# Mapping fire severity from satellite imagery for greenhouse gas emissions calculations, conservation management and operational use.

A. Edwards[a,b], S. Maier[b], L. Hutley[b], R. Williams[c], J. Russell-Smith[a]

[a] Bushfires NT, Northern Territory Government Department of Natural Resources Environment, the Arts and Sport, Australia – (andrew.edwards, jeremy.russell-smith)@nt.gov.au
[b] Charles Darwin University, Darwin NT 0909, Australia – (stefan.maier, lindsay.hutley)@cdu.edu.au
[c] CSIRO Sustainable Ecosystems, PMB 44, Winnellie NT 0822, Australia – dick.williams@csiro.au

**Abstract - The algorithm to calculate Greenhouse Gas (GHG) emissions from savanna fires relies upon a number of variables from the classification of satellite based optical imagery. The algorithm variables require continued refinement. Fire severity mapping will increase the accuracy of the spatial distribution of fuel consumed.**

**Fire severity is the post-fire effect of fire on the vegetation. The fire severity mapping algorithm developed in this study correlated helicopter-based spectra collected over a site using a hand held spectrometer and ground data describing the fire severity within the spectrometer field of view. The differenced Normalized Burn Ratio (ΔNBR) quite clearly distinguished between severe and not-severe fires ($r^2 = 0.94$). However, further discrimination into three or more classes required the development of other indices incorporating the region of the spectrum represented by MODIS band 6 (1628-1652 nm). This poses problems operationally as band 6 on Aqua is dysfunctional thus halving the available data.**

**Keywords:** Fire severity mapping, greenhouse gas emissions, conservation management, operational application.

## 1. INTRODUCTION

Fire severity is the post-fire effect of fire on the vegetation (Lentile*, et al.*, 2006; Keeley, 2009). Current landscape wide mapping does not describe the effect of fire. It describes its spatial and temporal occurrence, providing land managers with information regarding the habitat affected and the seasonality of occurrence. Russell-Smith and Edwards (2006) demonstrated there was valuable information to derive from fire seasonality. They determined the probability of occurrence of categories of fire severity within various habitats in the tropical savannas of northern Australia. However the data do not provide intra-seasonal descriptions of the effects of management imposed fire, applied regularly, and essential to reduce the high probability of wildfire across an extremely fire-prone landscape (Yates*, et al.*, 2008).

A field guide illustrating fire severity categories for the dominant savanna woodland matrix, describes simple metrics for characterising fire severity (Edwards, 2009). It uses the scorch height (i.e. the height to non-pyrolised fire affected foliage (Williams*, et al.*, 1998) and the proportion of ground patchiness. The categorisation is understood by users, as the input was derived from researchers and land managers in the tropical savanna region, Figure 1. Five categories were determined for use: 1. Patchy - small trees and shrubs scorched to 2m, < 80% burnt ground layer patchiness; 2. Low - small trees and shrubs scorched to 2m, ≥ 80% burnt ground layer patchiness; 3. Moderate - scorched leaves through the mid-storey (> 2 and ≤ 8 m) perhaps into the lower parts of the upper canopy; 4. High - complete canopy scorch and; 5. Extreme - all foliage removed or charred.

It is estimated that global combustion of vegetation is around 9,200 Tg (± 50%) on average, each year (Scholes and Archer, 1997). The tropical savannas are the largest single source of GHG and particulate emissions in Australia (Meyer*, et al.*, 2008) emitting 2% of Australia's annual GHG emissions in 2005. Savanna burning accounted for 39% of the Northern Territory's emissions from 1990-2005 (Tropical Savannas, 2004). Much of the north Australian landscape is rural and sparsely populated, containing a matrix of savanna grassland, woodland and open forest. The fuel from this biomass accumulates over time. The amount of fuel consumed by a fire determines the GHG emissions (Russell-Smith*, et al.*, 2009). Landscape analysis for strategic planning and greenhouse gas emissions calculations presumes that the proportion of biomass fuels is reset to zero post-fire (Meyer*, et al.*, 2008). Fuel accumulation relationships are derived on this basis. However, the level of effect of fire determines the proportion of fuel not consumed in one year. Fire history information incorporating fire severity will improve the fuel accumulation relationships. It will assist the strategic planning undertaken by land managers in their attempt to mitigate the occurrence of wildfire. The availability of landscape wide accurate fire severity mapping will provide vast improvements to fire management planning and calculations of GHG emissions.

