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PART IV:
MANAGEMENT AND ECOLOGY

CHAPTER 11

MODELING FIRE IN THE WILDLAND–URBAN INTERFACE: DIRECTIONS FOR PLANNING

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ABSTRACT

This paper describes the application of, enhancements to, and use of surface fire spread models in predicting and mitigating fire risk in the Wildland–Urban Interface (WUI). Research and fire management strategies undertaken in the East Bay Hill region (containing the 1991 Tunnel Fire) of the San Francisco Bay area over the past decade are reported. We ascertain that surface fire spread modeling has impacted policy and decision making, resulting in a regional strategic plan where large landowners and public agencies are able to implement fire mitigation practices. Although these practices involve extensive fuel management within a buffer zone between the wildland and residential properties, the residential property owners are still at risk, as no strategy within neighborhoods can be accurately mapped using the current scale of the data and models. WUI fires are eventually extinguished by fire fighters on the ground, up close, and at the backyard scale. We argue that large-scale (backyard scale) mapping and modeling of surface fire spread is necessary to engage the individual homeowner in a fuels management strategy. We describe our ongoing research and strategies, and suggest goals for

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future research and development in the area of large-scale WUI fire modeling and management.

INTRODUCTION

Fire is a natural element of the Mediterranean landscape[1] of California. Some argue that the current practice of fire suppression in this environment may be a misguided effort in land management strategies (Russell & McBride, 2003). While this is likely true for the wildland regions, on the urban fringe, where people live, the practice of fire suppression is regarded as sound policy. However, this practice of fire suppression often results in an accumulation of fire fuels, which leads to the even greater risk of catastrophic fires commonly referred to as *firestorms*.[2] Fire suppression policies must be coupled with fuel management strategies to reduce the probability of such firestorms in the wildland–urban interface (WUI). In this zone where a variety of natural and exotic species intermix with human built structures to form a complex heterogeneous environment, fuel management must be supported by effective fire spread models fueled by accurate and appropriate scale data. Only then can effective WUI fire policy be drafted, plans implemented, and firestorms avoided. This paper describes our efforts to build and fuel fire models at an appropriate scale for the WUI.

Wildland–urban interface fires are extremely difficult to fight. Unlike their wildland counterparts, they can cause extensive damage to both natural and human built landscapes in hours rather than days. For instance, the 1991 Oakland Tunnel fire destroyed 760 homes in the first hour and when it was eventually extinguished late in the day it had destroyed more than 2,700 structures, cost over a billion dollars, and taken 25 lives (Pagni, 1993; Radke, 1995). QA :1 Even in areas where the ‘‘the fire department is vastly experienced and effective at fighting interface fires’’ (Granito, 2003), catastrophic QA :2 losses still occur; a 1993 fire in Los Angeles County took 2,600 firefighters, 215 tankers, and 22 aircraft to minimize the loss at 155 homes and 40 other structures. The 2000 Bitterroot Valley, Montana interface fire claimed 72 homes (Granito, 2003) and the 2000 Los Alamos fire destroyed more than 220 structures, left 400 families homeless and was the beginning of the record-breaking wildfire season where 93,000 wildland fires burned close to 7.4 million acres (Hartzell, 2001). Two years later the many WUI fires of southern California would break that record in homes destroyed and overall costs (Rey, 2003).

While WUI fires are on the increase, the State of California is experiencing an unprecedented growth in population and it is predicted that 4.3 million new housing units will be built by the year 2020 (PG& E, 1999). Of QA :3 this new development only 20% will likely infill in existing urban areas with the rest expanding the urban fringe. The residents of this expanding WUI often find themselves in a foreign landscape where their inexperience with what can easily become a disaster often leads to them unknowingly becoming catalysts to fire storms (Granito, 2003). The WUI fire problem is becoming progressively worse (US General Accounting Office, 1999) and to effectively mitigate firestorm conditions, a sound fuel management plan is needed for these regions (USDA, 2000). The vast and diverse landscape of California insures this task will be difficult.

Fire models that are now popular in fighting and mitigating wildland fire will play a key role in the methods employed to formulate a WUI fuel management plan. The California Department of Forestry (CDF) has mapped and modeled fuels at a state wide scale in order to predict high risk regions and better allocate fire fighting resources (CBF, 2000). Modeling fire can lead to more accurate predictions to better fuel management prescriptions. These advancements can lead to sound land management planning, which in turn can produce change and a safer environment. The key to most fire models has been the identification of the fuels, their distribution on the landscape, and the weather conditions during the fire event. Although popular fire models, calibrated under wildland fire conditions, have proved valuable in wildland regions (Finney, 1998; Finney, McHugh, & Grenfell, 2005), there is growing doubt about their applicability to the WUI. Much of this doubt is based on the contrast of fuels between the two regions. Vegetation in the wildlands, where natural processes of succession and invasion apply, tends to be homogeneous. The WUI, dominated by humans with a variety of landscape tastes, is a heterogeneous patchwork of vegetative and structural fuels (Radke, 1995; Cova, 2005). The direct application of wild- QA :4 land fire models in the WUI will not likely lead to accurate and predictive results. New fire models (Cohen, Rigolot, & Valette, 2004) and data gathering techniques are needed if we are to predict fire spread and be successful at avoiding firestorms in the WUI.

