.[33] Additionally, these sensors cannot directly discriminate the vertical structure of biomass.[34] Most sensors cannot detect surface fuels due to canopy obstructions and have difficulty distinguishing between canopy and surface fuels even when surface fuels are not obstructed by canopies.[23] Additionally, sensors with spatial resolutions greater than 5 m have insufficient resolution to support extractions of structures, fire barriers or residential vegetation. Finally, Kean et al., (2001)[23] pointed out the difficulties in mapping wildland fuel models due to the subjective nature of these models.

Active sensor technology such as airborne Light Detection and Ranging (LIDAR) and RADAR have shown potential for overcoming some of the issues with passive remote sensing technologies. LIDAR does not saturate at high biomass levels[35] and, therefore, has potential for deriving vegetation crown bulk density.[36] Additionally, LIDAR directly measures the vertical structure of vegetation[37] and has shown potential for mapping surface vegetation. In the context of deriving inputs to physics based fire models such as WFDS, LIDAR has potential to derive the majority of inputs required with the exception of material properties of structures and vegetation properties such as moisture content.

LIDAR use in the wildland urban interface

LIDAR systems can be characterized by the methods used to record backscattered energy. Discrete return LIDAR records single or multiple return(s) from the target object represented as discrete points in time and space. In the context of this paper only discrete return LIDAR systems are discussed. Also potentially applicable for deriving WFDS inputs, but not examined here, are full-waveform LIDAR systems in which a continuous range of the energy is returned from each laser pulse providing full-waveform data. Very recent small footprint LIDAR systems are capable of recording both forms of backscattered energy. Figure 1 displays recording LIDAR backscattered energy as a full waveform or discrete returns.

LIDAR has become a routine method for creating high resolution terrain data[38], which are required for inputs to WFDS. Additionally, LIDAR data could become the main technology for the mapping of forest biophysical variables[39] due to the high degree of accuracy demonstrated in mapping these variables[40]. Forest biophysical variables such as tree height and crown width have been measured at the stand level[34], the plot level[41], and the individual tree level[32]. Studies focusing on deriving crown base height and crown bulk density are fewer and typically use allometric relationships or statistical inference to estimate these variables.[42] Many of these methods[40] derive forest biophysical variables using a raster data model, termed a canopy height model (CHM), where each cell in the raster represents a three-dimensional area of the land, vegetative or man-made surface.[43] It is less common to characterize the vertical space of vegetative canopies and these attempts focus on voxel[a] based approaches[44] and height bins[45]. Finally, many studies have examined the synergistic use of active and passive sensors for vegetative mapping[46,47] where the fusion of passive and active sensor data can be demonstrated to improve classification accuracy[48].

The use of LIDAR has also become prevalent for the extraction of structures with attempts being made from the interpolated point cloud of data or digital surface models[49] and using the raw point cloud of LIDAR data[50]. Integration of LIDAR and passive optical sensors has also been utilized to extract structure information.[51,52,53] While many of the above methods deal with extraction of roof geometry type, the extraction of roofing materials is a less studied problem with Lemp and Weidner (2004)[54] attempting roof surface classifications using the fusion of LIDAR and hyperspectral imagery.

Despite the promise shown in the above studies for deriving vegetative fuels, structures, fire barriers, and topography from LIDAR data there are certain limitations. Neither LIDAR nor passive remote sensors can overcome temporal issues with fuels that might be caused by extreme weather events.[23] Additionally, while LIDAR is superior to passive sensors in determining the vertical structure of vegetation occlusions under dense canopies might still result in difficulty in determining surface fuels and inter-canopy spaces even with a high density point cloud. LIDAR has also been shown to underestimate both canopy base height (in dense canopy conditions) and overall tree height.[55] Methods to derive crown bulk density from LIDAR are also reliant on allometric relationships between LIDAR metrics and field measurements resulting in utility outside of the respective study area untested. Finally, occlusions due to the geometry of natural and man-made features and flight paths can also affect structure and vegetation delineations.[56]

The majority of the studies listed above deal with the extraction of vegetative biophysical parameters and structure information individually. Only Haala and Brenner (1999)[57] and McNamara et al.

