PHYSICS-BASED MODELING OF COMMUNITY FIRES

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ABSTRACT

Physics-based modeling of fires in the wildland urban interface (WUI) is used to develop practical tools for fire hazard evaluation of landscaped properties. The approach differs from that used for wildland-fire operation models in that individual fuel elements, such as trees, shrubs, and buildings are resolved, and the ignition and burning characteristics of these fuel elements are identified separately. The model is an extension of capabilities of the widely used NIST Fire Dynamics Simulator (FDS). Burns of single dry Douglas-fir trees were conducted to measure peak heat release rates, burn durations and visible flame heights. The rise and fall in the heat release rate curve for the Douglas-fir trees is represented well by a simple triangular shape. Insights from the FDS simulations of WUI fires are used to construct a user friendly fire model that can demonstrate major effects of ignition by radiant flux. This model is being implemented in EcoSmart, a web-based software tool. It provides a method to evaluate the vulnerability of structures to ignition by considering the effects of mitigation actions, such as relocating landscape plantings, and removing the lower branches of tall trees.

INTRODUCTION

The protection of structures from unwanted fires is a concern for owners, building code authorities and the fire service. To reduce the threat of fire, building codes and standards address the ways in which communities can be built, the materials that can be used, and the infrastructure needed for fire fighting. Nearly 10 % of the land and over one-third (42 million) of the homes in the U.S. today are found in the wildland urban interface (WUI). The WUI is used to refer to both areas where housing adjoins heavily vegetated areas (interface) and those areas where houses and vegetation are intermingled (intermix).

In the WUI, structures and vegetation are intermixed and must be resolved, so that their three-dimensional fuel distributions, relative locations and characteristics can be taken into account to understand and/or predict the spread of fire. Since both the duration and intensity of burning structures are much greater than for burning vegetation, WUI fires cannot be represented well using current operational models for wildland fires. In operational models fuels are approximated as two-dimensional surface fuel beds. The fire propagates along the surface as a line defining the boundary between burned and unburned fuel. WUI fires must be

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treated as volumetric with the fuel distribution resolved to the scale of individual structures. Figures 1 shows a frame from video taken from a helicopter above the 2003 Summerhaven, AZ (USA), fire in which burning homes are surrounded by uninvolved trees. Figure 2 illustrates green Eucalyptus trees surrounding a neighborhood of totally destroyed homes in San Diego, CA (USA) after the 2003 fires. It is common in the aftermath of WUI fires to find homes totally destroyed adjacent to surviving vegetation. These pictures illustrate both the complicated nature of the WUI fires and the need to resolve them to the level of individual fuel elements.

Very little progress has been made in physics-based modeling of WUI fires, in part because the resolvable length scales are intermediate to those used to describe wildland fuels and to those associated with individual structures. Both individual structures and trees must be described three-dimensionally in some detail in order assess the fire risk for structures. One of the few studies to dealing with physics-based modeling of WUI fires was conducted by Maranghides[1]. That study concluded that scarce relevant burning data hampers the development of such models.

J. D. Cohen [2,3] advocates the concept of a Home Ignition Zone, defined as the area surrounding a house where heat transfer by radiation and/or convection from burning vegetation can ignite it. He is developing a mathematical/computational model called the Structure Ignition Assessment Model (SIAM) based in part on large scale experiments.

For wildland fires, mathematical models are regularly used to predict the likely burn development for expected meteorological conditions. These models, which are known as operational models, have largely developed through empirical correlations over the past few decades. In the United States, they include the Rothermel model[4], and models known as BEHAVE[5] and FARSITE[6], with the last one being the most recent and most highly developed.

Generally, these operational models have served well as long as the fires are confined to wildlands. They are based on the assumption that the fuels can be represented by continuum beds, which may be inhomogeneous and anisotropic, but nevertheless are continuous. Thus these models can address horizontal variation of fuel beds, but cannot address three-dimensional structure of fuels. Fire spread to buildings and transitions from ground to crown fires are among the fire phenomena that cannot be analyzed using these models.

