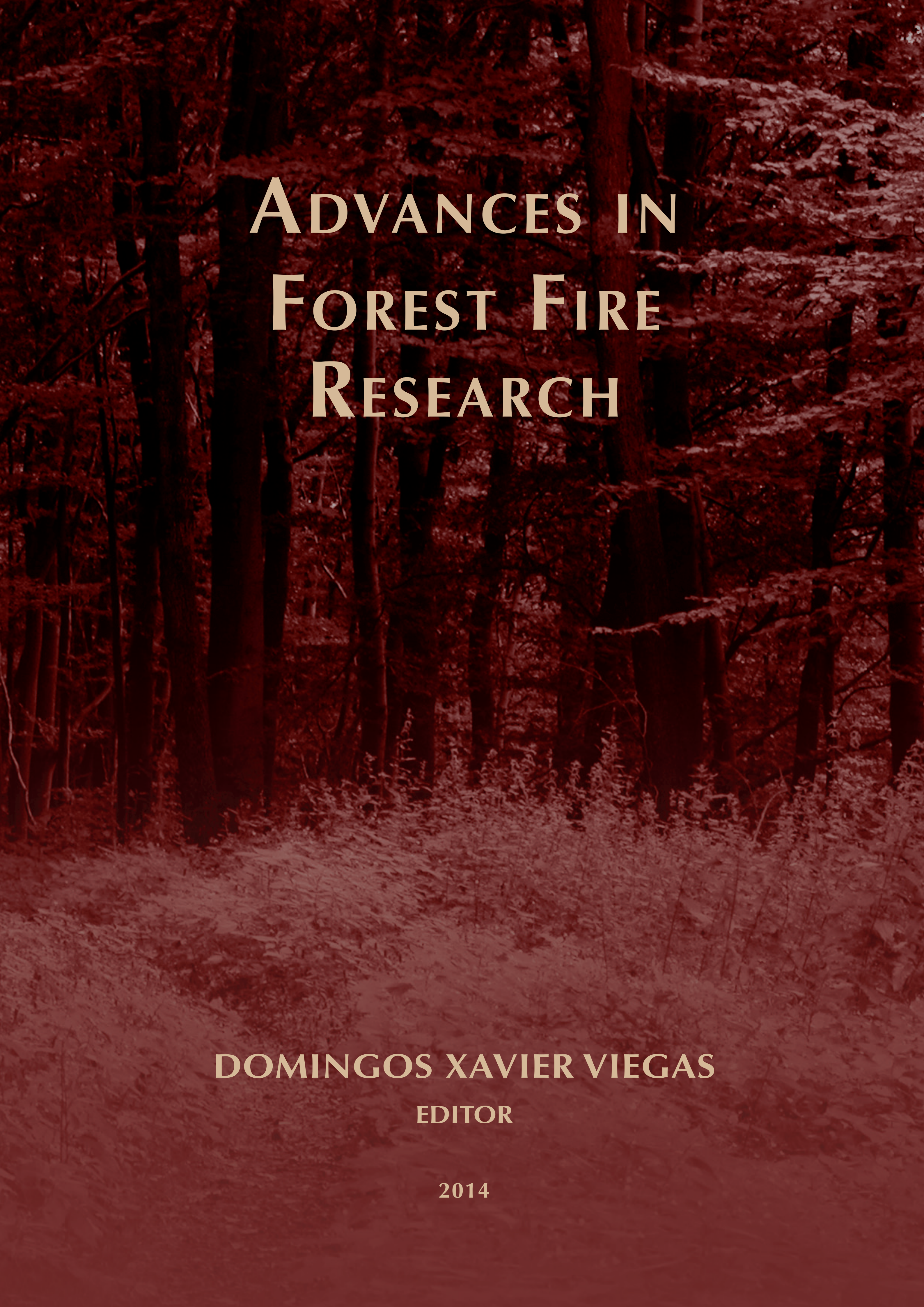

# Advances in Forest Fire Research

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# FireDST: a simulation system for short-term ensemble modelling of bushfire spread and exposure

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**Abstract**

The impact of bushfires in Australia can be enormous when considered in terms of loss of life, assets, infrastructure and productivity. The FireDST "proof-of-concept" system links various databases and models, including the Australian Bureau of Meteorology's new "high resolution" ACCESS (Australian Community Climate and Earth-System Simulator) numerical weather prediction system, the PHOENIX RapidFire fire behaviour model, the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) smoke dispersion model as well as infrastructure and demographic databases provided by Geoscience Australia. FireDST runs multiple simulations of a bushfire utilising varying inputs (such as different ignition points, different start times, different fuel characteristics and variations in the weather) based on an understanding of what may occur. FireDST amalgamates all the simulations into a single ensemble visualisation for the fire.

This paper provides an overview of the FireDST system and examines the potential for using ensemble simulations to predict short-term (1-2 days) potential impacts from wildfires. We introduce variability in the numerical weather prediction model for three case-study fires to demonstrate the ensemble modelling system. FireDST can produce both exposure and impact statistics for the ensemble fire spread, however only exposure is covered in this paper. Such information is potentially useful in assisting in the operational management of bushfires, landscape planning (such as locating infrastructure to reduce exposed to fire) and in education and training.