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a A voxel is a three-dimensional grid cell size.

(2009)[32] examine these two extraction scenarios coincidently. For deriving inputs for WFDS the three-dimensional (3-D) structure of buildings and trees must be resolved coincidently. Additionally, the synergistic use of active and passive remote sensor technology has been shown to increase the accuracy of fuel mapping.[58] Consequently, there is a need to develop methodologies and algorithms that deal with the extraction of vegetative biophysical parameters and building information concurrently in a complex environment such as is typical of the WUI, from high-resolution passive and active remote sensors.

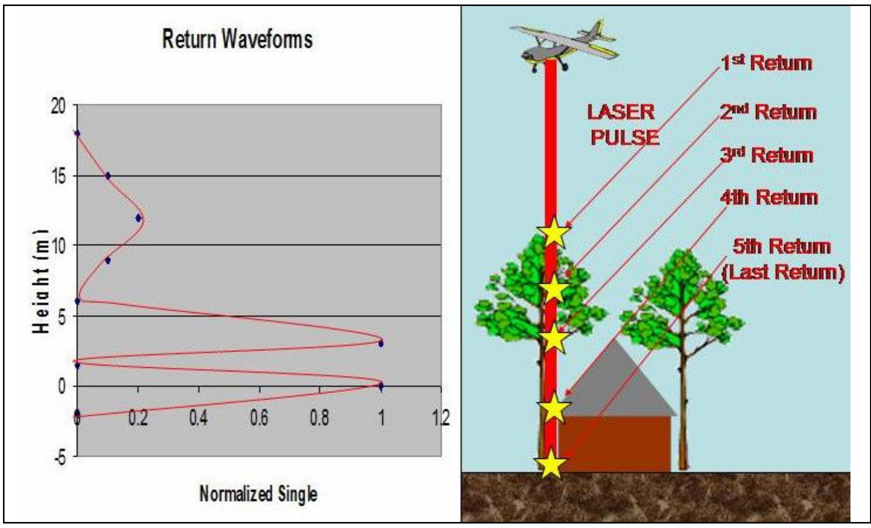


Figure 1: Examples of recording backscattered energy as a full waveform (line) or discrete (points) returns.

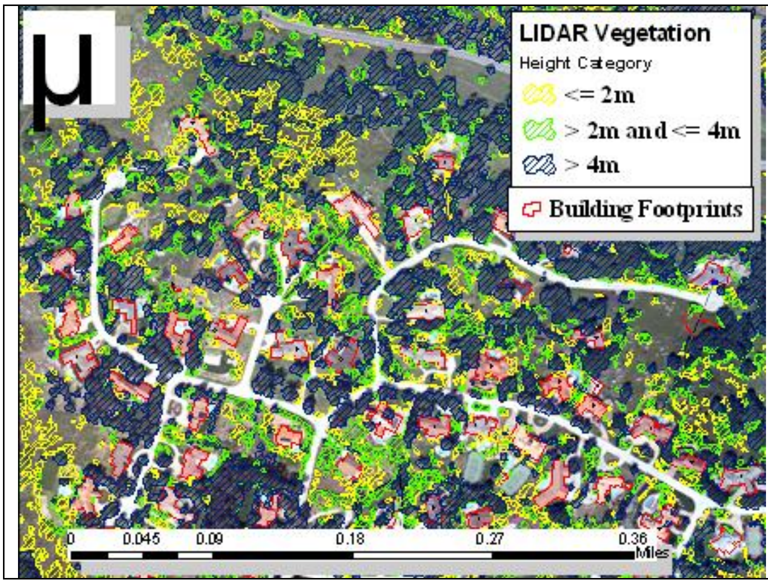


Figure 2: Vegetation and building feature extractions in The Trials WUI community in Rancho Bernardo, California, using customized LP360™,[b] software that analyzes LIDAR data. Both building and vegetation footprints are shown. The vegetation footprints are for three height categories: 2 m and below; 4 m to 2 m; and greater than 4 m.