Satellite derived fire information has been available to land managers in the tropical savannas of northern Australia through the North Australia Fire Information web site (www.firenorth.org.au) since 2005. A cost saving of > $10.5 million was estimated in the first 3 years of operation to conservation land management agencies alone (TSMCRC, 2005). Similar cost savings should be expected with the addition of fire severity mapping. It will inform land managers of the efficacy of their burning activities, i.e. was a fire, light to provide a break, of sufficient severity to mitigate a wildfire?

A near-ground top-down/bottom-up approach was adopted to derive data for the calibration of satellite based optical imagery. Such coupled approaches have been previously undertaken. Most notably, classification of the differenced Normalised Burn Ratio (ΔNBR) through calibration of field data using the Composite Burn Index (Key and Benson, 2006), or similarly, using ΔNBR with customised field data describing fire severity (Hammill and Bradstock, 2006; Smith*, et al.*, 2007; Allen and Sorbel, 2008; Chafer, 2008; French*, et al.*, 2008). In these instances calibration data are collected specifically for classification of a single image or small set of images. In this approach satellite imagery is replaced with near-ground helicopter-based reflectance data and detailed ground measurements.

There are three main improvements required in the development of an algorithm to map fire severity to meet the needs of fire managers in the tropical savannas of northern Australia. Firstly, automation due to high fire recurrence and the extent and continuity of fire in the landscapes. Secondly, the near-ground collection of reflectance spectra markedly decreasing geolocation error. Lastly, collaboration with researchers and land managers across the breadth of the region. This last requirement is the most significant as it will improve the calibration data for the models, it will assist in providing a geographically extensive validation dataset, and it will provide a sense of ownership and extended usage of the fire severity map product.

## 2. METHODS

### 2.1 Study area

The tropical savannas cover approximately 1.9 million km$^2$ of the northern tropical portion of the Australian continent, Figure 1. Rainfall is strongly seasonal, over 90% falling in the summer months, creating a distinct fire season. The assessment region is in the high end of the rainfall gradient. It extends across the Top End of the Northern Territory, lying between the city of Darwin, across the World Heritage Listed Kakadu National Park into the west of the Arnhem Land Aboriginal Land Trust, approximately 300 km east to west, Figure 1.
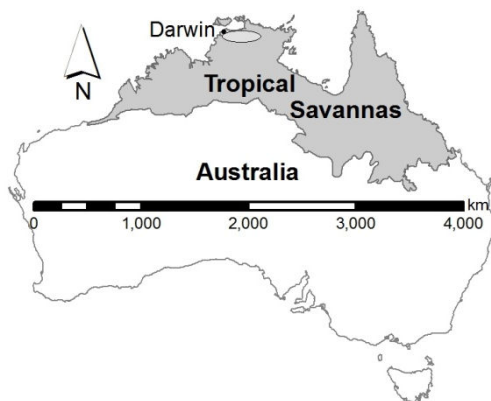


Figure 1. Location of the study region in the tropical savannas of northern Australia.

### 2.2 Data collection

Reflectance data collection occurred the morning after a fire event between 10:00 and 11:00 hours. Using a hand held ASD field spectrometer (Taylor, 2004) sensing 400 to 2500 nm at 1 nm intervals. Reflectance spectra were collected from a helicopter at a height of 100 m above ground. The helicopter was landed in the sampling region and the altimeter reset to zero prior to data collection. Site selection was random and stratified within burnt areas. The end of the optic fibre of the field spectrometer was suspended ~1 m horizontally from the side of the helicopter. Above the end of the supporting rod was a bubble level to ensure the sensor was pointing downward during measurement. Reflectance readings were averaged 250 times at each site. The proximity of the sensor to the ground, and GPS location averaging, greatly reduced geolocation error, Figure 2, to ensure
ground and reflectance data location correlated as accurately as possible.
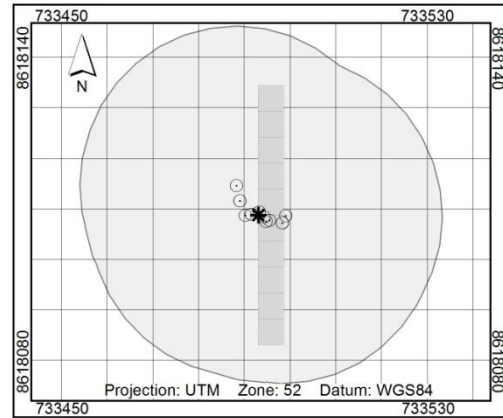


Figure 2. Ground site transect centred on mean GPS coordinate. Surrounding pixeloid represents spectrometer FOV.