***Keywords***: *wildfire hazard/impact simulation, ensemble modelling, integrated modelling*

## 1. Introduction

Extreme bushfires are complex physical phenomena that occur under extreme weather and environmental conditions. They are often exceedingly difficult to manage and cause sizable impacts on individuals, communities and the economy. For instance, the Victorian Black Saturday fires of February 2009 directly caused 173 deaths, over 800 admissions to emergency hospital care, destroyed 2133 houses and burned over 430,000 ha of land. It was also estimated that the fires caused a negative impact on the Australian economy of more than 4 Billion Australian dollars (VBRC 2010).

At the incident management level there have been many improvements in the ability to manage active bushfires. In particular, the last few decades have seen the development of computerised bushfire simulation models that produce a single deterministic simulation of the fire spread. These models include PHOENIX Rapidfire (Tolhurst *et al.*, 2008) in Australia, FARSITE (Finney, 1998), FlamMap (Finney, 2006) in the USA and PROMETHEUS, the Canadian wildland fire growth simulation model (Tymstra *et al*., 2009). All are able to assimilate information on the terrain, vegetation load and type and weather predictions (some also consider the built environment), to produce a single graphical output of the progress of a fire. The models, which are calibrated against how past fires have typically progressed, consider vegetation type, terrain and topography, a fire's perimeter, air temperature, wind, and humidity. They then model where a fire will go and when it will arrive at a certain location. Incident management teams then use these predictions to help manage public warnings, evacuations and the placement of fire fighting resources.

Unfortunately there are many uncertainties in the inputs to these models (such as variations in fuel moisture, wind speed and temperature) and uncertainties in the modelling of the physics of the fire environment. These uncertainties can lead to inaccurate predictions being generated by the software. Inaccurate predictions could lead to dangerous decisions in the incident control centre and sizable effort is required to improve these simulation models. Even though accuracy is improving with new developments such as higher resolution vegetation mapping and improved fire modelling, it may never be possible to produce sufficient accuracy in every case. Recently there has been a move to incorporate uncertainty into fire modelling. Systems such as the Wildland Fire Decision Support System- Fire Spread Probability Model (WFDSS-FSPro) (USDA Forest Service, 2012) use a Monte-Carlo method to introduce uncertainty into the weather, producing a synthetic weather stream to generate a long range weather forecast. These models require an advanced understanding of the past weather and the variability in the weather that usually occurs at the time of the fire to generate this weather forecast. FSPro generates thousands of possible long range forecasts (assuming a constant weather and wind for each day) and runs a fire simulation for each. The multiple fire simulation results are then amalgamated to produce a map of fire spread probability. FSPro also places an extra level of complexity on the users of the system in understanding what the output probabilities actually mean in a physical sense. Monte-Carlo methods to generate long range weather forecasts with uncertainty, producing fire shapes which consider uncertainty, have also been used in research by Anderson *et al.* (2007), Cruz (2010) and Finney *et al*. (2011).

In 2011 the Australian Bushfire Cooperative Research Centre initiated the FireDST research project (Fire Impact and Risk Evaluation Decision Support Tool). One of the main aims of the project was to develop a "proof-of-concept" system that would allow users to easily view and assess the short-term (1-2 days) impact of various uncertainties in the information supplied to any fire spread model. The approach taken to address this aim was novel in that the FireDST system would not define the probability of an uncertainty occurring. Instead it would build an ensemble from individual fire spread simulations each with a different variation in the input condition and initially weighting each with the same probability. For example FireDST could produce an ensemble from individual fire simulations where the temperature has been varied up or down by five degrees Celsius in steps of one degree. A number of meteorological variables are varied to produce the ensemble. This paper concentrates on uncertainties in the weather however the research has also been applied to uncertainties in the vegetation and fire ignition location as well as location of synoptic frontal systems.

After producing the individual fire simulations we investigated how they could be amalgamated into a single ensemble view of the fire spread. Ensemble prediction has been applied successfully for the modelling of weather (such as the UK Met office ensemble MOGREPS[1] system) and in modelling of the paths of tropical cyclones (Zhang & Krishnamurti, 1997, Buckingham *et al*. 2010). The fire spread ensemble was then used to calculate the exposure of the ensemble footprint on people and buildings. Finally we addressed whether the smoke and combustion products from the fire could also be modelled using an ensemble.

[1] http://www.metoffice.gov.uk/research/areas/data-assimilation-and-ensembles/ensemble-forecasting/MOGREPS

## 2. Methodology

### 2.1. Concept design

We designed the FireDST system to follow the information flow defined in the Bushfire Risk Assessment Framework (Jones *et al. 2012*). The framework defines an information flow for computational analysis of bushfires from the definition of the hazard, through exposure, vulnerability and impact to calculation of the bushfire risk.

The core of the FireDST system is the Ensemble Generator (Figure 1) which controls the generation of the multiple variations for input, simulates each individual variation and creates the ensemble. Initially the supplied weather is perturbed by the Weather Ensemble Generator to provide new weather sets containing the variation in humidity, temperature, wind speed and wind direction. The supplied fuel information is also perturbed to provide variations in fuel load. Finally, the ignition information is perturbed to provide variation in the ignition location and ignition time. Once all the variations in input conditions have been created, the Ensemble Generator simulates each individual fire and amalgamates them all into an ensemble footprint of the fire.