FIRE SPREAD MODELS

Although fire spread models have been well documented (e.g., Scott & Burgan, 2004; McKenzie, Peterson, & Alvarado, 1996; McKenzie, Prichard, Hessl, & Peterson, 2004), it is prudent to briefly review their origins and development here. Early wildland fire models such as the *McArthur meters model* widely used in eastern Australia (McArthur, 1966, 1967), and the QA :5 *Rothermel model* used in the United States as part of the US Forest Service's BEHAVE system of fire prediction (Rothermel, 1972; Burgan & Rothermel, QA :6 1984), were based on the assumption that radiation is the primary mode of fire spread. During a wildland fire, rapidly heated vegetation undergoes pyrolysis, decomposes emitting flammable gases, mixes with oxygen, and combusts. This combustion adds to the radiation, which in turn impacts combustion, and so the fire spreads. It is not surprising that the physically based, deterministic fire growth models are all built employing these principles. These wildland fire growth models: BEHAVE (Andrews, 1986), Farsite (Finney, 1998), Wildfire (Todd, 1999), Prometheus (CIFFC, 2004), and Fire Star (Cohen, Etienne, & Rigolot, 2002), simulate fire spread across landscapes composed of heterogeneous fuels on varied topography during specific weather events.

Rothermel's work revealed that fuel chemistry varies from plant species to plant species, impacts pyrolysis, causes some fuels to combust before others, and adds to the complexity of the fuel variable in fire model. In addition, this model included fuel moisture and external or physical properties such as surface area to volume ratio, to classify the fuel properties of vegetation. This resulted in the development of a number of fuel types characterized by moisture content, size, shape, quantity, and both horizontal and vertical spatial arrangement of vegetation over the landscape. These fuel types are now common inputs to the wildland fire growth models (Scott & Burgan, 2004) and are all typically derived from the original National Forest Fire Laboratory (NFFL) fuel models (Anderson, 1982).

Topography, a second variable of the wildland fire models, can influence the type and growth of vegetation as well as the spread of fire during an event. Fuels are impacted by: steepness of slope, exposure to sunlight and prevailing winds, amount of precipitation, and the drainage of soils (Alexander, Seavy, Ralph, & Hogoboom, 2006; Rollins, Morgan, & Swetnam, 2002). Besides the long-term impact on the growth of fuels, topography can become a catalyst during a fire by channeling winds up slope, causing a chimney effect, and prematurely lowering the fuel moisture content, thus accelerating combustion. In addition, winds fanning fire moving downhill from the crest can assist spotting with burning airborne materials (Taylor & Skinner, 2003). Even if it only serves to accommodate heavier burning debris to roll downhill, topography is an important ingredient to the spread of fire.

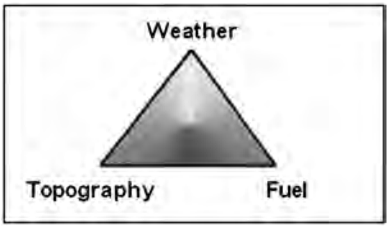

Fig. 1. Fire Triangle.

Weather is the final variable in the spread of wildfires. Wind, temperature, and humidity all factor into the equation (Alexander & De Groot, 1988; Goens & Andrews, 1998). Strong winds not only offer a good source of oxygen, they also serve to dry out the fuels in their path, push flames into new fuel sources, and can transport light burning debris downwind, igniting small spot fires (Randall, 2003). Video from the 1991 Oakland Tunnel fire provided evidence that WUI fires can generate their own winds, creating a firestorm. The air mass directly above the flames is superheated and rises, creating a vacuum at ground level that sucks in a fresh supply of oxygen from the fire's periphery. This continuous process can result in a tornado like effect, fanning winds, causing temperatures to rise, and intensifying combustion (Goens, 1992). The resulting firestorm can destroy everything in its path and be extremely difficult to control and extinguish.

Fuel, topography, and weather constitute the basic ingredients of the popular fire spread models as they impact the timing of and gases released through pyrolysis. It is important to measure these three phenomena, commonly illustrated as a triangle (Fig. 1), symbolically following the tradi- QA :7
tional fire triangle composed of oxygen, heat, and fuel (Brown, Dayton, Nimlos, & Daily, 2001; Rothermel & Rinehart, 1983; Beer, 1990). QA :8

MODELING RESIDENTIAL AND WILDLAND FIRE HAZARD: EAST BAY HILL CASE STUDY

The hills east of San Francisco Bay contain the right conditions for a *firestorm*. They are dominated by rugged topography, a shifting WUI, a Mediterranean climate, and a recent management practice of fire suppression. The 1991 Tunnel Fire was a wakeup call for a proactive approach as the traditional reactive response strategy of spending resources once the fire had begun had failed. Continued urban sprawl into the peripheral regions demanded a comprehensive fire response strategy, a preemptive strike, and a policy and management shift to practicing prevention to avoid a similar event in the future.

Following the 1991 Tunnel Fire, our research group at the University of California, Berkeley undertook the first fire spread modeling in the WUI region of the East Bay Hills (Radke, 1995). Our mission, to spatially enable a fire model by embedding it in a Geographic Information System (GIS), produced a Spatial Decision Support System (SDSS) that predicted high risk fire regions and supported fuel management and mitigation efforts by the local Vegetation Management Consortium. After a survey of the wildland fire models of that period, we chose to embed the *Rothermel* based BEHAVE system of fire prediction (Rothermel, 1972; Burgan & Rothermel, 1984).

QA :9

Spatially Enabling Fire Models (circa 1995): Oh BEHAVE

In 1995, the *Rothermel* based BEHAVE system of fire prediction (Rothermel, 1972; Burgan & Rothermel, 1984) was a cell-based spatially static model[3] that could not map or describe what the regional fire risk of an area was. To enhance this model, we spatially enabled it by embedding it into a GIS where the final plotted results mapped cumulative potential fire risk over the region. Using common GIS tools[4] to classify BEHAVE predicted risks, we were able to identify contiguous areas of high, medium, and low fire risk.

Applying the BEHAVE model to the heterogeneous WUI raised two important issues: (1) the resolution or scale of the data and subsequent modeling would have to increase from the traditional wildland applications scale (1:50,000 or smaller); and, (2) the urban residential region containing built structures would force a modification to the traditional wildland fuel inputs of the model that account for only natural landscape fuel. Fig. 2 maps our data gathering, processing and modeling effort, illustrating our two path approach to fire prediction.