When the built environment becomes involved in a fire current operational models are ineffective. These models cannot predict the spread of fire because the building fuel loads are larger and discrete. In these community-scale fires, buildings, as well as large landscaping trees, must be regarded as discrete fuel elements. At a fundamental level, the physical mechanisms controlling fire spread are very different than those in wildland fires. The empirical correlations upon which the wildland-fire models have been developed are no longer valid. No validated predictive models of fires in an urban or urban/wildland setting exist to our knowledge.

Over the past 25 years, the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) has been developing a physics-based mathematical and computational model known as the Fire Dynamics Simulator (FDS)[7-9], to predict fire spread in a structure. Over the past few years, it has also been used to predict smoke and hot gas plume behavior produced by outdoor fires. FDS is well documented and is widely used by fire protection engineers around the world. BFRL is expanding the model to include fire spread from structure to structure and generalizing FDS to include a means to predict fire spread in both continuous and discrete natural fuels. The current model, as well as its generalization, is both computationally and data intensive. For any specified region to be modeled, high-resolution, three-dimensional data to describe the geometry, fuels, and the ignition and burning characteristics are required.

FDS has been used to construct a simulation of burning and fire spread in the WUI that is useful for analyzing the fire hazards associated with urban properties including a structure and its surroundings. In FDS, structures and vegetation must be characterized as separate fuel elements with individual ignition and burning properties. As each element in the model can be modified, the value of actions taken by owners or land managers to reduce fire hazards can be analyzed. It is expected that when properly validated, using data yet to be obtained, FDS will be able to duplicate the well known fire spread characteristics in ground fuels, but will also have the capabilities of quantifying transitions of fire spread between fuel types. This includes the phenomena of transitions from ground fire to tree-crown fires as well as ignition and burning of structures intermixed with vegetation.

The current capabilities of the FDS to model WUI fires can be demonstrated by an example. Figure 3 shows a series of frames from a simulation produced by the Smokeview software from FDS calculations of fire spread on a parcel of land. Four structures, many trees, and shrubs have all been included in this simulation. It can be seen that simulations of fire events on the "neighborhood scale" are now possible. For the simulation, ignition and burning characteristics for each of the fuel elements – ground surface, shrubs, trees and the homes were selected. The selection of these properties was guided by experiments and other experience. From a single ignition point, the model predicts where and how rapidly the fire will spread. It considers heat transfer by convection and radiation, sensible and latent heat of pyrolysis absorption by material, ignition conditions for materials, the consumption of mass by burning, smoke generation, smoke blocking of radiation from fires, and the effect of wind.

Even though the graphical representation of the result is realistic, it should be remembered that underlying the pictures at every position (to the limit of the cell size in the computation) the gas and surface temperatures, gas velocity, heat flux, and materials burning can be quantified for each time step in the simulation. There is an enormous amount of detailed information available from the model. It is common to view the results as computer generated simulations and gain insight from the viewing as one would from seeing an actual fire event. The physical science basis for the FDS model provides confidence that even without the benefit of comparison with full-scale urban fire experiments it is capable of providing relative quantitative results between alternatives and accurate predictions of trends.

Recognizing that a tool was needed for property owners and local authorities to evaluate the benefits and risks of landscaping, the development of the web-based EcoSmart software was begun by the U.S. Department of Agriculture Forest Service, Pacific Southwest Research Station in 2002. To evaluate the resistance to WUI fire threat, an algorithm was needed to quantify possible ignition of structures for different placement of trees and other ignitable vegetation. Landscape design to reduce fire risk may conflict with the design of plantings to reduce cooling costs and storm water runoff also evaluated by the EcoSmart software. Information from this study was used to construct a model that estimates the likelihood of structure ignition from a fully involved burning Douglas-fir. Conifers dominate the landscape of South Lake Tahoe, CA (USA), the primary study area for initial use of this software tool.

BURNING CHARACTERISTICS OF DOUGLAS-FIR TREES

Although landscaping trees and shrubs, if ignited, can endanger near-by structures, very little quantitative information exists about tree and shrub ignition and burning characteristics. Generally, experiments carried out to measure the heat release rate (HRR) of trees have been conducted to assess the hazards of Christmas tree fires [10-12]. Also, two studies were found in which the burning characteristics of shrubs were measured [13,14].