Ground data collection occurred at sites in the 48 hours subsequent to the fire event. Detailed 50 m transects were laid out, north to south, centred on the average of the GPS locations, Figure 2. Measurements of the percentage occurrence of the ground variables in each of four strata were taken (Table 1).

Table 1. Ground data collection: variables measured for each of 4 strata: Upper > 5 m; Mid 2 to 5 m; Lower 0.5 to < 2 m; Ground ≤ 0.5m. PV = photosynthetic vegetation. NPV = non-photosynthetic vegetation. Sc = scorched foliage, fire affected but not pyrolised. Char = partly pyrolised PV or NPV. Ash = completely pyrolised PV and NPV.

| Variable | Upper | Mid | Lower | Ground |
|---|---|---|---|---|
| %PV | x | x | x | x |
| %NPV | x | x | x | x |
| %Sc | x | x | x | x |
| %Char | x | x | x | x |
| %Ash | | | | x |
| %Dry Grass | | | | x |
| %Bare Soil | | | | x |

Table 2. Ground data collection: Floristic and structural data collected from all plant stems ≥ 5 cm diameter at breast height (DBH, measured at 1.3 m above the base of the stem).

| Structural Measurement | Variable | Derived Parameter |
|---|---|---|
| Plant Position | $x, y$ | stem density (ha$^{-1}$) |
| Basal area | BA (m$^2$) | total basal area (m$^2$ha$^{-1}$) |
| Species ID | Genus species | floristic class |
| Total Height | $z$ (m) | structural class |
| Canopy Radii | $r_1, r_2, r_3, r_4$ (m) | canopy area (m$^2$) |
| Canopy Height | $h_c$ (m) | canopy volume (m$^3$) |

Estimation of the fire severity category was recorded for the whole site as given in the field guide. A continuous fire severity parameter, FSIv, was calculated, as a measure of the scorch height (SH) weighted by ground patchiness, for correlative analyses. Measurements of scorch height and char height were averaged at 5m intervals for each plant 10m either side of the transect. Ground patchiness was derived from a point-line

intercept at 1m intervals along the 50 m transect. Floristic and structural information was collected in a 50 x 5 m swath on the eastern side of the transect for all plants ≥ 5 cm diameter at breast height (DBH), Table 2.

## 2.3 Data analysis
FSIv was calculated from:

$$FSIv = (100 - (\%PV_G + \%NPV_G)) / 100 * SH \qquad (1)$$

where $\%PV_G$ = the proportion of photosynthetic vegetation in the ground stratum and $\%NPV_G$ = the proportion of non-photosynthetic vegetation in the ground stratum.

A cluster analysis of FSIv produced FSIc. An accuracy assessment of FSI versus FSIc was then undertaken to determine the suitability of the metrics from the field guide. FSIv was correlated with the summed proportions of each of the normalised ground variables to determine the main drivers of the effects of fire on the savanna vegetation. FSIv was correlated with normalised averages of discrete spectra representing the MODIS channels, and derived spectral indices, the normalised differenced vegetation index (NDVI) and NBR. A candidate set of ground and reflectance models was assessed using Akaike's Information Criteria analysis, for a small number of variables (AICc), for suitability to map fire severity.

The models selected from AICc analysis were applied to a time series of MODIS imagery for the study region (Figure 1) in the fire season of 2009. A burnt area algorithm was previously applied to mask the imagery, so that fire severity classification occurred only in known burnt areas. The threshold values between fire severity categories in the experimental dataset were calculated for the models and applied to classify the image data for each fire event as determined from the burnt area mapping. An extensive validation dataset, collected aerially using the methods as outlined by Edwards *et al.* (2001) was used for accuracy assessment.

