MODELLING BURN SEVERITY FOR THE 2003 NSW/ACT WILDFIRES USING LANDSAT IMAGERY

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Abstract
In summer 2003, south-eastern Australia experienced one of the most extreme fire seasons recorded in the last century. Many fires, ignited by a dry lightning storm, resulted in the burning of over two million hectares of native vegetation and farmland. This project mapped and quantified the impact of these unprescribed fires on native vegetation (burn severity), using multitemporal Landsat ETM imagery. The normalised burn ratio (NBR), derived from 2 infra-red bands sensitive to changes caused by fire in vegetation, was applied to model burn severity. Severity was reflected in the magnitude of change in NBR ($dNBR=NBR_{prefire} - NBR_{postfire}$). The continuous dNBR values were classified into more descriptive burn severity classes reflecting the proportion of green canopy affected by the fire. Vegetation structure, which influences dNBR, was modelled and used to stratify the study area, this allowed dNBR cut-off values to be calculated separately within each strata. This is the first study of its kind to consider vegetation structure when modelling burn severity using satellite imagery. Further work is required to determine the relationship between dNBR and vegetation structural classes in a range of Australian ecosystems. To date, fire ecology research has often focused on the effect of fire frequency on Australian ecosystems and has relied upon the mapping of fire footprints. This study has shown that within the fire footprint the impact of the fire on ecosystems varies greatly. Without modelling this internal variation it is not possible to investigate the true ecological impact of fire at a regional scale. The fire severity map produced from this study has also been used to model erosion and slope stability in Kosciuszko National Park. This approach to mapping burn severity is cost effective and has many research and operational applications. It is recommended that the technique be further refined and incorporated into routine state-wide monitoring programs.

Introduction
On 8 January 2003 a major storm event occurred across north-eastern Victoria, southern NSW and the ACT associated with the passage of a cool change. Only limited rain fell during the storm (in many areas where fires ignited, no rain was recorded), and the dryness of the forests and woodlands resulted in lightning igniting 87 fires in Victoria, at least three in the ACT and 72 in NSW. The resulting fires burnt over 2.8 million hectares of southeast Australia (1.34 million hectares in Victoria and at least 1.5 million hectares in NSW and ACT). Due to the very large area affected by these wildfires Landsat Imagery was chosen to model the impact of the wildfires on the native vegetation. Government funding for post fire monitoring provided the resources to purchase six Landsat images and postfire orthorectified 1:25,000 air photos covering the entire burnt area in NSW and the ACT. There were two major components to the study, vegetation structure mapping and fire severity modelling, both using Landsat ETM imagery.

Materials and Methods
Measuring fire severity using the Normalised Burn Ratio (NBR)
The Landsat satellite has eight sensors that record the level of solar radiation reflected from the earth's surface. Each of the eight sensors is sensitive to different parts, or 'bands', of the electromagnetic spectrum. Surface characteristics such as water content, vegetation structure, productivity, and mineral composition all have a unique 'signature' defined by the degree of reflectance or absorption of each electromagnetic band. A measure called the Normalised Burn Ratio (NBR) was developed by the U.S. Geological Survey (USGS) and US National Park Service (Key and Benson 1999, 2004a) and is calculated from Landsat ETM imagery captured just before and just after the fire event. The NBR burn severity index is based on Landsat bands 4 (near-infrared, 0.76-0.90 microns) and 7 (short-wave or mid infrared, 2.08-2.35 microns). Studies have shown that these two bands respond most strongly to the surface affects of burning (Key and Benson 1999, 2004a, Kitchin and Reid 1999), especially when combined in the NBR (equation 1).

Equation 1 $$\mathbf{NBR = (R4 - R7) \div (R4 + R7)}$$

Where the *R* values are the calculated per-pixel "at satellite" reflectance quantities per band, which have been corrected for atmospheric transmittance. To contrast burnt from unburnt areas and to provide a quantitative measure of fire severity, the NBR dataset derived after the fire (postfire) is subtracted from the NBR dataset obtained before the fire (prefire), see equation 2.