USING GEOSPATIAL DATA FOR WFDS FIRE MODEL INPUTS

The usefulness of LIDAR in deriving the 3-D distribution of natural and man-made fuels is demonstrated by the availability of commercial software to perform these tasks. For example, by customizing the LP360™ Extractor™,[b] tools vegetation can be segmented by height category and vegetation LIDAR points traced to create vegetation polygons as shown in Figure 2. Additionally, the software product LIDAR Analyst[b] has been used to test extraction of building footprints in the WUI.[59] Figure 3 shows the Worley Idaho study site where a combination of remotely sensed and existing GIS data was used to create WFDS inputs. Exact procedures for the delineation of man-made and natural

[b] Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST, nor does it imply that the products identified are necessarily the best available for the purpose.

fuels as well as fire barriers are described in McNamara et al., (2009). A combination of National Agriculture Imagery Program (NAIP) multispectral imagery and airborne LIDAR data was used to extract vegetation and man-made features in the study area. The specifications for the NAIP imagery and LIDAR acquired data are shown in Table 1. The combination of these two data sources for deriving WFDS inputs is a realistic scenario, given the repeated acquisition of NAIP imagery in many states and ongoing initiatives to acquire LIDAR data (e.g. Idaho LIDAR Consortium, Oregon LIDAR Consortium and Puget Sound LIDAR Consortium). Automated techniques were tested as described in McNamara et al. (2009)[32] with final model inputs files being created from manually corrected automated feature extractions when appropriate.

GIS-WFDS Linkages

Regardless of how fire model inputs are derived, a means is required to incorporate the above described spatial data into the respective model. Fire models such as FARSITE[8] utilize spatial information in raster format for inputs and to display outputs in a GIS environment. Most GIS platforms are well suited to the storage of 2-D or 2.5-D data (for example DEM with pixels and a value representing height). The storage of truly 3-D data in a GIS environment is only recently being exploited.

McNamara et al., (2009)[32] describe initial efforts to create WFDS input files from GIS data derived from remote sensors, ground surveys and existing GIS data. Customizations of the ESRI™[, b] software platform have resulted in a loose coupling of GIS to WFDS in the form of a software application termed GEOWFDS to allow for the creation of 3-D WFDS input files from 2-D and 2.5-D geospatial data. These WFDS input files have the point-wise location of the terrain, structures, and vegetation (both surface and raised fuels) on the computational grid and the additional physical attributes of the vegetation (not derived from LIDAR) of bulk density, moisture, and surface area-to-volume ratio. The resulting landscape is visualized using Smokeview[60], the companion visualization tool to WFDS and FDS developed at NIST. Vegetation can be visualized by points or, when appropriate, by standardized 3-D shapes (e.g., cones for conifers – see Figure 7). Additionally, fuels can be input as distinct vertical profiles derived from the LIDAR data as shown in Figure 4. In this example, the height values in the LIDAR point cloud are re-classified such that all ground points have an elevation of zero and other points (e.g. vegetation and structures) have elevation values representing above ground heights. This allows for the creation of a set of raster data products, termed tomographic LIDAR, which can be input into GEOWFDS along with topography to create 3-D WFDS input files representing the vertical and horizontal extent of fuels. Alternatively, and more appropriately for lower density point clouds if not inputting vegetation as points, two canopy height models (CHM) can be input: one representing the top of height canopy and one representing the canopy base height. Additionally, building footprints are input as 2-D vector data to describe the horizontal extent of buildings and heights can be associated with vector data as an average building height or come from a digital building height model derived from the LIDAR data, more precisely representing the roof geometry as shown in Figure 5. Finally, fire barrier features are input as a raster product displaying the elevation of the respective fire barrier feature. Included with GEOWFDS is a spatial database to store material properties of vegetation and man-made features that can be associated with the raster and vector GIS inputs.

