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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 several 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 focussed on fuel treatments in either wildland fuels or residential fuels. There is a need for a well-characterised, systematic testing of these approaches across a range of community and structure types and fire conditions. Laboratory experiments, field measurements and fire behaviour 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.

Additional keywords: fuel treatments, wildfire, wildland fires.

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 of and need for research in other aspect of the WUI fire problem, such as suppression of wildland fires or large-scale community evacuation (see also Cleaves 2001), 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 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 on its physical 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 California 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 US. For this reason, the focus of this paper will be on the WUI fire problem in the US.

The purpose (and organisational 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 the National Institute of Standards and Technology (NIST) to address some of the research needs.

Background

The potential for WUI fires to be a significant problem in southern California has been recognised since at least the 1970s (Butler 1976). Since then, the severity of the wildland and WUI fires in the US has increased. Of the top 10 fire-loss incidents in the last 100 years, 6 are WUI fires, all of which occurred within the last 20 years and in the western US (all but one in California) (NFPA 2008). This is due to several factors generally accepted in the literature (e.g. Cleaves 2001; GAO 2007*a*; Quadrennial Fire Review 2009), including long-term drought and the build-up of hazardous wildland fuels (especially in parts of the western US), and an increasing number of homes in the WUI.

On average, wildland fires annually burned 70% greater area from 2000 to 2005 than in the 1990s; the average federal funding for suppression and wildland fuel treatments increased from US$1.3 billion annually during 1996 to 2000 to US$3.1 billion during 2001 to 2005 (GAO 2007*a*). A major component of the rising suppression cost is protecting private property and communities from wildfires (USDA 2006; Quadrennial Fire

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Review 2009). This is occurring within the context of significantly more wildland fuel treatments. From 1995 to 2000, a total of 3.6 million hectares (9 million acres) of federal, state, and private lands were treated, compared with a total of 7.6 million hectares (19 million acres) during 2001 through 2006 (USA 2006). However, 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 *v.* wildland is the presence of structures. A definition of 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 prioritise risk-reduction activities at local, regional, and national scales.

The US 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 (NASF 2003). However, the Federal Register allows alternative definitions, depending on whether housing density or population density is used as a distinguishing metric. Several 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 the *Appendix*.

Methods for reducing and assessing the risk of a WUI community to wildland fire can be categorised as being focussed, 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 organisations. 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-characterised, scientifically based, repeatable experiments. Statistical analysis produces formulae 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 formulae 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 environmental factors in a manner that is consistent with natural processes.

Physics-based models use 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

Table 1. Definition of interface, intermix, and occluded WUI communities and resulting land area from the Federal Register (2001), Stewart *et al.* (2003) and Theobald and Romme (2007)

For reference, the land area of the contiguous US is 808 million hectares; 1 ha = 2.47 acres. HU, housing units

	Description	Federal Register (2001)	Stewart *et al.* (2003)	Theobald and Romme (2007)
Interface	Clear demarcation between structural and wildland fuels	>7.5 HU ha^{-1} or >1 person ha^{-1}	>1 HU per 16 ha and $<50\%$ vegetation	>1 HU per 2 ha and >10 ha patch
Intermix	Structures dispersed; continuous wildland fuels	>1 HU per 16 ha or $11 <$ people ha^{-1} < 96	>1 HU per 16 ha and $>50\%$ vegetation	1 HU per 2 ha to 1 HU per 16 ha
Occluded	Structures surround wildland fuel area	<400 ha wildlands	Not considered	Not considered
Distance to untreated wildlands[A]		Not specified	2.4 km	0.8, 1.6 and 3.2 km
Extent of WUI			70 million ha	47 million ha

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

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.

Current risk-assessment and risk-reduction tools based on wildland fuels

Risk assessment based on wildland fuels

There is currently no standardised method of risk assessment that can be applied nationwide to WUI communities in the US (USDA and USDI 2006; Fong 2007). It should be noted that because there is not a clear understanding of how a given wildland fuel treatment changes the wildland fire behaviour (see the *Risk reduction through wildland fuel treatments* section), a risk-assessment method based on a given fuel treatment will have inherent limitations. A 2003 field guidance report (NASF 2003) and appendix A in USDA and USDI (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 the *Background* section of the present article (and in detail in the *Appendix*). 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 related to a structure's fire exposure conditions and its response to those conditions). Also, as discussed in the *Background* section, the Federal Register definition of the WUI is ambiguous. Perhaps the definition of interface and intermix WUI communities closest to that of the Federal Register is used by Stewart *et al.* (2003). Using their approach, $\sim$70 million hectares of WUI land area in the US is at risk.

