Wildland Fire Behaviour Simulations Employing an Integrated Weather-Topographical-Fuel Datasets and Satellite Remote Sensing

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Abstract
Several countries have developed fire spread and simulation models with little attention being paid to the evaluation of existing fire simulation tools. In this study, NASA's LANDFIRE database at 30-metre pixel resolution derived from Landsat 5 and 7 imagery was utilised over the Woodacre and Glen Ellen regions near San Francisco, California to compare fire simulation models over two Californian landscapes representing different terrain and vegetation regimes. This paper includes a brief discussion of the models, their assumptions and limitations, how to assemble data to build landscape input datasets and also outlines interpretation of outputs/results. The outputs of these models are beyond two-dimensional static maps/images, and in turn provide the fire managers and field staff with three-dimensional interactive and immersive visualisation of the spatial variation of the terrain and wind/fire speed/direction and the fire growth areas across the wildfire perimeter. The assessment of FARSITE, FlamMap and WindWizard simulations revealed that these technologies offer appropriate capabilities to predict the fire growth process and assess resources at risk which holds promise for real-time simulation of wind-driven wildland fires. Australia needs to initiate and develop a national bushfire spread forecast system to guide Authorities and communities readiness for fire suppression actions and rescue operations.

1. Introduction

With the rapid escalation of population and critical infrastructures the world's exposure to natural hazards (e.g. floods and tsunamis, wildland fires, earthquakes, cyclones and tidal waves, landslides) is unavoidably increasing. The strongest population growth is mostly positioned in coastal areas and within major metropolitan cities where there is an exponential increase in disasters. In particular, wildland fires are a part of the American and Australian way of life, and the economic, environmental and personal costs experienced from wildland fires are significant. The International Association of Wildland Fire Board of Directors in the US has recognised the recent assessments and consensus of the Intergovernmental Panel on Climate Change (IPCC) that considers the prospective impacts of climate change on wildland fire to be a significant scientific and management priority for this century. Scientific reports related to climate change and wildfires occurrence indicate that fire-related impact is very likely to increase drastically and catastrophically within the century. For example, studies in the US, Australia and Europe revealed that climatological variables (e.g. increases in temperature and decreases in relative humidity) are increasing the number of days of high and extreme fire danger (based on the energy release component index) (Forghani et al., 2007). Wildland fires require appropriate management, forecast, planning and response in event of the disaster. The recent catastrophic and tragic wildland fires in California (e.g. October 2007 Southern California fires) and Australian wildland fires (e.g. 2006 Grampians fire, the Long Plain Range complex fire of February 2007, Canberra fire of 2003 and the 2002 Sydney fires) are clear indications that the occurrence of wildland fires is increasing. There is also an increasing demand for applying wildland fire spread models to maintain fuel treatment planning (such as prescribed burning) and also to generate fire risk assessment maps for land managers in fire prone communities in the US and Australia. Several countries have developed fire spread and simulation models with little attention

