bushfire CRC

NORTHERN FIRE MAPPING: DEVELOPING ROBUST FIRE EXTENT AND SEVERITY MAPPING PRODUCTS FOR THE TROPICAL SAVANNAS

FINAL REPORT FOR THE NORTHERN FIRE MAPPING PROJECT

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Cover:
Left – A prescribed burn in the savanna woodlands. Photo by Andrew Edwards.
Right – Andrew Edwards demonstrating how a Spectrometer will be used during a helicopter flight over the savannas.

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Program	Understanding Risk
Project Title	Northern Fire Mapping: Developing robust fire extent and severity mapping products for the tropical savannas
Project Leaders	Dr Jeremy Russell-Smith and Dr Mick Meyer
Lead End User	Dr Neil Burrows
Researchers	Dr Andrew Edwards

Executive Summary

This final report summarises the activities and deliverables undertaken and provided since the commencement of the project in September 2010. The project staff have been with the project for its entirety including Researcher Dr Andrew Edwards and Project Leaders Drs Jeremy Russell-Smith and Mick Meyer. The project has been a major success. Key support to the project came from Bushfires NT staff and Research colleagues, the indigenous ranger groups and conservation and fire agencies, and Bushfire CRC administrative staff. Core risk management components of the project are to receive ongoing funding in the new Bushfire and Natural Hazards CRC program.

The main theme of the project was to develop fire severity mapping for application to fire management in the tropical savannas and rangelands, and to then apply these data to ecological-risk assessments including greenhouse gas emissions, tree carbon sequestration, biodiversity and erosion. Both activities were successful with fire severity mapping displayed for scrutiny on the North Australia Fire Information website, and a seminal paper outlining the ecological analyses and results soon to be submitted for publication.

State of knowledge pre-project

The key component of this project was to develop a method to accurately measure and map the effect of fire across the whole 1.9 million km^2 of remote and sparsely inhabited tropical savanna vegetation (Russell-Smith et al. 2012). However, rather than extrapolating a modelled effect, we proposed to operationalise PhD research sponsored by the Bushfire CRC and undertaken by our key researcher (Edwards 2011; Edwards et al. 2013).

Maps illustrating and describing the effect of fire on tropical savanna vegetation, fire severity mapping, had not previously existed. Burnt areas had been mapped in various parts of the region from satellite imagery since the 1980's, at appropriate land management scales (Russell-Smith et al. 1997; Edwards et al. 2001; Russell-Smith et al. 2003; Yates and Russell-Smith 2003; Felderhof and Gillieson 2006; Edwards and Russell-Smith 2009). Mapped regularly, this information intrinsically described the timing and occurrence of fire, however questions often arose as to the extent of the effect of both prescribed burning and wildfire on vegetation, and associated effects such as greenhouse gas emissions, carbon sequestration, biodiversity and erosion under the many fire management regimes (Russell-Smith and Yates 2007; Yates et al. 2008; Woinarski et al. 2011). Research activities located at long term fire management plots indicated that the severity was variable throughout the season. Wildfires in particular produced a mixture of low, moderate and high severity fires, but prescribed burning could produce severe fires (~21%), albeit a small, but again variable, proportion (Russell-Smith and Edwards 2006).

Traditional indigenous knowledge suggested that recent fire regimes in northern Australia were more destructive to current ecosystems than in the past (Yibarbuk et al. 2001; Garde et al. 2009; Ritchie 2009). This information and similar observations by concerned land managers and researchers lead to a body of research that characterised the effect of fire on key ecological and physiological systems, producing robust models that generally always featured fire effects (Price et al. 2005; Woinarski et al. 2005; Russell-Smith et al. 2006; Edwards and Russell-Smith 2009; Murphy et al. 2009; Russell-Smith et al. 2009; Murphy et al. 2010; Woinarski et al. 2010; Russell-Smith et al. 2012; DCCEE 2013).

The fire effect variable, in the case of calculating greenhouse gas emissions and its potential abatement, is the seasonality of fire (Russell-Smith et al. 2009), however in calculating the potential annual carbon storage of savanna trees the key effect variable is the severity of the fire (Murphy et al. 2010). Similarly, for modelling savanna vegetation health, the best model to calculate the recruitment of adult northern Cypress pine (a strong indicator of landscape health (Bowman et al. 2001; Edwards and Russell-Smith 2009)) uses the frequency of severe fires as its sole variable (Edwards and Russell-Smith 2009). Whilst the best model to calculate the numbers of highly vulnerable longer lived obligate seeder shrub

taxa, requiring 3 or more years to mature and produce seed, applies the frequency of all fires (Russell-Smith et al. 2012). The savannas constitute highly erodible soils (Townsend and Douglas 2000), wet season rainfall is intense, soil movement off slopes is twice as great when an area has been burnt early in the previous dry season, however 4 times as great if burnt in the late dry season (Russell-Smith et al. 2006). This body of robust models, derived from extensive empirical datasets (see references above), could be readily and more accurately extrapolated for the region with spatially explicit mapping which in many cases must include fire severity mapping.