Equation 1 $\mathbf{dNBR = NBR_{prefire} - NPR_{postfire}}$

This change in NBR value represents a measure of the impact the fire had on the vegetation and soil. The change in NBR measure or delta NBR (dNBR) is a continuous variable which typically ranges from -1 to 1.5 where low values represent no change or an increase in NBR value and larger values represent a drop in the NBR value caused by fire. The larger the decrease in NBR the greater the impact the fire had on the vegetation. The values actually observed usually range from -0.5 to 1.5. These are then multiplied by 1000 to facilitate image processing and data storage resulting in a range of values between -500 to 1500. dNBR has been shown to be influenced by the following fire related changes (Key and Benson 2004a); a decrease in aboveground green biomass and vegetation cover, an increase char and consumption of fuels, an increase in exposure of mineral soil and ash, a change to lighter coloured soil and ash and a decrease in moisture content.

Another index that is commonly used to assess burn severity is the Normalized Difference Vegetation Index (NDVI), (Chafer et al. 2004 and Hammill and Bradstock 2005). The NDVI and is calculated using the formula shown below in equation 3, where TM4 and TM3 are Landsat bands 4 (near-infrared) and 3 (visible red). One advantage of the NBR index over NDVI is that the visible red band (TM3) is reflected by smoke in the atmosphere whereas the mid infra-red band (TM7), used in the NBR, penetrates through and is not reflected to the same degree.

Equation 2 $\mathbf{NDVI = (TM4 - TM3) \div (TM4 + TM3)}$

The degree of change in NBR or dNBR can be grouped into three broad categories. Areas where dNBR equals zero or near-zero experienced little or no change between the two image capture dates. Negative dNBR values (NBR increase) indicate that the vegetation has become greener between the two dates and this can occur in burnt areas if the postfire image is captured one or more growing seasons after the fire. Positive dNBR values within the fire footprint are a result of the fire and have been shown to correlate with fire severity. For a more detailed technical description of the dNBR method see Key and Benson (2004a). To produce more descriptive and informative maps of fire impact, that reflect what is actually seen on the ground, it is necessary to identify categories of burn severity. Table 1 summarises the categories that were identified and used in this study. From field observations it was found that the dNBR is also influenced by the vegetation structure and the greeness of the environment before the fire event. A wetter, 'greener' landscape resulted in a larger NBR difference than that produced by a fire of the same intensity in a dryer, 'browner' landscape. This was especially the case in dry open woodland vegetation types where a high severity fire did not necessarily result in high dNBR values (Dawson 2005).

Table 1 Categories used in the burn severity maps

Category	Explanation
No Data	All images were cloud or snow affected in these areas
Excluded	Non-natural features (pasture, roads etc.) excluded from analysis
Very Low Severity (ground fire only) or Unburnt	Unburnt or very low intensity ground fire
Low Severity	Mix of green and scorched canopy with understorey burn
Moderately High Severity	Majority of top level is scorched (80% - 100% scorched)
High Severity	All scorched with some vegetation consumed
Very High Severity	Totally consumed (80% - 100% consumed)

Due to the influence of vegetation structure on the fire severity index (dNBR), the cut-off values that define each severity class needed to be calculated separately for each vegetation structure class. Consequently an important step in the fire severity modelling method is the stratification of the study area based on broad vegetation structure.

Image processing

The study area lies on the boundary of two Landsat paths (90 and 91), for his reason two sets of prefire and postfire digital Landsat ETM (Landsat 7) multispectral images were obtained. Two prefire images were selected, these were the most cloud-free images captured closest to the start of the fires. Selecting postfire scenes was more problematic because in addition to cloud cover the fires were actively burning and producing smoke plumes during all of January and most of February. All images were rectified and projected using the Australian Map Grid (AGD66) projection. Each Landsat scene is comprised of seven images, each one recording a different spectral band. The value attributed to each pixel represents the raw Landsat band brightness value (density number, or digital number). This value must be

transformed into "at satellite" reflectance which, for each spectral band, is the ratio of detected surface brightness to the incoming solar radiation available at the top of the atmosphere. This conversion process must be carried out when any analysis that involves quantitative comparison of different Landsat scenes is undertaken. The process standardises the bands, accounts for drift in the multi-spectral scanner and normalizes daily variation in sunlight. The formulas and method used to convert the images to 'at satellite' reflectance can be found in the Landsat 7 Science Data Users Handbook (NASA 2005). All subsequent procedures and classifications were carried out independently on each prefire/postfire Landsat image pair. The reason for this approach was to ensure that scene specific differences caused by atmospheric haze, smoke or climatic factors were identified and accounted for.