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being paid to the evaluation of existing fire simulation tools. Wildland fire behavior models predict fundamental fire behavior characteristics using fuel load, weather variables, and topographical information. There are several fire models in use today that are based on fire-spread relationships (e.g. Rothermel, 1972, 1983, Finney, 1998, Van Wagner 1969, 1987, McArthur, 1966, Noble et al., 1980, and Tolhurst and Chong, 2007). In the US, bushfire authorities are using several fire-spread tools (eg BEHAVE) fire behavior prediction system (Andrews, 1986), FIRECAST (Cohen and Bradshaw, 1986), FARSITE (Finney, 1998), Fire Family Plus (Bradshow et al., 2000), BurnPro (Davis and Miller, 2004), FlamMap (Finney, 2005), and FSPro (Finney, 2006) that are based on the Rothermel's (Rothermel, 1972) spread model. FARSITE and FlamMap fire spread models and Wind Wizard computational fluid dynamics model developed by the Fire Sciences Laboratory in Missoula, United States Department of Agriculture were assessed. All the above models and systems incorporate three environmental factors (fuel, weather, and topographical variables) affecting fire behavior. The majority of these models have been developed into Geographic Information Systems (GIS) fire spread modeling tools (e.g. BurnPro FlamMap, FARSITE, and Phonenix) and have led to practical in-the-field tools that require simple point or two-dimensional surface values of meteorological fields such as wind as input (Coen, 2003). Environmental parameters within the models have been evaluated by Arca et al., (2007), Krasnow et al., (2009) and Bar Massada et al., (2009). The importance for developing custom fuel models for different vegetation communities is vital to improving the accuracy of FARSITE, as found by Arca et al., (2007). The accuracy of FARSITE simulation in Mediterranean maquis was improved using a custom fuel model developed to take into account the vegetation dynamics of the study area (Arca et al., 2007*)*. Fuel mapping efforts that utilise local area information and biotic as well as abiotic predictors will more accurately simulate fire spread rate using FARSITE than do current LANDFIRE data products (Krasnow et al., 2009). Bar Massada et al., 2009 found that LANDFIRE was the best available data for large scale fire simulation. However LANDFIRE has issues, including inaccurate mapping of burnable fuel types and inconstancy of mapping of unburnable surfaces. Bar Massada et al., (2009) used TIGERLINE road data to overcome the latter of theses inconsistencies. Along with improving the fuel model input in FARSITE Arca et al., (2007) results confirmed the performance of FARSITE is affected by the spatial and temporal resolution and accuracy of wind data. It was found that high spatial resolution wind field data, calculated by computational fluid dynamics models was the best available wind data. Overall the variability inherent in the parameters controlling and influencing wild land fire behavior in these systems has performed adequately and fire simulation models have been accepted as valuable tools in the industry (e.g. Sneeuwjagt and Peet, 1985, Cheney and Gould, 1997, Finney, 1998, Bar Massada et al., 2009 and Carmel et al., 2009). Including for the uses in fire risk assessments where using FARSITE for large areas is feasible and provides important information for land managers (Bar Massada et al., 2009). Other researchers (e.g. Clark et al., 2004, Linn et al., 2002 and Coen, 2003) have bridged atmospheric models such as WRF-Fire at the National Center for Atmospheric Research (NCAR)'s Weather Research and Forecasting Model (WRF) to fire behavior spread simulators to explore the mechanism between a fire and the local weather, ranging from small-scale fire whirls to generation of supercell-like circulations affecting regional weather. At the cost of adding computational complexity this approach gives insights into fundamental aspects of fire spread behavior (Coen, 2003). Scientists at NCAR are developing verification metrics to assess forecasted fire/weather model results in comparison to remote sensing data and have recently released a beta version of WRF-Fire for community user evaluation (Forghani et al., 2007 and Forghani, 2007). FARSITE and FlamMap fire spread models and WindWizard computational fluid dynamics model developed by the Fire Sciences Laboratory in Missoula, United States Department of Agriculture were assessed. In this study, NASA's LANDFIRE database at 30-metre pixel resolution derived from Landsat 5 and 7 imagery was utilised over the Woodacre and Glen Ellen regions near San Francisco, California to compare fire simulation models over two Californian landscapes representing different terrain and vegetation regimes. The models employed the following input datasets; vegetation/ground cover type, crown stand height, crown base height, crown bulk density, temperature, humidity, precipitation, slope, aspect, elevation, wind speed and direction. This paper includes a brief discussion of the models, their assumptions and limitations, how to assemble data to build landscape input datasets and also outlines interpretation of outputs/results. The outputs of these models are beyond two-dimensional static maps/images, and in turn provide the fire managers and field staff with three-dimensional interactive and immersive visualisation of the spatial variation of the terrain and wind/fire speed/direction and the fire growth areas across the wildfire perimeter.