Previously, the HRRs of dry Scotch pine trees were measured using the instrumented hood in the Large Fire Laboratory at NIST[10]. However, the study included only one size tree. The same is true for the study of Douglas-fir tree burning carried out by Babrauskas[11]. To take advantage of existing data, cut Douglas-fir trees were burned in this study. Three different commercial sizes were selected for the experiments, with the largest limited by the HRR capacity of the NIST Large Fire Laboratory exhaust hood. The tree burns provided data on how the peak HRR, flame height and burn time scale with tree size. To our knowledge, these scaling data were not available. Further experiments are needed to extend the range of these data.

EXPERIMENTS

Douglas-fir trees were purchased from a local nursery. Three trees, each with commercial sale heights of 1.2 m, 2.4 m, and 3.7 m (4 ft., 8 ft. and 12 ft.), were cut on July 6, 2003 and delivered to NIST. Prior to burning, the cut Douglas-fir trees were allowed to dry outdoors. For the trees 17 – 21 days elapsed from the time they were cut to the time burned. The weight loss of each tree was recorded during drying. The trees were measured and photographed before burning. An important characteristic, the crown height was recorded. The crown height is the height from the bole (height of the first live branches) to the top branch. This differs from the commercial height of the tree that is measured from the base to the tip of the stem. The crown height best represents the burnable fuel height by eliminating the top of the stem and base of the tree up to the bole height. During each burn, the HRR, weight loss, flame height, vertical temperature profiles and radiant heat flux emitted from the fire were measured.

1. Douglas-fir tree identifications and physical measurements

Tree	Test No.	Crown Height (m) [±0.01 m]	Bole Height (m) [±0.01 m]	Total Height (m) [±0.01 m]	Weight 7/7/03 (kg) [±0.01 kg]	Weight 7/17/03 (kg) [±0.01 kg]	Weight Pre-burn (kg) [±0.01 kg]	Weight Pre-burne/ Initial (7/7/03)
4-1	Test 1	1.37	0.08	1.45	5.16	3.01	2.85	0.552±0.003
4-2	Test 4	1.30	0.19	1.49	3.54	1.61	1.55	0.438±0.004
4-3	Test 7	1.42	0.22	1.64	8.40	4.52	4.37	0.520±0.002
8-1	Test 2	2.31	0.27	2.58	23.11	17.60	17.60	0.762±0.001
8-2	Test 5	2.62	0.43	3.05	24.40	18.10	17.64	0.723±0.001
8-3	Test 8	2.44	0.48	2.92	40.83	29.61	28.75	0.704±0.001
12-1	Test 3	3.10	0.69	3.78	38.17	30.12	29.92	0.784±0.001
12-2	Test 9	3.20	0.71	3.91	41.26	33.08	31.92	0.774±0.001
12-3	Test 6	3.33	0.50	3.82	38.34	29.34	29.14	0.760±0.001

The trees were burned in the NIST Large Fire Laboratory located on the NIST site in Gaithersburg, MD (USA). The facility has several instrumented hoods that employ oxygen consumption calorimetry to measure the HRR. The largest calorimeter hood, which was used for the tree burns, has a maximum capacity for heat release rate of approximately 15 MW. The hood measures 9 m x 12 m and the lower edge of the hood is 4.5 m above the floor level. At its highest point, the center of the hood is 7.9 m above the floor.

Each tree was ignited at the base of the crown using a propane torch with two flames for simultaneous ignition of the crown on opposite sides of the stem. Depending on the moisture content, some trees required 5 seconds of torch application to ignite, others required 15. Once ignited, all but one tree were consumed by rapid burning in approximately 60 seconds. Tree 12-1 (Test 3) did not become fully involved and required a re-ignition to sustain burning. Because of this unusual burning behavior the results for Test 3 are not included in the analysis. Figure 4 shows a series of photographs typical of the burning.

Flame Heights

The mean flame height, H_{flame} was determined for each tree burn by analyzing video and still photos showing both the burning tree and the installed thermocouple supports, used for elevation indicators. The flame height (see figure 5) is the distance from the base of the flame near the tree bole to the top of the flame where the intermittency is 0.5. A flame intermittency of 0.5 means the visible flame is seen half of the time. Still photographs were used to determine the flame height, guided by the video record showing flame intermittency.