Although the USGS Digital Elevation Model (DEM) data were the standard dataset used to calculate slope for wildland fire models, the heterogeneous nature of the WUI forced us to increase the scale and accuracy of our surface model. By the mid 1990s advances in data collection and computer processing, along with national programs for data archiving and dissemination, made it possible to obtain and accurately model the *topography* of the East Bay Hills within a GIS. We combined USGS digital

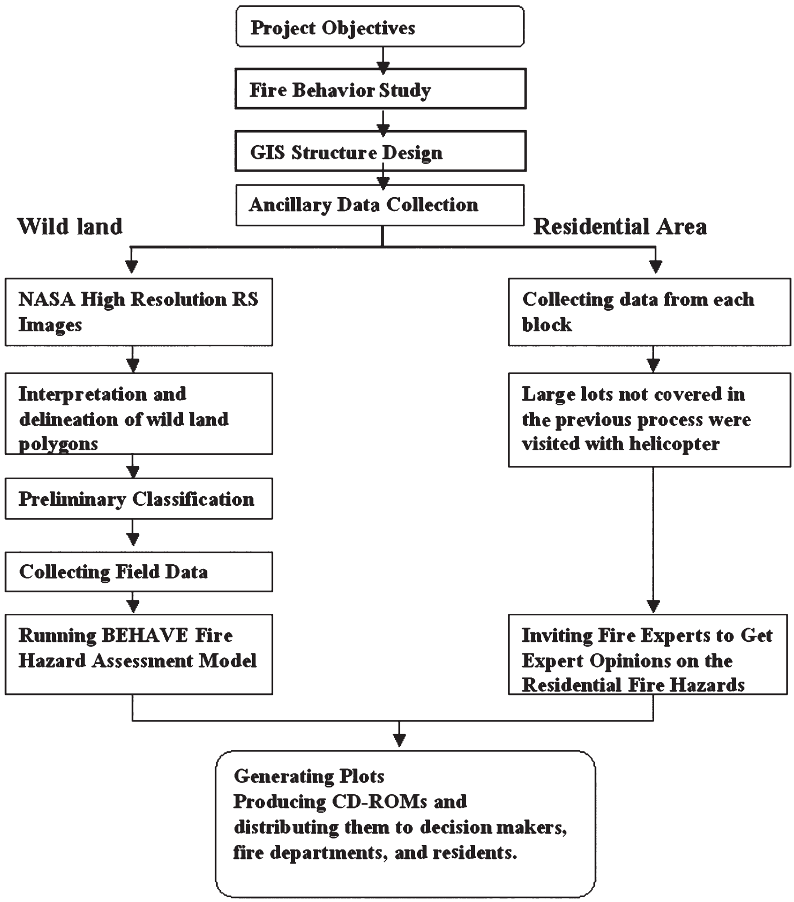

Fig. 2. Data Flow and Modeling for the WUI.

hypsography, hydrology, and DEM data from the 7.5 min USGS quad series (1:24,000 scale data) to build a digital terrain model represented as a Triangulated Irregular Network (TIN). From this TIN we were able to calculate accurate aspect and slope datasets to complete the topographic input for our fire models.

Regional weather stations made it possible to measure and interpolate weather conditions during real fire events to also satisfy the *weather* requirement for our fire models. Although five historic fires had burned a cumulative 1,200 acres, during onshore winds from San Francisco Bay, the catastrophic winds are the offshore winds from the east. Known as the Diablo winds, with velocities in excess of 20 miles per hour, temperatures in excess of 80 degrees Fahrenheit and measured humidity of less than 20%, these are the winds that fuel firestorms and were used to parameterize our fire models.

Unlike typical wildland regions, *fuels* in the WUI are complex and include both vegetation and human built structures. The East Bay Hill landscape had transformed from a predominantly grassland in the 1920s to one that has fringe forests dominated by volatile eucalyptus (*Eucalyptus globulus*) and Monterey pines (*Pinus radiata*) today. Grassland, planted exotic garden vegetation, winding narrow roads, and residential structures of various sizes and construction materials all add to the heterogeneous nature of the WUI. Fig. 3 illustrates the vegetative evolution of the Lake Chabot region from the 1920s to 1990s and serves as an excellent example of conditions necessary for a catastrophic fire.

These complex conditions forced us to alter the scale and process for gathering data on fuels in the WUI. Rather than employing Landsat imagery (30 m^2 resolution) which is often the case in wildland vegetation assessment, or the standard aerial photos used in the production of the USGS 7.5 min quad series, we used imagery from the NS001 sensor aboard a NASA aircraft on a low altitude mission (7 m^2 resolution) and hi-resolution aerial photos from the same mission to better map the smaller clusters of common-type fuels. Fig. 4 is an infrared image from this sensor of a small area on the edge of the 1991 fire. In the wildland region, homogeneous patches of vegetation were registered, digitized, and then visited in the field for identification and classification.

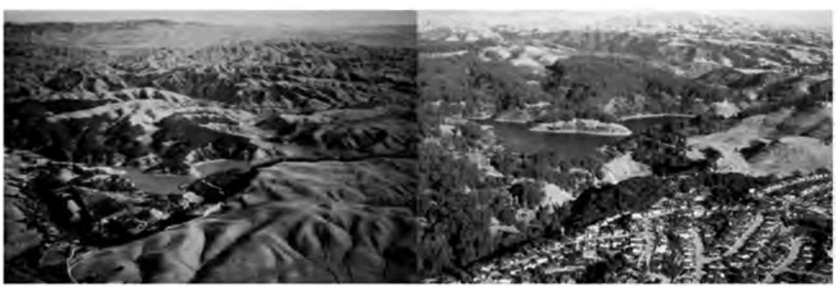

Fig. 3. Lake Chabot Region 1920s and 1990s.