2. Descriptions of Wildfire and Wind Simulators

The FARSITE, FlamMap fire spread models and WindWizard simulator are briefly described here:

2.1 Fire Area Simulator (FARSITE)

FARSITE developed by the Department of Agriculture, Forest Service's Missoula Fire Sciences Laboratory (Finney, 1998) is a two-dimensional fire simulator model of fire growth which spatially and temporally simulates the fire spread and its behavior using topography, fuels, and weather data. FARSITE propagates fire across a terrain using the fire behavior models found in the one-dimensional fire model BEHAVE (Andrews, 1986, Burgan and Rothermel, 1984 and Rothermel, 1972). It is a deterministic, equation-driven fire spread simulator that models fire propagation as a wave front spreading from multiple vertices (a series of ellipses) along a fire front, based on Christian Huygens' principle (Anderson, 1982 and Finney, 2002). This principle has formed the foundations of many existing fire growth models (Finney, 1998). Every point of an advancing light wave becomes the source of new light waves, and then dimensions of the ellipses are computed from the fire behavior predictions. These collectively generate fire perimeters at specific instances in time. FARSITE then connects all points at the end of the smaller waves using topological algorithms. FARSITE includes a well-developed user interface, and inputs/outputs are GIS-based.

2.2 FlamMap

FlamMap also developed by the Department of Agriculture, Forest Service's Missoula Fire Sciences Laboratory (Finney, 1998) that maps fire behavior across an entire landscape; hence calculations are carried out based on each pixel independently using quantified fuels information for a single point in time. FlamMap uses the same input datasets as FARSITE (vegetation/ground cover type, crown stand height, crown base height, crown bulk density, temperature, humidity, precipitation, slope, aspect, elevation, wind speed and direction).

2.3 WindWizard

WindWizard is based on the FLUENT computational fluid dynamics (*www.fluent.com*) platform. It assumes the atmosphere is neutrally stable and a constant temperature, while wind flow and turbulence is modeled applying turbulence models (e.g. Jones and Launder, 1972; Yakhot and Orszag, 1986). WindWizard is considered as an integral part of fire simulation in which the US bushfire authorities have widely applied it to produce fire forecast spread products (e.g. Butler and Forthofer, 2004 and Finney et al., 2006). This tool simulates the effect that terrain has on synoptically driven surface wind flow and generates gridded (cell-based) wind speed and direction at the 60.96-91.44 meters (100-300 feet) horizontal scale, (for which wind information at this spatial detail is not available from the weather service). The WindWizard tool performs simulations of what the wind flow would be under different general (synoptic) wind speed and direction scenarios.

3. Methodology

An overview of research workflow in relation to data processing and fire spread simulation is shown in Figure 1

3.1 Test Sites

Woodacre: the site is located approximately 8 km (5 miles) north of San Francisco, covering a major portion of Golden Gate National Park, Golden Gate Biosphere Reserve and the township of Woodacre and its surroundings just near to the San Andreas Fault, a major rift in the earth's surface. It offers an ideal case study because of particular characteristics of vegetation composition and structure; land cover and land use dynamics, weather, terrain, human activities and practices, and has notably rich biological diversity due to the variety of habitat and unique geology. The changes in bedrock along with microclimatic and topographical differences between tectonic plates make this region unique and highly diverse including coastal redwood forests, the world's tallest tree species. The area has strong spatial heterogeneity, in terms of composition and structure of the ecosystem as well as the spatial distribution and arrangement. Major vegetation consists of mixed evergreen forests, redwood forests, Douglas fir forests, Bishop pine forests, oak forests, woodlands and savannas, coastal scrub, chaparral, coastal dune, coastal strand, grasslands, marshes and their associated animals such as cougars and Tule elk. *Glen Ellen:* the site extends an area from the township of Glen Ellen in Sonoma County, California. It contains Jack London State Historic Park, agricultural lands, eucalyptus trees, redwood forests and oak woodland. The most common plant community is the oak woodland, which has a canopy of coast live oak, Sequoia sempervirens, Garry oak, Black oak, Pacific Madrone, Bigleaf maple and California laurel.