ILLUSTRATIVE EXAMPLES OF WFDS SIMULATIONS

The wildland-urban interface fire dynamics simulator[15] (WFDS) is an extension of NIST's structural fire simulation tool the fire dynamics simulator (FDS)[61] to outdoor fire spread and smoke transport problems that include vegetative and structural fuels and complex terrain. The methods of computational fluid dynamics (CFD) are used to solve the 3-D (or 2-D) time-dependent equations governing fluid motion, combustion, and heat transfer. The numerical model is based on the large eddy simulation (LES) approach and provides a time-dependent, coarse-grained numerical solution to the governing equations for mass momentum and energy. Two methods are used for the representation of vegetative fuels: one for surface fuels only (boundary fuel method[20]) and another for surface and/or raised fuels (fuel element model[15]). In each case, the vegetation is assumed to be composed of fixed, thermally thin, optically black, sub-grid solid fuel. The thermal, radiative, and drag properties of the vegetation is determined from the bulk density of the thermally thin vegetation in a grid cell and the surface area-to-volume ratio of the individual vegetation element. Laboratory-scale validation for individual tree burns[15] and field-scale validation using grass fire measurement[20] have been conducted. WFDS has been applied to investigate the influence of bark beetle caused tree morality on crown fire hazard[62] and the effects of the spatial distribution of crown biomass on fire behavior[63]. Additional validation using laboratory and field measurements is underway. In this section, examples illustrating the use of WFDS for community scale simulations will be presented.

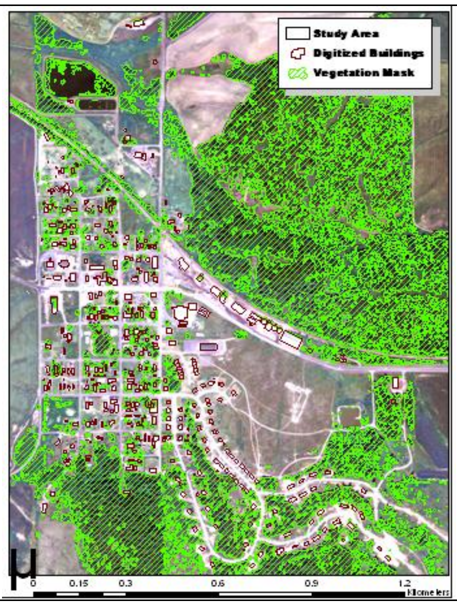
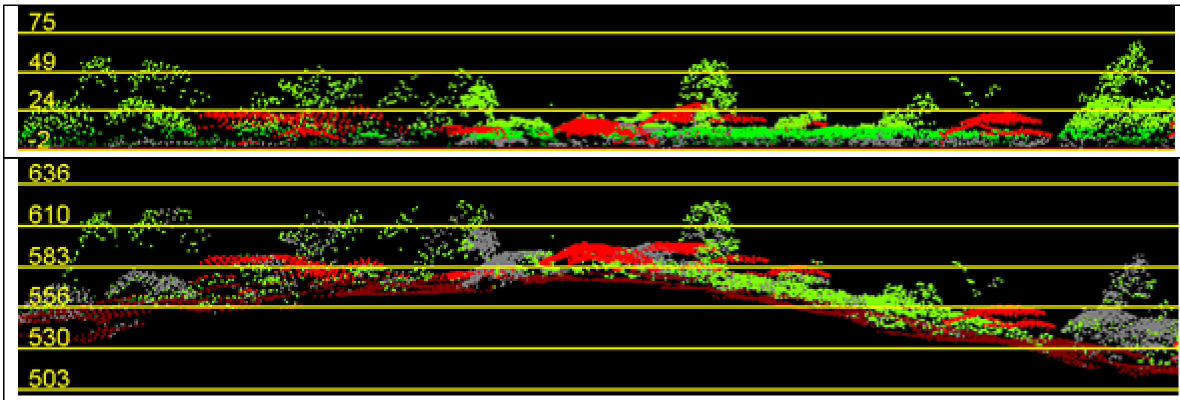


Figure 3: The Worley, Idaho, WUI community with building footprints and vegetation. Exact procedures (which used a combination of NAIP imagery and LIDAR data) for the delineation of man-made and natural fuels as well as fire barriers are described in McNamara et al., (2009)[32]. Structure material types from on the ground wildland fire hazard assessments conducted following the NFPA form 1144A[64] can be used to map structure vulnerability.

