# A SPATIAL DECISION SUPPORT SYSTEM FOR MAPPING BUSHFIRE HAZARD POTENTIAL USING REMOTELY SENSED DATA

*Christopher.J. Power*
*Spatial Information Services, Office of the CIO, Organisational Services, Gold Coast City Council*
*School of Geography, Planning and Architecture, University of Queensland*
*powerch@optusnet.com.au*

## Abstract

This paper describes a proposed method for mapping potential bushfire hazard. Subject to endorsement by the Queensland Department of Emergency Services, it is proposed to utilise this methodology to fulfil the Gold Coast City Council's responsibility under the *Queensland Integrated Planning Act 1997*, in relation to mapping potential bushfire hazard pursuant to the *State Planning Policy 1/03 Mitigating the Adverse Impacts of Flood, Bushfire and Landslide (SPP 1/03)*. The method utilises high-density, small footprint LIDAR and high-resolution multispectral IKONOS data in combination with Gold Coast City Council (GCCC) GIS datasets to produce an accumulated fine fuel model and an elevated fuel model. Fuel parameters generated using these (cartographic) models are combined with slope and aspect data generated using standard algorithms and customised data scaling techniques applied to a detailed digital elevation model (DEM) interpolated from LIDAR data. Data analysis and aggregation is achieved in a spatial decision support system using multi-criteria evaluation (MCE) and weighted linear combination (WLC) to produce a high resolution, continuous scale hazard surface. Bushfire hazard factors and constraints are scaled and weighted to conform to recommendations outlined in the SPP 1/03 appendix 3. The spatial decision support system described here produces a highly detailed cartographic product that is suitable for identifying properties and assets at risk from bushfire, and provides a valuable tool for bushfire managers and town planners.

## Introduction

*The Queensland Integrated Planning Act 1997* provides a framework for managing development in the State. As part of this framework, State Planning Policies provide (under Schedule 4) a way of ensuring that the development requirements of the State are integrated with those of local governments. *State Planning Policy 1/03 Mitigating the Adverse Impacts of Flood, Bushfire and Landslide (SPP 1/03)* took effect on 1 September 2003. Information and advice for interpreting and implementing SPP 01/03 is provided as *State Planning Policy 1/03 Guideline – Mitigating the Adverse Impacts of Flood, Bushfire and Landslide*, and within this document, *Appendix 3, Undertaking Natural Hazard Assessment – Bushfire, (SPP 1/03 Guideline)* deals specifically with the recommended methodology for defining bushfire hazard potential in the landscape.

Problems with the methodology include a limited ability to account for fine scale spatial variability. The system employs a two-step categorical classification process that results in scalar insensitivity. Additionally the vegetation community criterion is often reliant on categorical classes for vegetation communities (such as regional ecosystem maps) that do not account for spatial variation within or between communities such as variations in stand density and biomass, or ecotone effects. Similarly fine scale variations of slope or aspect values are lost within broad classes. Given that bushfire is a local scale phenomenon and its behaviour is significantly influenced by variations within the landscape, it follows that hazard level can be described using continuous scale factors. Relatively invariant factors such as potential fuel load, slope and aspect can all be measured at a continuous scale using remotely sensed data, and a data aggregation solution capable of combining bushfire hazard criteria while retaining continuous scale measurement can be found in spatial decision support systems (SDSS).

## Background

The process of defining bushfire hazard potential under the requirements of the *Queensland Integrated Planning Act 1997* considers the relatively invariant bushfire factors because of town planning time horizons. These are slope, aspect and vegetation communities, all of which can be measured using remotely sensed data. Measurements for slope and aspect are routinely extracted from digital elevation models (DEMs). Small footprint, high density LIDAR is capable of delivering a high-resolution detailed DEM using iterative interpolation routines. LIDAR can also be used to measure structural properties of vegetation communities such as canopy height, canopy base height and understorey densities (Peterson et al.., 2003). Extraction of measurements for both slope and aspect involves straight forward DEM transformations, which provide inputs to a SDSS with minimal additional processing. Extraction of vegetation structural properties from LIDAR (in this study) involves the extraction of above ground heights from non-ground returns, and multiple grid generation.