Heat Release Rate and Weight Loss

Figure 6 shows a plot of the measured HRR for each of the tree-burns. The peak HRR occurs at different times in part because of variation in ignition times. Peak HRR and weight loss measured during the test are recorded in Table 2. Notice that the largest Peak HRR was measured for tree 8-3 with a crown height of 2.44 m. This tree was noticeably fuller in branches and needles and had a weight loss during burning similar to tree 12-2 that produced nearly the same Peak HRR when burned.

2. Measured flame heights, peak heat release rates and radiative fraction

Tree	H_{crown} (m) [±0.01 m]	H_{flame} (m) [±0.3 m]	H_{flame}/H_{crown}	HRR_{peak} (kW) [±15%]	Radiative fraction of HRR_{peak} [±20%]	Weight Loss (kg) [±0.1 kg]	Weight loss / pre-burn weight
4-1	1.37	4.2	3.1±0.2	780		1.4	0.49±0.04
4-2	1.30	3.5	2.7±0.2	720	0.30	1.0	0.65±0.07
4-3	1.42	4.4	3.1±0.2	1660	0.40	2.7	0.62±0.03
8-1	2.3[illegible]	4.6	2.0±0.2	3350		9.[illegible]	0.52±0.0[illegible]
8-2	2.62	5.1	1.9±0.2	3400	0.22	8.6	0.49±0.01
8-3	2.44	5.6	2.3±0.2	5040		12.5	0.43±0.0[illegible]
12-1	3.10	N/A	N/A	N/A		N/A	N/A
12-2	3.20	5.1	1.6±0.[illegible]	4980		13.5	0.42±0.0[illegible]
12-3	3.33	4.7	1.4±0.1	40[illegible]0	0.19	7.9	0.27±0.0[illegible]

ANALYSIS OF EXPERIMENTS

The series of tree-burn experiments provided data for development of the fire source portion of the algorithm to predict structural ignition from burning vegetation. Other observations from the data, not used directly in the development of the algorithm, are recorded in this section for possible use in other models for wildland-urban interface fires.

Flame Height

The mean flame heights (H_{flame}) were compared to the crown height, H_{crown}, to determine if there was a correlation between a tree's height, and the resulting flame height. Looking at the measured results in Table 2, generally the larger trees produced a flame height twice the crown height. The smallest trees produced a flame three times the crown height. But these data are also influenced by differences in initial moisture content. From the data in Table 1, the smallest trees lost about one-half of the initial weight before burning. The larger trees lost only one-fourth of the initial weight before burning. More experiments are needed to understand the effect of moisture and crown height on flame height. At this time, the best estimate of flame height for application to WUI fire prediction are the measurements for the larger trees that were not as dry as the smaller trees burned in this study. That is $H_{flame} / H_{crown} = 2.0$

Heat Release Rate

NIST tree-burn experiments demonstrated that the larger trees took longer to ignite, and have a steeper rate of increase in HRR, but once the fire was steadily increasing, peak HRR was obtained in approximately 30 seconds for all trees (see Figure 6). Figure 7 shows the HRR curves aligned such that the peak values occur at 30 seconds. From this figure, it is apparent that the size of the tree plays a large role in determining the peak HRR, but has a relatively minor affect on the length of the burn.

Using 60 seconds as a common time interval for major burning, the HRR of the burning Douglas-fir trees can be represented well by a simple isosceles triangle shape. In this case the base of the triangle is 60 seconds and the height is the peak HRR. Figure 7 shows this approximation as it applies to two of the measured HRR curves (tree 4-3 and tree 12-2). This result is not used in the algorithm developed in this study, but may be an important and useful approximation in future modeling of crown fires.

The burning of Douglas-fir trees has also been studied to evaluate the hazards of Christmas trees in homes. In an extensive study of Christmas tree burns by Babrauskas[11], peak HRRs were correlated with total mass of the tree and the moisture content of the needles as

$$\dot{q}_{peak}/\text{mass} = e^{5.84-0.017M} \qquad [1]$$

where,

$\dot{q}_{peak}$ is the peak heat release rate [kW],
mass is the total pre-burn mass of the tree [kg],
M is the moisture of the needles [percent by weight].