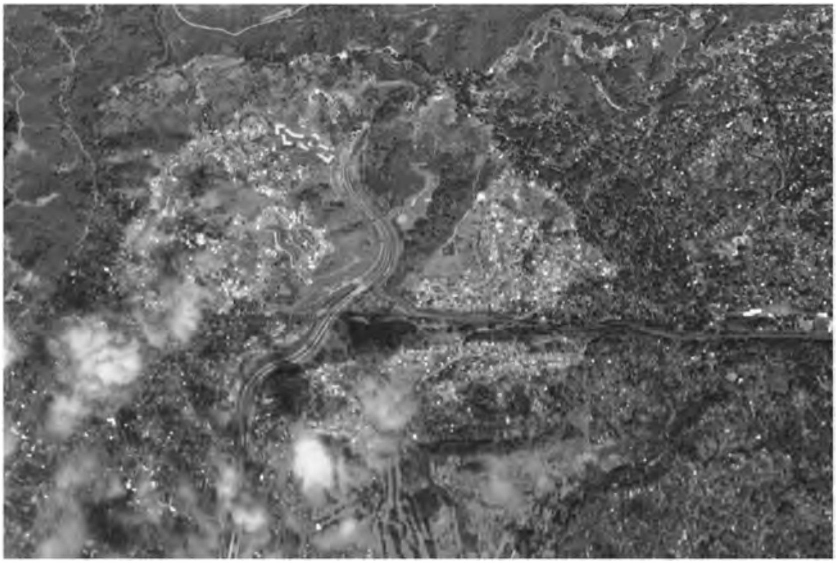

Fig. 4. An Infrared Image Over the 1991 Tunnel Fire Area.

In the residential areas of the WUI, the combination and variety of vegetation and structures made it impossible to define and classify polygons based on a single fuel condition. Here we made observations at point locations distributed throughout the study site and later classified the various fuel conditions into data layers. The conditions observed were not based on an individual property or structure, but on the characteristics of a neighborhood. The same observer evaluated groups of structures to establish the sample neighborhood of similar attributes. Observations were taken at regular intervals and adjusted when one or more of the eight fuel characteristics being monitored and changed. The 3,200 plus observations were spatially decomposed into a set of Voronoi polygons and each fuel characteristic being monitored was represented as one of eight mapped layers.

The data inputs from the wildland region were run through the BEHAVE model and mapped. However, the urban areas of the WUI produced a new variety of fuels and fuel conditions that had never been calibrated in a mathematically derived fire model such as BEHAVE. Here we proposed a new model: a residential fire hazard assessment model (RFHAM), based on knowledge from fire experts and a set of rules formulated to select criteria for fuel assessment and fire risk prediction. From observations while fighting the 1991 Tunnel Fire, fire hazard conditions in the WUI were divided into two classes: (1) vegetation type and its distribution with respect to structures; and (2) structural materials and building design. Expert knowledge from fire fighters was used to create the WUI data dictionary (Table 1) and fuel the RFHAM. Fig. 5 maps the combined results from the two spatially enabled fire models mapping ordinal hazardous conditions.

Our results showed that almost fives times the area burned by the 1991 Tunnel Fire, over 7,600 acres or 47% of the residential region in the hill area, was in high hazardous vegetation conditions. In addition, over 5,500 acres or 35% of the residential region was considered high hazard with regard to structural fuels such as wood shingled roofs and overhanging wooden decks.

POLICY IMPLICATIONS

Now that the areas most prone to a WUI firestorm were identified and mapped, the East Bay Vegetation Management Consortium (EBVMC), a group formed by nine local cities and agencies that manage public lands and regulate private lands in the East Bay Hills (Acosta, 1994), began a long process of setting policy, developing a strategic plan, and implementing a fuels management program. This EBVMC is part of a larger network of groups that address fire issues in the hills and includes: the Hills Emergency Forum (HEF) made up of city managers and CEOs of seven cities and special districts, and the East Bay Hills Fire Chiefs' Consortium (EBH FCC) made up of 16 Fire Chiefs in the region (Fig. 6).

With the existing conditions and potential hazards in both the residential and wildlands identified, the EBVMC undertook a yearlong process of developing a plan that would recommend appropriate mitigation measures for hazard reduction and establish standards for a regional approach to vegetation management. Input to the plan came from a Technical Advisory Committee, a Citizens Advisory Committee, the general public, and local homeowner associations. A draft plan (*1995 Fire Hazard Mitigation Program & Fuel Management Plan*) was forged and comments sought at a number of public presentations.

The plan identified hazard reduction programs targeting three critical factors involved in WUI fires: ignition, fire spread and behavior, and "values at risk" or vulnerable receptors such as houses and adjacent landscapes. Using direct output from our GIS based fire risk model, the plan recommended several strategies to establish a network of fuel modification zones

QA:11

Table 1. Fire Fighter Knowledge Derived Structural Data Dictionary (From Radke, 1995).

	Fuel Characteristics	Measurement	Low	Moderate	High	Extreme
Structural Fuels	Combustible roof materials	% structures with wood roofs	None	< 0%	20–50%	> 50%
	Siding, decking, and fencing	% structures with combustible siding, decking, or fencing	None visible	< 20%	20–50%	> 50%
Vegetation Fuels	Surface fuel density	% surface area supporting combustible surface fuels	< 20%	20–50%	50–70%	> 70%
	Aerial fuel density	% surface area covered by tree canopy	0–10%	10–30%	30–70%	> 70%
	Vertical continuity	Presence of ladder fuels and crown fires potential	None	Isolated ladder fuels individual trees to crown	Widespread ladder fuels Stand-wide crown fire expected	
	Tree height	Tree height	Short = < 50 ft	Intermediate = 50–90 ft	Tall = > 90 ft	
	Flammability	Overall flammability of fuels	Irrigated grass, ornamental hardwoods	Cured grasses native hardwoods Cultivated landscapes	Pyrophytes (Juniper, pine, eucalyptus, etc.)	
	Fuel clearance	Clearance distance of combustible material from structure	Poor = < 10 ft	Moderate = 10–30 ft	Good = 30–100 ft	Excellent = > 100 ft