Mapping vegetation structure

A review of existing vegetation structure mapping failed to find a suitable vegetation structure or vegetation density map, so a project was undertaken to produce one. A more detailed account of methodology can be found in Eco Logical Australia (2005). Three classes of forest structure (dry, moderately wet and wet forest) as well as two non-forest classes (native grasslands and shrub/heathlands).

Air Photo Interpretation (API) of burnt areas

The postfire air photos were captured on cloud-free days over a period between late February to late April at a scale of about 1:25,000 by NSW Land and Property Information (LPI). The hard-copy photos were then scanned into digital images and ortho-rectified by LPI. This digital product proved to be invaluable for all aspects of the fire mapping project. The API specialist delineated areas of burnt natural vegetation that were homogeneous in respect to burn severity and structure onto clear acetate overlays. The API polygons from the overlays were then transferred to a digital GIS layer using on-screen digitising with orthorectified digital air photos as a reference back-drop. For each polygon, the proportion of unburnt, scorched and consumed vegetation was assessed for the tree, shrub and ground strata. Table 2 illustrates the format of the API proforma used to record attribute information. In addition to these fields the broad vegetation type (such as; tall heath, grassland, snowgum) of each polygon were recorded.

Table 2 Example of table used to record API polygon attributes

	Stratum	**Proportion of each burn class in polygon (%)**								
		Tree			**Shrub**			**Ground**		
Polygon ID	**Photo Frame**	Unburnt (Green)	Scorched (Brown)	Consumed (Black)	Unburnt (Green)	Scorched (Brown)	Consumed (Black)	Unburnt (Green)	Scorched (Brown)	Consumed (Black)
1	KB R8/141	100	0	0	30	30	40	30	30	40
2	KB R9/13							0	0	100

Where one or more of the shrub and/or ground strata could not be seen, because the tree strata was too dense, the values in the attribute table were left blank. Using this feature and the comments field the structure of each polygon was labelled as; forest, shrub only or ground layer only.

