

FUELCEL

A High Resolution Web Based Remote Fuel Monitoring and Bushfire Simulation System

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Abstract – FuelCel is intended as a high resolution, continuously updated view of current fuel hazard levels in the landscape, coupled with a cost distance based bushfire behavior simulation model. At the centre of the system is a pair of remote-sensing based fuel models that account for accumulated litter and elevated fuel in terms of volume and structure respectively. Model outputs are adjusted using satellite derived fire scar data and Rastermatics surface moisture model, which is continuously updated using radar rainfall and gauge observation data. In terms of remotely sensed data, FuelCel employs: USGS/EROS Landsat TM & ETM+ multi-spectral data; small footprint, high density, multiple return LiDAR data; high resolution multi-spectral data; Meteor 1500 S-Band Doppler Radar echo data; and High resolution RGB image data. The system brings together data on fuel loads, vegetation structure and density, terrain, bushfire history and meteorological conditions into a single focal point that provides substantial analysis of bushfire hazard as near real time, high resolution, interpretive spatial data. The web interface and associated geo-processing models can be constructed and delivered using the ArcGIS Server environment. FuelCel is intended to provide a range of bushfire management tools including: Current fuel hazard assessment; bushfire history/frequency analysis; Temporal image loops showing fuel hazard conditions; ‘design’ fire weather based on statistical probability; and the FuelCel bushfire simulation tool. Modeled results and associated data are accessible in a variety of common spatial data formats for use by bushfire management professionals. This paper is intended as an overview of the system.

Keywords: Bushfire, Fuel Model, LiDAR, Landsat, RADAR, Fire-Scar, Simulator.

1. INTRODUCTION

Bushfire management is primarily concerned with activities aimed at reducing the instances and severity of bushfires in the landscape. Bushfire is a spatial phenomenon and bushfire managers are heavy users of spatial information. Appropriately targeted spatial information is an essential part of both mitigation and response, and should be available to decision makers on demand via a seamless and timely platform. Such a platform should assist decision makers in six primary areas:

1. Monitor/tracking current bushfire locations
2. Monitor/tracking bushfire response activities.
3. Monitor/tracking bushfire protection activities.
4. Modeling/monitoring bushfire mitigation activities.
5. Modeling/monitoring fuel volume, structure and condition.
6. Bushfire behavior prediction.

The system outlined here (FuelCel) is designed to assist decision makers with the fifth and sixth primary areas by providing an up-to-date assessment of fuel hazard that is directly linked to a rapid predictive capacity. All primary inputs for the system are derived using remote sensing data and raster data processing techniques, which enhance system suitability for broad-scale implementation as well as frequent updates of components.

In terms of update cycles, FuelCel consists of two major parts. Firstly, reasonably static components such as terrain derivatives and fuel rasters require considerable processing and data resources. These data are predominantly LiDAR derived, and form the structural basis of the system. Updates of these inputs should be linked to a broader LiDAR data acquisition cycle and recaptured in one – three year time steps. The second part focuses on more dynamic components such as fuel volume and condition, which are affected by fuel reduction process (e.g. bushfire) and meteorological status. Fuel reduction processes and meteorological status are modeled continually and act as primary modifiers for current fuel hazard (CFH).

Fire-Scar residual impacts over time are modeled weekly using a natural log after Olsen (1963). Fire Scar data is derived from USGS/EROS Landsat satellite multi-spectral image data, and is updated as data becomes available. Landsat satellites (5 & 7) each capture data in 16 day cycles (8 days in combination – depending on cloud cover, signal anomalies and data gaps).

Meteorological data is sourced via FTP from the Bureau of Meteorology. Rain field data captured by weather radar is provided in six minute time steps, and observational data is provided half hourly.

2. FUELCEL COMPONENTS

Fire Scar Mapping

Retrospective firescar mapping is required in order to both define fuel hazard levels as well as to model bushfire behaviour. A comprehensive fire history database also provides a valuable information source for analysis of historical bushfire trends in terms of fire weather, burn frequency, bushfire extents and fire ecology. Once a comprehensive fire history survey is completed, system operations require fire scar mapping updates, coupled with a weekly recalculation of residual impacts. Residual fire-scar impacts are declared as an 8-bit raster (0-255) where zero equals no impact and 255 equals 100% fuel reduction. The data is then confined to 32bit 0-1 real number range and implemented as a reduction multiplier.