Based on wildland fuel treatment activity reported during 2001–06 (USHF 2006), $\sim$0.7 million hectares are treated in WUI areas per year at current funding levels. This is $\sim$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 prioritising WUI communities according to WUI fire risk (e.g. exposure conditions from wildland fire) – not just the housing or population density. It is also recognised that the private sector must increase their 'buy-in' in wildland fuel treatments on public lands (USDA and USDI 2006), 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 (NASF 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, and Menakis *et al.* (2003) and Theobald and Romme (2007) for the conterminous US.

Menakis *et al.* (2003) combined three Geographic Information System (GIS) data layers to map the fire risk to structures in the US 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 mapped 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 $\sim$40 million hectares were at risk, 0.8 million hectares were at high risk, and 2 million hectares at moderate risk. Of both the moderate and high risk classes, 23% were on federal lands.

Theobald and Romme (2007) used a combination of land-cover datasets ($\sim$1 km^2 resolution), three wildland fire hazard classes, specialised 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 Menakis *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 towards using wildland fuel information. Although it is expected that the LANDFIRE project (see http://www.landfire.gov, accessed 27 February 2010) 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 that depends on the structural characteristics, the immediate surroundings of the home (i.e. the 'home ignitability zone'; Cohen 2000, see the *Current risk assessment and risk reduction tools based on wildland fuels* section), and expected exposure conditions due to WUI fire behaviour that change with time owing seasonal variation in fuel and weather conditions. Such information could be used in the risk-mapping approaches summarised above for further refinement of risk.

Risk reduction through wildland fuel treatments

The well-known 'fire triangle' identifies the necessary conditions for fire to be present as 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 focussed on decreasing the negative ecological impact of a wildfire and/or decreasing the risk of injury, 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; USDA and USDI 2006) and to contain the costs of wildland fire preparedness and suppression (GAO 2007*a*). Over 65% of the US fuels treatment budget and over 50% of the treated acres were in the WUI during 2001–04 (USDA and USDI 2006). 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 behaviour. 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 behaviour. 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 behaviour, 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 for developing and evaluating fuel treatments. A report by the US General Accountability Office has also stressed the need for an improved understanding of how wildland fire will respond to a given fuel treatment (GAO 2007*b*).

Current risk-assessment and risk-reduction tools based on residential fuels

Residential fuels include structures and vegetation. The role of structure-to-structure fire spread in WUI settings has not been given as much attention as vegetative-to-structure fire spread. A focus on vegetative-to-structure fire spread is valid for WUI communities with sufficiently low housing density. However, large losses in WUI fires have not been restricted to low housing densities (Rehm *et al*. 2001). For example, in the 1991 Oakland Hills fire, which had a housing density of $\sim$7.5 housing units (HU) per hectare (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 Canberra, ACT bushfire (Blanchi and Leonard 2005) found that structure-to-structure fire spread played a key role in the overall fire behaviour. Heat fluxes from both the flame fronts and firebrands produced by structures were instrumental in maintaining fire spread 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 behaviour 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 for wildland fires, no measurements of exposure conditions during WUI fires have been made. What is known regarding WUI fire behaviour is primarily based on either anecdotal information (i.e. personal observations of responders) or post-fire investigations.

Homeowner education, guidelines, and the home ignition zone

Several web-based resources are available to homeowners. The four most heavily used are (ICC 2008): Firesafe (www.firesafecouncil.org), Firefree (www.firefree.org), Firewise (www.firewise.org/resources/homeowner.htm), and Firesmart (www.partnersinprotection.ab.ca) (all websites last accessed 22 February 2010). 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 (owing to established and recently developed building material fire-resistance test standards (see the *Standard test methods for structure components* section)). 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 (www.firewise.org, accessed 22 February 2010).

Recommended homeowner actions for the structure and landscaping can also be found in the form of checklists. Examples are on the Firewise website (www.firewise.org) and the International Wildland–Urban Interface Code (ICC 2006). Checklists for structures include, without prioritisation, 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 categorise 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 idealised 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, 15 states provide information for homeowners to use when choosing fire-resistant ornamental plants (www.firewise.org).

