The Wildland-Urban Interface Fire Problem
Current Approaches and Research Needs

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ABSTRACT

Wildfires that spread into wildland-urban interface (WUI) communities present significant challenges on a number of fronts. In the United States the WUI accounts for a significant portion of wildland fire suppression and wildland fuel treatment costs. Methods to reduce structure losses are focused on fuel treatments in either wildland fuels or residential fuels. There is a need for a well characterized, systematic, testing of these approaches across a range of community and structure types and fire conditions. Laboratory experiments, field measurements, fire behavior models can be used to better determine the exposure conditions faced by communities and structures. The outcome of such an effort would be proven fuel treatment techniques for wildland and residential fuels, risk assessment strategies, economic cost analysis models, and test methods with representative exposure conditions for fire resistant building designs and materials.

KEYWORDS: wildland-urban interface, wildland fires, wildfire, fuel treatments

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1. INTRODUCTION

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 powerlines, arson) causes. 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 structure ignition (e.g., Cohen, 2008). For this reason, the current state and need for research in other aspect of the WUI fire problem, such as (see also Cleaves, 200a) suppression of wildland fires or large scale community evacuation, will not be addressed here. 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 (Cohen, 1995). The likelihood of a structure's ignition is dependent both its physical

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attributes (e.g., roofing material, decks, vents) and the fire exposure conditions (e.g., magnitude and duration of heat flux from flames and firebrands).

WUI fires are a serious threat to communities in many countries. Significantly destructive WUI fires have occurred in Florida in 1998, southern during 2003 and 2007, Greece in 2007, and most recently in Victoria, Australia, during 2009. These events can produce damages in the billions of dollars. The authors are most familiar with the current state of tools and research related to WUI fires in the U.S.. For this reason, the focus of this paper will be on the WUI fire problem in the U.S..

The purpose (and organizational structure) of this paper is to provide an overview of the WUI fire problem, a short review of current approaches to addressing the WUI fire problem and reducing structure ignitions, a discussion and assessment of further needs, and an overview of the ongoing work at NIST to address some of the research needs.

2. BACKGROUND

The potential for WUI fires to be a significant problem in southern California has been recognized since at least the 1970s (Butler, 1976). Since then the severity of the wildland/WUI fires in the U.S. has increased. Of the top ten fire loss incidents in the last 100 years, six are WUI fires all of which occurred within the last twenty years and in the western US (all but one in California) (NFPA, 2008). This is due to a number of factors generally accepted in the literature (e.g., Cleaves, 2001; GAO, 2007a; QFR, 2009) including long term drought and the build up of hazardous wildland fuels (especially in parts of the western U.S.), and an increasing number of homes in the WUI.

On average, wildland fires annually burned 70% more acreage from 2000 to 2005 than in the 1990s; the average federal funding for suppression and wildland fuel treatments increased from $1.3 billion annually during 1996 to 2000 to $3.1 billion during 2001 to 2005 (GAO, 2007a). A major component of the rising suppression cost is protecting private property and communities from wildfires (U.S., 2007c; QFR, 2009). This is occurring within the context of significantly more wildland fuel treatments. In 1995 to 2000 a total of 3.6 million hectares (9 million acres) of federal, state, and private lands were treated, compared to a total of 7.6 million hectares (19 million acres) during 2001 through 2006 (U.S., 2006b). But by some measures, hazardous wildland fuels are accumulating three times faster than they are treated (Fong, 2007). These trends suggest not only that the WUI problem is real and not diminishing, but that current approaches to dealing with the problem are not adequate.

The basic distinction between land areas that are WUI versus wildland is the presence of structures. A definition WUI land areas has not been unequivocally determined. A standard definition is needed in order to consistently track the extent of the WUI, measure the cost of the

WUI problem, implement risk assessment methods, and prioritize risk reduction activities at local, regional, and national scales.

The U.S. Federal government identified three categories of WUI: interface, intermix, and occluded (Federal Register, 2001). This definition has been adopted by the National Association of State Foresters (States, 2003). However, the Federal Register allows alternative definitions, depending on whether housing density or population density is used as a distinguishing metric. A number of researchers have developed estimates for WUI land areas based on modifications of the Federal Register (2001). Table 1 provides a brief description of WUI definitions from the Federal Register (2001), Stewart et al. (2003), and Theobald and Romme (2007) and the resulting amount of WUI land area. Details of these WUI definitions are given in Appendix A.

Methods for reducing and assessing the risk of a WUI community to wildland fire can be categorized as being focused, to a first approximation, on either the wildland fuels or residential fuels. The former is traditionally the responsibility of the federal (e.g., US Forest Service), state, or local governments and the latter that of homeowners or local community organizations. The following sections provide an overview of the approaches taken, with some examples, in these two categories. Note that other factors, such as terrain and weather, are also important risk factors, but these can apply equally to fire spread in wildland and residential fuels.

In this paper, we will refer to three different model types: rule based, empirical, or physics based. By rule based we mean "rules of thumb" (such as fires spread faster upslope than on level ground). They result from observation and expert opinion and are the most straightforward to use. Empirical models are derived from well characterized, scientifically based, repeatable experiments. Statistical analysis produces formulas expressing a quantity (such as the head fire spread rate) as a function of key environmental parameters (such as wind speed, moisture, fuel type). Empirical formulas can simplified to be as straightforward to use as rule based models but, in general, are more quantitative and include the influence of different driving environment factors in a manner that is consistent with natural processes.

Physics-based models used computers to numerically solve the equations (in some approximation) governing fluid flow, heat transfer, smoke transport, and the thermal degradation of solid fuel. Physics-based models can vary in the physical fidelity of their model equations and the computational cost required to solve them. The trends from, or interpretations of, suitably validated physics-based simulations can be used to further an understanding of physical phenomena and identify driving physical mechanisms or environmental conditions.

3. CURRENT RISK ASSESSMENT AND RISK REDCUTION TOOLS BASED ON WILDLAND FUELS

3.1 Risk Assessment based on Wildland Fuels

There is currently no standardized method of risk assessment that can be applied nationwide to WUI communities in the U.S. (U.S., 2006a; Fong, 2007). It should be noted that since there is not a clear understanding of how a given wildland fuel treatment changes the wildland fire behavior (see Sec. 3.2), a risk assessment method based on a given fuel treatment will have inherent limitations. A 2003 field guidance report (States, 2003) and Appendix A in U.S. (2006), prepared by the National Association of State Foresters, defined a community to be at risk of wildland fire if it meets the Federal Register (2001) definition of a WUI community discussed in Sec. 2 (and in detail in Appendix A). Note that this approach to determining WUI land areas that are at risk is only based on housing density or population density, not on a measure of exposure conditions (i.e., independent of risk factors). Also, as discussed in Sec. 2 the Federal Register definition of the WUI is ambiguous. Perhaps the definition of interface and intermix WUI communities closest to the Federal Register is used by Stewart et al. (2003). Using their approach approximately 70 million hectares of WUI land area in the U.S. are at risk.

Based on wildland fuel treatment activity reported during 2001 – 2006 (USHF, 2006), approximately 0.7 million hectares are treated in WUI areas per year at current funding levels. This is approximately 1% of the total WUI land area identified by Stewart et al. (2003), which places a great emphasis on developing a well founded method for identifying and prioritizing WUI communities according to WUI fire risk (e.g., exposure conditions from wildland fire) – not just the housing or population density. It is also recognized that the private sector must increase their "buy-in" in wildland fuel treatments on public lands (US, 2006a), such as prescribed burning or mechanical thinning, if the problem is to be made tractable.

Risk assessment methods based on the wildland component of the WUI that do attempt to account for exposure conditions, do so by assessing the degree of wildland fire threat over landscape scales. It is recommended (States, 2003) that this assessment be based on wildland fuel conditions and past fire occurrence in the WUI land area. This allows the use of existing, mostly rule based, tools for wildland fuels mapping and hazard assessment. Examples of such an approach are the studies of Haight et al. (2004) for Northern Michigan; Menakis et al. (2003) and Theobald and Romme (2007) for the conterminous U.S..

Menakis (2003) combined three Geographic Information System (GIS) data layers to map the fire risk to structures in the U.S. at a coarse scale (1 km^2). The three data layers were: Potential Fire Exposure, Extreme Fire Weather Potential, and Housing Density. The measure of Potential Fire Exposure maps the fire intensity of the vegetation based on weather conditions. The Extreme Fire Weather Potential mapped land areas with wind, temperature, and humidity thresholds that identify extreme weather. The Housing Density layer rated the potential for homes to be destroyed by wildland fire based on the number of houses per acre. The analysis found that a total of approximately 40 million hectares were at risk, 0.8 million hectares were at

high risk, and 2 million hectares at moderate risk. In both the moderate and high risk classes 23% were on federal lands.