High resolution, multi-spectral satellite data is also used to describe vegetation characteristics. In particular band ratios such as normalised difference vegetation index (NDVI) and the red vegetation index (RVI) have been shown to be good indicators for fuel accumulation potential (Brandis & Jacobson, 2003). The increasing availability and utility of remotely sensed image helps to reduce uncertainty in mapping fuels and improve our ability to assess spatially and temporally variant characteristics to a level that is simply not possible with traditional vegetation mapping techniques. A number of models aimed at deriving measurements relevant to fine fuel accumulation from multispectral satellite imagery have been shown both theoretically and empirically to predict bio-physical parameters relevant to fuel accumulation (Gong et al., 2003).

## Spatial Decision Support Systems

Spatial decision support systems (SDSS) provide a powerful and easy to use interface to combine cartographic models and other image data to define solutions to unstructured and semi-structured problems. SDSS supports a range of decision-making styles and approaches by generating a series of feasible alternatives through an interactive and recursive process in which decision making proceeds by multiple passes, sometimes involving alternative routes rather than a simple linear path. Examples where SDSS techniques have been used in fire management include Varela et al. (2005), Barrett et al. (1999), and Jones et al. (2004).

The basic strategy is to divide the problem into well-defined smaller pieces, analyse each piece separately, and then integrate the pieces logically to produce a solution, following Jankowski's (1995) general framework. Decision criteria are formally evaluated and allocated a score based on expert opinion regarding the weight each criteria will carry within the decision making process. In many instances this process is achieved using multi-criteria evaluation (MCE) and, in this instance, expert input and guidance has been provided both through the SPP Guideline 1/03, and through its principal author (Ray Robinson, pers. comm. 2005). Integration of MCE techniques and the Gold Coast City GIS framework is achieved through weighted linear combination (WLC).

The criteria considered in definition of potential fire hazard are slope, aspect and vegetation communities. Following the additive system (ranked classification) recommended in the SPP Guideline 1/03 where a linear scale (0 – 18.5) is used, the following criteria weightings are developed: Slope = 0.27; Aspect = 0.19; Vegetation Communities = 0.54.

## Slope

The influence of slope is integral with that of aspect and wind. The complex interaction of these factors are responsible for the mechanics of bushfire spread rate and direction in the landscape. When the direction of increasing elevation of a slope aligns with wind direction the rate of spread of a fire is increased. For stable meteorological conditions and fuel loading, the advance of a bushfire up a slope of 10 degrees has been reported to be double the rate of spread of bushfire on level ground. The rate of spread (ROS) of the fire up a slope of 20 degrees is said to be four times the rate of spread of the fire on level ground (McRae, 1998). The interactive effects of wind and slope are the principle determinants of the direction of fire spread, and the magnitude of this effect is dependant on wind speed. At low wind speeds slope is the predominant determinate of spread direction, however as wind speed increases, this factor becomes the dominant influence on spread direction. Strong winds can drive a fire front perpendicular to slope (Cheney et al., 1998).

The effect of slope in bushfire dynamics has been described in terms of the delivery of both convective and radiative heat, and the enhanced proximity of available fuel. In a sense the effect is comparable to that of elevated fuel, in that increasing slope places available fuel closer to the path of convective currents and radiative heat, thereby increasing the proximity of flash point temperatures to adjacent fuel sources. Nobel et al. (1981) and others have considered the effect of slope to be exponential to rate of spread.

The 30% slope threshold suggested by both the SEQ fire and biodiversity consortium and the SPP Guideline 1/03 represents an important point at which the behaviour of bushfire is considered to become more dynamic in terms of ROS and intensity (according to available fuel). Bushfire dynamics are increasingly influenced at higher slope percentages (the Gold Coast LGA contains slope percentages that often range to and above 200%), and setting the slope criterion at the 30% threshold defines the entire range above the threshold at a high risk. While this seems like a blanket classification, the use of this approach is supported by operational constraints. For example, slopes above 30% present significant access constraints for both men and machinery and hence the establishment of fire breaks and other mitigation works.