Guidelines specific to regions (e.g. the southern US from the Centers for Urban and Interface Forestry, see http://www.interfacesouth.org/) and individual states are also available (www.firewise.org). The National Association of State Foresters has produced a guide for preparing a Community Wildfire Protection Plan (CWPP). State-recommended approaches (www.firewise.org) 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 standardised 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 2007*a*). 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 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-based (i.e. expert opinion and observation) or from empirical models or well-characterised experiments that 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.

Empirical studies on structure ignition from flame fronts

As part of the International Crown Fire Modelling Experiment, seven experiments included mock structural walls of untreated and unpainted plywood placed 10, 20 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 assumed worst case scenario (i.e. uniform fire front that was 50 m wide, 20 m high and lasted 60 s) was used to obtain the incident radiant heat flux. As expected, the predictions overestimated the likelihood of ignition: all walls out to 28 m ignited. A similar use of the empirical 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 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 ~30 m. Consistent with this, many of the risk assessment and 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.

Standard test methods for structure components

It has been recognised that many of the established building material tests are not representative of WUI fire conditions (Beall *et al*. 2001). Beall *et al*. developed test methods for wall, deck, and roof and 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 2007*b*). These performance-based codes were effective from 1 January 2008. As an example, a wall assembly test for flame penetration consisted of placing a 10×100-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 min. No wind was imposed but channelling of the entrained flow by the side walls caused the fire to lean towards the wall assembly. Unfortunately, it is not clear what WUI fire exposure conditions this test is intended to represent.

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 in 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 characterise (1) the structure exposure conditions (heat flux from flames and firebrands generated by burning vegetation 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 described in the previous two sections and new tools (e.g. field measurement and data collection methods, standard test methods, economic and fire behaviour models) to assess and reduce the risk of structure ignition.

Research needs on exposure conditions and structure vulnerability

Based on the review of wildland fuel treatments described in the *Risk reduction through wildland fuel treatments* section, a systematic, science-based, field research effort is needed to characterise how wildland fuel treatments alter the fire behaviour 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 characterising exposure to WUI communities.

A common need throughout the previous two sections 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 *v.* 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 and S. L. Manzello *et al*., unpubl. data, 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 and 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 or firebrand fluxes.

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 *et al*. 2003). This will provide a measure of the influence of larger-scale variations in terrain, fuels and wind on fire behaviour. 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 the *Standard test methods for structure components* and *Overview of ongoing WUI research by NIST and collaborators* sections).

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-characterised, systematic research on the production and ignition potential of firebrands is just beginning (see *Overview of ongoing WUI research by NIST and collaborators* section). For this reason, current guidance on homeowner actions to prevent firebrand ignitions is a best guess.

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 standardised data collection approach. This will create well-characterised 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 ($\sim$1 m) is finer than LANDFIRE maps (nominal pixel size of 30 m). Individual trees, hedges, decks and fuel distribution in home ignition zones (0–30 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-characterised accounting of human intervention (e.g. Maranghides and Mell 2009) during the fire event (e.g. suppression of fires, movement or reduction of fuels near homes). Although 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 standardised 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 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. 1). 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 2008) but guidance to homeowners is the same, regardless of housing density.

Research needs on fire behaviour, smoke transport and economic models

Computer models can also be used for improving our understanding and characterising 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