Table 1: NAIP imagery and LIDAR data specifications for vegetation and building mapping in Fig. 3.

NAIP Specifications		**LIDAR Specifications**	
Flight Height (m)	6,900	**Flight Height (m)**	1800
Capture Season	Full Agricultural Growth	**Field of View (degrees)**	25
Cloud Cover	10%	**Number of Flight Lines**	82
Raw Data Spatial Resolution (m)	0.9	**Number of Flight Line km**	2700
Final Product Spatial Resolution (m)	1	**Swath Width (m)**	800
Spectral Resolution	3 color bands: Optional infrared band	**Line Spacing (m)**	560
Radiometric Resolution	8 bit	**Maximum Along Track Spacing (m)**	1.8
Horizontal Accuracy	+/- 3 meters of reference digital ortho quarter quads (DOQQs)	**Maximum Cross Track Spacing (m)**	2.6
Orthorectified	Yes (10m or 30m USGS DEM)	**Nominal Post Spacing (m)**	2
		Estimated Horizontal Error (m)	0.21Nadir; 0.22 FOV
		Estimated Vertical Error (m)	0.15 Nadir

An example of WFDS application to WUI fuel treatment effectiveness, in the case of a crown fire, is shown in Figure 6 (taken from Ginger et al., 2010[65]). The surrounding wildland fuels, which are user prescribed (not based on remote sensing data) are composed of lodgepole pine (700 stems per acre) and surface fuels are high load, forest litter with shrub understory (fuel model TU5 of Scott and Burgan, 2005[66]). Three simulations are shown, each has a different fuel treatment. Figure 6(a) shows the untreated scenario in which wildland fuel is present up to 2 m from the structures. Figure 6(b) has fuel treatments within 10 m of the structures (see figure caption for details). Figure 6(c) shows a FIREWISE recommended fuel treatment out to 30 m from the structures (see figure caption for details). The incident radiant heat flux on the structures was computed (not shown) and then input into an empirical structure ignition model that was successfully tested by Cohen (2004)[6] in field measurements of wall ignition during crown fires. In the untreated case, Figure 6(a), (which was not considered in the field experiments[6]) structures were predicted to ignite. In the figure 6(b), the incident radiant heat flux exceeded the critical heat flux for ignition, but not long enough to cause ignition (this is consistent with the crown fire experiments). For figure 6(c), the incident radiant heat flux is well below the critical ignition heat flux (walls were unaffected by the fire in the field experiments under these radiant heat flux conditions).



(a)
(b)

Figure 4: LIDAR height profiles in the Trails at Rancho Bernardo WUI Community. Green and grey points are vegetation by height category; red are buildings; dark red are ground. (a) Flattened LIDAR point cloud to obtain vertical height above ground (feet) measurements for fuels. (b) Original scene showing height above sea level (feet) measurements.