The Rastermatics fire scar mapping system uses temporally sequential 8-bit Landsat (USGS/EROS) data to generate 24-bit raster data in order to build a combined “before and after” dataset relating to each capture date. This approach allows the use of multi-date change detection focussed on a 7:5 normalised band ratio yielding a relatively narrow classification target range. Each 24-bit composite is processed to isolate the target range, and this data is referenced against a vegetation footprint in order to remove non-vegetation

returns. The output of this operation is provided to a decision based interface where an operator makes a final determination of the classification result using reference imagery (i.e. corresponding Landsat image as RGB) in combination with available relevant data such as agency based records/reports and Modis (hotspot) data. Although the first couple of classification steps lend themselves to automation, recurrent remote sensing issues such as signal anomalies, cloud cover, and data gaps, currently require operator intercession, which is facilitated via a decision support interface. These processes output 8-bit raster data sets describing firescars which are grouped according to the relevant Landsat capture dates, and used to adjust fuel volumes over time.

LiDAR Derivates

LiDAR processing is undertaken in order to derive initial system data as follows:

- Digital Elevation Model (DEM).
- ABVGRD data calculated as the vertical distance between a bare earth Digital Elevation Model (DEM) and all LiDAR strikes.
- Digital Canopy Model (DCM), which is derived from ABVGRD data by limiting the influence of non-vegetation LiDAR strikes.
- Multi-Grid Composite (MGC) data (figure 1), which is derived from ABVGRD data, where vegetative LiDAR strikes between 0.6 metres and 4 metres were grouped into height classes, gridded, and combined in RGB thereby providing a 24-bit colour, interpretative dataset describing structural elements of understorey vegetation (Power, 2006).
- Surface Moisture (SM) base data, is derived using Rastermatics iterative combination of directional flow and cost distance algorithms, which is used as a spatially explicit descriptor of surface moisture gradients (Power, 2009).
- Bushfire Hazard Terrain data to be derived from the DEM and calculated using adjusted slope and aspect data.

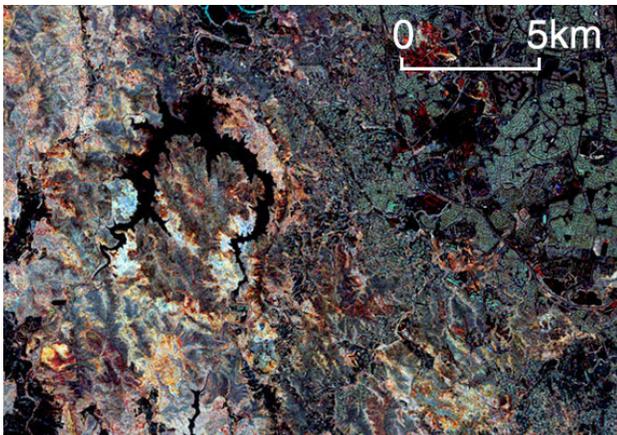


Figure 1. MGC data showing understorey structure. The data shows the lower 4m of the vegetation profile separated into three height classes and displayed through RGB colour channels.

Multi-Spectral Reflectance Data

Multi-spectral reflectance data is employed for two principle purposes:

- Calculate a seven year (approx.) average simple ratio of red and infrared spectral bands (RVI) (Deering, et al. 1975). This is to reduce the impact of seasonal variations in the data so that it can be used as part of Rastermatics ‘steady-state’ accumulated litter model. This is derived from Landsat TM data and is accessed from the USGS/EROS archive.
- A Boolean classification of vegetation/non-vegetation generated from a normalized difference vegetation index (NDVI) calculated using high resolution satellite imagery such as Quickbird, Ikonos, Worldview etc*.

Accumulated Fuel Model (AFM).