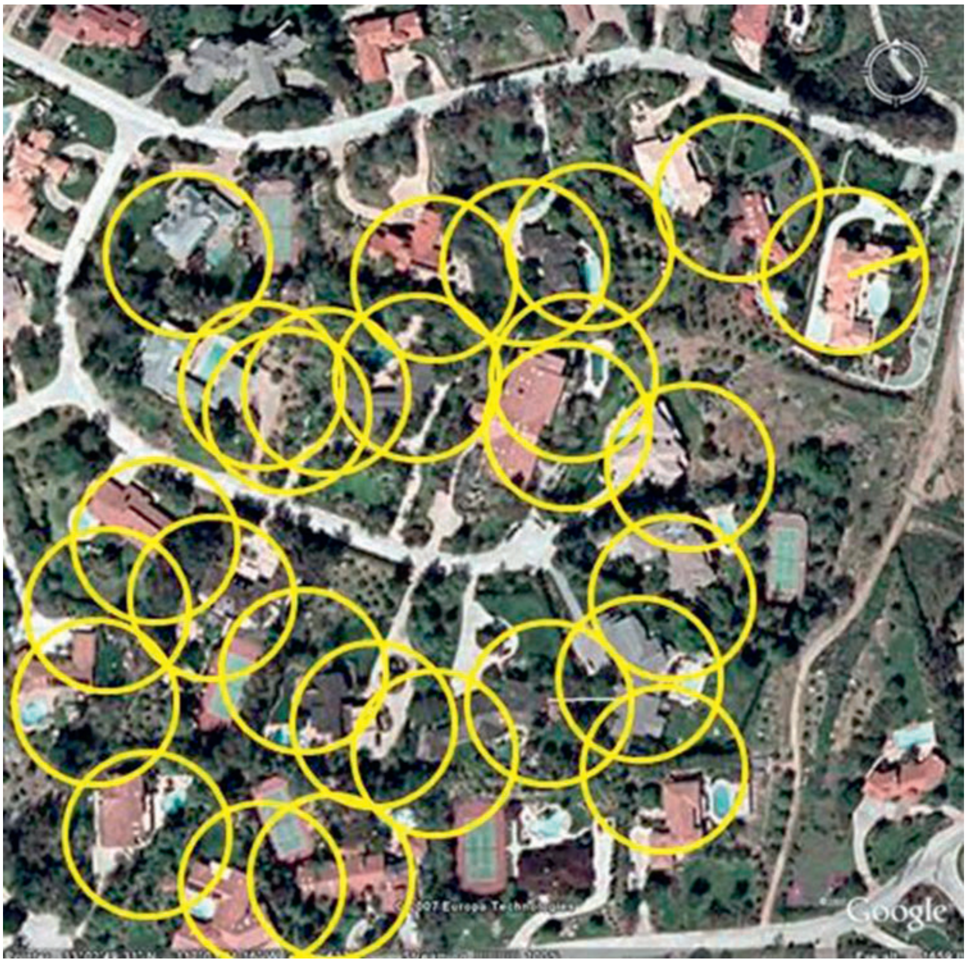

Fig. 1. Image of a portion of the WUI community under study before the fire (Maranghides and Mell 2009). Circles of 30-m radius centred on the structures are shown. It can be clearly seen that the home ignition zones within 30 m can significantly overlap.

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 of the input (e.g. fuel characteristics, wind).

Physics-based models can be used to probe the dynamics of important physical processes (e.g. Hanson *et al*. 2000). A range, in terms of complexity and computational cost, of modelling 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 are an important component of prescribed burn planning. Extended periods of smoke exposure from wildland fires are a major health issue (Quadrennial Fire Review 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 behaviour 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 owing to their cost (GAO 2005). For this reason, there is a clear need for economic tools that provide benefit and 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 with 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.

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 behaviour and economic modelling (NIST, Wildland–urban interface fire program, see