Theobald and Romme (2007) used a combination of land cover data sets (~1 km^2 resolution), three wildland fire hazard classes, specialized mapping algorithms for housing (1 ha resolution), and their definition of the WUI (with 3.2 km buffer zone) to determine that there were 47 million hectares at risk in the year 2000. Approximately 65% of the 47 million WUI hectares were at high risk and 11% were on non-federal lands.

Both Menekis et al. (2003) and Theobald and Romme (2007) assumed for simplicity that all homes are easily ignitable. This is consistent with a macroscopic risk assessment approach weighted toward using wildland fuel information. While it is expected that the LANDFIRE project (LANDFIRE, 2009) will produce consistent nationwide data on wildland fuel and fire regimes it will not provide any additional information on residential fuels. Thus, WUI risk assessment tools using LANDFIRE will also be based on very simple assumptions with regard to fire risk in residential fuels.

A more informative WUI fire risk assessment at a community scale would include information on home ignitability which depends on the structural characteristics, the immediate surroundings of the home (i.e, the "home ignitability zone" Cohen, 2000; see Sec. 3), and expected exposure conditions due to WUI fire behavior that change with time due seasonal variation in fuel and weather conditions. Such information could be used in the risk mapping approaches summarized above for further refinement of risk.

3.2 Risk Reduction through Wildland Fuel Treatments

The well known "fire triangle" identifies the necessary conditions for fire to be the presence of sufficient oxygen, heat, and fuel. From a practical point of view, modifying the fuel (vegetative and structural) offers the best path for risk reduction in the WUI. Much effort has been spent on changing the conditions of wildland fuels through fuel treatments. In the past, the objectives of wildland fuel treatments have been focused on decreasing the negative ecological impact of a wildfire and/or decreasing the cost and effort of wildland firefighting (by decreasing the spread rate, intensity, or flame length of a fire).

More recently it has become a national priority to use wildland fuel treatments as a protection strategy for WUI communities (Stratton, 2004; U.S., 2006a) and to contain the costs of wildland fire preparedness and suppression (GAO, 2007a). Over 65% of the US fuels treatment budget and over 50% of the treated acres were in the WUI during 2001-2004 (U.S., 2006a). These wildland fuel treatments are implemented with the view of modifying the wildland fire so that it is less intense, more easily controlled and, therefore, less likely to spread into WUI areas.

However, our understanding of fuel treatment effects on wildland fire intensity is far from complete (Martinson and Omi, 2003).

Carey and Schumann (2003) provide a review of the effectiveness of wildland fuel treatments (prescribed fire, mechanical thinning, and combined thinning and burning) in modifying wildland fire behavior. Most of the over 250 studies considered were based on personal observations (rule based methods) and did not, therefore, provide an adequate science based accounting of the relevant environmental conditions. Empirical studies, which did provide relevant pre- and post-fire measurements, were the least frequent. One of their overall findings was that fuel treatments do modify wildland fire behavior. Graham et al. (2004) arrived at a similar conclusion.

However, a clear link has not been established between specific fuel treatments (e.g., reducing tree density or raising crown base height) and the resulting change in wildland fire behavior, especially over a range of environmental conditions. For this, and other, reasons Carey and Schumann (2003) recommend that more studies based on scientific methods (e.g., empirical methods) are needed to provide a credible means to developing and evaluating fuel treatments. A report by the U.S. General Accountability Office has also stressed the need for an improved understanding of how wildland fire will respond to a given fuel treatment (GAO, 2007b).

4. CURRENT RISK ASSESSMENT AND RISK REDUCTION TOOLS BASED ON RESIDENTIAL FUELS

Residential fuels include structures and vegetation. The role of structure-to-structure firespread in WUI settings has not been given as much attention as vegetative-to-structure firespread. A focus on vegetative-to-structure is valid for WUI communities with sufficiently low housing density. But large losses in WUI fires have not been restricted to low housing densities (Rehm, 2001). For example, in the 1991 Oakland Hills Fire, which had a housing density of approximately 7.5 HU/ha (i.e., medium to high housing density) more than 2500 structures were destroyed.

Post fire analysis on both the Oakland Hills (Trelles and Pagni, 1997) fire, Angora fire in South Lake Tahoe (FUSEE, 2007; Murphy et al., 2007), and the ACT Bushfire (Blanchi and Leonard, 2003) found that structures-to-structure fire spread played a key role in the overall fire behavior. Heat fluxes from both the flame fronts and firebrands produced by structures were instrumental to maintaining firespread to surrounding structures and vegetation. In the numerical simulations of Trelles and Pagni (1997) fire winds created by the concurrent burning of over 259 structures significantly influenced local weather patterns and the overall fire behavior in a manner consistent with observations.

Risk reduction methods for residential fuels are analogous to risk reduction in wildland fuels in that both involve fuel treatments. In residential fuels the goal is to decrease the likelihood of structure ignition by treating both the structure and residential vegetation. However, unlike wildland fires, no measurements of exposure conditions during WUI fires have been made. What is known regarding WUI fire behavior is primarily based on either anecdotal information (i.e., personal observations of responders) or post-fire investigations.

4.1 Homeowner Education, Guidelines, and the Home Ignition Zone

A number of web based resource are available to homeowners. The four most heavily used are (ICC, 2008): Firesafe (2009), Firefree (2009), Firewise (2009), and Firesmart (2009). The most commonly available tools for homeowners and community planners to assess and reduce the risk of fire spread to structures are guidelines for rating the potential for structure ignition. These guidelines are largely rule based when applied to vegetative fuels and more empirically based when applied to structural fuels (due to established and recently developed building material fire resistance test standards (see Sec. 4.3)). Examples of homeowner guidelines are the structure assessment guide and rating form in the National Fire Protection Association's (NFPA) Standard for Protection of Life and Property from Wildfire (NFPA, 2007) and the Wildland/Urban Interface Fire Hazard Assessment Methodology guide (Firewise, 2009).

Recommended homeowner actions for the structure and landscaping can also be found in the form of checklists. Examples are on the Firewise Website (Firewise, 2009) and the International Wildland-Urban Interface Code (ICC, 2006). These include with no prioritization, for structures, the use of fire-resistant or non-combustible building materials, wire screening behind ventilation openings, and proper maintenance of gutters, roofs, and eaves.

The risk assessment and reduction guidelines can use the concept of home or structure ignition zones (NFPA, 2007) or defensible space (ICC, 2006) to categorize the recommended treatment of structure and vegetative fuels. The structure ignition zones begin at the structure (materials and design) and proceed outward, accounting for vegetative fuels. In practice, these ignition zones may, and often do, extend beyond a homeowner's property lines. In an idealized view, in which the vegetative fuels change only with distance from the structure and the terrain is flat, the home ignition zones start with the structure and extend outward as concentric circles. Vegetative fuel treatment is most intense near the structure and relaxes with distance. These treatments include choosing less flammable ornamental vegetation and reducing the spatial continuity and loading of the vegetation. Currently, on the Firewise Website fifteen states provide information for homeowners to use when choosing fire resistance ornamental plants (Firewise, 2009).

Guidelines specific to regional (e.g. the southern U.S., FL (2007)) and individual states are also available (Firewise, 2009). The National Association of State Foresters have produced a guide for preparing a Community Wildfire Protection Plan (CWPP). State recommended approaches

(Firewise, 2009) differ because local conditions differ and, as a result, the definitions of home ignition zones also differ. The availability of the many guidelines available has led to some confusion (WFPS, 2006), highlighting the need for a standardized approach applicable for nationwide use, while accounting for local differences due to terrain, weather, vegetation types and housing density

The California Department of Forestry and Fire Protection (CALFIRE) identified firebrands to be a major cause of home loss during WUI fires (CA, 2007a). Their building code for exterior wildland exposure (CA, 2006) attempts to limit the penetration of firebrands through attic and exterior wall vents by placing a non-combustible wire mesh behind the vents. The recommended mesh size is 6 mm (1/4 inch). This mesh size is consistent with the recommendations given in the NFPA 1144 Standard for Reducing Structure Ignition Hazards from Wildland Fire (NFPA, 2007) and in the International Wildland-Urban Interface Code (ICC, 2006). The Wildfire Mitigation Guide in Florida (FL, 2004) recommends a mesh spacing of 3 mm (1/8 inch). Using screens to block the passage of firebrands is a reasonable risk reduction practice, but to our knowledge the mesh size recommendations of 3 mm or 6 mm are not the result of scientifically based testing.