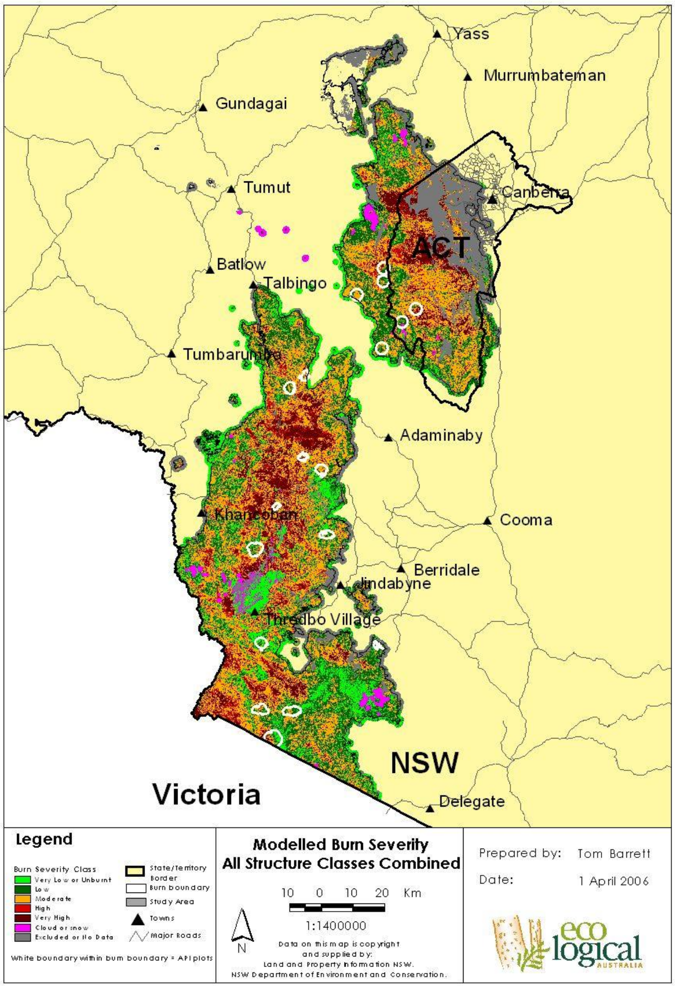

Figure 1 Modelled burn severity also showing API plots

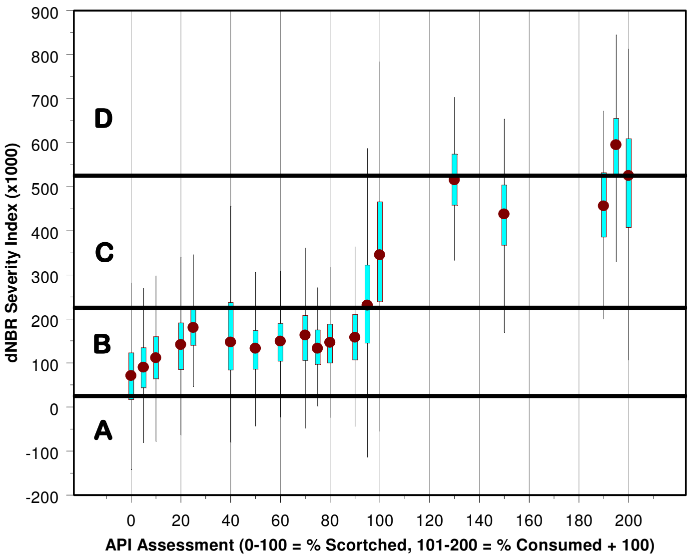

Figure 2 Distribution of dNBR values under API severity assessment polygons, box-plot showing median (dot) +/- one quartile (box) and range (tail)

Deriving the dNBR cut-off values

The dNBR cut-off values for each severity class within each vegetation structure class were derived using several methods. One method was to group API severity polygons into severity classes and intersect these with the dNBR grid. The outputs from each of these intersections represent the distribution of dNBR values for the burn severity classes identified in the API mapping. The dNBR cut-off values were then inferred from these graphed distributions. The derived cut-offs were then visually validated on-screen by using the postfire orthophotos as a reference. Another approach was to summarise the distribution of dNBR values for each API severity polygon and the result from this analysis can be seen in figure 2. Four dNBR datasets were derived from the four prefire/postfire image combinations. For each of the four dNBR datasets the cut-off values were used to classify the data into burn severity categories. There was considerable spatial overlap between the four classified dNBR layers. Where there was spatial overlap the maximum burn severity class was attributed to the combined layer. This was done to remove the affect of cloud shadows that resulted in artificially low dNBR values. Figure 1 illustrates the final distribution of modelled severity classes.

Validation of classified severity map using field based measure

Environment ACT undertook a post fire field survey where they measured percent of the canopy that was green (unburnt), scorched and black (consumed), (Carey et al. 2003). The tree canopy, upper shrub and lower shrub strata were all assessed in this way. These measures where converted into the same classes used by the API component of this study and correlated with the corresponding burn severity class in the burn severity map. The pixel that the survey point landed on was buffered by one pixel to give a total of nine pixels, the most common severity class amongst these nine pixels was used in the correlation calculations.

Results and Discussion

The distribution pattern in the more open, dry forest and non-forest vegetation types was not always clear and in some cases this can be attributed to a lack of sample pixels. This is demonstrated in the 'Mostly consumed' API class that did not sample many shrub/heath vegetation structure class dNBR pixels. In one Landsat image pair the dNBR cut-off values were consistently lower than those in the other image combinations. This may be due to the amount of smoke observed in the post fire image compared to the other post fire images.

Although there needs to be more work undertaken to validate the burn severity model output (map) the outcome of the correlation between modelled burn severity and field measures shows some interesting trends. There was a positive correlation between the model and field measured severity in the tree canopy strata for the moderately dry (r^2=0.62) and moist forest (r^2=0.60) structure classes but only a weak correlation in the dry forest class (r^2=0.11). The correlation coefficient was stronger when the analysis was restricted to sites that fell on a pixels surrounded by pixels of the same severity class (dry forest (r^2=0.44), moderately dry forest (r^2=0.75)). The relationship between the dNBR burn severity value and the proportion of canopy that is either green, scorched or totally consumed by fire, is represented hypothetically in figure 3. The four zones in figure 3 labelled A, B, C and D can be discussed separately. Zone A represents green, unburnt, canopy. In open forest, woodlands and non-forest areas this represents unburnt. Whereas in densely forested areas there is a possibility that there has been a fire in the understorey. This zone is easily mapped by the use of the dNBR model. Zone B represents a mix of green, unburnt canopy and brown, scorched canopy. In dense forest there is a good chance that the relationship between the proportion of canopy scorched and the dNBR value can be found. This relationship may be more difficult to establish in open, dry forest areas as the dNBR value represents a mix of understorey and tree canopy condition. Zone C represents a mix of brown, scorched canopy and black, consumed canopy. In dense forest it is likely that the relationship between the proportion of the canopy consumed and the dNBR value can be quantified. This relationship may be harder to find in open, dry forest areas as the dNBR value represents a mix of understorey and tree canopy condition. Zone D represents vegetation where the canopy has been totally consumed by the fire. In all vegetation structure classes this represents the same outcome, although it may not represent the same fire intensity. This zone is easily mapped by the use of the dNBR index model. There will also be areas where there is a mix of both consumed and unburnt without any scorched zones. This has been observed in heathlands but is rarely seen in forested areas.