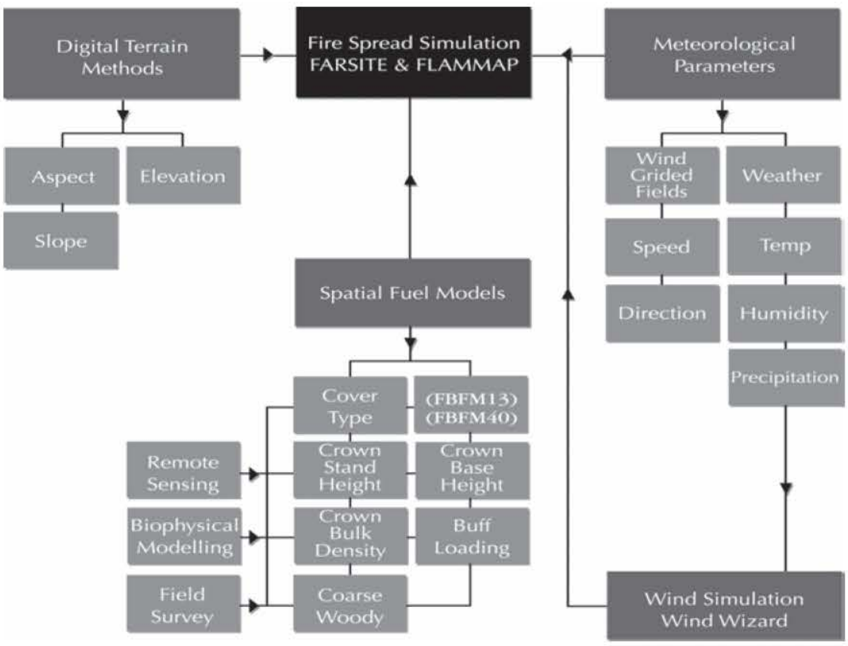

Figure 1: Conceptually represents key components of fire growth and behavior simulation process

Fire spread modeling operates on three major environmental variables that influence fire behavior spread. These include weather, topographical (terrain) and fuel data that are briefly discussed here.

3.2 Weather Variables

3.2.1 Weather data

For the 2006 fire season, all Western Region Offices offer automatic 7-day FARSITE weather data. The FARSITE weather data consists of a "wind" file (WND file extension) and a "weather" file (WTR file extension) at 2.5 km grid resolution points (Gibson and Gorski, 2003) acquired from Digital Forecast Database of the National Oceanic and Atmospheric Administration's National Weather Service Digital Forecast Database (DFD). Data in the WTR file include month, day, daily precipitation (inches), local time of minimum temperature and maximum relative humidity percentile, local time of maximum temperature and minimum relative humidity, minimum temperature, maximum temperature, maximum relative humidity, minimum humidity and elevation in meter for the forecast location. In the WND files, each line shows month, day, hour (local), wind speed (km/h), direction and percentile of cloud cover.

3.2.2 Gridded wind data from WindWizard

Digital Elevation Model data was ingested into the WindWizard fluid dynamics predictive tool to simulate surface wind speed and direction at the 100m scale on the terrain surface. In this study, the actual fire perimeters were not available to compare the overestimated and underestimated fire growth perimeters/areas after and before using gridded wind data into the fire simulation. However, previous studies (e.g. Butler and Forthofer, 2004 and Finney et al., 2006) demonstrate that the incorporation of gridded wind data clearly improves prediction of fire growth perimeters. These types of simulations provide a "*…snapshot at one point in time of what the local surface wind speed and direction would be for a given ridge top or synoptic wind scenario*" (Finney et al., 2006). Generating gridded wind data consists of a number of consecutive stages including (Stratton, 2004):

- Collecting/assembling DEM and ingest into WindWizard as an ASCII raster digital elevation data file.
- Building computational mesh grid cells and computing a surface roughness parameter based on user input of the dominant vegetation types such as forest, shrub and grass.
- Solving the Navier-Stokes equations[1] (e.g. Polyanin et al., 2002) recounting the wind flow based on user input of the ridge top or synoptic wind conditions.