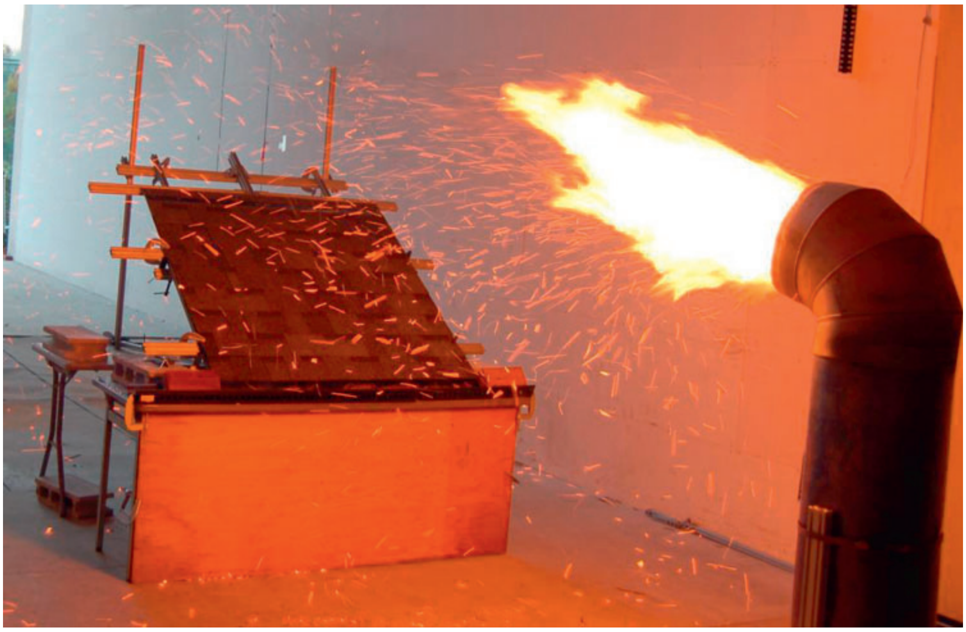

Fig. 2. Snapshot of NIST (National Institute of Standards and Technology) firebrand generator operating in the BRI (Building Research Institute) wind tunnel (9 m s^{-1} wind). The target for the firebrand assault is a section of a roof.

http://www.fire.nist.gov/wui, accessed 22 February 2010). 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 provide validation checks for the fire behaviour models. The fire behaviour 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, and the effectiveness of water application or retardants to the exterior of structures.

Exposure conditions and structure vulnerability

In collaboration with the University of Florida and the US 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 al.* 2006*a*) to provide guidance to homeowners. The flammability of four commonly used mulches was also studied (Long *et al.* 2006*b*). These studies used pilot ignition of the ornamental shrubs or mulches.

Bench-top-scale wind-tunnel experiments were conducted to characterise the potential of disk (Manzello *et al.* 2006*a*, 2006*b*) and cylinder-shaped (Manzello *et al.* 2008*a*) firebrands to ignite several 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*a*) and Korean pine trees at the Building Research Institute (BRI) in Japan (Manzello *et al.* 2009*a*). 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.* 2009*b*).

A firebrand generator (Manzello *et al.* 2008*b*) 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*. 2009*a*), has been developed. This allows studies of firebrand ignition in the large-scale wind tunnel (5 m wide, 4 m tall) at Japan's 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, 3 or 1.5 mm) in a 9 m s^{-1} wind (Manzello *et al.* 2007*b*). Further testing is under way 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.* 2009*c*) or ceramic tiles (Manzello *et al.* 2010) is also being studied in the BRI wind tunnel; see Fig. 2. Depending on construction choices and maintenance, these roofs 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

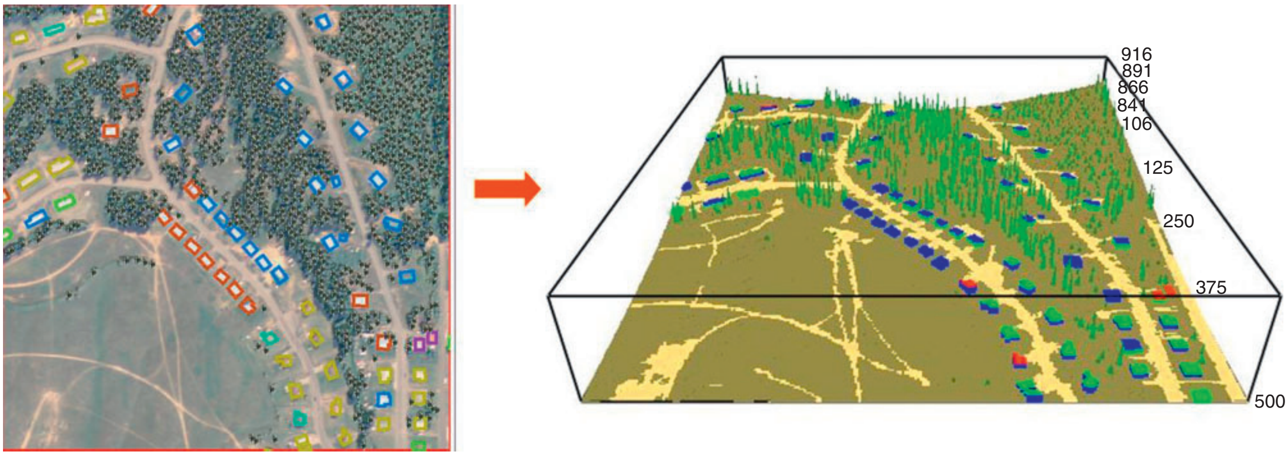

Fig. 3. Two representations of the same WUI (wildland–urban interface) community. The figure on the left is created from colour imagery. The figure on the right is the vegetation, structure, terrain and roads extracted from LiDAR data of the same study area. The rendering on the right is created by Smokeview (the visualisation package for NIST's (National Institute of Standards and Technology) Fire Dynamics Simulator (FDS) and Wildland–urban interface Fire Dynamics Simulator (WFDS) fire models) and shows the information that is input into the WUI fire model WFDS.