The AFM (see figure 2.) accounts for litter fuel at the forest floor in terms of volumetric distribution. This fuel class contributes to hazard levels at a fundamental level. Litter fuel provides fuel continuity and accommodates fire spread. The volume and condition of the class are key indicators of bushfire hazard, with moisture content, which is highly dynamic and very sensitive to humidity and rainfall, providing the most important risk factor in terms of fuel hazard.

This data is derived as the combination of long term average RVI, DCM and SM base data. The specific equation is not shown here however, results of regression analysis for this data show that the numeric relationship between field samples (adjusted for moisture content) and Rastermatics ‘steady state’ AFM is a very good fit and returns an accurate account of litter fuel by volume (Power, 2010).

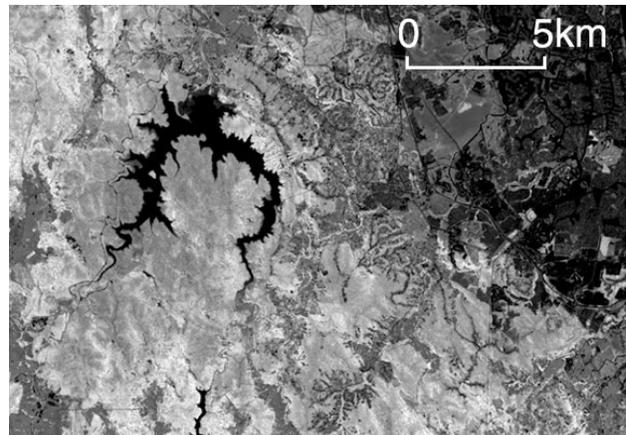


Figure 2. AFM data showing litter fuel by volume. Litter volumes are modelled using a specific combination of RVI, DCM and SM data. The greyscale indicates higher volumes as lighter tones.

Elevated Fuel Model (EFM)

The EFM is focussed primarily on understorey fuels. This fuel class has the capacity to contribute significantly to hazard levels as it acts as a fuel ladder and can accelerate flame development and rate of spread. LiDAR has a considerable capability to penetrate canopy and provides a means to produce an accurate account of understorey fuel distribution and density at high resolutions. The EFM is derived from LiDAR based MGC data and is focussed specifically of the lower four metres of the vegetation profile. EFM data also provides an important input for bushfire behaviour simulation by assisting calculations for flame length and rate of spread. EFM also may be used to indicate ember launch zones.

Additionally, MGC data (from which EFM data is derived) provides a crucial point of reference for mitigation planners. Temporal analysis of these data, particularly with reference to bushfire history, provides an insight into the dynamic behaviour of understorey. For

example, analysis of these data was recently shown to support the view that the inappropriate use of fire in the landscape can lead to an increased bushfire hazard in the longer term. Field reports made by SEQ bushfire management personnel, suggest that prescribed burning conducted under conditions that promote the consumption of the fuel bed to the A-horizon (organic soil), has a propensity to adversely impact floristic composition in terms of succession. It has been observed that a number of prescribed burns of this character have resulted in the replacement of grassy understorey with successional understorey species such as black wattle or lantana. Temporal analysis of MGC and bushfire history data adds weight to these observations, as it can be used to show a clear link between specific bushfire events, antecedent meteorological conditions and longer term outcomes in terms of understorey dynamics. Results for the EFM model have been assessed in the field severally, by SEQ bushfire management personnel (eg. QFRS, DERM, BCC, GCCC), (Power, 2006).

Surface Moisture Model (SM+)

Rastermatics' Surface Moisture base data (SM) (see figure 3.) is used to describe local surface moisture gradients. Surface moisture and curing rates vary locally according to topography and runoff (contributing area). For example, gully and riparian vegetation have access to more water, for longer periods, than vegetation communities on ridges and spurs.