[1]It describes the movement of fluid substances (e.g. liquids, gases and wind) as an application of Newton's second law to fluid. The Navier-Stokes equations create that changes in impetus in microscopic volumes of fluid are basically the computation of dissipative viscous forces (similar to friction), changes in pressure, gravity, and other forces performing contained by the fluid: http://en.wikipedia.org/wiki/Navier-Stokes_equations

- Displaying and visualizing the wind speed and direction (6m above the terrain surface at a resolution specified by the user) on a GIS software package such as ArcGIS. This aids fire managers and field staff for representing and interpreting the spatial variation of the wind speed and direction particularly to detect high/low wind speed areas across the fire perimeter and the terrain effects.

- Loading the wind vector files into FARSITE/FlamMap for consequence fire behavior simulations and analysis (Figure 2).

3.3 Terrain Derivatives

The USGS regular gridded 30m x 30m digital elevation model (DEM) was used to derive elevation, slope and aspect parameters utilizing the ArcGIS's Spatial Analyst tool. The above three layers were input directly to fire simulation, and DEM data were also used to generate wind variables in WindWizard.

3.4 Fuel Datasets

Fuel includes live fuel and dead fuel (eg forest floor needles, cured grasses, and twigs and branches) that play critical role in fire behavior. NASA's LANDFIRE database (*http://www.landfire.gov*) contains fuel variables at 30m resolution that are derived from satellite imagery, terrain modelling and biophysical and local field knowledge. These datasets were used to build Anderson's 13 Fire Behaviour Fuel Models (FBFM13), Scott and Burgan's 40 Fire Behaviour Fuel Models (FBFM40) (see Burgan, 2005 and Keane et al., 2006). These fuel models were ingested to the FARSITE fire growth simulation model and FlamMap fire potential simulator. The FBFM40 provides a better representation of fuel across the landscape, leading to an improvement in surface fire intensity prediction and increased precision in determining crown fire behaviour.

3.5 Assembly of Data to Build Landscape Files

The raster GIS datasets acquired and processed over the study area include all of the fuel and vegetation layers (FBFM13 and FBFM40), canopy bulk density, height to base of live canopy, canopy cover, and stand height described in Burgan (2005) and Keane et al., (2006) and terrain data (elevation, slope, aspect) and weather data. Fuel load data were converted into raster grid, then to ASCII files for input to the FARSITE and FlamMap, which makes landscape (.LCP) file. The inputs should have a common projection, format, cell size and origin (the same min X and Y coordinates/spatial extent) prior to conversion to ASCII files (Stratton, 2004). There are a number of user-defined parameters such as the perimeter resolution of the fire front that FARSITE requires. To determine appropriate FARSITE and FlamMap parameters, several simulations were conducted in consultation with Fire Sciences Laboratory associates.

4. Fire Spread Simulation Results

FARSITE and FlamMap generate several spread modeling scenarios and outputs; a couple of generated fire behavior maps are reported in this paper (Figure 2a-c). Fire growth perimeters were generated using FARSITE, and maximum spread direction, flame length and fireline intensity were the outputs from the FlamMap model. Determining simulation parameters (fine-tuning) is important in the fire modelling process. Once the model parameterisation was established, FARSITE was run over the two study areas to predict fire growth under given inputs (weather, terrain and fuel). For example, a fire simulation using FARSITE over Woodacre (wind direction =180°, wind speed = 15 mph, temperature = 35°; and humidity = 15%) revealed that a wildfire could spread quickly throughout the central and central-east part of study areas respectively. The fire simulation estimated that 634.142 hectares (1567 acres) of national park lands would be burnt in the first 18 hours in the Woodacre experiment, while about 804.11 hectares (1987 acres) of vegetation would be burnt in the first 23-hour in the Glen Ellen area (Figure 2b). A spread rate adjustment factor of 1.0 was utilized for all fuel models. Critical fire behaviour assessment requires comparing these outputs with field observations. However, these observations can be undertaken using the example of recent Australian wildfire events. In addition to the above outputs, graphics of total fire area (for all fires) over time of horizontal and topologic values of fire area, fire characteristics in terms of spread rate and heat density (heat per unit area) were generated. These aid interpretation of fire behavior in relation to temporal and spatial changes for each fuel type input since different fuel models can result in distinct clusters of points and have their own envelope of fire response to environmental conditions (Figure 2c). The successive perimeters and the ignition are superimposed on the FBFM40 (green map), final fire perimeter is overlaid on the wind vectors (upper-right) and wind vectors superimposed on Google map (down-left), then superimposed over DEM of Woodacre site (down-left).