method. These unique full-scale and reduced-scale test methods are being used to provide guidance in adopting future building codes and standards aimed at resisting firebrand intrusion into attic and crawlspace vents.

The conditions simulated by the firebrand experiments summarised 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 (S. L. Manzello, S.-H. Park and T. G. Cleary, unpubl. data).

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 $\sim$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 because they emphasise 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 *et al.* 2009*a*). 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 behaviour 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 firebrand transport. NIST and San Diego State University are in the initial stages of a 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.

Pre- and post-fire data collection methods in WUI communities

In collaboration with the Coeur d'Alene Indian Tribe GIS group, CALFIRE, 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 a PC tablet with GIS software, GPS-enabled camera, and rangefinder.

In collaboration with the Coeur d'Alene Indian Tribe GIS group, methods for obtaining building footprints, vegetation distribution, firebreaks, and terrain from LiDAR and colour 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

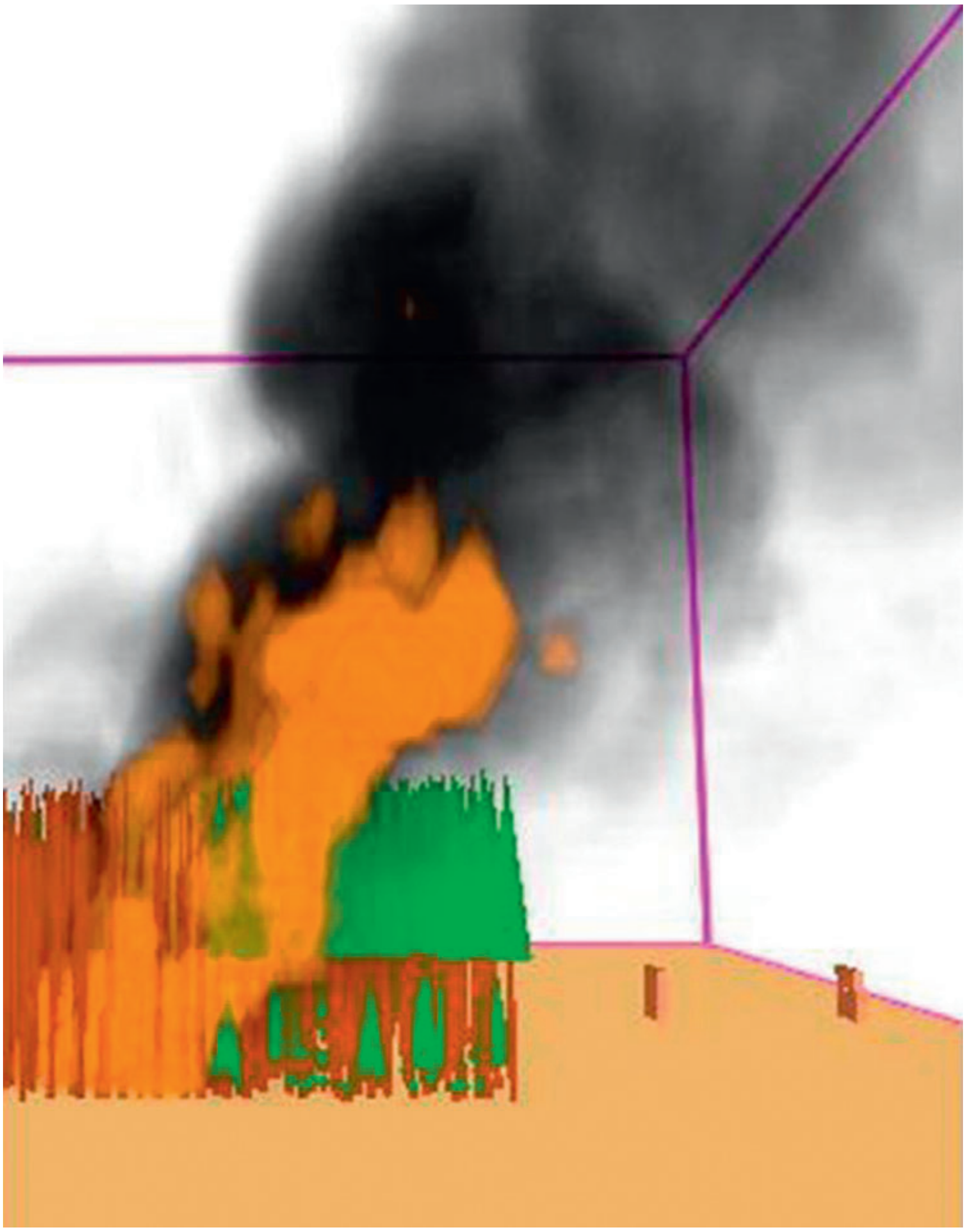

Fig. 4. A snapshot from a Wildland–urban interface Fire Dynamics Simulator (WFDS) simulation of a crown fire based on the experiments reported by Cohen (2004). Mock walls can be seen at 10 and 20-m distance from the edge of the wildland plot.

checks for the development of fire behaviour and economic models.

Fire behaviour, 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 fire spread through WUI fuels and the resulting smoke transport. Currently, WFDS is being validated for fire spread 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 Modelling Experiments (Stocks *et al.* 2004). A snapshot of a preliminary crown fire simulation with walls 10 and 20 m distant from the edge of the stand, as in the International Crown Fire Modelling Experiments (Cohen 2004), is shown in Fig. 4.

The current implementation of WFDS is for research applications because it requires significant computational resources and 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 behaviour that can be more widely used. These simpler models, by necessity, will have more approximations of the physical processes and their limitations need to be determined through comparison with field measurements and more complete models. Several simpler approaches are being investigated. These include models that account for the entrainment of air by burning buildings and its effect on a spreading grass fire on flat (Rehm 2008) and hilly (Rehm and Mell 2009) terrain.