Within each home ignition zone the suggested characteristics of both surface and elevated vegetation, and their spatial distribution, are provided in a qualitative, rule based, manner. It is important to note that the guidelines for homeowners need to be sufficiently straightforward or they won't be used. Checklists satisfy this and they can be created from rule base (i.e., expert opinion and observation) or from empirical models or well characterized experiments which can systematically include the important environmental factors. Examples of the use of field and laboratory experimental work to address aspects of the structure ignition problem follow.

4.2 Empirical Studies on Structure Ignition from Flame Fronts

As part of a the International Crown Fire Modeling Experiment seven experiments included mock structural walls of untreated and unpainted plywood placed 10 m, 20 m, and 30 m from the downwind edge of the wildland burn plot (Cohen, 2004). All vegetation was removed between the edge of the forest stand and the mock walls. The crown fire induced flaming only on the 10 m distant walls and only in three of the six experiments. Firebrands were not found to play a role in the ignition of the walls.

Predictions of what wall distance would result in an ignition were made based on the experimental correlation (Tran et al., 1992). An incident heat flux from an assumed for a worst case scenario of a uniform flame 50 m wide and 20 m high that lasted 60 s. As expected the predictions overestimated the likelihood of ignition: all walls out to 28 m ignited. A similar use of the empirically model was used in a preliminary development of a structure ignition assessment model (Cohen, 1995; Cohen and Saveland, 1997).

In practice, the results of the crown fire experiments suggest that by limiting vegetative fires to distances of 10 m to 20 m from a structure the potential for structure ignition, via heat flux from the flame front, will be significantly reduced. As noted by Cohen (2004), the experimental crown fires represent only a limited set of environmental conditions (e.g., fuel loading, wind speed, and terrain). For this reason, Cohen (2004) recommended that guidance on safe distances should be based on a worst case scenario, yielding a distance of approximately 30 m. Consistent with this, many of the risk assessment/reduction guidelines identify the home ignition zone farthest from the home to be at a distance greater than 30 m (or 100 feet) for flat to gentle slopes.

4.3 Standard Test Methods for Structure Components

It has been recognized that many of the established building material tests are not representative of WUI fire conditions (Beall et al. 2001). Beall and colleagues developed test methods for wall, deck, and roof/eave assemblies subject to heat fluxes from flaming fronts produced by a burner. The heat release rate of the burner was chosen to be representative of burning ornamental vegetation. A 300 kW heat release rate was stated to be representative of a moderately sized mass of burning vegetation. However, information was not provided on the vegetation types considered, how the representative heat release rates were obtained, or how long the vegetation burned with a heat release rate of 300 kW.

The test methods developed by Beall and colleagues (e.g., Quarles and Beall, 2002; Beall, 2007) serve as the basis of WUI testing standards in California for exterior walls, exterior windows, under eaves, and decking (CA, 2007b). These performance based codes were effective January 1, 2008. As an example, a wall assembly test for flame penetration consisted of placing a 10 cm x 100 cm propane burner lengthwise 2 cm from a 1.2 m wide and 2.4 m tall wall at the back of a 0.6 m deep channel. The burner's heat release rate was 150 kW for the length of time required for the flames to penetrate the wall assembly, or for combustion of the wall to be complete, or for a duration of 70 minutes. No wind was imposed but channeling of the entrained flow by the side walls caused the fire to lean toward the wall assembly. Unfortunately, it is not clear what WUI fire exposure conditions this test is intended to represent.

5. DISCUSSION AND OVERVIEW OF RESEARCH NEEDS

It has been expressed in the literature and elsewhere that no further WUI research is needed, and that homeowners simply need to implement current guidelines to significantly reduce the risk of structure ignition (e.g., Tidwell, 2006). We agree that, when the recommended guidelines can be implemented and maintained, it is reasonable to assume that the risk of structure ignition will be reduced. However, there is a need to assess the effectiveness of the guidelines across a range of WUI community types and exposure conditions. For example, current guidelines for homeowners are based on scenarios that are representative of housing densities that are lower than many WUI communities, including those that have been burned by WUI fires.

The research needs discussed below arise from the need to better identify and characterize (1) the structure exposure conditions (heat flux from flames and firebrands generated by burning vegetation and/or burning structures) for a range of WUI fire settings (e.g., housing density, terrain, vegetative fuels, winds, wildland fuel treatments) and; (2) the vulnerability of a given structure design or building material when subject to a given exposure. Advances in these areas will result in improvements to the approaches in Secs. 3 and 4 and new tools (e.g., field measurement and data collection methods, standard test methods, economic and fire behavior models) to assess and reduce the risk of structure ignition.

5.1 Research Needs on Exposure Conditions and Structure Vulnerability

Based on the review of wildland fuel treatments in Sec. 3.2, a systematic, science based, field research effort is needed to characterize how wildland fuel treatments alter the fire behavior and firebrand and smoke generation from wildland fires. This has not been done sufficiently for wildland fires (Carey and Schumann, 2003) and even less so with the objective of characterizing exposure to WUI communities.

A common need throughout Sec. 3 and Sec. 4 is an expanded understanding of the range of characteristic structure exposure conditions (from both flames and firebrands) in a WUI fire. Exposure conditions will vary depending on the wildland fuels, terrain, weather, and characteristics of the community (e.g., housing density, extent of community perimeter adjacent to wildlands). Qualitative measures of exposure (e.g., role of firebrands versus heat flux in structure ignition) can be, and has been, obtained from post WUI fire studies (e.g., Blanchi and Leonard, 2005; Cohen, 2008; Maranghides and Mell, 2009).

However, more field measurements in prescribed fires (e.g., Cohen, 2004; Manzello et al., 2009 both conducted measurements at point locations), wildfires, and WUI fires are needed to obtain quantitative measures of heat and firebrand fluxes across a range of wildland/WUI fire conditions. This has relevance to both fire safety and economically efficient WUI construction and homeowner retrofit (IBHS, 2001; FL, 2004). A laboratory test method to be used for screening WUI building material should either reproduce, or be an appropriate bound on, realistic heat fluxes due to firebrands and/or a flaming front.

There is also a significant need for field measurements that capture the time development of an extended portion of a fireline. Examples, include airborne visual and infrared measurements during prescribed fires or the placement of many inexpensive ground based measurement devices (Kremens, 2003). This will provide a measure of the influence of larger scale variations in terrain, fuels, and wind on fire behavior. Field measurements can be used to validate computer models and develop laboratory approaches that better approximate actual exposure conditions. Such laboratory experiments can more reliably be used to investigate the vulnerability of structure components and materials, and improve existing, and develop new, structure

suppression and retardant technologies (water sprinklers and foam or gel applications to structure exterior), and standard test methods for building materials (e.g., walls, roof covering) and structural components (e.g., vents) (see Sec. 4.3 and Sec. 6).

A specific example of a research need to better quantify exposure conditions is structure ignition via firebrands. Firebrands, from both vegetation and structures, are often a major source of structure ignition in WUI fires (e.g., Cohen, 1995; Blanchi and Leonard, 2005; Maranghides and Mell, 2009). Well characterized, systematic, research on the production and ignition potential of firebrands is just beginning (see Sec. 6). For this reason, current guidance on homeowner actions to prevent firebrand ignitions is a best guess.

5.2 Research Needs on Pre- and Post-Fire Data Collection Methods in WUI Communities

Firewise and the concept and premise of home ignition zones are a good first step to reducing the risk of structure ignitions and are valuable for community education and guiding research. However, there is a pressing need for pre- and post-fire field efforts that systematically use a standardized data collection approach. This will create well characterized databases to help determine how much and how well homeowners are using the suggested risk reductions practices.

New methods of collecting WUI and wildland fuels information that use remote sensing (e.g., Light Detecting and Ranging (LIDAR)) can be advantageous. The necessary spatial resolution needed for mapping WUI fuels (~ 1 m) is finer than LANDFIRE maps (nominal pixel size of 30 m). Individual trees, hedges, decks and fuel distribution in home ignition zones (0 m – 30 m from the structure) are all unresolved in LANDFIRE. The databases could also be used to assess effectiveness of WUI risk reduction approaches (both wildland and residential fuel treatments). Analysis of the data will also help guide and support research (field measurements during fires, laboratory experiments, and model development and validation) to improve homeowner guidelines and wildland fuel treatment approaches.