Slope definition algorithms applied to a detailed digital elevation model (DEM), interpolated from Lidar ground returns, produce a raster slope surface. Using attribute value files, cell values are reassigned to reflect the classification outlined in the SPP guideline 1/03. Figure 1 shows the effect of assigning continuous scale values from 5% to 30%, and Figure 2 shows the results of assigning the SPP slope class values (both images are rescaled to the 8-bit raster integer value range 0-255 in order to standardise inputs for WLC). It can be seen from these results that the major difference is in continuity. The stepped effect of the SPP slope class image (right) is ameliorated by the use of continuous scale (left).

Figure 1: Slope reassigned in continuous scale

Figure 2: Slope in SPP classes

## Aspect

On the Australian eastern sea board (particularly at Gold Coast latitudes) the difference between south-easterly and north-westerly air flow is quite marked. The effect of moisture laden south-easterly winds present a stark contrast to the hot dry westerly and north-westerly winds that arrive from across the arid interior. Westerly and north-westerly winds are strongly associated with hazardous bushfire conditions, and slopes facing these

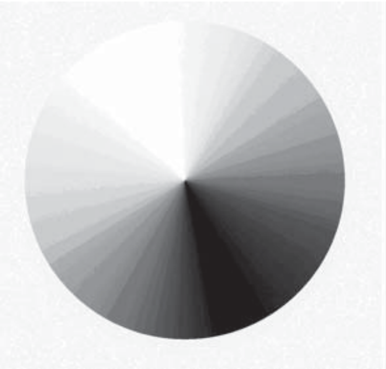


Figure 3: Aspect reassigned in continuous scale


Figure 4: Aspect in SPP **classe**s

aspects are exposed to early afternoon high temperatures and hot, dry air flows. Figure 3 shows the effect of declaring the aspect criterion reassigned in continuous scale for a cone, and Figure 4 shows the effect of assigning values corresponding to the SPP aspect classification.

## Vegetation Communities

Vegetation communities are considered in terms of fuel types. This criterion is split between two fuel models: 1. An accumulated fine fuel model generated using a combination of NDVI and GCCC GIS data, and 2. An elevated fuel model generated using small foot print LIDAR. Polygon based GCCC vegetation maps are used to account for vegetation types described in the SPP Guideline 1/03 (Appendix 3) as virtually fire proof (i.e. intact rainforest, mangrove forest, intact riverine rainforest).

## Accumulated fuel model

Fine fuels are organic materials less than 6 mm in diameter at the surface. Fine fuel in eucalypt forests (litter) consists predominately of leaves, twigs, woody fruits and bark. Cheney et al.. (1992) also considers grasses, herbs and bracken (near-surface fuels) as contributing to the fine fuels category, and Corbeels (2001) makes a further distinction based on the stage of decomposition. The fine fuels fraction of total fuels has also been described as 'flash' fuels (principally USA e.g.. Keely et al., 1999) because it is readily ignited during periods of fire weather. There is strong agreement that the contribution of fine fuels in bushfire dynamics is very significant. Fine fuels provide continuity of flammability and promote rate of spread. The report of the inquiry into the 2002-2003 Victorian bushfires (State Government of Victoria, 2003), nominates fine fuels as being responsible for the creation of the fire front.

The rate of fine fuel accumulation is a required input to determining fuel availability, and these factors are closely related to the large body of work conducted as part of global efforts to implement carbon accounting systems (e.g. Corbeels 2001; Saabe & Veroustrate, 2003; Boresjö Bronge & SwedPower, 2004). In this context researchers have developed a number of models that use satellite data inputs (principally band ratios) to produce measurements such as Net Primary Production (NPP) (Tans et al., 1990); fraction of photosynthetically active radiation (FPAR) absorbed by green plants (Chen & Cihlar, 1996); leaf area index (LAI) (Chen and Black, 1992; Hua et al., 2001); and light use efficiency (LUE) a measure of the efficiency which APAR (absorbed photosynthetically active radiation) is converted to biomass (Gower et al., 1999). There have been numerous examples where this approach has been applied to mapping fuel properties (e.g. Kötz et al., 2003; Brandis and Jacobson, 2003).