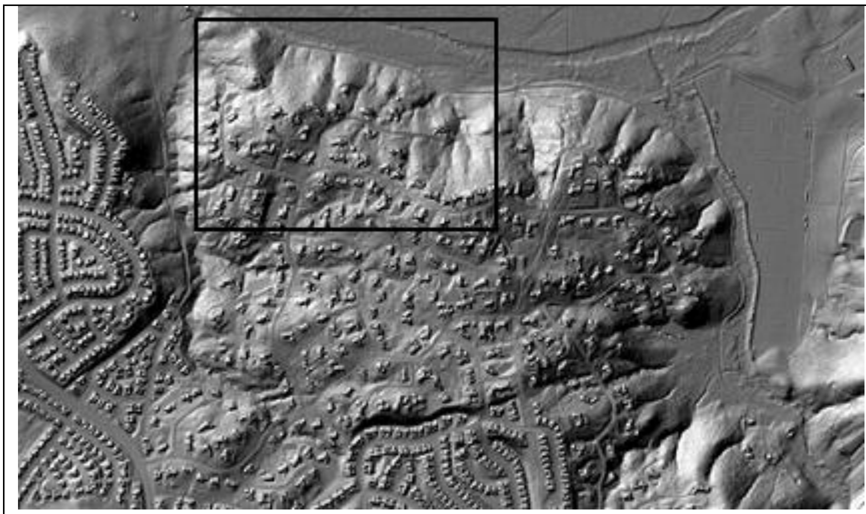


Figure 5: Digital surface model used to create WFDS input files from GEOWFDS portraying building heights with vegetation and other features removed. The total area shown is approximately 2600 m east/west and 1500m north/south. The area enclosed by the black rectangle is also shown in the vegetation and building mapping example of Fig. 2.

WFDS simulations with inputs from remote sensing

Currently, data from remote sensing is being analyzed for two WUI communities (as presented above) in order to provide WFDS input information. Remote sensing derived quantities for these communities are shown in Figure 3 (Worley, Idaho) and in Figures 2, 4, and 5 (The Trails in California). The Trails community was damaged during the 2007 California firestorm and is currently the subject of an ongoing study.[19] Figure 7 shows a snapshot from a WFDS simulation using the Worley dataset.

Structures material vulnerabilities (siding, roofing) are illustrated with colors based on ground surveys using NFPA form 1144.[64] The location of the fire is chosen arbitrarily (this community has not be subjected to a wildland fire). The location of the buildings, roads, and conifer trees were obtained from a combination of NAIP imagery and LIDAR data with vegetation being input as a single point with associated geometry from LIDAR (tree height, crown based height and width) to form cone shaped tree crowns and prescribed material properties (e.g., bulk density and moisture).[32] Figure 8 is a snapshot from a WFDS simulation of a fire in the Trails community. The terrain is more pronounced than in the Worley community. Green point clouds (obtained from LIDAR) show the location of the over story. Unlike the Worley community, which was dominated by cone shaped conifers, the over story vegetation does not have a distinct shape.

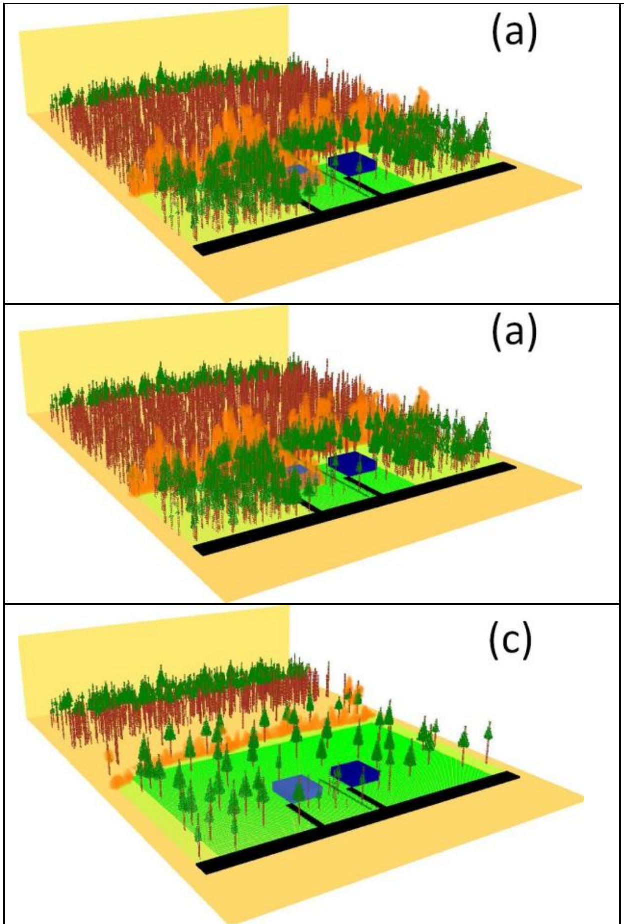


Figure 6: WFDS simulations of a wildfire approaching two homes with three different fuel treatments. (a) Untreated, 700 lodgepole pine trees per acre up to 2 m from homes and TU5[66] surface fuels. (b) Lodgepole trees within 10 m of the homes were removed and TU5 surface fuels were replaced by nonflaming irrigated lawn. (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 TU1[66] (low load grass and/or shrub with litter). Images are from Ginder et al., 2010.[65] 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.[60] 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).[15]