Thorough post-fire studies in WUI communities require a consistent and well characterized accounting of human intervention (e.g., Maranghides and Mell, 2009) during the fire event (e.g., suppression of fires, movement and/or reduction of fuels near homes). While it is nearly impossible to account for all defensive actions taken during the fire event, if no accounting is done then a post-fire interpretation of structure ignitions will be based on incomplete information. Structures may be concluded to have survived the exposure conditions for the wrong reason.

Systematic and standardized post-fire studies will also provide an assessment on how implementable and effective current homeowner guidelines are for WUI communities with higher housing density. The standard scenario used to illustrate home ignition zones (e.g., GAO,

2005; NFPA, 2007; Cohen, 2008) is a single structure surrounded by 30 m to 60 m of land available for implementing vegetative fuel treatments. Many WUI communities have structures that are separated by less than 30 m (see Fig. 3). WUI communities with higher housing density have suffered extensive damages from WUI fires (e.g., Blanchi and Leonard, 2005; Maranghides and Mell, 2009). The occurrence of overlapping home ignition zones has been noted (Cohen and Stratton, 2006) but guidance to homeowners is the same, regardless of housing density.

5.3 Research Needs on Fire Behavior, Smoke Transport, and Economic Models

Computer models can also be used for improving our understanding and characterizing structure exposure conditions over a range of environment conditions including extreme conditions that are difficult to measure in the laboratory or in the field. Physics-based models have the ability to provide predictions of structure exposure conditions. It is a given that any model needs to be validated against laboratory and field measurements whenever possible and that users are aware of the model's limitations. The results of a model also depend on the quality input (e.g., fuel characteristics, wind).

Physics-based models can be used to probe the dynamics of important physical processes (e.g., Hanson, 2000). A range, in terms of complexity and computational cost, of modeling approaches would be valuable tools that provide insight into, for example, the effectiveness of fuel treatments on reducing the production and transport of firebrands or smoke transport from prescribed burns to downwind communities.

Obscuration from smoke complicates tactical response, strategic planning, and safe community evacuation. Estimates of the generation and downwind transport of smoke is an important component of prescribed burn planning. Extended periods of smoke exposure from wildland fires is a major health issue (QFR, 2009). Models for smoke transport exist over regional and landscape scales but they employ simplified fire models and, therefore, smoke generation models. Physics-based fire behavior models that include more of the processes of combustion and thermal degradation could provide more accurate smoke predictions over landscape scales.

Homeowners can be reluctant to follow risk reduction guidelines due to their cost (GAO, 2005). For this reason, there is a clear need for economic tools that provide benefit/cost analyses of candidate risk reduction practices. These tools would be particularly useful if they were sensitive to the location of a structure within a community. For example, structures located on the perimeter of a community may require different risk reduction approaches compared to structures in the interior. Developing these differing approaches would require a sufficient understanding of how exposure conditions are expected to change with location in a community.

6. OVERVIEW OF ONGOING WUI RESEARCH BY NIST AND COLLABORATORS

WUI research at NIST's Building and Fire Research Laboratory has been in the areas of laboratory experiments, field measurements, post-fire data collection, and fire behavior and economic modeling (NIST, 2009). Work in these areas is complementary and integrated. For example, field work motivates the laboratory studies and provides full-scale validation checks of the models. Laboratory results provide insight into interpretation of field observations and also provides validation checks for the fire behavior models. The fire behavior models are used to help design laboratory experiments and to interpret both the laboratory and field results.

An overview of the work to date, which includes studies funded by NIST Fire Research grants, is given below. Important areas in which NIST has not been active, to date, include the effectiveness of wildland fuel treatments in reducing a WUI community's exposure to heat fluxes from flame front and firebrands, remote or ground based sensing of extended portions of a spreading fireline, or the effectiveness of water application or retardants to the exterior of structures.

6.1 Exposure Conditions and Structure Vulnerability

In collaboration with the University of Florida and the U.S. Forest Service Southern Research Station 34 species of ornamental shrubs were burned in NIST's Large Fire Laboratory (LFL) to quantify and rank their flammability (Long et at., 2006a) to provide guidance to homeowners. The flammability of four commonly used mulches was also studied (Long et al., 2006b). These studies used pilot ignition of the ornamental shrubs or mulches.

Bench top scale wind tunnel experiments were conducted to characterize the potential of disk (Manzello et al., 2006b) and cylinder shaped (Manzello et al., 2008a) firebrands to ignite a number of fuel bed types (surface fuels and structural fuels). The disk shape was chosen based on the assumption that it was representative of the shapes of firebrands produced from burning structures (e.g., fragment of siding or roofs). Cylinder shaped firebrand dimensions were based on Douglas fir tree burn experiments in NIST's LFL (Manzello et al., 2007) and Korean pine trees at BRI (Manzello et al., 2009a). Both the disk and cylindrical firebrands induce flaming ignition of a fuel bed if the firebrand is flaming. Ignition by glowing firebrands was more likely in cases with more or larger firebrands and higher wind speeds. Recently, additional bench scale experiments were conducted to determine the range of conditions for firebrand ignition of common building materials (Manzello et al., 2009b).

A firebrand generator (Manzello et al., 2008b) that produces glowing firebrands, with size and mass characteristics similar to those produced by the Douglas tree burns, as well as Korean Pine Trees (Manzello et al., 2007d) has been developed. This allows studies of firebrand ignition in the large scale (5 m wide, 4 m tall) wind tunnel at Japan's Building Research Institute (BRI). Firebrand ignition potential of different structure elements and materials is being tested. Firebrands were found to penetrate steel screens placed behind a gable vent (screen mesh sizes

were 6 mm, 3 mm, or 1.5 mm) in a 9 m/s wind (Manzello et al., 2007e), see Fig.2. Further testing is underway to assess the ignition potential of the firebrands that do pass through the vents. Note that ventilation, and other, constraints may put a minimum bound on the mesh size. The potential for firebrands to ignite roofs of shingles (Manzello et al., 2008c) or ceramic tiles (Manzello et al., 2009c) is also being studied in the BRI wind tunnel. Depending on construction choices and maintenance these roof can also be vulnerable to firebrand ignition. Measurements of firebrand transport, for model validation are also being conducted.

A new bench scale wind tunnel is being coupled to a reduced scale firebrand generator to determine if the reduced scale test method is able to capture the salient physics of firebrand penetration through building vents observed using the full scale test method. These unique full scale and reduced scale test methods are being used to provide guidance in adopting future building codes/standards aimed at resisting firebrand intrusion into attic and crawlspace vents.

The conditions simulated by the firebrand experiments summarized above need to be placed in the context of an actual WUI fire. One of the ways this will be done is ground based measurements of exposure conditions. The first steps is this direction have been the development and testing (in a prescribed fire) of a rapid response instrument package to measure, at point locations, heat fluxes, wind speeds, and firebrand characteristics during prescribed fires (Manzello et al., 2009d) .

Exposure condition information is also being gathered via a post fire study of a community burned by the Witch and Guejito fires during the October 2007 southern California Firestorm (Maranghides and Mell, 2009). Through field surveys, technical meetings with first responders, and homeowner input a timeline of the fire event and defensive actions was constructed. The fire destroyed 30% of the structures within the fireline; 40% of the structures on the perimeter (in closest proximity to wildland fuels) and 20% in the interior were destroyed. This illustrates the importance of understanding the dependence of structure exposure conditions on locations within a community.

Firebrands ignited at least 60% of the destroyed structures. Direct ignition by firebrands accounted for about 25% of the destroyed structures. This shows a clear need for an understanding of the exposure conditions related to firebrands and an improvement of current homeowner guidelines since they emphasize reducing the potential for structure ignition via heat flux from radiation or flame contact. Potential firebrand ignition scenarios were identified for further wind tunnel study with the firebrand generator in the BRI wind tunnel (e.g., Manzello, 2009a). One out of every three homes was defended by the homeowners, fire or police department personnel (60% of these were saved). These defensive actions significantly affected fire behavior and structure survivability and should be an essential component of WUI post fire

case studies. Further study is ongoing to, in part, apply current risk assessment methods to the community to assess their effectiveness and need for improvement.