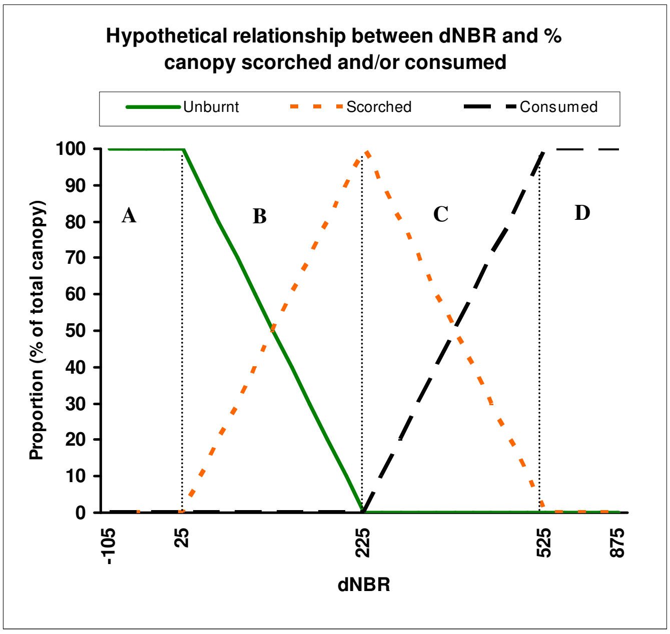

Figure 3 Hypothetic relationship between dNBR and canopy scortched and consumed

There is scope for more work to be undertaken to refine and validate the dNBR method of quantifying burn severity in Australian native vegetation. More investigation should be carried out into the correlation between field measures of percent canopy cover or Leaf Area Index, (LAI) such as that undertaken by Coops et al. (1998). This correlation may vary in different vegetation types. Field validation is essential to determine the accuracy of the burn severity model. In the absence of field validation sites this study has demonstrated that API mapping can be used to determine the correlation between dNBR values and field severity where each pixel in the API polygons are considered as a survey reference points.

Much work has been done by the USGS in North America to develop field survey methods to assess burn severity classifications. Key and Benson (2004b) developed a field based measure called the Composite Burn Index or CBI and have shown that it correlates with the dNBR burn severity measure. This approach may need to be modified if it is to be successfully applied in Australian native vegetation types. There may be other sources of field based burn severity assessment that have been undertaken since the Environment ACT plots (Carey et al. 2003) and potentially by NSW Department of Environment and Conservation. Ideally these assessments should be incorporated into further analysis and validation. When new field sites are being investigated for further field measurements of burn severity, it would be recommended that sites are located well within large homogeneous areas of mapped burn severity. This would prevent edge effects from interfering with the final accuracy and correlation analysis.

Conclusions

This project successfully modelled high and low fire severity burns in all vegetation structure types. In denser forests all dNBR burn severity classes were positively correlated with field measures while the correlation was not strong in the dryer open forest or non-forest vegetation types. More rigorous field validation is required to better quantify the accuracy of the model. More work is also required to investigate the response of the dNBR measure in more open vegetation types where ground and shrub layers are contributing to the dNBR value. With more investigation the relationship between dNBR and the proportion of canopy that is scorched and/or consumed could be quantified. It is also recommended that a follow up study is undertaken to map recovery one or two growing seasons after the fire. The same methodology could be applied to assess recovery. Because of the value of these practical applications and the important role of fire in Australian native ecosystems, it is recommended that the burn severity modelling method described in this paper be further refined and incorporated into routine post fire monitoring programs.

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