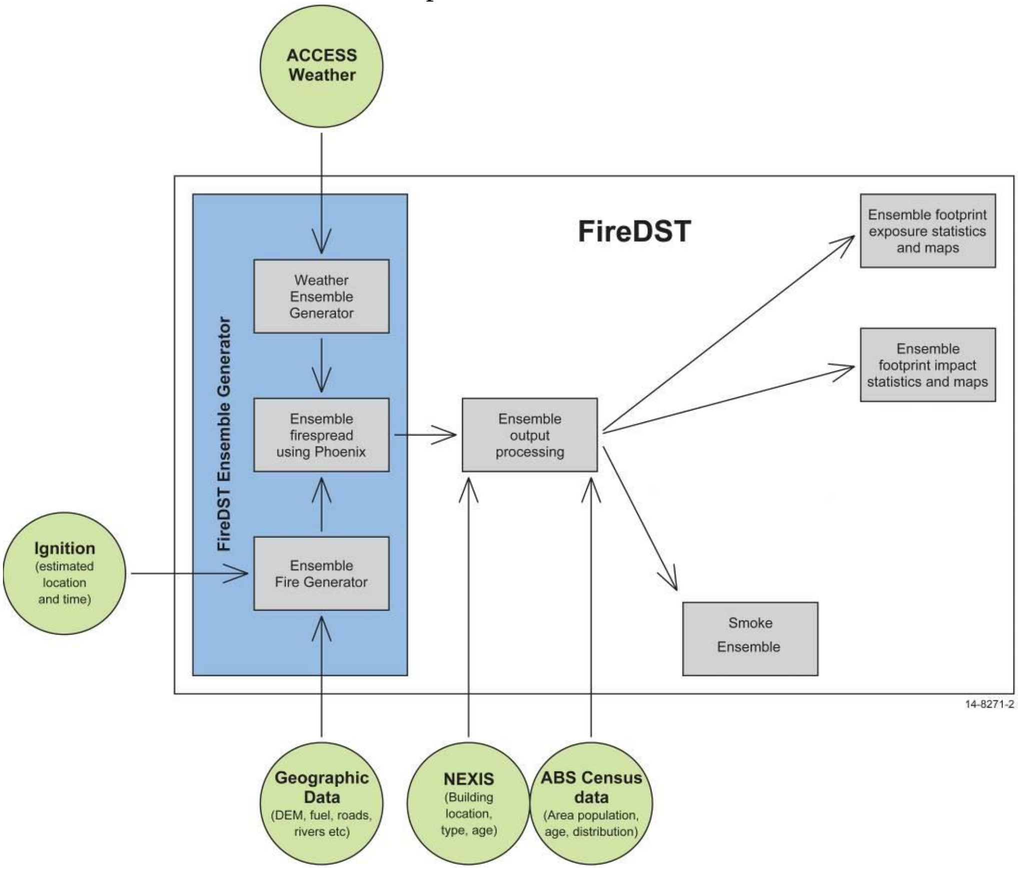


*Figure 1. Information flow in FireDST*

### 2.2. FireDST Ensemble Generator

The weather is one of the most critical inputs required for simulating bushfires. The Australian Bureau of Meteorology supplied an ACCESS (Australian Community Climate and Earth-System Simulator)(Puri, 2011) research mode numerical weather prediction for 48 hours in 5 minute time steps at horizontal grid spacing of 0.036° latitude/longitude grid spacing, which is approximately 4.0 km in the north-south direction. Each ACCESS simulation included separate grids of temperature, relative humidity, wind speed and wind direction.

The Weather Ensemble Generator allows the user to define a set of rules for creating a weather ensemble every time a new ACCESS weather forecast is produced by the Bureau of Meteorology. The Weather Ensemble Generator modifies the weather grids to produce different combinations of weather that the user considers likely to occur (i.e. takes into account some of the uncertainties in weather conditions). Simple rules were used to modify individual weather scenarios. Examples are changing the wind speed grid to increase all wind speeds by five meters per second, or changing the temperature grid to increase the temperature by two degrees. The rules also allow a more complex weather scenario by creating a profile that includes a combination of changes to humidity, temperature, wind speed or wind direction. These weather variations are stored as a weather ensemble for later use when a fire ignition location is supplied to FireDST. For this research we did not attempt localised weather change in particular areas within each weather file.

FireDST uses PHOENIX RapidFire (Tolhurst *et al*. 2008) to run each single simulation of the fire. To create a fire ensemble, FireDST uses the ignition point rules to generate other fires around the user specified ignition point (e.g. 200 meters to the North, South, East and West). 200m is the minimum distance utilised as the PHOENIX Rapidfire grid cell size is 180m in size and we wanted to ensure that each new ignition started in a new cell. Ignition time was varied from 20 minutes before to 20 minutes after the actual ignition in steps of 5 minutes. The rules can also vary the vegetation conditions (such as variations in fuel load and moisture) and their application for each weather ensemble. The FireDST Ensemble Fire Generator rules also allow the modification of wind speed based on the local terrain/topography using the Wind Ninja system (Forthofer *et al*., 2009). The user also specifies the information that is required by PHOENIX Rapidfire including the fuel type grid, a digital elevation model, road disruptions and fire history database.

The Ensemble Fire Generator then combines all of the individual PHOENIX simulations into a single ensemble view of the fire. This is achieved by taking the simulated fire area of the individual fire and converting the area inside the fire shape to “1” and everything outside to “0”. An ensemble fire shape is produced by overlaying each converted fire spread simulation shape and adding the area values. For example where two fires cover the same location the ensemble fire location then contains “2”, where there is no overlap the ensemble shape just contains “1”. Everywhere else is “0”. An example of how this is undertaken is shown in Figure 2. The overlap values are then converted to a percentage overlap in the final shape which can be displayed in discrete intervals. Typically, either half-hourly or hourly time increments are used to understand the progression of the fire.