The ambient wind is a major influence on fire front progression and fire brand transport. NIST and San Diego State University are in the initial stages of project on field measurements of wind. The long term objective of the study is to gather sufficient wind measurements in terrain and high wind conditions similar to those present in the WUI community under study during the fire event. These measurements will provide insight into firebrand transport, validate computer simulation of wind, and provide a point of reference for the ongoing wind tunnel firebrand studies.

6.2 Pre- and Post-Fire Data Collection Methods in WUI Communities

In collaboration with the Coeur d'Alene Indian Tribe GIS group, CAL FIRE, and California county and city fire departments methodologies for pre- and post-fire data collection, at the homeowner parcel scale, in WUI communities are being developed and will be implemented by ground crews. This will include a standard field procedures and data collection kit. The collection kit will be composed of PC tablet with GIS software, GPS enabled camera, and range finder.

In collaboration with the Coeur d'Alene Indian Tribe GIS group, methods for obtaining building footprints, vegetation distribution, firebreaks, and terrain from LiDAR and color imagery are being developed (McNamara, 2006, 2007). The remote sensing data, along with the ground-based parcel-scale data described above, can be used to create a robust community-scale dataset of WUI fuels (vegetation and structures), terrain, roads, and other cultural features (e.g., swimming pools, tennis courts). For an example see Fig. 3 for a WUI dataset from LiDAR. Both datasets will be used to investigate the effectiveness and improve existing risk assessment and risk reduction methods. The datasets will also provide input and validation checks for the development of fire behavior and economic models.

6.3 Fire Behavior, Smoke Transport, and Economic Models

NIST's computer model for time dependent, three-dimensional simulations of structure fires, the Fire Dynamics Simulator, has been modified to include fire spread in vegetation. The resulting computer model, the wildland-urban interface fire dynamics simulation (WFDS), will be used to model firespread through WUI fuels and the resulting smoke transport. Currently WFDS is being validated for firespread in vegetation. This includes simulations of Australian grassland fire experiments (Mell et al., 2007) and tree burning experiments conducted at NIST (Mell et al., 2009). These experiments facilitate the development of WFDS for application to fire spread for larger scale fires such as the International Crown Fire Modeling Experiments (Stocks et al., 2004). A snapshot of a preliminary crown fire simulation with walls 10 m and 20 m distant from

the edge of the stand, as in the International Crown Fire Modeling Experiments (Cohen, 2004), is shown in Fig. 4.

The current implementation of WFDS is for research applications since it requires significant computational resources, computer time, and can be demanding in terms of input information (wind, fuel, and terrain conditions). There is a need for simpler, faster, computer models of fire behavior that can be more widely used. These simpler models, by necessity, will have more approximations to the physical processes and their limitations need to be determined through comparison to field measurements and more complete models. A number of simpler approaches are being investigated. These include models that account for the entrainment of air by burning buildings and its affect on a spreading grass fire on flat (Rehm, 2008) and hilly (Rehm and Mell, 2009) terrain.

Due to the difficulty of estimating the benefits of homeowner risk reduction actions (i.e., the FIREWISE guidelines) there is little, if any, empirical evidence of their cost effectiveness. The dependence (spillover effect) between the risk reduction actions performed on neighboring structures and a given structure's fire risk exposure level also complicates benefit-cost analysis. Failure to account for this interdependent risk can lead to inefficient levels of risk reduction investment by homeowners and at-risk communities. Theoretical models for identifying direct and spillover benefits of homeowners' risk reduction actions are being developed and used to evaluate the economics of various risk reduction approaches at a community scale (Butry and Donovan, 2008). For example, the costs and benefits can be compared between community funded risk reduction actions weighted toward fuel treatments of the vegetation surrounding the community versus more localized, single homeowner funded, risk reduction actions on homeowner parcels.

7. SUMMARY

The current expectation is that WUI fires will continue to be a serious and costly issue in the U.S. (ICC, 2008) and internationally. There is a significant need to better understand the effectiveness of wildland fuel treatment in reducing the exposure on WUI communities. Existing guidelines for homeowner risk assessment and risk reduction need to be tested. This requires standardized and systematic pre- and post-fire data collection methods. The existing guidelines need to be expanded to include realistic ranges in WUI housing density and account for exposure conditions from firebrands and heat fluxes over a range of WUI fire conditions.

A comprehensive, coordinated, scientifically based research effort with targeted experiments, well characterized field measurements and observations, and a range of modeling approaches suitable for fire spread in WUI areas is needed to better determine structure exposure conditions. Physics-based models can provide fire behavior predictions over a realistically broad range of wildland and residential fuel types under a variety of weather and terrain conditions. A range of

model approaches, with sufficient experimental and field measurement support, could be used to test and improve risk assessment and mitigation strategies for realistic WUI fuels and environmental conditions. Results from experiments and field measurements would also support the development of new building test methods and standards. While such a program, especially with large-scale field measurements, would be expensive, the cost of not undertaking such a research program is even more expensive in the long run.

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REFERENCES

1. Beall FC, Jennings CM, Quarles SL (2001) Mitigation of fire damage in the urban-wildland interface, *Proceedings of the 2nd Annual Conference on Durability and Disaster Mitigation in Wood-Frame Housing*, November 6-8, 2000, Madison, WI. pp. 123-130.
2. Beall (2007) Performance-based standards for the urban-wildland interface. http://nature.berkeley.edu/~fbeall/PBS.html
3. Blanchi, F. and Leonard, J. (2005) Investigation of Bushfire Attach Mechanisms Resulting in House Loss in the ACT Bushfire 2003, draft CMIT Doc., http://www.bushfirecrc.com/research/downloads/ACT%20Bushfire%20CRC%20Report.pdf
4. Butler, C.P., (1976) The Urban\Wildland Fire Interface, *Fireline*, June 1976
5. Cleaves D, (2001) Fires in the wildland urban interface: Dilemmas of duality and the role of national science leadership, presented to Natural Disasters Roundtable, June 26, 2001.
6. CA (2006) Materials and construction methods for exterior wildfire exposure. June 21, 2006 Emergency Supplement to the 2001 California Building Code, Section 704A http://www.fire.ca.gov/wildland_content/downloads/Part_2_CA_Building_Code_CH_7A.pdf
7. CA (2007a) Fact sheet: Wildland-urban interface building codes. *California Dept. of Forestry and Fire Protection*, May 2007 http://www.fire.ca.gov/wildland_content/downloads/BSR_fact_sheet.pdf
8. CA (2007b) Living & Building in California's Fire Prone Areas, http://www.fire.ca.gov/wildland_codes.php
9. Carey H, Schumann M (2003) Modifying wildfire behavior – The effectiveness of fuel treatments, the status of our knowledge. National Community Forestry Center, Southwest Region Working Paper 2, http://www.theforesttrust.org/images/swcenter/pdf/WorkingPaper2.pdf
10. Cohen JD (1995) Structure Ignition Assessment Model (SIAM), pp. 85-92 in The Biswell Symposium: Fire issues and solutions in urban interface and wildland ecosystems. *USDA Forest Service Gen. Tech Rep.* PSW-GTR-158.
11. Cohen JD, Saveland J (1997) Structure ignition assessment can help reduce fire damages in the W-UI, *Fire Management notes*, **57**, 19-23.
12. Cohen JD (2000) Preventing disaster, home ignitability in the wildland-urban interface, *J. Forestry*, **98**, 15-21.
13. Cohen JD (2004) Relating flame radiation to home ignition using modeling and experimental crown fires, *Canadian Journal of Forest Research*, **34**, 1616-1626.
14. Cohen, JD (2008) The Wildland Urban Interface Fire Problem, *Forest History Today*, Fall 2008, 20-26.
15. Federal Register (2001) Federal Register Notes 66(3), pp. 751-777, January 4, 2001.
16. Firesafe (2009) http://www.firesafecouncil.org
17. Firefree (2009) http://www.firefree.org
18. Firewise (2009) Firewise communities, Website of the National Firewise Communities program, http://www.firewise.org/resources/homeowner.htm