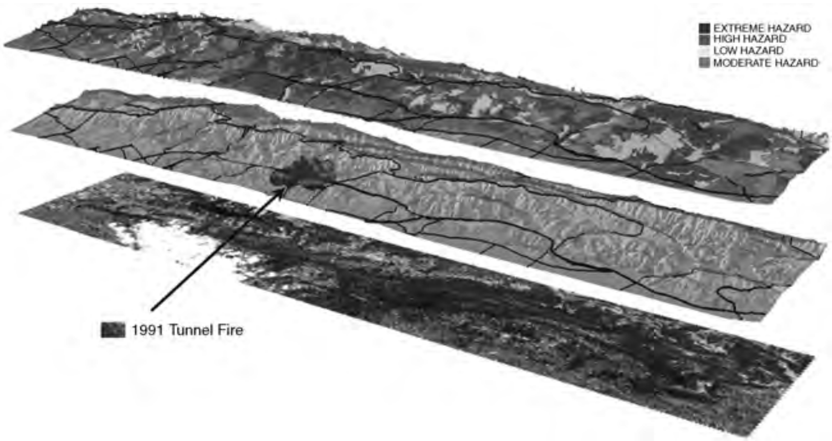

Fig. 5. The Combined Results from the Two Spatially Enabled Fire Models.

Fig. 6. A Sign Posted Near the Site of the 1991Oakland Tunnel Fire.

and fuel breaks that would provide a protective buffer zone between the developed urban areas and adjacent wildlands (Kent, 2005). These protective buffer zones were identified, mapped, and targeted as vegetation treatment polygons by our WUI fire modeling efforts. They were classified as prime targets for defensible space programs that would create areas of more benign fire behavior, as well as locations from which to attack and potentially control a wildfire. The plan was approved by the East Bay HEF October 1995 and accepted by many of its member agencies the following year.

The East Bay Regional Parks District (EBRPD), one of the largest landowners in the hill area, voted to accept it in October 1996 and approved an implementation process in October 1997 which instructed the General Manager to prepare amendments to hill park Land Use Development Plans (LUDP) and Environmental Impact Reports (EIR) for the California Environmental Quality Act (CEQA) compliance, necessary for implementing new projects. The quantified measurements from our GIS based fire modeling effort were adopted by the EBRPD Fire Hazard Reduction EIR/NEPA Working Group as they developed their wildfire problem statement in 2001 which was eventually adopted December of 2003. The same year the park district teamed with the California Office of Emergency Services (OES) through the FEMA Hazard Mitigation Grant Program under a Presidential Disaster Declaration to implement the vegetation management project and mitigate fire risk on a polygon by polygon basis as identified by our fire modeling research (Kent, 2005). To continue to their long term wildfire protection and plan for the future, the EBRPD successfully put Measure CC on the November 2, 2004 ballot which will provide more than $45 million over the next 15 years for essential maintenance.

Although the HEF mission was building interagency consensus on the development of fire safety standards and codes, and developing fuel reduction strategies, several of its members chose to pool their resources in mitigating initiatives. The University of California, Berkeley joined with its neighbors, Lawrence Berkeley Laboratory (LBL), East Bay Municipal Utilities District (EBMUD), the City of Oakland, and the EBRPD to reduce the fire risk in their region by removing invasive eucalyptus trees (Fig. 7) and decadent brush from ridge top locations (Klatt & Mandel, 2005).

They all agree that ignition cannot be completely eliminated from this region, but by removing large stands of potential firewood from the WUI, they can greatly reduce the risk of repeating the 1991 firestorm.

LESSONS LEARNED

Many large landowners have and continue to remove fuels and improve the hazardous conditions on their lands adjoining the residential neighborhoods

Fig. 7. Removal of Invasive Eucalyptus Trees.

in the WUI. Some neighborhoods led by citizen-based non-profit organizations play a significant role in drafting and setting vegetation management policy. The Claremont Canyon Conservancy formed January 2001 in response to wildfire hazards and "advocates an integrated fire management plan (IFM) where all parties share in the responsibility of creating defensible space to reduce potential damage and to aid firefighters in their role of fire suppression" (Claremont Canyon Conservancy, 2006). However, many neighborhoods in the region remain much the same as they did a decade ago: high fire hazard zones.

Although a protective buffer zone has been established, the regional scale of our study did not directly map the conditions in an individual's backyard. This leaves the residential property owners at risk in areas with no fire strategy aimed at the neighborhood level. In order to engage the individual homeowner in the process and prescribe property based mitigation technologies, larger scale data and modeling are necessary.

Within the neighborhood is where the WUI fires are eventually extinguished by fire fighters, on the ground, up close, and at the backyard scale. Here driveways, or even sidewalks, are the critical fuel breaks where defensible space between houses and vegetation is measured in feet and houses themselves contribute a huge concentrated amount of fuel. It is clear that WUI fires are neither wildland, nor urban, and fighting them, modeling them, and prescribing mitigation technologies is leading us toward a larger spatial scale of at least 1:2,000. If we are to effectively model WUI fire spread and risk, we need to undertake fuel mapping at the individual property or yard level where an individual tree canopy and house can be mapped. New fire models (Cohen et al., 2004) built specifically for WUI fires require data gathering techniques beyond what we have employed to date.

WUI MODELING: TOWARD A LARGER SCALE

Farsite (Finney, 1998), developed mainly for simulating the spread pattern of wildland fires, is by far the dominant fire spread model in use today. Following the use of Farsite in the WUI region of Claremont Canyon (Kim, 2001), we discovered the model made predictions that were too coarse to be useful and it was not sensitive to the heterogeneity of the region. Firebreaks that might serve as a resource for stopping a fire were simply overrun by several iterations of the model. This appears to be true for all popular wildland fire models and suggests a new WUI model is needed at the property or backyard scale. We are joined in this assertion by Morvan and Dupuy (2001) who found that in the Mediterranean Regions of Europe, in order to more accurately delineate fuel breaks, they had to increase the scale at which they mapped fuels. Parallel to the fire modeling approach we took (Luo, 2004) they modeled fuel distribution at a large and more appropriate fuel break scale by employing cellular automata (CA).