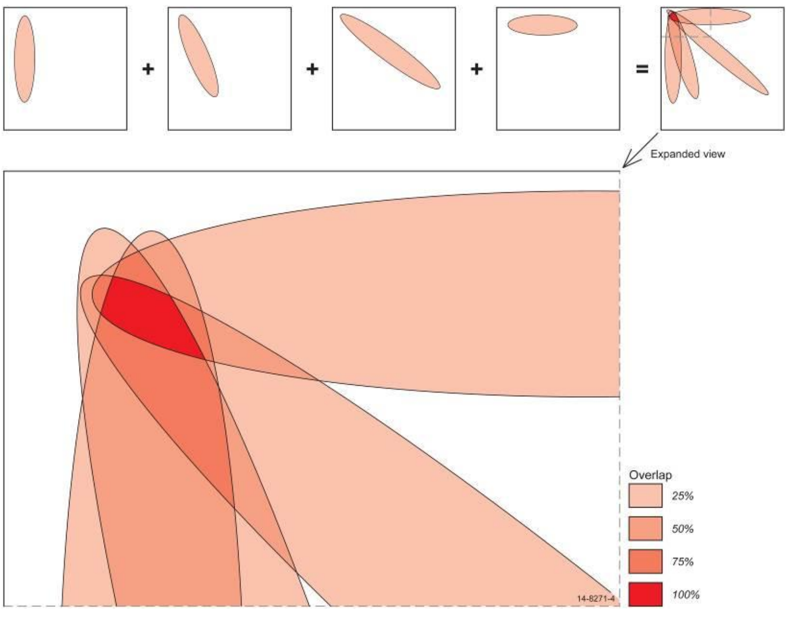


***Figure 2. Example of how an ensemble likelihood shape is produced. The fire scars of the four different notional fire simulations are combined to compute the likelihood that a particular location will burn.***

### 2.3. Ensemble Output Processing – Exposure Statistics

FireDST has been setup to display statistics and maps of residents and structures exposed to the ensemble fire spread. Geoscience Australia supplied the building database National EXposure Information System (NEXIS) (Nadimpalli *et al*. 2007; Canterford, 2011). NEXIS identifies the house location and attributes of the house (age, wall construction, roof type). NEXIS also contains quantity surveying information such as estimated building replacement cost and estimated contents value. Population statistics were extracted from the 2006 Australian Bureau of Statistics (ABS) Census at the Collection District reference level and allocated as averages to all the individual houses in that collection district. The 2006 Census information contains 14 vulnerability indicators (fields) that have been included in FireDST (Canterford 2011). The exposure statistics are produced by overlaying the ensemble fire footprint with each building location (which includes the population and vulnerability indicator statistics).

### 2.4. Ensemble Output Processing – Smoke Dispersion

Finally, all the individual fire simulations included in FireDST's ensemble can be passed to a new atmospheric numerical model (supplied by CSIRO Marine & Atmospheric Research) that simulates the spread of gaseous fire combustion materials such as smoke, ozone, particles smaller than 2.5 microns in size ($PM_{2.5}$), Nitrogen Monoxide (NO) and Carbon Monoxide (CO) from a single fire. Information regarding the supplied atmospheric model and smoke dispersion technique can be found in Cechet *et al.* (2014). FireDST takes the individual fire atmospheric spread results and amalgamates them into two ensemble maps of the concentration and percent overlap of the various products of bushfire combustion. The amalgamation technique is the same as described in Figure 2. These maps can be overlaid with the population statistics and building locations to display the impacted population. These maps can be useful to assist in managing public health warnings and in the movement of people and emergency service teams.

### 2.5. Case studies

FireDST was tested in Australia on three case studies. The Kilmore fire of 9 February 2009 was selected because the fire progressed through various terrain types and there was a high level of fire reconstruction information available. The Kilmore fire started around 11:45 and burnt 125,383 hectares, resulted in the deaths of 119 people and destroyed 1,242 homes. A comprehensive assessment of the Kilmore East fire can be found in Chapter 5 of the Victorian Bushfires Royal Commission report (VBRC, 2010). A comparison of the ACCESS weather simulation with all the Automated Weather Stations (AWS) in the region indicated a good match for temperature, humidity, wind direction and the timing of the wind change. However the 10 metre wind speed comparison found that the simulation of the wind speed was under-predicted by 5 to 7m s-1. A summary of the comparison is contained in the FireDST final report (Cechet *et al*. 2014). This deficiency in wind speed was able to be corrected by calculating wind speed bias correction factors that were then applied to the ACCESS wind speed file. This technique is fully discussed in the Kilmore Case Study report (French *et al*. 2014a). Smoke dispersion simulations were only conducted for this case study due to the excessive computer time necessary to run these simulations.

The second case study was the South Australian Wangary bushfire of 10 January 2005 which resulted in the burning of 77,964 hectares of mainly farmland, in the deaths of nine people and the destruction of 93 homes on January 11 (SA Coroner 2007). On January 10 the fire appeared to be contained, however the fire broke out at three locations during the morning of the 11th. The fire progressed through very open terrain and mainly crops, providing a contrast to the terrain and vegetation of the Kilmore fire. As with the Kilmore case study, comparison of the ACCESS weather with all the AWS observations in the region indicated a good match for temperature, humidity, wind direction and the timing of the wind change. However the 10 metre wind speed comparison found that the simulation under predicted the actual wind speed. A summary of the comparison is contained in the FireDST final report (Cechet *et al*. 2014). The Wangary case study report (French *et al*. 2014b) contains details of the wind speed bias correction factors that were calculated and used in this case study.