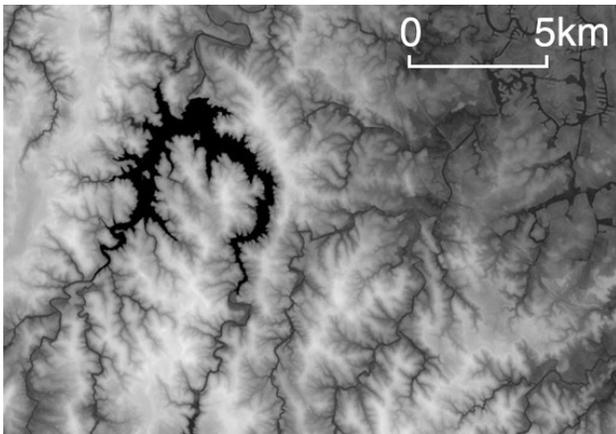


Figure 3. SM base data showing surface moisture gradients. This data is produced using an iterative combination of directional runoff and cost distance algorithms. Lighter tones indicate faster drying surfaces.

Rastermatics' SM+ incorporates Bureau of Meteorology (BOM) Radar rainfall, observation and forecast data in order to model the impact of weather on bushfire fuels. There is no doubt that weather makes the most dynamic and significant contribution to bushfire hazard levels. Excellent data and data facilities made available by the Bureau allow these impacts to be rapidly assessed in near real time. Radar rainfall data overcomes significant spatial generalization problems (particularly at local scales) caused by the use of extrapolated rainfall gauge data. Even casual weather observers would notice that rainfall can vary markedly, with significant differences found within a kilometer or so. This is particularly significant to bushfire fuels when rainfall is low. Radar capabilities significantly enhance our ability to more accurately map spatial and temporal rainfall patterns, and this enhances our ability to model the impact on bushfire fuels and simulate bushfire behavior at the local scale.

The SM+ model uses rainfall data to calculate continuous antecedent precipitation index (API) after Fedora and Beschta (1989). API is used in concert with SM base data, current temperature data and vapor pressure calculations in order to produce an 8-bit raster, which is used as a reduction multiplier in the same way as the fire-scar residual impacts raster mentioned previously.

Model Integration

AFM and EFM are combined (via WLC) in order to generate an 8-bit Total Fuel Hazard raster (TFH). TFH is modified using Fire-Scar residual impacts (weekly), and SM+ outputs (hourly), to produce a Current Fuel Hazard raster (CFH), which is published hourly.

Continuous API is produced hourly by adding 10 x 6 minute radar rainfall files (NetCDF), converting the daily reduction factor to an hourly reduction factor and re-distributing it according to established time classes in order to account for diurnal differences in surface moisture reduction. Hourly dew point and air temperature gauge observations are interpolated to generate equivalent raster data for the model area. Dew point observations are converted to vapor pressure using the Bureau of Meteorology method (BOM, 2011), and these are directed as inputs to CFH calculations. CFH data is further integrated with terrain data in order to produce a Current Bushfire Hazard (CBH) data set, which is also published hourly and made available as layer option inside the web-interface. These operations are implemented via geo-processing models in the Arc Server environment. Hourly processing is initiated by the server clock (allowing for a reasonable time delay in posting files at BOM), and proceeds sequentially, resulting in the publication of hourly API, SM+, CFH and CBH. Hourly processing sequences are estimated to take around twelve minutes to generate and publish all four hourly data sets. These four datasets are further processed in order to provide 12hour, 12 day (9.00am and 3.00pm) and 12 week (9.00am and 3.00pm average) image loops. Fire-Scar residual impacts are recalculated and applied weekly.

Bushfire Simulation

Bushfire simulation is an area of dynamic development. Although many simulation applications, including those developed at considerable cost by large institutions, seek to execute a large number of calculations in small time steps, one of the fundamental goals of bushfire behavior simulation is to provide timely and reliable advice regarding the projected location of a bushfire front. This requires computational economy while maintaining an appropriate resolution and accuracy. It should be noted that mathematically complex raster simulations lose a lot of their elegance when input data is generalized beyond practical limits. For example a 20 hectare bushfire footprint represented by five raster cells is unlikely to be considered favorably in an operational context regardless of the mathematics, particularly if requires a super computer and a team of experts in order to achieve it. What is required is a tool that is as simple to use as an i-phone application, but which provides a quick return, high resolution predictive capacity to assist decision making in the short term.