## 3. RESULTS

The overall accuracy in the comparison of FSI and FSIc was 76%. However, when the comparison was severe (high fire severity) versus not-severe (low and moderate fire severity pooled) the accuracy increased to 92%. The normalised summed percentage of PV (%PV) explained 72% of the variability in fire severity. %PV, in combination with other significant ground variables, %NPV and %Scorch Leaves (%Sc), provided a candidate set of models for AICc analysis. The "best" model was determined to be %PV + %NPV + %Sc.

The linear transformed reflectance channels representing the short wave infra-red region (MODIS bands 6 (SWIR1) and 7 (SWIR2)) were significant when correlated with FSIv, explaining the greatest variation, 67% and 52 % respectively. The NBR and NDVI indices were significant and explained 39% and 41% respectively. Whilst in the near infra-red, MODIS band 5 (NIR2) explained only 38%, but was significantly correlated. The significant variables and combinations of the variables were selected for the candidate set for AICc analysis.

In a visual assessment of the mean values for each fire severity category ΔNBR best discriminated severe from not-severe fire events. Although not the best model, parsimony and simplicity for further data manipulation of large satellite image datasets, suggested ΔSWIR1 for discriminating low from moderate fire severity. Unfortunately from an operational perspective the

dysfunction of the SWIR2 (band 6) of the MODIS sensor on the Aqua satellite excludes its application. SWIR2 was removed from the candidate set of models. AICc analysis revealed the product of NIR1, NIR2 and SWIR2 (NIR1*NIR2*SWIR2) explained 60% of the variation.

The nested algorithm was developed by first applying ΔNBR to discriminate severe from not-severe fire severity. Then by applying the product of NIR1, NIR2 and SWIR2 to discriminate low from moderate fire severity within the previously classified not-severe class. The accuracy assessment of the ΔNBR classification resulted in an overall accuracy of 94%. The result for NIR1*NIR2*SWIR2 was 60%.

## 4. DISCUSSION

The results suggest that a binary fire severity map for the north Australian tropical savannas can be produced with a high degree of accuracy. However, the categories of low and moderate severity are not yet calibrated accurately to clearly differentiate them. Similar accuracies were reported in other biomes where canopy cover is < 50%, (Epting*, et al.*, 2005; Hammill and Bradstock, 2006; Kasischke*, et al.*, 2008). Change in the PV, NPV and bare soil matrix due to fire is possibly more complex than this simple categorisation can explain (Hutley and Beringer, 2010). It would seem prudent to develop a mapping legend based on a continuum, applying the continuous fire severity index. Thus indicating mixed types of disturbance rather than specifying specific thresholds of effect. A continuous variable is more pertinent for a range of applications. The continuous variable has improved benefit for burning efficiency assessment. Ground data sampling of the proportions of fuel types consumed for various habitats under various fire conditions include measurements of mean scorch height and ground patchiness (Russell-Smith*, et al.*, 2004). The scorch height weighted by the ground patchiness provides a continuous fire severity ground variable. Therefore the data used to derive fuel accumulation relationships also equate to a continuum of fire severity.

The ground truth data, collected aerially, did not sufficiently indicate the severity class. To improve the classification they require modification and calibration from higher resolution ground based measurements.

## 5. CONCLUSION

Operationally the fire severity mapping can be incorporated into on-line resources currently available at the North Australia Fire Information web site (www.firenorth.org.au). This will allow intra-seasonal analysis of strategic burning efforts undertaken to mitigate wildfire through hazard reduction burning. Inter-seasonally the data indicate a relative proportion of fuel consumed. This information can be applied to strategic planning for the coming fire season, and has major benefit to conservation management planning when used as a measure of habitat affect.

Fire seasonality currently defines the proportion of biomass consumed by fire for GHG emissions calculations, as the date of fire occurrence is available from fire mapping. The fire severity of a habitat relates directly to the proportion of biomass consumed. A spatially explicit layer of fire severity will provide improved, landscape wide, accuracy to GHG emissions calculations.

The categories of fire severity as outlined in the field guide developed for tropical savanna land managers (Edwards, 2009) provide a quick and simple method of data collection. An expanded set of calibration/validation data for a future map product will rely upon the input from a collaboration of many researchers and land managers. Data collection and accuracy will be facilitated by simplified data collection methods.

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