The third case study was a portion of the Mt Hall fire that occurred on 24 December 2001 in New South Wales. The Mt Hall fire was ignited by lightning on the 24th of December 2001 in a rugged region of the Blue Mountains. The fire was not contained on the 24th due to excessive weather conditions and crossed Lake Burragorang at around 13:00 on the 25th of December 2001. The fire then impacted the townships of Warragamba and Silverdale destroying 30 properties. The case study covered this fire from when it jumped the lake until it impacted the townships, primarily to evaluate whether an ensemble could be used to model part of a bushfire. Comparison of the ACCESS weather with the AWS observations showed that significant aspects of the AWS meteorological observations were missing or otherwise inadequately represented. The relatively poor simulation may be due to the initial conditions, the complex topography or that the synoptic forcing was weaker. A summary of the comparison is contained in the FireDST final report (Cechet *et al*. 2014). Unfortunately due to the distance of this fire from the nearest AWS there was no ability to calculate wind speed bias correction factors.

Simulation Variability

The main uncertainty in calculating fire spread is a combination of changes in the environmental inputs particularly the meteorological parameters. This paper uses variability in the weather to demonstrate FireDST ensemble functionality. The standard perturbations initially used in each case study are outlined in Table 1. These values were chosen based on the Bureau of Meteorology's comparison of the ACCESS simulation and the observations for Kilmore and Wangary. This results in a standard set of 31 simulations including a simulation with the supplied weather.

***Table 1. Standard variability initially used in all case studies***

| | Minimum | Maximum | Increment | Units/Comment |
|---|---|---|---|---|
| Temperature | -2 | +2 | 1 | Degrees Celsius |
| Humidity | -2 | +2 | 1 | Percent |
| Wind Direction | -2 | +2 | 1 | Degrees |
| Wind Speed | -5 | +5 | 1 | Meters/second |
| Ignition Time | -10 | +10 | 5 | Minutes |
| Ignition point | | | | 200m to the N, S, E and W of the original ignition |

### 2.6. **Ensemble Validation**

Ensemble validation was conducted by comparing the ensemble shape at various time steps in the footprint with a reconstruction of each of the case studies at the same time step. Individual fire simulations were also compared with the reconstruction using the Area Difference Index (ADI) technique defined in Pugnet *et al*. (2013). This technique has the ability to also compare individual simulations that will in time assist to constrain the variability in the input parameters considered for use in the ensemble.

## 3. **Results**

### 3.1. **Weather variability results**

A 30 member ensemble for the Kilmore case study is displayed in Figure 3. Displayed on top of the ensemble are the blue isochrones of the reconstruction of the Kilmore fire at the same time. The reconstruction, which fitted in the ensemble footprint, indicates that the choice of ensemble members provided a wider range of variation than actually occurred in the real fire.

The Wangary fire was contained to a swamp area on 10 January 2005, but there were three outbreaks to the south-east in the morning of the 11 January. Figure 4 shows that if an ensemble was constructed on the 11th and initiated with the actual location and time of each of the breakouts, the ensemble would accurately predict the fire impacting the township of North Shields (which was impacted by the fire).

Despite many attempts it proved difficult to get a realistic ensemble using the standard perturbations for the Mt Hall fire. More variability was required in both wind direction and wind speed to achieve a realistic ensemble shape. Figure 5 is an ensemble simulation for the Mt Hall fire to 1930 EDT on 25th of December 2001. The ensemble fire spread has clearly impacted both Warragamba and Silverdale. The ensemble spread also shows the continuing path of the fire to the east. Although this ensemble simulation closely resembles the reconstruction, the choices of individual simulations in the ensemble had the largest variation from the ACCESS model output compared to the other two case studies. For example in this ensemble the minimum wind direction was increased to 25 degrees less than the ACCESS model output and the wind speed was increased to 20 $m.s^{-1}$ higher than the ACCESS model.

Table 2 displays the actual variability used to produce these ensembles. Mt Hall ensemble had the largest variation, probably due to the fact that the ACCESS weather simulation validated poorly for the available weather observations. Despite the extra variations, the ensembles still produced fire shapes that reflected the actual fire shapes.