Because these results contain a quantification of the effect of moisture on the peak HRR and the trees burned were similar to those burned in this study, the results published by Babrauskas can be used in the algorithm to estimate the peak heat release rates of Douglas-fir trees. Unfortunately, Babrauakas normalized his peak HRR using the entire mass of the cut Douglas-fir tree. For live trees, this is not a useful normalization. It is more useful to normalize the peak HRR data with the mass burned. Based on bums conducted in this study, for similar size cut trees, approximately half the pre-burn weight was lost during burning (see table 2). Assuming the same was true for the tree bums reported by Babrauakas, simply multiplying the exponential in equation [1] by a factor of 2.0 would re-normalize the correlation for peak HRR with respect to the mass burned.

Radiative fraction of the peak heat release rate

The radiative fraction is that portion of heat release rate emitted as thermal radiation. This fraction was evaluated from data using the point source method of Drysdale[15]. The measured heat flux to a position remote from the flame (in this case 10 m) was taken as the average value over a 10 m spherical surface centered at the mid-point of the flame. Table 2 lists the results for the peak radiative fraction values for several of the burns. The average of these values is 0.28±0.06.

IGNITION OF STRUCTURES ALGORITHM FOR ECOSMART

In wildland-urban and residential community areas, fire can spread rapidly, often driven by the wind, to threaten homes and other structures. There are several modes by which burning vegetation can threaten a home [16-23]. For example, flames from burning trees and shrubs close to a home can ignite combustible exteriors by direct contact. In addition, small fires in collected debris, such as dry leaves and needles dropped on and around the home, can start fires at comers and in small crevices of the structure. Furthermore, ground fires, which propagate in dead debris such as leaves or pine needles or in dry live fuels such as grasses, can ignite an exterior wall. All of these mechanisms depend essentially on direct contact (convection and/or conduction) for the heating and ignition of the combustible exterior materials of the structure. Alternately, hot brands from burning trees remote from the property can be carried by the wind and blown up against the exterior or even into homes through small openings to ignite the structure. Or, finally, for large fires, thermal radiation emitted from the flames can be transported in line-of-sight directions across open spaces to be absorbed by and ignite the structure.

Of these possible modes of fire spread, the most quantitative understanding exists for fire spread by ignition from thermal radiation. For example, radiative heating of a surface is simply additive; therefore, the radiative heat flux at a position on the surface, from two identical non-interacting burning objects oriented similarly with respect to that position, is just twice that of one of them. In addition, radiation becomes a more dominant transport mechanism as fires become larger. Crown fires, which burn hot and spread rapidly, are well-known examples of fires where radiation is a dominant mode for fire spread. The fact that the heat transfer by radiation from burning trees to a structure could be quantified through knowledge of the geometric relationship between the two fuel elements, lead to the selection of this mode of ignition as the first to be quantified in EcoSmart [3, 24-25]. This was done with full knowledge that more often structures are ignited by other means that are not well quantified as discussed above. A simple algorithm was constructed to determine the thermal radiation transport from burning trees to structures.

The fire spread algorithm can be used to examine a class of scenarios for fire spread from vegetation to structures. The algorithm provides means to calculate the radiative heat exposure to structures from burning trees with flames located at arbitrary positions in 3-dimensions relative to structural elements.

Even though it is well known that ignition of combustible materials depends both on the magnitude of the incident radiative heat flux, and on the duration of this flux [3, 24-25], the model algorithm uses a simple critical flux assumption for ignition of structures. To be consistent with the capabilities of the initial version of EcoSmart the effects of burning duration were eliminated from the algorithm ignition model. Fire spread from vegetation to the structure is assumed to occur if the value of the thermal radiative flux exceeds a critical value for ignition. The critical flux for ignition depends on many factors including: the material, its thickness, orientation, and wind conditions.