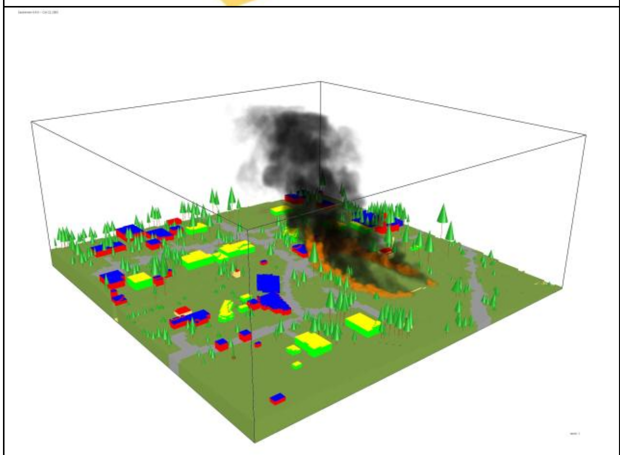


Figure 7: Illustrative example, visualized using Smokeview[60], of a WFDS simulation of a WUI fire in Worley, Idaho. NAIP and LIDAR remote sensing data were used to determine the terrain, roads (shown in gray), and location of structures and trees.[32] Conifer trees are displayed as cones. Building material vulnerability is colored based on NFPA 1144a[64] ratings. 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.

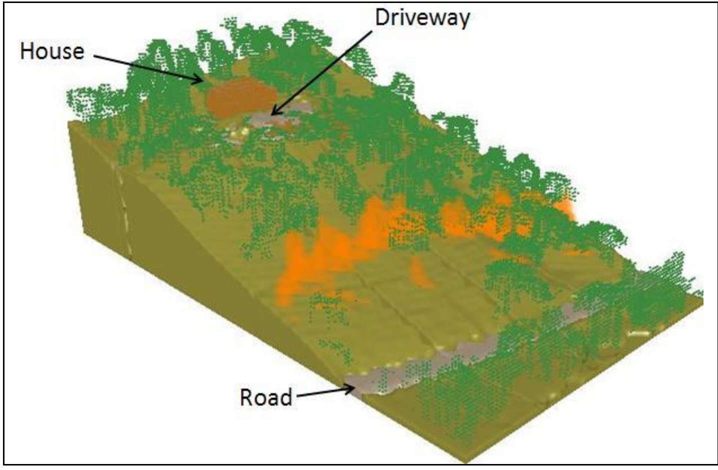


Figure 8: Illustrative example, visualized using Smokeview[60], of a WFDS simulation showing the area near a house in the Trails community in California. The terrain and raised vegetation were derived from LIDAR data. The computation domain is 100 m by 160 m, horizontally, and 80 m vertically, with cubic grid cells 1 m on a side.

A final example of the use of WFDS is shown in Figure 9, along with a simple level set based fire spread model currently under development (see figure caption for details).[67]

Figure 9: Simulation of firespread over a 2 km x 2 km region with complex terrain encompassing the Trails WUI community. Results from two models are shown: the physics based WFDS on the left and a level set based method on the right. The level set method uses spread rates determined from WFDS. The terrain was obtained from LiDAR data. For simplicity, and as a first step in model testing, the entire domain is covered in grass (image showing the roads, structures, and vegetation is used for ease of reference when comparing the figures). The WFDS [level set] simulations required 41 million [2000] grid cells; 16 [1] processors; and were 400 times slower [5 times faster] than real time.

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