The FuelCel bushfire simulation system is designed as an iterative anisotropic cost distance operation. The operation relies on a CFH data inputs in combination with modified wind speed and direction data to generate an inverse rate of spread that is employed as a friction surface. Bureau of Meteorology wind observations are modified using WindNinja software (Forthofer, et. al. 2009), and rate of spread modifications are implemented iteratively with reference to continuously updated source data using localized

wind/slope direction correction equations (eg. Sharples, 2008). The use of anisotropic friction encourages simplified calculations and works to reduce repetition as data need only be recalculated due to forecast (or actual) changes in meteorological conditions, or to update fuel rasters with reference to mitigation actions such as mechanical clearing or back burning.

This approach facilitates computational economy by focusing on distance traveled per time step in preference to cell to cell fire spread calculations. Importantly, time steps are uncoupled from cell size and this allows the use of high resolution inputs. As a result high resolution outputs offer the prospect of being useful for the management of small and medium sized planned burns and bushfires, as well as large and/or catastrophic bushfires. Although the coupled fuel model and bushfire simulator means that the simulator tool is only available for areas with corresponding fuel model coverage, virtually all inputs are derived from standard remote sensing products, and this suggests that a simulation capacity can reasonably be implemented for any area there is radar rainfall, and standard weather observation and forecast data available. The key limitation in determining this is a lack of 'training' data. Calibrating rate of spread variations for empirical models requires a level of statistical significance that currently not available, although there are well tried and trusted equations available that are based on previous work (e.g. McArthur, 1966). The cost-distance approach is a further move away from theoretical heat flow models. While initial results appear promising, further calibration and testing of the bushfire simulation tool is required. Initial calibration and testing have been conducted using both McArthur's (1966) results and data published as part of Project Vesta (Gould et al. 2008).

3. DISCUSSION

There is a need for rationalization in the area of spatial analysis for bushfire management. Until relatively recently the work of Surveyors and Cartographers could be characterized with the same sense of permanency as statutory documents or standard operating procedures. Spatial science has since become a very dynamic field, now integrally involved with remote sensing, spatial modeling, monitoring, and tracking. Spatial data options for mapping various criteria are changing. For example the use of LiDAR permits the structure of understorey fuels to be represented in raster format rather than being allocated a score per polygon object.

An important aspect of FuelCel is the integrated nature of the continuously updated fuel models and the simulator. A limiting factor in the propagation of behavior models between regions and jurisdictions has been the use of fuel models derived from vegetation polygon data. The practice of mixing and matching vegetation communities and attributes, with model requirements is contentious. Vegetation mapping can be uneven in quality, incomplete in coverage, and out of date. To propagate a bushfire behavior model with the proviso the potential users generate fuel models based on vegetation polygons is not likely to result in a consistent predictive capacity between regions and jurisdictions.

The FuelCel fuel model and bushfire simulation system accounts for topography, meteorology and biomass in terms of

volume, structure and condition. While the system appears to produce valid results, it is acknowledged that further testing and calibration are required, and this raises the need for observational data about rate of spread. The robust, and some what ubiquitous character of McArthur's (1966) results, suggests that the rates of spread derived there from should be reasonably correct. Prudence urges however, that it may be beneficial to everyone involved with bushfire management to take advantage of evolving technologies in order to capture a wide ranging dataset for the purpose of enhancing our predictive capacity and general understanding in relation to bushfire. Indeed steps could be taken in order to incorporate the capture incidental rate of spread data more broadly as part of bushfire management activities across multiple jurisdictions. One means of accomplishing this in situ is by deploying micro UAV mounted thermal imagers (eg. Honeywell RQ-16 T-Hawk). In this scenario trained operators would coordinate a series of unmanned flights above the field of operations for the purpose of capturing video stream and thermal images. This would facilitate the capture of calibration datasets and also provide a valuable opportunity to access a real-time video stream of the event from an aerial perspective.

The FuelCel web delivery system is not intended as a public web site, but as a bushfire management tool. For further details, contact the author at: chris@rastermatics.com.au

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