19. Firesmart (2009) http://www.partnersinprotection.ab.ca
20. FL (2004) Wildfire mitigation in Florida, Florida Dept. of Community Affairs and Florida Dept. of Agriculture and Consumer Services, Drummond Press, Jacksonville, Floria http://edis.ifas.ufl.edu/FR076
21. FL (2007) Interface South. http://www.interfacesouth.org/
22. Fong PK (2007) Statement before the senate committee on energy and natural resources. United States Dept. of Agriculture, Office of Inspector General, January 30, 2007. http://www.senate.gov/public/_files/fongwildfiretestimony.pdf
23. FUSEE (2007) Angora fire: Burning homes, not crownfire, fueled an urban conflagration, Firefighters United for Safety, Ethics, and Ecology; July 20, 2007 http://www.dailykos.com/storyonly/2007/7/20/35546/2769
24. GAO (2005) Technology Assessment: Protecting Structures and Improving Communications during Wildland Fires, GAO Report to Congressional Requesters, April 2005, U.S. Gov. Accountability Office GAO-05-380. http://www.gao.gov/cgi-bin/getrpt?GAO-05-380
25. GAO (2007a) Wildland fire management: Lack of clear goals or a strategy hinders federal agencies' effort to contain the costs of fighting fires. Report to congressional requestors. June 2007. U.S. Gov. Accountability Office, GAO-07-655. http://www.gao.gov/cgi-bin/getrpt?GAO-07-655
26. GAO (2007b) Wildland Fire Management: A cohesive strategy and clear cost-containment goals are needed for federal agencies to manage wildland fire activities effectively. Testimony before the Subcommittee on National Parks, Forests and Public Lands, Committee on Natural Resources, House of Representatives, Robin M. Nazzaro, Director Natural Resources and Environment, June 19, 2007. U.S. Gov. Accountability Office, GAO-07-1017T http://www.gao.gov/cgi-bin/getrpt?GAO-07-1017T
27. Graham RT, McCaffrey S, Jain TB (2004) Science basis for changing forest structure to modify wildfire behavior and severity, U.S. Dept. of Agriculture Forest Service Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-120
28. Haight RG, Cleland DT, Hammer RB, Radeloff VC, Rupp TS (2004) Assessing fire risk in the wildland-urban interface. *Journal of Forestry* 41-48.
29. Hanson, HP, Bradley, MM, Bossert, JE, Linn, RR, Leland, WY (2000) The potential and promise of physics-based wildfire simulation, *Environmental Science & Policy*, **3**, 161-172.
30. IBHS (2001) Is your home protected from wildfire disaster? A homeowners guide to wildfire retrofit. Institute for Business and Home Safety. http://www.ibhs.org/publications/downloads/130.pdf
31. ICC (2006) International wildland-urban interface code. *International Code Council*, Country Club Hills, IL, U.S.. http://www.iccsafe.org/
32. ICC (2008) The Blue Ribbon Report on Wildland Urban Interface Fire, *International Code Council*, 500 New Jersey Avenue, Northwest, Washington, D.C. 20001 http://www.iccsafe.org/government/blueribbon/

33. Kremens, R, Faulring, J, Gallagher, A, Seema, A, Vodacek, A (2003), Autonomous field-deployable wildland fire sensors, *Intnl. Journal Wildland Fire*, **12**, 237-244.
34. LANDFIRE (2009) Homepage of the LANDFIRE project, U.S. Dept. Agriculture, Forest Service; U.S. Dept. Interior. http://www.landfire.gov
35. Long AJ, Behm A, Zipperer WC, Hermansen A, Maranghides A, Mell W (2006a) Quantifying and ranking the flammability of ornamental shrubs in the southern United States, *3rd Intn'l Fire Ecology and Management Congress*, San Diego, Nov. 13-17, 2006.
36. Long A, Hinton B, Zipperer W, Hermansen-Baez A, Maranghides A, Mell W (2006b) Fire spread and structural ignitions from horticultural plantings in the wildland-urban interface, *3rd Intn'l Fire Ecology and Management Congress*, San Diego, Nov. 13-17, 2006
37. Manzello SL, Cleary TG, Shields JR, Yang JC (2006a) On the ignition of fuel beds by firebrands. *Fire and Materials*, **30**, 77-87.
38. Manzello SL, Cleary TG, Shields JR, Yang JC (2006b) Ignition of mulch and grasses by firebrands in wildland-urban interface fires. *International J. Wildland Fire,* **15**, 427-431.
39. Manzello SL, Maranghides A, Mell WE (2007) Firebrand generation from burning vegetation. *International J. Wildland Fire*, **16**, 458-462.
40. Manzello SL, Shields JR, Yang JC, Hayashi Y, Nii D (2007e) On the use of a firebrand generator to investigate the ignition of structures in wildland-urban interface (wui) fires. *11th International Conference on Fire Science and Engineering (INTERFLAM)*, September 3-5, 2007, London, UK.
41. Manzello SL, Cleary TG, Shields JR, Maranghides A, Mell W, Yang JC (2008a) Experimental investigations of firebrands: Generation and ignition of fuel beds. *Fire Safety Journal*, **43**, 226-233.
42. Manzello SL, Cleary TG, Shields JR, Yang JC, Maranghides A, Mell WE, Hayashi Y, Nii D (2008b) On the development and characterization of a firebrand generator. *Fire Safety Journal*, **43**, 258-268.
43. Manzello SL, Shields JR, Hayashi Y, Daisaku, N (2008c) Investigating the vulnerabilities of structures to ignition from a firebrand attack, *Fire Safety Science*, **9**, 143-152.
44. Manzello SL, Maranghides A, Mell WE, Hayashi Y, Nii D (2009a) Mass and Size Distribution of Firebrands Generated from Burning Korean Pine Trees. *Fire and Materials*, **33**, 21-31
45. Manzello, SL, Park, SH, Cleary, (2009b) Investigation on the Ability of Glowing Firebrands Deposited Within Crevices to Ignite Common Building Materials, *Fire Safety Journal*, accepted in press.
46. Manzello SL, Hayashi Y, Yoneki T, Yamanoto Y, (2009c) Firebrand attack on ceramic tile roofing materials, *Fire and Materials*, in review
47. Manzello SL, Park S-H, Cleary TG, (2009d) Development of rapidly deployable instrumentation packages for data acquisition in wildland-urban interface (WUI) Fires, *Fire Safety Journal*, in review.

48. Maranghides A, Mell WE (2009) A case study of a community affected by the Witch and Guejito Fires, *International J. Wildland Fire*, in review
49. McNamara D (2006) Extracting building footprints from LiDAR and aerial imagery in the wildland-urban interface, *NW GIS Conference 2006, GIS: Visualizing Our Past, Present, and Future*, September 13-15, 2006, Spokane, Washington. http://gis.cdatribe-nsn.gov/projects/lidarbuilding.aspx
50. McNamara D (2007) Enhancing the Fire Dynamics Simulator for modeling wildland-urban interface fires, *2007 ESRI International User Conference Proceedings*, http://proceedings.esri.com/library/userconf/proc07/papers/abstracts/a2154.html
51. Mell WE, Jenkins MA, Gould JS, Cheney NP. (2007) A physics-based approach to modeling grassland fires, *International Journal of Wildland Fire*, **16**, 1-22.
52. Mell WE, Maranghides A, McDermott R, Manzello SL (2009) Numerical simulation and experiments of burning Douglas fire trees, *Combustion and Flame*, in revision.
53. Menakis, JP, Cohen J, Bradshaw L (2003) Mapping wildland fire risk to flammable structures for the conterminous U.S., *Proceedings of Fire Conference 2000: The First National Conference on Fire Ecology, Prevention and Management.* pp. 41-49, Editiors: Galley KEM, Klinger RC, and Sugihara NG. Miscellaneous Pub. No. 13, Tall Timbers Research Station Tallahasse, FL. http://www.firelab.org/media/menakis_map_wildlandfrisk.pdf
54. Murphy K, Rich T, Sexton T (2007) An assessment of fuel treatment effects on fire behavior, suppression effectiveness, and structure ignition on the Agora Fire. U.S. Dept. of Agriculture, R5-TP-025.
55. NIST (2009) Wildland and wildland-urban interface fires. Web page of NIST's project, recent results, and experimental data. http://www.fire.nist.gov/wui
56. NFPA (2007) NFPA 1144: Standard for reducing structure ignition hazards from wildland fire, 2008 Edition, *National Fire Protection Association*, Quicny, MA, USA http://www.nfpa.org
57. NFPA (2008) Deadliest/Large-Loss Fires, 25 Largest Fire Losses in U.S. History, *National Fire Protection Association*, Quincy, MA, UAS http://www.nfpa.org/
58. QFR (2009) Quadrennial Fire Review 2009, Final Report, January 2009.
59. Quarles SL, Beall FC (2002) Testing protocols and fire tests in support of the performance based codes. *Proc. of the California 2001 Wildfire Conference: 10 Years After the 1991 East Bay Hills Fire*, October 10-12, 2001, Oakland, CA. pp. 64-73. Technical Report 35.01.462. Richmond CA: University of California Forest Products Laboratory.
60. Rehm RG, Hamins A, Baum HR, McGrattan KB, Evans DD (2001). Community-scale fire spread. *Proc. of the California 2001 Wildfire Conference: 10 Years After the 1991 East Bay Hills Fire*, October 10-12, 2001, Oakland, CA. pp, 126-139. Technical Report 35.01.462. Richmond CA: University of California Forest Products Laboratory.
61. Rehm RG (2008) The effects of winds from burning structures on ground-fire propagation at the wildland-urban interface, *Combustion Theory and Modeling*, **12**, 477-496.