Simple Algorithm for Structure Ignition by Burning Landscape Trees

The structure ignition algorithm (version 1.0) utilizes the crown height and burnable mass of the tree as two parameters that need to be given in order to determine the burning properties of the tree. As this study examined only Douglas-fir trees, generalization of results to other tree species is not recommended. The foliar mass (m_{foliar}) of the tree is the mass of the fine fuels, small branches and needles that bum easily. The foliar mass of the tree is the best commonly available estimate of the amount of mass that will be burned. Based on measurements in this study the flame height at peak burning for the Douglas-fir trees is twice the crown height with the base of the flame located at the height of the tree bole. The peak heat release rate is obtained from the correlation reported by Babrauskas [11] and modified by information from this study so that results are in terms of the burnable mass. Using the foliar mass of the tree as the burnable mass, the modified Equation [1] becomes:

$$\dot{q}_{peak} = 2m_{foliar}e^{5.84-0.017M} \quad [2]$$

where

$\dot{q}_{peak}$ is the peak heat release rate [kW]

m_{foliar} is the burnable mass of tree [kg]

M is the moisture content of the needles in percent of the needle mass

The fraction of heat emitted from the fire as thermal radiation (radiative fraction) is fixed at 0.28, the average value measured for Douglas-fir burns in this study.

The heat flux at any part of the exterior surface of the structure is determined by a calculated view factor [26]. The view factor is based on radiation from a vertical right cylinder body representing the flame oriented in 3-dimensions relative to the structure. A right circular cylinder with height equal to the flame height and diameter equal to the largest diameter of the tree branches is used as an approximation to the emitting surface of the flame. The base of the cylinder is located at the tree bole position. View factors are calculated between the flame source and the receiving surface of the structure to estimate the heat flux. The algorithm assumes no attenuation of the radiation by absorbing media between the flame and the structure.

The ignition criteria for the structure is based on a critical radiant flux condition. There is no dependence on exposure time. A single value of 31.5 kW/m^2 is used. This value is based on criteria developed by the Department of Housing and Urban Development for safe spacing of housing from potentially large fires [27-28]. However, without any time dependency for the ignition model in the algorithm and using only the peak radiant energy as exposure, the value, 0.28, is consistent with the level of accuracy contained in the current model algorithm.

ECOSMART WEB-BASED TOOL FOR EVALUATION OF LANDSCAPING

Implementation of the Structure Ignition Algorithm

The fire model algorithm was selected to be physics-based and to harmonize as much as is practical with the other modules of EcoSmart. Many choices that were made in the development of the algorithm for ignition of structures by burning vegetation were made specifically to work within the limitations of the EcoSmart software design. There is a greater quantitative understanding of fire spread from vegetation to structures than is implemented in the software. Full and detailed models of fire development on landscaped properties have been performed with the NIST developed Fire Dynamics Simulator (FDS) software [29-30]. Direct use of that advanced computational method in EcoSmart is prohibitive at this time. Using the algorithm developed where ignition of structures is based solely on fire radiant exposure should only be regarded as one indicator of fire spread potential from burning vegetation to structure.

As many potentially important fire spread mechanisms have been omitted, conservative choices that favored structure ignition have been made for the fire scenarios. This is customary practice in safety analysis where considerable uncertainties exist. Examples of these choices are:

? all vegetation bums at the maximum burning rate;
? all surfaces ignite if exposed to a critical flux for ignition;
? duration of burning for the sources of heat are not considered; and
? duration of exposure for the materials being ignited is not considered.

The first version of EcoSmart implements a model of structure ignition by thermal radiation; other important ignition threats to structures have been deferred for later research, development and implementation.

User Interface

EcoSmart is accessible through a web-site maintained by the U.S. Department of Agriculture Forest Service. To facilitate use for evaluation of landscaping a graphic user interface (GUI) was developed. Using the GUI a description of the property is entered. Figure 8 shows a parcel with a house and landscape vegetation typical of South Lake Tahoe, CA (USA). A slider bar on the left side of the screen displays different lengths and colors to indicate the relative hazard posed by nearby vegetation in the event that wildfire strikes the community. Users can prune, remove, plant, and reposition vegetation on the simulated parcel to identify configurations that are aesthetically pleasing and fire safe. Results for the fire hazard may be combined with other analysis of energy conservation and property hydrology so the user can be aware of the total impact of landscaping decisions.

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Figure 1 Homes in Summerhaven, Arizona bum amid tall trees during The 2003 Aspen fire. [Photo courtesy Of KTVK News Channel 3, Phoenix, Arizona.]

Figure 2 Unburned Eucalptus trees surround a neighborhood of burned out homes in San Diego, CA (USA). [Denis Poroy, Associated Press from the Washington Post October 28, 2003.