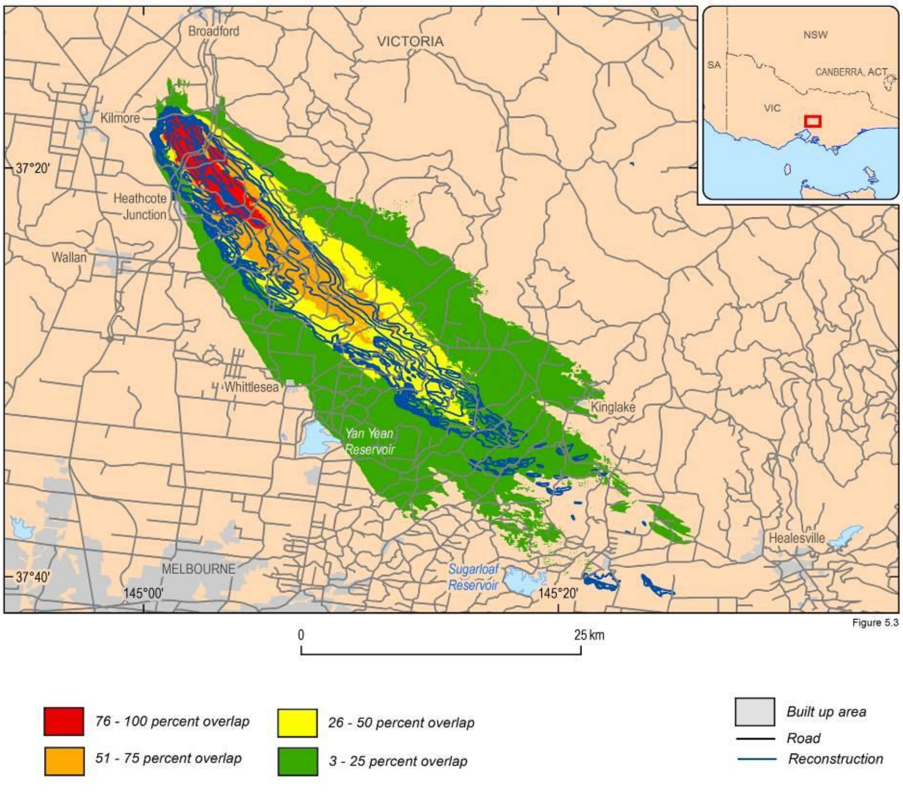


***Figure 3. 30 member ensemble simulation for the Kilmore fire with the actual fire reconstruction from Gellie et.al (2012) (blue isochrones).***

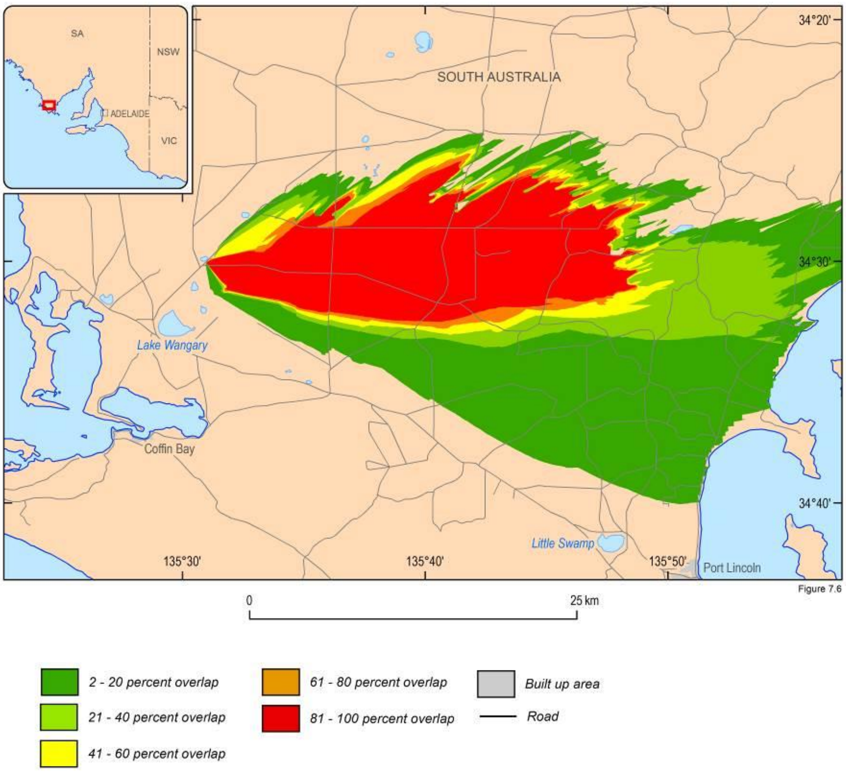


***Figure 4. 39 member ensemble shape file output for Wangary to 15:50 CDT using the actual location and time of the fire breakouts on 11/1/2005.***