The blue vectors represent wind direction and other vectors show different wind speed categories from 0-26km/h (right).

Fire simulation over Woodacre assumes uniform wind speed and direction from the south to north of the study area.

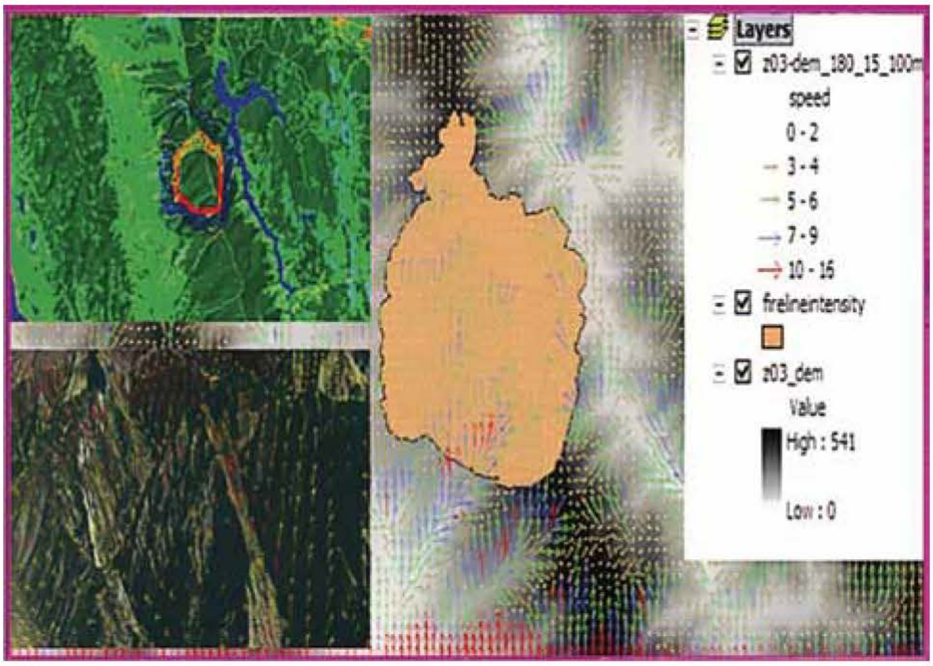

Figure 2a: FARSITE displays the simulation over Woodacre, during 3-5 August 2006. The successive perimeters and the ignition are superimposed on the FBFM40 (green map), final fire perimeter is overlaid on the wind vectors (upper-right) and wind vectors superimposed on Google map (down-left), then superimposed over DEM of Woodacre site (down-left). The blue vectors represent wind direction and other vectors show different wind speed categories from 0-26km/h (right). Fire simulation over Woodacre assumes uniform wind speed and direction from the south to north of the study area