Cellular automata (CA) models can be considered counterparts to the vector based Farsite model. Rather than map fire spread along an elliptical front (like Farsite), they treat space and time as discrete and all interactions are local. The state of any cell depends on the state and configuration of other cells in its neighborhood, which is defined as the immediate adjacent set of eight cells. During fire propagation, cells are ignited one after another contiguously, illustrated in Fig. 8. These model characteristics make CA

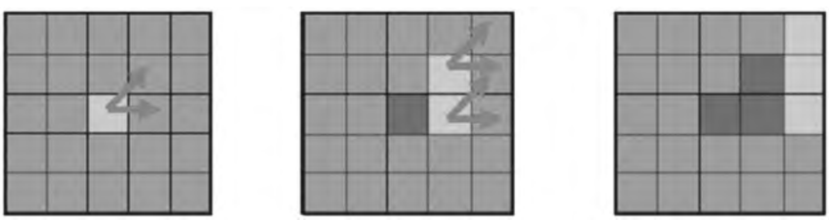

Fig. 8. The Process of Fire Propagation in a Cellular Automata Fire Model (Luo, 2004).

Fig. 9. Comparing the Results from Farsite (left) and Luo's (2004) Cellular Automata Fire Model (right).

models ideal for handling the heterogeneity of the WUI and share some similarity with our first spatially enabled BEHAVE model (Radke, 1995). QA :10

Although several studies have applied CA to fire (Karafyllidis & Thanailakis, 1997; Hargrove, Gardner, Turner, Romme, & Despain, 2000), it was Berjak and Hearne (2002) who added Rothermel's fire physics equations to regulate the fire spread rate and produce a more realistic outcome. However, their model prediction accuracy was tied to the choice of cell size and the predicted rate of spread. If fire spreads quickly and covers one cell size in less than one time step, the fire spread rate is under-estimated. If cells are enlarged to accommodate rapid spread rate, they become weak in accounting for fuel heterogeneity. By modifying this model (Luo, 2004) and allowing multiple iterations in each time step, smaller cell sizes are possible with flexible directional spread.

Modeling the spread of fire in Claremont Canyon using both Farsite and a modified CA model (Luo, 2004) suggests in Fig. 9 that CA models, with their ability to accommodate heterogeneous data and map individual streets as firebreaks, are a promising approach to predicting fire spread in the WUI.

LARGE-SCALE MAPPING IN THE WUI

If a shift to large-scale (approaching 1:2,000) fire model inputs is to be realized, some new technologies must be built. If we consider the three edges of the fire triangle as inputs, moving to a larger scale requires new technologies for both *fuel* and *weather* mapping. Our work to this point suggests the following goals for future research and development in the area of large-scale WUI fire modeling and management (Fig. 10).

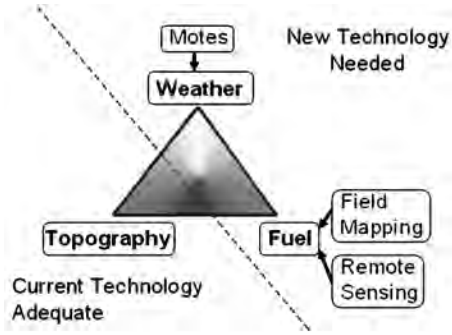

Fig. 10. Large-Scale Fire Research Requires New Technologies for Data Mapping.

MAPPING LARGE-SCALE FUELS

Identification and modeling of fuel regimes in the WUI is complex, boundaries between fuel types are often discrete and extreme, and fuels are constantly changing from year to year. In order to build and execute realistic WUI fire models, a dynamic process for detecting and mapping fuels at a large-scale is needed. In order to make this process practical and useful for mitigation and planning in the many communities experiencing rapid growth, it must be affordable and thus based on easily available data sources. Remote sensing is looked upon as a resource and technology that can deliver under such constraints. It is relatively automatic, cheap per km^2, temporally repetitious of the same region, and able to produce data in near real time. Although spatial resolution or scale was an issue in the 1990s limiting mapping to a regional or neighborhood scale at best, new sub meter resolution satellite sensors such as IKONOS and QuickBird have graduated remote sensing to a scale approaching backyard or property extent.

The greatest challenge to fuel mapping for these new remote sensors lies in image interpretation. With such high spatial resolution data, structural fuels (houses) with asphalt shingles on their roof reflect a similar signature to asphalt driveways and roadways. The houses are intense sources of fuel that assist in the formation of a firestorm, while roads and driveways provide a firebreak. In addition, structures and roadways are often masked by tree canopy over head, rendering them difficult to interpret. The difference between an asphalt base under a tree or shrubs forming a vertical ladder from the ground to the tree canopy, is critical in determining the volatility of fuels as input to a fire model.

Traditional supervised maximum likelihood classifications solely based on spectral properties, do not perform well in a heterogeneous image of the WUI. Hybrid approaches (Kim & Landgrebe, 1991) using morphological filters (Koskinen, Astola, & Neuvo, 1991; Soille & Pesaresi, 2002) that employ set operators to correct object shapes and preserve even the smallest or thinnest objects, appear promising for solving unstable outcomes from spectral classifications. The shape of houses versus the shape of roadways can prove quite valuable during pixel classification. However, in the WUI where overhanging tree canopies mask much of the roadway, misclassified pixels still occur (Luo, 2004) rendering the human image interpreter critical to the process.