62. Rehm RG, Mell W (2009) A simple model for the wind effects of burning structures and topography on WUI surface propagation, *Intnl J. Wildland Fire*, submitted.
63. States (2003) Field Guidance: Identifying and prioritizing communities at risk. *National Association of State Foresters*, http://www.stateforesters.org/reports/COMMUNITIESATRISKFG.pdf
64. Stewart S, Radeloff VC, Hammer RB (2003) Characteristics and location of the wildland-urban interface in the United States. In '2nd International Wildlans Fire Ecology and Fire Management Congress", Orlando, FL, 19 November 2003. Available https://ams.confex.com/ams/pdfpapers/65316.pdf
65. Stocks BJ, Alexander ME, Wotton BM, Stefner CN, Flannigan MD, Taylor SW, Lavoie N, Mason JA, Hartley GR, Maffey ME, Dalrymple GN, Blake TW, Cruz MG, Lanoville RA (2004) Crown fire behavior in a norther jack pine – black spruce forest. *Canadian J. Forest Research*, **34**, 1548-1560.
66. Stratton RD (2004) Assessing the effectiveness of landscape fuel treatments on fire growth and behavior. *J. Forestry*, October/November, pp. 32-40.
67. Theobald DM (2007), personal communication.
68. Theobald DM, Romme WH (2007) Expansion of the U.S. wildland-urban interface, *Landscape and Urban Planning*, in press.
69. Tran HC, Cohen JD, Chase RD (1992), Modeling ignition of structures in wildland/urban interface fires. *Proceedings 1st International Fire and Materials Conference*, Arlington, VA, 24-25 September 1992. Inter. Science Communications Ltd., London, pp. 253-262.
70. Trelles JJ, Pagni PJ (1997) Fire induced winds in the 20 October 1991 Oakland Hills fire, *Proceedings 5th International Symposium of Fire Safety Science*, International Association of Fire Safety Science, Hasemi Y editor, March 3-7, 1997, Boston, MA. pp. 911-922.
71. U.S. (2006a) Protecting people and natural resources: A cohesive fuels treatment strategy. US Healthy Forests and Rangelands Plan, U.S. Dept. of Agriculture and U.S. Dept. of the Interior http://www.forestsandrangelands.gov/resources/documents/CFTS_03-03-06.pdf
72. U.S. (2006b) A collaborative approach for reducing wildland fire risks to communities and the environment. 10 year comprehensive strategy implementation plan. December 2006. Available at http://www.forestsandrangelands.gov/plan/documents/10-YearStrategyFinal_Dec2006.pdf
73. U.S. (2006c) Audit report: Forest service large fire suppression costs. US Department of Agriculture, Office of Inspector General Western Region, November 20, 2006, Report No. 08601-44-SF. http://www.usda.gov/oig/webdocs/08601-44-SF.pdf
74. USHF (2006) Healthy forests report: FY 2006 Final Accomplishments, from U.S. Healthy Forests and Rangelands website, http://www.forestsandrangelands.gov/reports/documents/healthyforests/2006/2006_year_end_report.pdf

75. WFPS (2006) Report on 2nd wildland fire policy summit. February 9, 2006. Washington, D.C., International Association of Wildland Fire http://www.iawfonline.org/pdf/2006_Policy_Summit.pdf

Table 1: Definition of Interface, Intermix, and Occluded WUI communities and resulting land area from the Federal Register (2003), Stewart et al. (2003), and Theobald and Romme (2007). (HU = housing units; ha = hectare). For reference the land area of the contiguous USA is 808 million hectares; 1 ha = 2.47 acres.

	Description	Federal Register (2003)	Stewart et al. (2003)	Theobald and Romme (2007)
Interface	Clear demarcation between structural and wildland fuels	> 7.5 HU/ha or > 1 people/ha	> 1 HU/16ha and < 50% vegetation	> 1 HU/2ha and > 10 ha patch
Intermix	Structures dispersed; continuous wildland fuels	> 1 HU/16ha or 11 < people/ha < 96	> 1 HU/16ha and > 50% vegetation	1 HU/2ha to 1 HU/16ha
Occluded	Structures surround wildland fuel area	< 400 ha wildlands	Not considered	Not considered
Distance to untreated wildlands*		Not specified	2.4 km	0.8 km, 1.6 km, 3.2 km
Extent of WUI			70 million ha	47 million ha

*By untreated wildlands we mean no fuel treatments have been implemented to mitigate wildland fire risk to the WUI community.

FIGURE CAPTIONS

Figure 1 Image of a portion of the community WUI community under study before the fire (Maranghides and Mell, 2009). Circles of 30 m radius, centered on the structures are shown. It can be clearly seen that the home ignition zone within 30 m can significantly overlap.

Figure 2 Snapshot of NIST firebrand generator operating in the BRI wind tunnel (9 m/s wind). The target for the firebrand assault is a wall with a gable vent and wire screening of different mesh sizes downwind of the vent.

Figure 3 Two representations of the same WUI community. The figure on the left is created from color imagery. The figure on the right is the vegetation, structure, terrain, and roads extracted from LiDAR data, of the same study area. The rendering on the right is created by Smokeview (the visualization package for NIST's FDS and WFDS fire models) and shows the information that is input into the WUI fire model WFDS.

Figure 4 A snap shot from a WFDS simulation of a crown fire based on the experiments reported by Cohen (2004). Mock walls can be seen at 10 m and 20 m distance from the edge of the wildland plot.