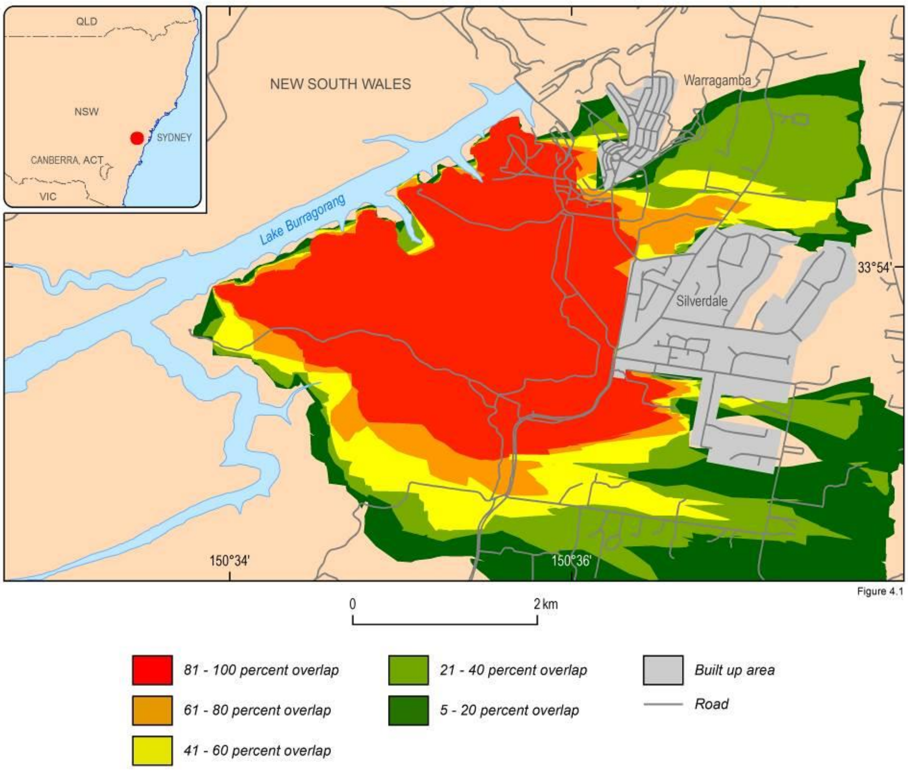


***Figure 5. 25 member ensemble simulation for the Mt Hall fire to 19"30 on 25/12/2001***

*Table 2. Actual variability initially used in the case study examples where the letter "S" stands for the supplied information*

| | Kilmore | | Wangary | | Mt Hall | | |
|---|---|---|---|---|---|---|---|
| Members | 30 | | 39 | | 25 | | |
| | Min | Max | Min | Max | Min | Max | Units/Comment |
| Temperature | -2 | +5 | S | +10 | S | +10 | degrees Celsius |
| Humidity | -2 | +5 | -5 | S | -5 | S | percent |
| Wind Direction | -10 | +10 | -5 | +25 | -5 | +25 | degrees |
| Wind Speed | -5 | +5 | S | +10 | -5 | +20 | meters/second |
| Ignition Time | S | S | S | S | S | S | minutes |
| Ignition point | Y | | S | | S | | 200 to the north,south,east and west |

### 3.2. Exposure of buildings to the firespread ensembles

Figure 6 shows an example for the Kilmore case study of how the house locations can be displayed overlaid on the ensemble footprint. This overlay provides a direct visual representation of the exposure of the buildings to the ensemble footprint. FireDST can then automatically calculate from the building location the number of buildings and people that are potentially exposed to this fire.

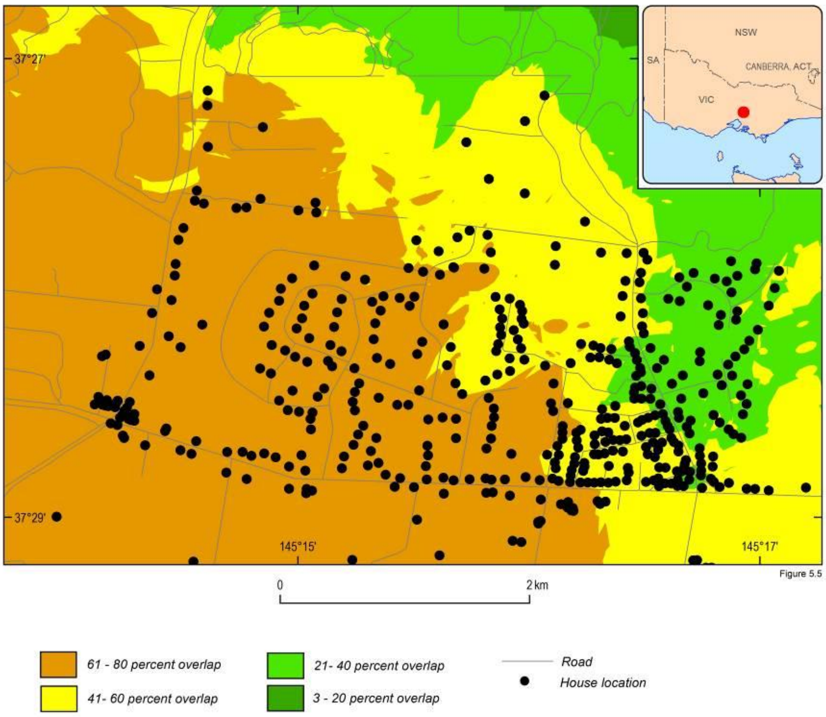


*Figure 6. Kilmore fire, ensemble fire spread with house locations displayed.*

### 3.3. Exposure of buildings/people to the bushfire smoke ensembles

FireDST is able to extend the ensemble approach to smoke and combustion element spread from a bushfire. The ensemble smoke spread was only completed for the Kilmore fire due to the computer processing time taken to produce the multiple simulations (Meyer *et.al*. 2013). Figures 7 and 8 show an example for the maximum concentration and percent overlap of Carbon Monoxide (CO) for an ensemble of 4 fire spread simulations that had different ignition points 500m to the North, South, East and West of the Kilmore ignition point. The two images are required to be considered together.