To improve interpretation and solve the large-scale fuel classification problems we merge high resolution remotely sensed imagery with ground based yard scale mapping, removing the disadvantages of field survey by enlisting the help of a volunteer public who stand to gain the most from the results of successful WUI fire modeling. This workforce, the homeowner, is the same volunteer group that insures their vegetation-to-structure clearance meets local guidelines. If compliance is not achieved, the local government deploys a crew to do the property and the homeowner is required to pay the cost (Table 2).

Traditional labor intensive, costly, and slow field surveys are replaced with a massively parallel homeowner based observation and reporting system. We avoid the disadvantages of field survey with a simple and efficient

Table 2. Comparative Fuel Survey Approaches.

	Field Surveys	Remote Sensing
Advantage	✓Accurate ✓House and yard scale	• Automatic • Cheap • Fast • Real-time Possible
Disadvantage	✓ Labor Intensive ✓ Costly ✓ Slow	• Less Accurate • Often neighborhood to regional scale

⇕

iMap

web based solution to gather, map and maintain a comprehensive database on fuel conditions. We developed a bi-directionalKoskinen et al., 1991Web based GIS-mapping instrument called ***iMap*** that is based on a new web-mapping component (.dll) included in an ActiveX Web-information platform (.ocx) (Radke, Repetti, & Xu, 2005; Xu & Radke, 2005). This grass-roots technology allows data, such as the latest imagery from a high resolution satellite (0.6 m^2 resolution), to be downloaded from a server through a common Web protocol, interpreted, delineated and documented locally, and uploaded to the server in real time or at some later date. The users of the technology, often homeowners, view high resolution imagery of their property or their neighborhood, identify and draw boundaries around the vegetation and structural fuels, and encode their information into a common database.

The ***iMap*** technology allows data, from the eyes of the community, to be incorporated into the production of the fuels database that is necessary for the shift in scale of the WUI fire modeling effort. Data describing the fuels and used as input to the fire models is greatly enhanced. The ***iMap*** system is currently undergoing testing in Claremont Canyon (Figs. 11 and 12).

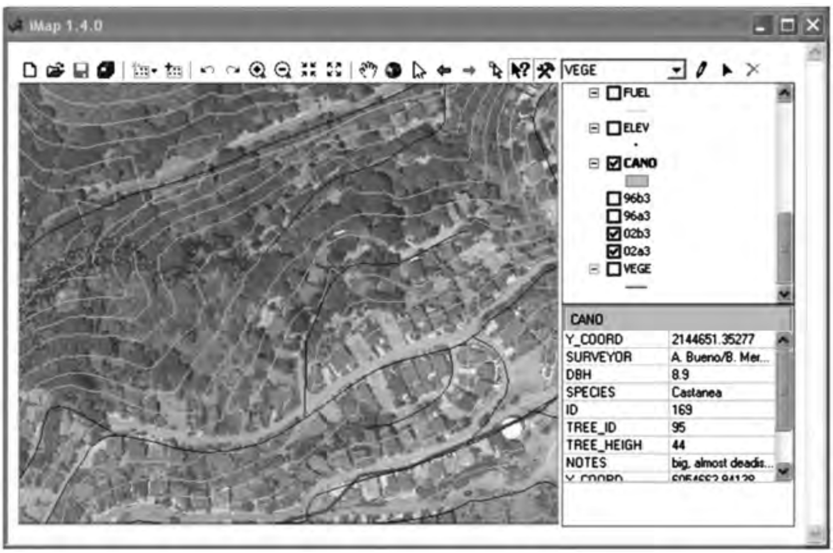

Fig. 11. Graphic User Interface of iMap version 1.4.0.

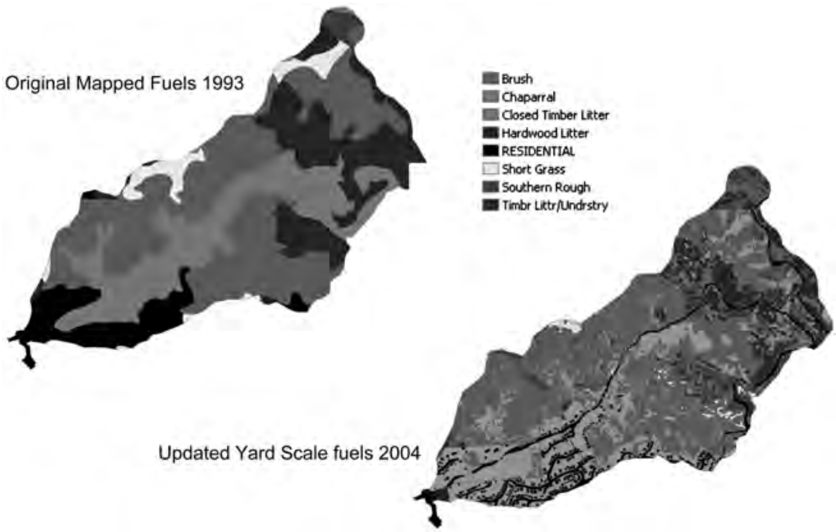

Fig. 12. A Shift from Small to Large-Scale Mapping of Fuels in Claremont Canyon.

MAPPING LARGE-SCALE WEATHER

In 2002 and 2003, the University of California sponsored two wildfire physics workshops to explore the development and use of wildland fire models in predicting event outcomes. At those workshops, Michael Bradley introduced a physics-based computer simulation system running on the Lawrence Livermore National Laboratory's supercomputer that predicted wildfire behavior for specific weather conditions, types of vegetation, and terrain (Bradley, 2002). This atmospheric based approach was the first attempt to model large-scale weather by simulating 10 m resolution data, or the micro weather occurring in the back yard. Bradley's research team correctly pointed out that current fire models not only failed to map important local and often dramatic terrain and vegetation change, they did not account for local weather patterns and rapidly changing winds that determine rate and direction of fire spread. To effectively model WUI fires, high resolution weather data are needed.