Owing 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 neighbouring 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 towards fuel treatments of the vegetation surrounding the community and more localised, single-homeowner-funded risk-reduction actions on homeowner parcels.

Summary

The current expectation is that WUI fires will continue to be a serious and costly issue in the US (ICC 2008) and internationally. There is a significant need to better understand the effectiveness of wildland fuel treatment in reducing the exposure of WUI communities. Existing guidelines for homeowner risk assessment and risk reduction need to be tested. This requires standardised 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-characterised field measurements and observations, and a range of modelling approaches suitable for fire spread in WUI areas is needed to better determine structure exposure conditions.

Physics-based models can provide fire behaviour 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. Although 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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Appendix. 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^{-1} (3 HU $acre^{-1}$) or, alternatively, population density is at least 96 people km^{-2} (250 people $mile^{-2}$), where HU, housing unit. 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 per 16 ha (1 HU per 40 acres) or, alternatively, a population density between 11 and 96 people km^{-2} (28–250 people $mile^{-2}$). 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^{-1}, is more representative of WUI interface communities of relevance to fire managers. By assuming that there are 2 people HU^{-1} (D. M. Theobald, pers. comm., 2007), they determined that the interface housing density corresponding to at least 96 people km^{-2} is at least 1 HU per 2 ha. Another requirement is that the interface area is at least 10 ha in extent. Intermix areas have housing densities from 1 HU per 16 ha to 1 HU per 2 ha. Occluded WUI communities were not considered.

Stewart *et al*. (2003) define the WUI interface and intermix communities as both having at least 1 HU per 16 ha. 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 characterised by the density of housing units. Three levels of housing density were considered: high (>7.5 HU ha^{-1}); medium (1 HU per 2 ha to 7.5 HU ha^{-1}); and low (1 HU per 2 ha to 1 HU per 16 ha). 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 is meant by 'vicinity'. Stewart *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, 1.6 and 3.2 km (0.5, 1 and 2 miles 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 behaviour or fire risk considerations. By fire risk, we mean a measure of how easily a fuel, under given fire assault conditions (i.e. radiative or convective heat flux or firebrand attack), can ignite and undergo a transition from ignition to sustained flaming.