The fundamental connection between carbon accounting and bushfire fuel mapping is that bushfire fuel is essentially a transient state of carbon in the vegetation carbon cycle. In a theoretical and logical sense fuel accumulation can be represented as a percentage of forest productivity (per unit area per unit time) that is determined by both the rate of litterfall and the rate of decomposition. This suggests that LAI calculations (after Hua et al. 2001) can be linked to litter turnover calculations using Olsen's (1963) negative exponential decomposition equation, provided that accumulation and decomposition rates can be adequately defined.

Olsen's (1963) equation relates fuel accumulation over time to canopy biomass which can be approximated using LAI - (e.g. Boresjö Bronge & SwedPower, 2004), or by RVI (red vegetation index or simple ratio) and canopy height - e.g. (Brandis & Jacobson, 2003). Brandis and Jacobson (2003) and Fox et al., (1979) deduced that rate of accumulation could be applied as a function of canopy biomass despite short term temporal variability due to weather impacts on foliage. Statistical analyses of field measurements show longer-term stability in the fuel accumulation rate in SEQ Eucalypt forests (Birk, 1979).

The use of NDVI to define biophysical parameters such as LAI is quite common however it is not straightforward. Remotely sensed multi spectral image data contains reflectance information that is affected by numerous causes. Phenology, growth rate and disturbance induce inter-annual and seasonal changes in biophysical properties, while sensor conditions such as viewing angle, atmospheric path length, signal contamination produced by water vapour, aerosols and background soil colour represent extraneous information in the context of mapping accumulated fuels.

Minimisation of sensor and most signal anomalies can be optimised by careful scene selection and by rigorous geometric, radiometric and atmospheric correction. Time related NDVI variability is usually accounted for using time series data e.g. (Danaher et al., 1992, Hua et al. 2001), however, in this instance (due to cost constraints) a single date image data set has been used. This meant that NDVI time series based methods of defining the herbaceous /woody partition were unavailable, and because account must be taken of the spectral reflectance differences between herbaceous and woody surfaces (in order to avoid inaccuracies produced by applying woody biomass transformations to herbaceous cover such as pastures and other grasslands), LIDAR data was manipulated to yield a canopy height surface which presented a simple means of distinguishing the partition. The WLC use of relative scale data sets rather than absolute scale allowed the NDVI/LAI conversions to be effected using two pre-existing equations without developing site specific regression equations.

The equations used for the NDVI/LAI conversions used here are:

| | |
|---|---|
| Woody LAI | LAI = -1.51 + 1.17RVI |
| Herbaceous LAI | LAI = -0.9 + 0.72RVI |

*Note: NDVI and RVI can be inter-converted (after Hua et al. 2001)*

The SPP Guideline 1/03 (Appendix 3) categorises grasslands and pasture principally according to the degree of disturbance, i.e. grazed or slashed grasslands are ranked lower than undisturbed grasslands. While these LAI transformations account for differences between woody and herbaceous vegetation components, the difference between disturbed and undisturbed grasslands and pasture is less clear. In this context GCCC GIS inputs - landuse maps and grass mowing contract maps, were used to define (spatially) the distinction between disturbed and undisturbed grasslands and to rank the degree of disturbance based on established mowing categories as well as grazing pressure information. Herbaceous LAI differences attributable to disturbance were weighted to reflect the SPP guideline 1/03 (Appendix 3) ranks for disturbed and undisturbed grassland and pasture (i.e. this component is further reduced by a factor of up to 0.4 to reflect SPP Guideline 1/03 scores i.e. undisturbed grassland ranked at 5/10 and disturbed grassland at 2/10).