Figure 3 Selected frames from FDS / Smokeview simulation of "neighborhood scale" fire spread from a single ignition. The fire spreads from ground fuels, through ladder fuels to the tree-crowns. Structures are ignited by heat flux from the burning vegetation.

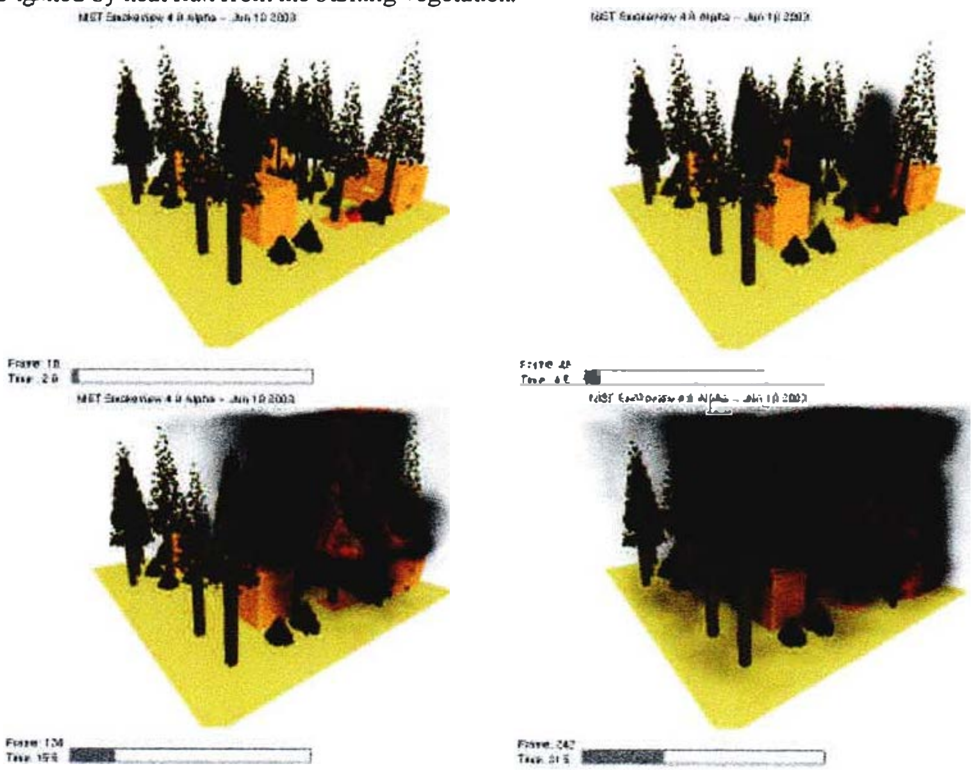

Figure 4 Douglas-fir burn, Test 8-1

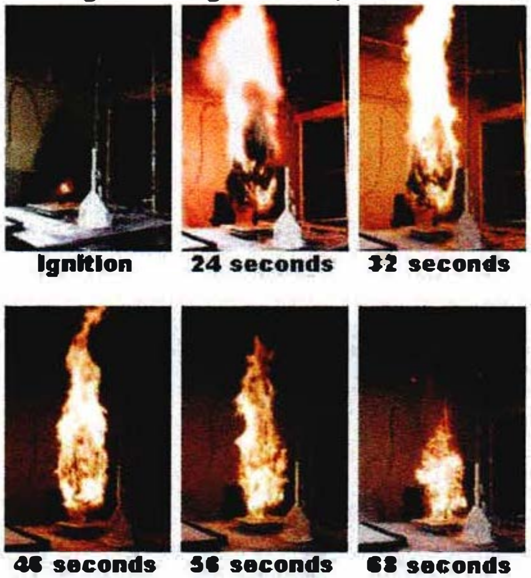

Figure 5 Flame height