With significant advances in Micro-Electro-Mechanical Systems (MEMS) and Nanotechnology (Pister, Kahn, & Boser, 1999; Warneke, Last, Leibowitz, & Pister, 2001; Lawlor, 2005), it is now possible to develop and deploy self-configuring, self-healing, scalable, and dynamic wireless sensor networks from unmanned aerial vehicles (UAVs) (Warneke & Pister, 2002). Moving beyond weather simulations we attempt to gather large-scale or micro weather data for our fire models by deploying portable, wireless weather sensors (motes) ahead of the fire line. With funding from the National Science Foundation (2002, ITR/IM-0121693) we begin to develop and test an adaptive real time mesh sensor network of Global Positioning System (GPS) enabled mote computers based on TinyOS (Culler, Hill, Buonadonna, Szewczyk, & Woo, 2001) and with onboard temperature, pressure and relative humidity sensors. Initial results of sensor testing (Doolin & Sitar, 2005) indicate this approach looks promising for delivering the backyard scale weather data needed for large-scale CA fire modeling.

Although still in its basic research phase, weather sensor motes will either be hand deployed or dropped by an air vehicle, such as a UAV or helicopter, in strategic locations ahead of the fire line. Their drop pattern is critical for configuring a successful network of signals, and a spatial coverage to complete a grid of micro climate sensors for fire model input. Once on the ground the motes begin to wirelessly communicate with one another and employ an adaptive and self-configuration capability to quickly establish a mesh network after which data transfer begins. The GPS chip is activated on each mote and its location is transmitted over the network to a base station where a spatial pattern of mote deployment is calculated, mapped, and transmitted to a web-enabled GIS.

With mote location information in hand, the Incident Commander can assess the coverage and either issues a second deployment to sensor deficient regions or if the pattern of the motes is deemed spatially adequate, orders the activation of the mote-based weather sensors. The weather data streams across the mesh network and eventually fuels the fire model with real time, large-scale data (Fig. 13).

One of the main hazards to these motes is the fire itself and eventually some or all of the first deployment will fail (Fig. 14).

Fig. 13. A Second Deployment of Motes Completes the Mesh Network.

Fig. 14. A Weather Sensor Mote Before and After a Burn.

Fig. 15. Accountability for Fire Protection at the Backyard Level.

As the fire spreads and motes fail, a strategic deployment plan is activated where second, third, and more deployment missions are ordered and the mesh network migrates ahead of the fire line. Although our experiments have been oriented to answering basic research questions and mote deployment has been extremely orchestrated, it is likely these miniature mobile weather stations will soon satisfy the large-scale sensing of weather data needs.

MAPPING LARGE-SCALE TOPOGRAPHY

Although it is possible to satisfy our current fire modeling needs with relatively accurate large-scale surface models, new technologies are emerging that offer more information with greater accuracy and less uncertainty. Models now built by combining a DEM with hypsography and hydrology data from archived government sources are slowly being replaced with topographic models born from LIDAR (LIght Detection And Ranging), which uses laser pulses to determine the distance to an object or a surface. When combined on an airborne platform with navigation instruments such as a GPS receiver and an Inertial Measurement Unit (IMU) tracking velocity and attitude, a very high resolution topographic surface model can result.

With this ability to measure the surface of the earth at a very high resolution, houses and even individual tree structures can be realized providing the data necessary to accurately model the built structure of the WUI. Although still in very exploratory stage, this will lead to more sensitive fire modeling and predictions.

CONCLUSION

While our early neighborhood approach to mapping WUI fire potential was a step in the right direction, our recent research into this significant problem reveals that the heterogeneity of conditions on the WUI, along with the regional scale at which we were addressing the problem was not sufficient. After applying new wildland forest models to the WUI, we discovered they were not effective where heterogeneous fuels of both vegetation and structures dominated the landscape. The models were not sensitive to the many subtle firebreaks that dominate the WUI landscape and act as useful barriers for supporting firefighters' efforts to contain a fire. By shifting to a large-scale (backyard level) fuel modeling scheme, and adopting a CA approach to fire spread modeling, we can better address the heterogeneity issue in the WUI to more accurately identify and map potentially high fire prone areas.

Although fire spread research has come along way in the past decade, the WUI still remains a relatively uncharted region where models and devices such as the ones we introduce here, should prove helpful. Knowledge gained here will help us better prescribe and mitigate, reducing fuels in the WUI and maintaining a safe environment.

Claremont Canyon has been the site of our most recent data gathering, processing and modeling efforts as we shift the scale of our research to map the hazards in a citizen's backyard. Our "GIS based modeling has helped to bring fire management to the individual parcels where we can identify property owners, both public and private, educate non-fire people about wildland fires and motivate neighbors to work together on wildfire management issues" (Rein, 2005 pers. comm.). It is this up close and personal scale where firefighters engage and extinguish fires. It is at a large-scale that vegetation can be mapped, monitored, and fuels mitigated. It is at this parcel-by-parcel scale where it is necessary to engage the public in preparing, protecting, and preventing WUI fires (Fig. 15).

President Clinton's initiatives in 2000 created the National Fire Plan (GAO-02-259). However, to combat and win over WUI fires, they must be fought in the backyard with local policy that addresses individual parcel characteristics.

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NOTES

1. Mediterranean landscape is characterized by drought-tolerant plants, including pines and flammable shrubs that thrive in a climate of warm dry summers, mild wet winters, and relatively low annual rainfall.

2. "In reality, the very definition of 'extreme fire behavior' is framed within the context of human perceptions, with 'extreme' defining our limited ability to control it and its potential impact on firefighter safety." (Close, 2005)

3. A cell-based spatially static model is one where the value of each grid cell is assessed individually, without considering the impact of interaction with neighboring cells.

4. Common GIS tools include data synthesizing, classification, and interpolation techniques employed in thematic, choropleth, and isopleth mapping.

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