## Elevated fuel model

The spread of fire into elevated fuel layers can significantly alter fire behaviour. Higher fuel loads due to the presence of shrubs and the effects of convection cause larger flames and a higher rate of spread (ROS). Shrub layers contribute to flame development by providing a vertical path for ignition and thereby increase the risk of crowning. Shrubs act as a lattice for suspended fuel and increase the likelihood of spotting and ember attack through convective activity. McArthur, (1966) noted that the collapse of a convection column at a fuel break can precipitate an ember attack. Elevated fuel (including bark fuel) is closely associated with ember attack, and at the urban/bushland interface it poses a significant threat. Buckley (1994) reported from a forest site in Gippsland that the presence of shrub fuels increased the available fuel by a factor of 2.5 and noted that up to 42% of the shrub layer fuel weight could be made up of suspended (dead) fuel.

LIDAR data can be manipulated to indicate the presence/absence of shrub layer fuel. This is achieved through the following processes by, firstly, partitioning the data into ground and non-ground returns using a progressive morphological filter (e.g. Zhang et al., 2003). A detailed digital elevation model (DEM) is interpolated using LIDAR ground returns and LIDAR non-ground returns are updated with DEM values to provide ground elevation values for each non ground point. The difference between non-ground and ground elevation values produces an 'above ground' value for all non-ground returns. Non-ground returns with aboveground values of 4 m or less, are divided vertically into three files per unit area in a GIS . The lowest 0.6m is not considered so as to avoid the significant error range of the morphological filter resulting in an increased likelihood of including mis-classified ground returns rather than non-ground returns. Three gridded files are prepared per unit area from non-ground returns using the above ground ranges 0.6m–2m; 2m–3m and 3m–4m. Ground return points with standardised *Z values (equal to the lower limit of the aboveground increment range minus 3m) substituted for the original Z value are included in the gridding process in order to increase definition. Additional points (also with Z values equal to the lower limit of the aboveground increment range minus 3m) are created over water bodies and included in the interpolation in order to control the 'undershooting' effect associated with minimum curvature interpolation. The resultant gridded files are rescaled as 8-bit raster objects and then combined using the equation;

{(0.6m–2m * 0.5) + (2m–3m * 0.25) + (3m–4m * 0.25)}. Note that this equation weights the lower file more heavily due to the broader range as well as the significant role of near ground fuel in fire behaviour.

*Z values refers to reduced level.

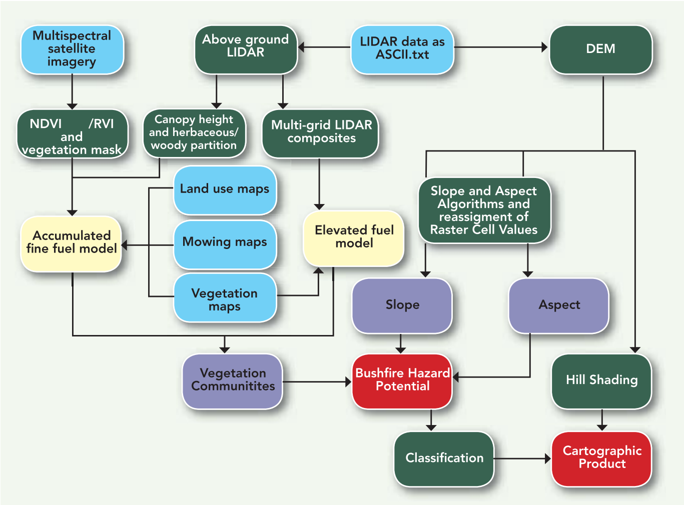
## Field Verification

Field verification carried out in April 2005 at the Lower Beechmont Conservation Area and Coombabah Lakelands shows a high correlation between field observations of elevated fuel and the LIDAR based elevated fuel model. Multi-grid composite surfaces generated following the methodology described here were used to plot coordinates representative of various levels of elevated fuel. A field team then navigated to these coordinates (using Trimble Geo Explorer XT GPS enabled PDAs), and photographed and classified elevated fuel levels in situ. A total of 32 points were sampled with an accuracy rate of 87% in predicting the presence of elevated fuel in the form of a shrub layer. Six percent were found to be an error associated with mis-classified ground returns caused by platform instability (pitch, roll and yaw) at swath edges (which can be corrected in a GIS). The remaining 5% error is thought to be associated with regrowth between the LIDAR collection dates (2001) and the date of field sampling (2005).