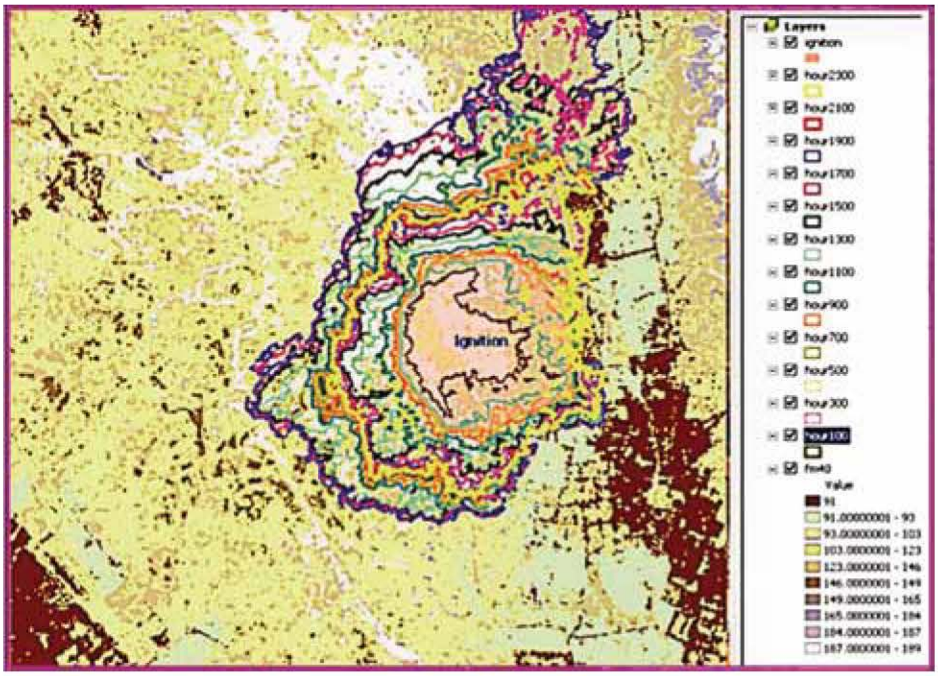

Figure 2b: Presents FARSITE's simulation over Glen Ellen. The successive perimeters and the ignition are draped over the FBFM40 fire behavior fuel models

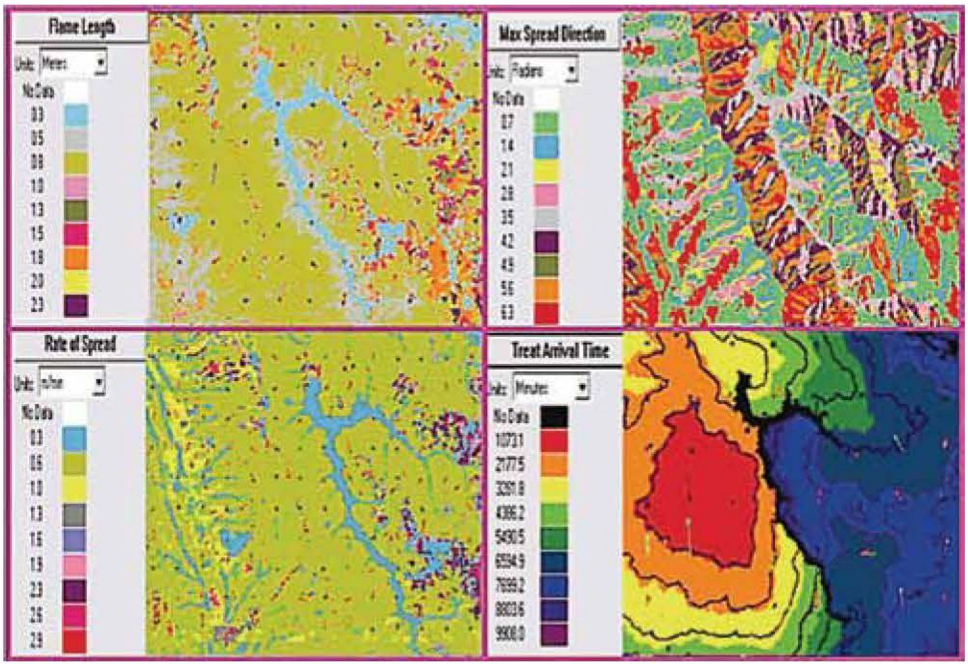

Figure 2c: Presents FlamMap fire behavior outputs such as flame length, rate of spread, maximum spread direction, and treat arrival time over Woodacre