FIGURES

Figure 1

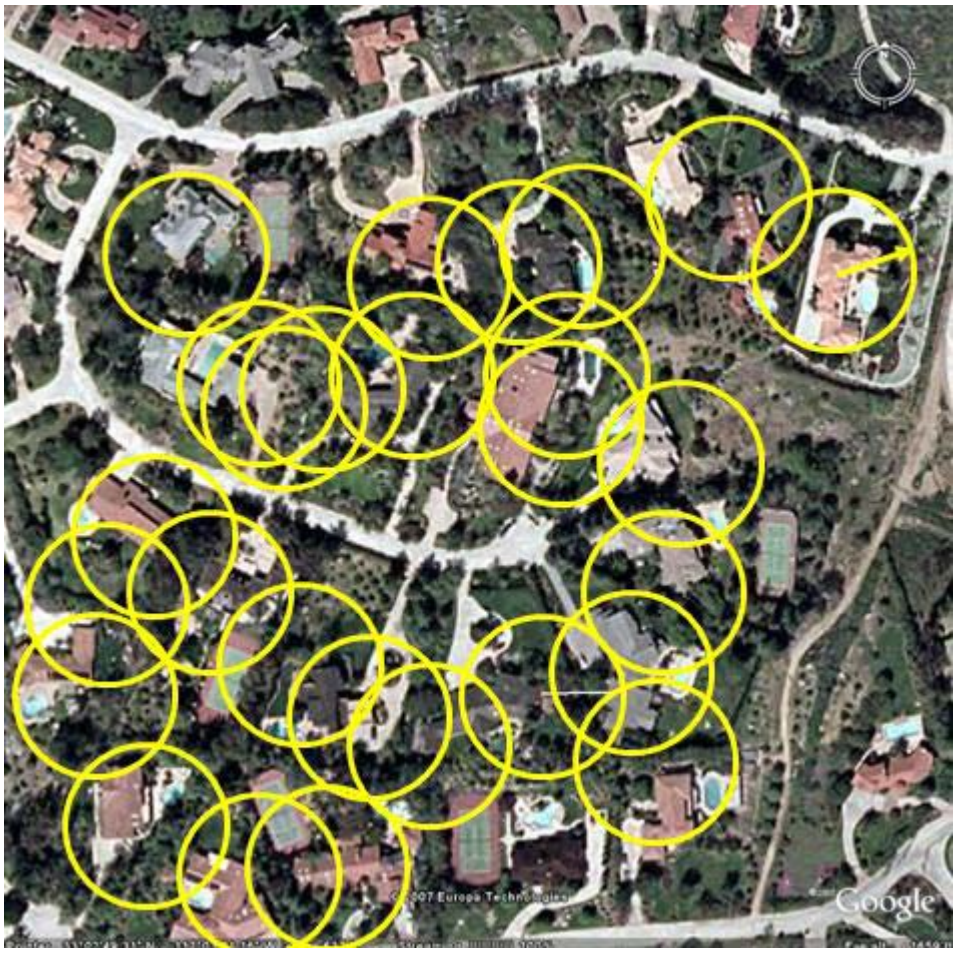


Figure 2

Figure 3

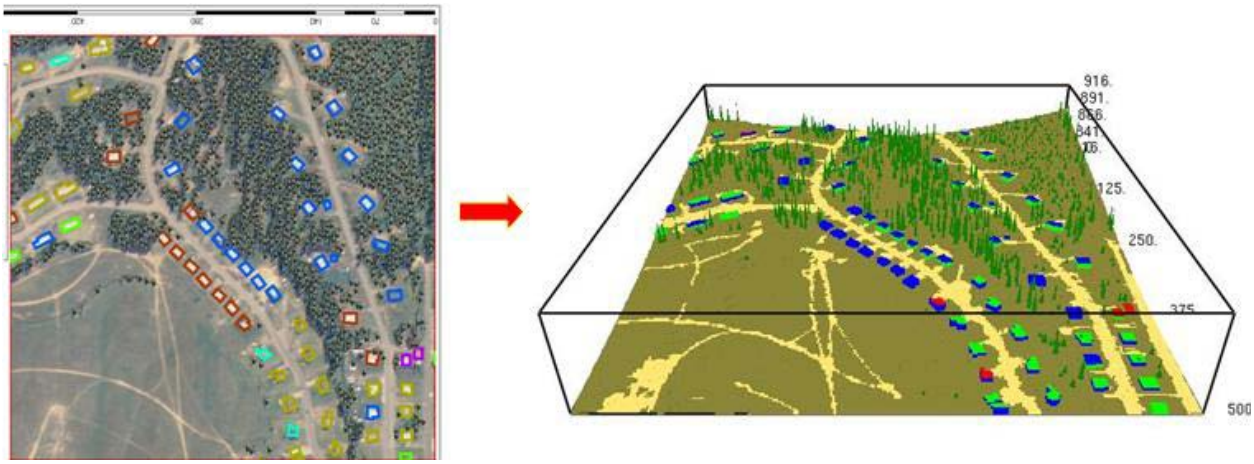
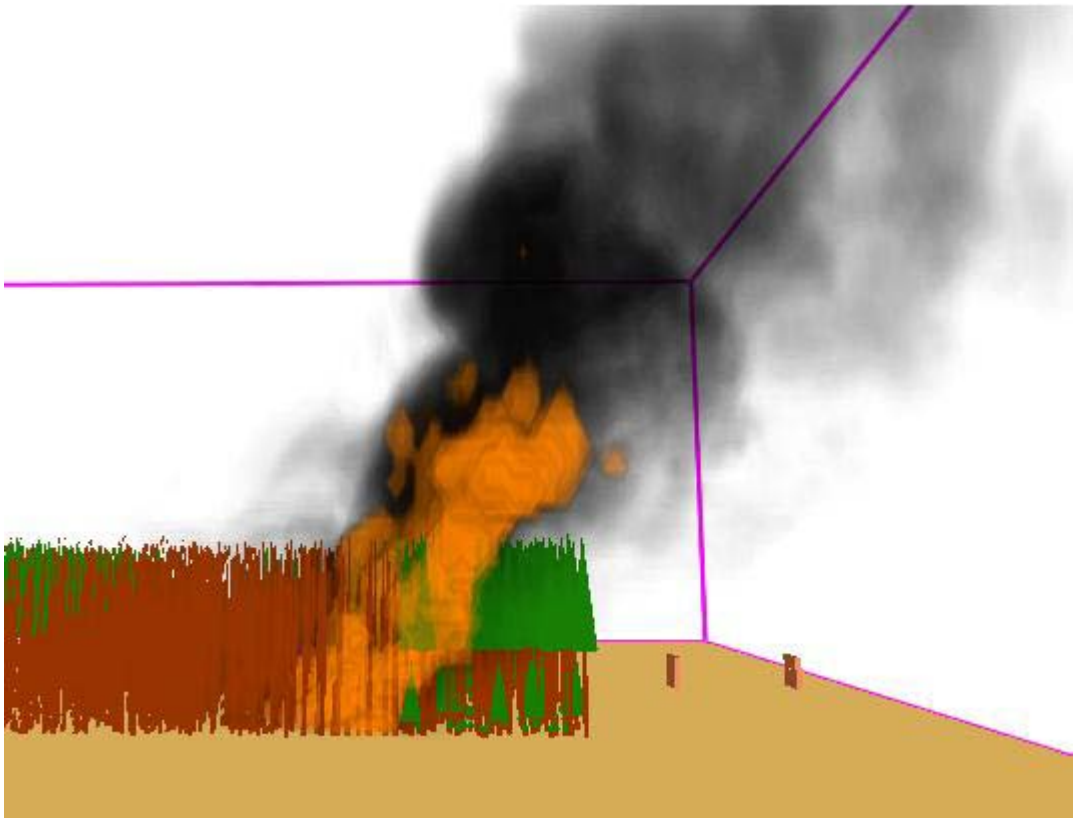


Figure 4



Appendix A WUI Definitions

The Federal Register (2001) defines interface WUI communities as having a clear demarcation between wildland fuels and the community development area; structure density is at least 7.5 HU/ha (3 HU/acre) or, alternatively, population density is at least 96 people/km^2 (250 people/mi^2); where HU = housing unit, ha = hectare, km = kilometer, and mi = mile. Intermix WUI communities have no clear line of demarcation, structures are scattered, and wildland fuels are continuous throughout the developed area. Structure density ranges from structures very close together to 1 HU/16 ha (1 HU/40acre) or, alternatively, a population density between 11 – 96 people/km^2 (28 – 250 people/mi^2). Occluded WUI communities have structures surrounding an area of wildland fuels usually less than 400 ha (1000 acres) in size. Structure density is similar to WUI interface communities.

Theobald and Romme (2007) found that the measure of at least 96 people/km^2, as opposed to at least 7.5 HU/ha, is more representative of WUI interface communities of relevance to fire managers. By assuming that there are 2 people/HU (Theobald, 2007) they determined that the interface housing density corresponding to at least 96 people/km^2 is at least 1 HU/2ha. Another requirement is that the interface area is at least 10 ha in extent. Intermix areas have housing densities from 1 HU/16ha to 1 HU/2ha. Occluded WUI communities were not considered.

Stewart et al. (2003) define the WUI interface and intermix communities as both having at least 1 HU/16ha. Interface areas are defined to have less than 50% vegetation and are within 2.4 km of an area that is both over 500 ha in extent and more than 75% vegetated. Intermix areas are defined to have more that 50% vegetation. As presented in Table 1 of Stewart et al. (2003), both the interface and intermix can be characterized by the density of housing units (HU). Three levels of housing density were considered: high (> 7.5 HU/ha); medium (1 HU/2ha to 7.5 HU/ha); and low (1 HU/2ha to 1 HU/16ha). Occluded WUI communities were not considered.

The Federal Register (2001) also specifies that at-risk interface communities are in the vicinity of untreated wildlands, but does not quantify what in meant by “vicinity.” Steward et al. (2003) use a distance to untreated wildlands of 2.4 km (1.5 mile) to identify at-risk interface WUI areas. This is based on the observation that firebrands from wildfires can be lofted 2.4 km downwind and cause spot fires. Theobald and Romme (2007) use three different distances based on typical fuel treatment buffer zones: 0.8 km, 1.6 km, 3.2 km (0.5 mi, 1 mi, 2 mi respectively).

It is important to note that, with the exception of using the distance to untreated wildland fuels to identify WUI at-risk interface communities, the definitions of the WUI listed above are not based on any fire behavior or fire risk considerations. By fire risk we mean a measure of how easily a fuel, under given fire assault conditions (i.e., radiative and/or convective heat flux or firebrand attack), can ignite and undergo a transition from ignition to sustained flaming.