## Data Aggregation

Data aggregation is achieved using the following data flow: base data → data transformations and processing routines → map algebra → WLC → cartographic output. The frame work (Figure 5) summarises the process. In general, slope and aspect are derived from the DEM, fine fuel and elevated fuel models are described above and the final aggregation is achieved using WLC after Voogd (1983), where the process follows the form: $S = \Sigma wx$, so that the final hazard score (S) is the sum of criterion scores (x) by their respective weightings (w). This is shown graphically in Figure 6. This example is based on the standard 1:10 000 Nerang map sheet area and shows how the SDSS criteria (elevated fuel and fine fuel share the 0.54 weighting for vegetation communities), are combined as 8-bit raster

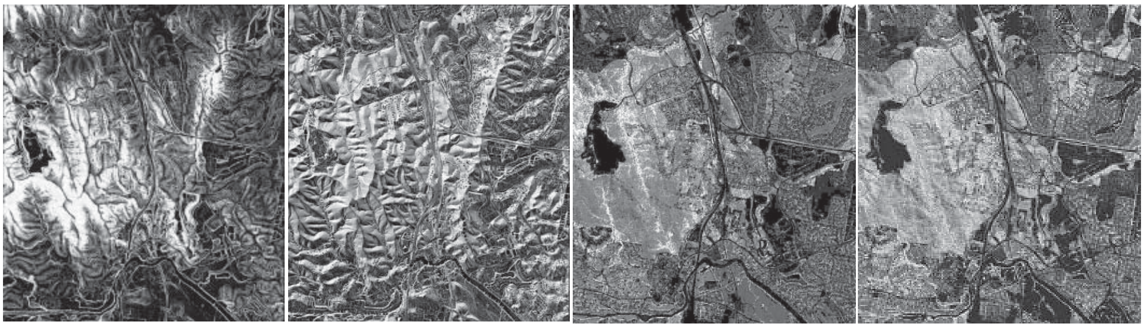
### Figure 5 Data aggregation framework




data scaled from 0 - 255. The result of data aggregation process is shown as Figure 7. This image indicates the level of high hazard as lighter and low hazard as darker. Bushfire hazard potential is quantified as a continuous scale raster surface.

The cartographic output is achieved by classifying the raster hazard surface to match the SPP 1/03 thresholds. In this case the upper threshold was adjusted due to the characteristically skewed image histogram associated with high resolution image data. The 'high' class was defined as 152 - 255 (which corresponds to 179 - 255 when a 10% clip is applied to the histogram) and the 'low' defined as 0 - 89. A 5x5 adaptive median filter was applied to eliminate stray pixels. The result is then combined with hill shading to assist cartographic interpretation, and supplied as an .ecw image file.

### Figure 6. Graphic representation of the WLC process



(Slope x 0.27) + (Aspect x 0.19) + (Elevated fuel x 0.27) + (Fine fuel x 0.27)

### Figure 7 Bushfire Hazard Surface

## Discussion

Among the benefits of using this method for mapping bushfire hazard potential is the utility of deploying derivations of the same data inputs to closely related mapping objectives such as predictive fuel load modelling/mapping, and rate of spread modelling. Also it should be noted that this is only a basic use of decision support systems and their utility as a management tool can account for multiple objectives as well as multiple criteria. Many additional criteria (factors and constraints) can be included within MCE processes regarding bushfire hazard potential. Barrett et al. (1999) and Jones et al. (2004) show that the flexibility and recursive character of SDSS can assist with achieving consensus among decision makers by stripping the components of a decision back to nuts and bolts.

The use of remotely sensed data helps to address the limited capacity for polygon based mapping to account for important fine scale spatial variation. The applications of remote sensing in the areas of fuel moisture content, fuel type and fire risk mapping are manifold and advancing at a great rate. The technology and capacity to provide a wide range of spatial solutions to bushfire managers using remote sensing and cartographic modelling is well advanced and well proven. Many bushfire/wildfire management response agencies in Southern Europe and the United States have recognised the utility of this kind of work and have adopted the systems into their management toolkits. Support for R & D in this area continues to produced tangible results and enhance public safety through technological advance.

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