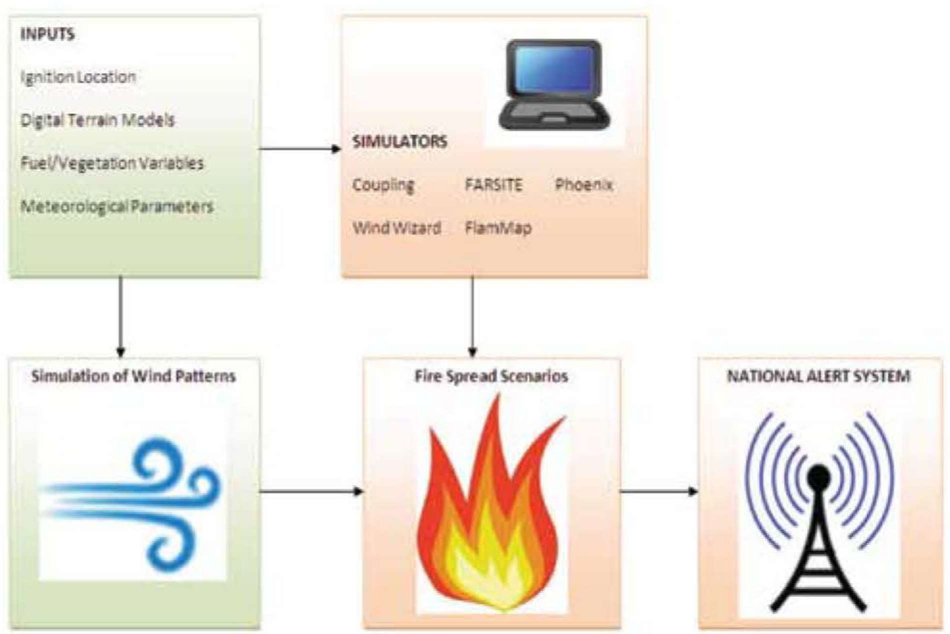

Figure 3: Conceptual bushfire forecasting and simulation system

5. Conclusions and Recommendations

The research exercised different fire spread scenarios over the study areas that produced various rates of spread and intensity under the same fuel conditions when weather variables changed. A fire simulation using FARSITE over Woodacre (wind direction =180°, wind speed = 15 mph, temperature = 35°; and humidity = 15%) revealed that a wildfire could spread quickly throughout the central and central-east part of study areas respectively. The test showed that 1567 acres of national park lands would be burnt in the first 18 hours in the Woodacre experiment, while about 1987 acres of vegetation would be burnt in the first 23-hour in the Glen Ellen area. It was noted that higher or lower spread rates compared to the actual fire spread rate may be due to deficiencies in the fuel models used (Finney, 1998 and Finney et al., 2006). The assessment of the aforementioned fire and wind simulators (FARSITE, FlamMap and WindWizard) hold promise for simulating wind-driven wildland fires. However, field data, local knowledge, and historical fire information is critical to calibration of the fire spread model. Calibration involving comparison of predicted fire growth with observed fire was not achievable for this project due to availability of real fire data. The outputs of these models are beyond two-dimensional static maps/images, and in turn provide the fire managers and field staff with three-dimensional interactive and immersive visualisation of the spatial variation of the terrain and wind/fire speed/direction and the fire growth areas across the wildfire perimeter. The assessment of FARSITE, FlamMap and WindWizard simulations revealed that these technologies offer appropriate capabilities to predict the fire growth process and assess resources at risk which holds promise for real-time simulation of wind-driven wildland fires. Future studies should compare and validate FARSITE, FlamMap and Phoenix models over local fuels and weather regimes for Australian landscapes such as 2006 Grampians bushfire, the Long Plain Range Fire Complex of 3 February 2007, and the 2002 Sydney bushfire. A pre-requisite of the above type of comparison is to build fuel load maps that are fundamental base information for many fire spread/behavior simulations and fire risk modeling systems. The project methodology then can be replicated to produce a national map of fire fuel and wildland fire risk assessment model. It is recommended that Australia needs to initiate and develop a national bushfire spread forecast system to guide Authorities and communities readiness for fire suppression actions and rescue operations (Figure 3). This will require an integration of existing fire spread simulators such as Phoenix, FARSITE, FlapMap, etc.

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