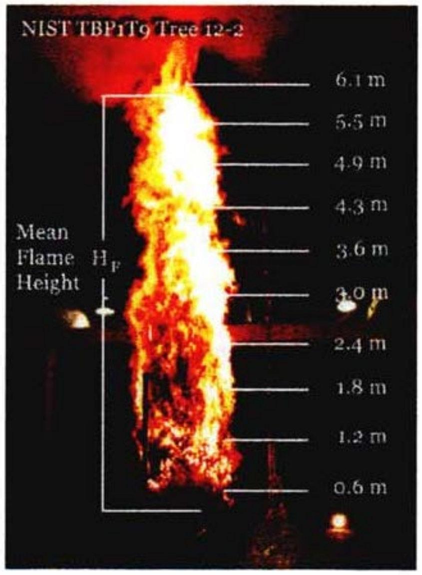

Figure 6 Heat release rates from Douglas-fir burns

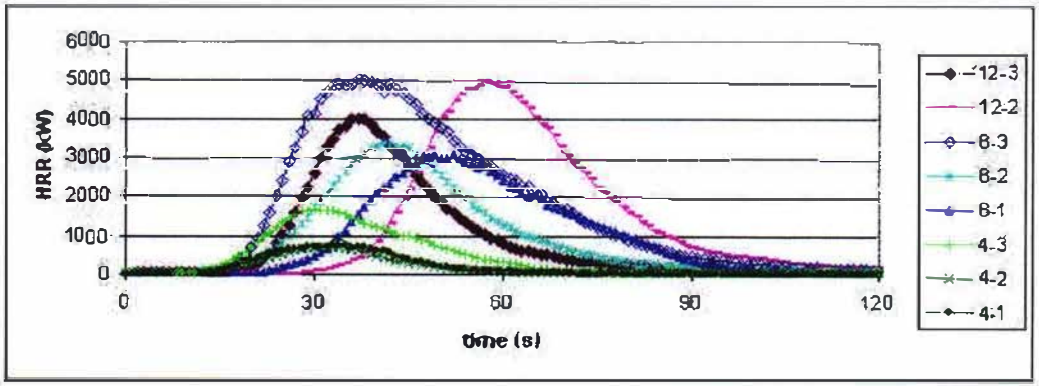

Figure 7 Heat release rates of Douglas-fir trees with peak rates aligned.
Two examples of triangle shaped approximations to these curves

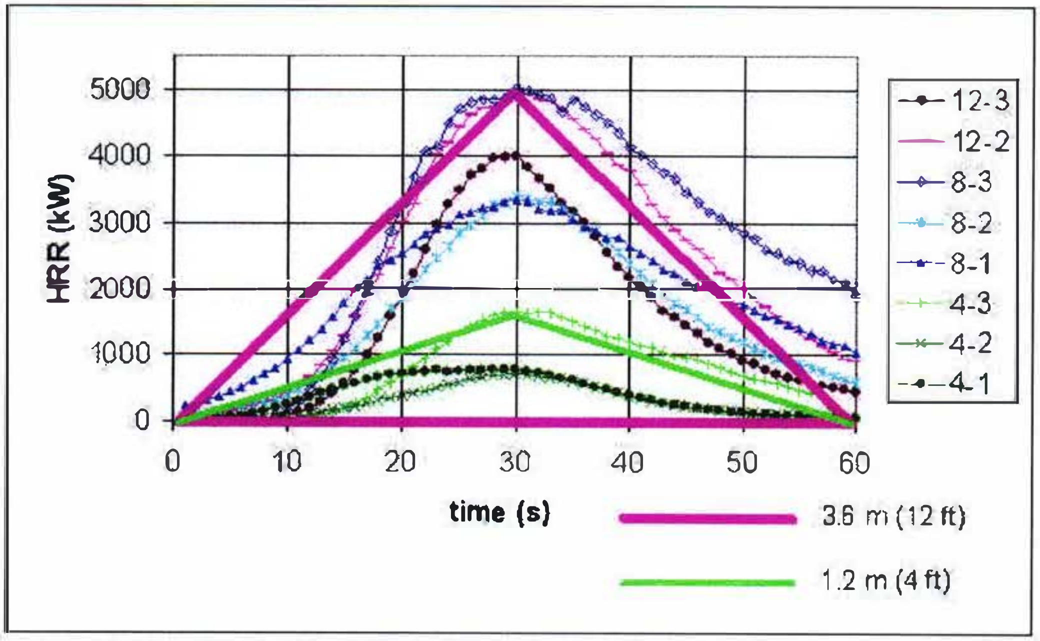

Figure 8 Major features of the fire portion of the EcoSmart software are displayed and explained