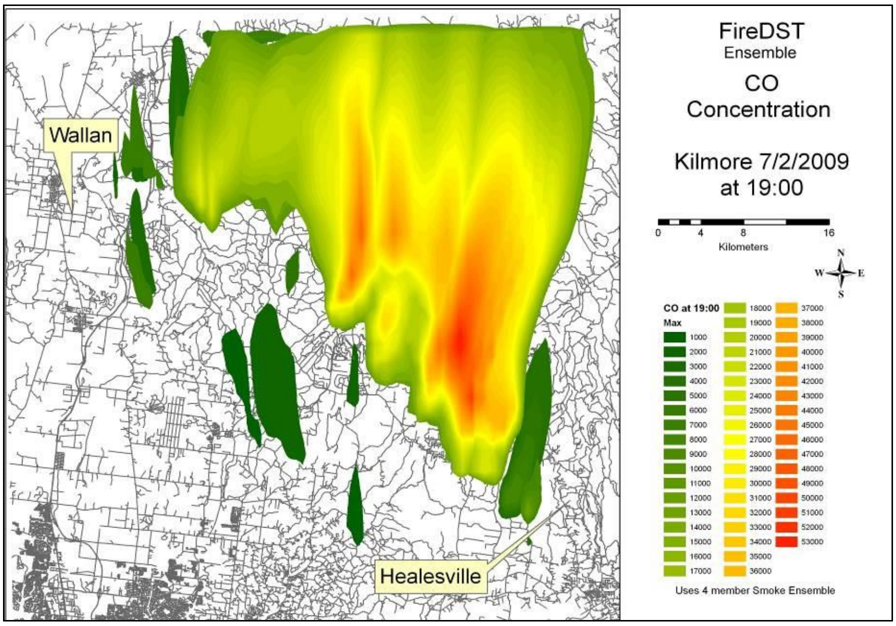


***Figure 7. Map of the concentration of CO at 1900 for the 4 simulations of the Kilmore fire. This concentration map must be used in conjunction with the probability map.***

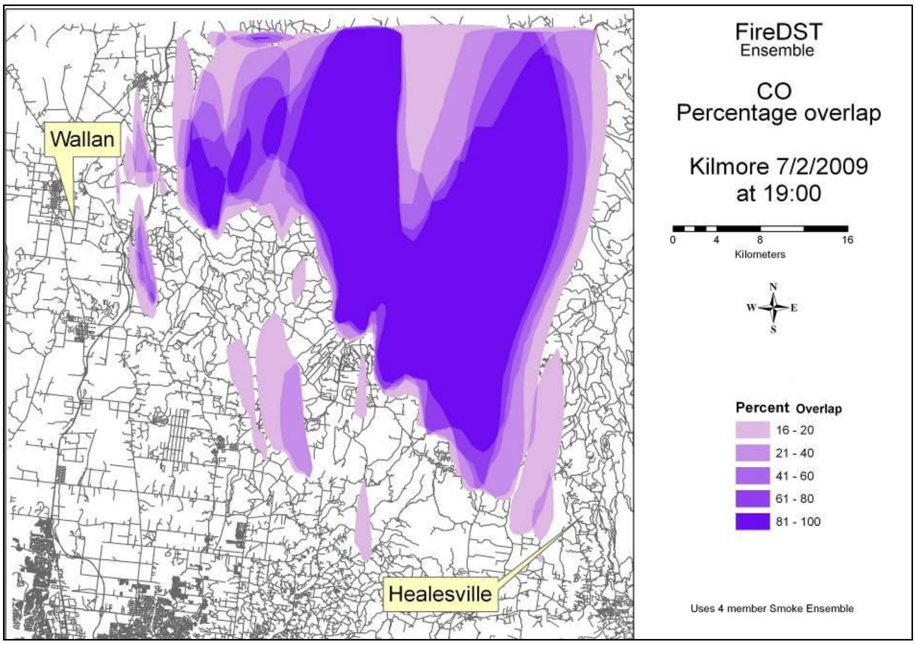


***Figure 8. Ensemble map of the percentage overlap of CO at 1900 for the 4 simulations of the Kilmore fire. This probability map must be used in conjunction with the concentration map.***

## 4. Discussion, Conclusions and Future Work

With the FireDST "proof-of-concept" system we have demonstrated the successful generation of short-term ensemble fire spread as well as modelling associated exposure. FireDST has shown the utility of generating multiple scenarios and generating an ensemble fire spread. FireDST has also demonstrated the ability to derive and display statistical information about people and buildings that are exposed to the ensemble footprint. Graphs and tables can be displayed showing the exposure across the ensemble footprint (e.g. an estimate of those houses and people in the 76-100% probability area for the simulations considered in the ensemble).

This research has shown the development of a simple ensemble overlap of all the individual fire simulations. However it may be possible in the future to include known probabilities for the likelihood of occurrence of each of the individual simulations. The probabilities could be supplied as part of a weather ensemble similar to the weather ensemble produced by the UK Meteorological Office. The probabilities can then be incorporated into the ensemble to produce a probabilistic fire spread which informs users of the likelihood of each ensemble area occurring (i.e. the 3-25% percent overlap area might only have a 10 % likelihood but the 76 to 100% area would have a 100% likelihood.

The next challenge is the operational implementation of this new technology. More work is needed in association with the fire agencies to define a business case for predictive models such as FireDST and a sustainable implementation plan that includes further research, training and field trial validation. A national collaborative effort among Australian fire agencies is clearly required. As a prototype, FireDST has already revolutionised fire simulation modelling. The methodologies developed in the project promise to be an invaluable asset to fire managers working under pressure to make quick decisions that affect lives and infrastructure. Operational fire decision support models could conceivably produce continually updated simulations of severe fire events which address the uncertainty in the input parameters (including the assimilation of fire ground intelligence and real-time performance statistics relating to the fire weather predictions). These simulations, developing products relating to fire spread and impacts, could provide valuable decision support for emergency management. Fire agencies face a steep learning curve in dealing with scenario information which attempts to capture the outcome sensitivity by considering the uncertainty in model inputs. The development of a national approach to fire spread and impacts, as well as standardisation and consistency with the underpinning datasets, would help enable all fire managers to become accustomed to 'what if' scenarios, and to allow transparency in utilisation, validation and learnings across state boundaries.

## 5. Acknowledgements

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