Progression of research

Overall the project tracked the milestones originally set out. There were some delays due to the vast body of data collected by a single researcher, who, relying on the assistance of colleagues for field work, then had to adapt to and work within *quid pro quo* arrangements. Data then had to be collated and the information analysed, whilst attending relevant training, conferences, forums and seminars. Detailed outlines of the timeframes, methods and results for the two main activities are provided in this report: Activity 1. describes the development of a robust model for timely and accurate fire severity mapping and, Activity 2. the risk assessment from the effects of fire on ecological attributes, which resulted in a paper, being submitted to Ecography, providing strong supporting evidence for Payment for Ecosystem Services (PES) programs. The key findings of these analyses are given below.

Key Research results

Large fires regularly sweep across large tracts of the north, our assessments determined that in the high rainfall region of the far north, approximately 450,000 km^2, an average of 53% of the landscape was fire affected annually from 2008-2012, and 34% by hot, mostly severe, late dry season fires. In this same period 5.7 ($\pm$ 0.9) Megatonnes of carbon dioxide equivalents (methane and nitrous oxide) were emitted annually, 640 ($\pm$ 20) kilotonnes of carbon stored in tree biomass were consumed by fire, and on hill slopes an excess of 50 tonnes per hectare of soil movement, all due to the currently extreme fire regimes. We also demonstrated that an improved fire regime, such has been instigated in the west Arnhem Land region (~28,000 km^2) since 2005, would improve fire management such that the

danger of wildfires to natural and cultural infrastructure, smoke emissions to human health and the effects on livelihoods has been markedly reduced in that region.

Most interestingly we found that there is enormous financial incentive for improved fire management through the payment for ecosystem services, such that the reduction in greenhouse gas emissions from savanna burning, and carbon sequestration in trees, has the potential to earn land managers $33 million and $132 million, respectively, annually, under current value in the carbon market (i.e. @$24/tonne). There are also benefits to indigenous traditional owners who can earn incomes managing their own land, giving them greater choice to determine their own futures and live and work on country, this has been clearly demonstrated to improve both their physical and mental health. The co-benefits of these improved fire regimes to biodiversity have been calculated through statistical models derived from extensive empirical datasets, and simple robust methodologies have been developed and published. Interestingly, with improved fire management, we found a 142% increase in adult recruitment of the long lived obligate seeder Cypress pine, *Callitris intratropica*, indicative of positive recruitment of many other rare and threatened species. These simple but robust models provide measures of the potential to improve our environment through fire management, not in an unattainable ideal situation, but rather, through a living example. Greater detail of the methods for these analyses is given in Activity 2. in this report, and in the publication:

Edwards, A. C., J. Russell-Smith and C.M. Meyer (2014). "Assessing Fire Regime Risks to Key Ecological Assets and Processes in North Australian Savannas." Ecography. *unpublished*.

Outputs

The main outputs expected from the project were fire severity mapping, a broad scale ecological assessment of fire regimes and, communications of these products to stakeholders, all of which were completed. The development of a robust algorithm and methods for semi-automated mapping of fire severity has resulted in an historical archive and operational map product covering nearly 2 million square kilometres of northern Australian tropical savannas, now being displayed for operational use on the North Australia Fire Information (NAFI) website. This dataset, and other fire mapping also available on the

NAFI website, were then applied in the ecological assessment culminating in a paper for international publication.

Communication activities were vigorous throughout the project with presentations to end user groups, key being the North Australia Fire Managers' forum, ABC National News and regular ABC Country Hour interviews, most appropriate in terms of rural end user communications. However, the most prolific end user communication occurred through the NAFI website users, who provide much needed criticism from a grass roots land manager's perspective. A list of the major presentations is given in **3.1 Presentations**, whilst publications are given in **3.2 Publications and other media**. Samples of posters presented at the annual AFAC conference are given in **3.3 Annual AFAC posters** and other interactions with stakeholders is outlined in **3.3.1 The Research Advisory Forum**, **3.3.2 Assistance of Indigenous agencies** and, **3.3.3 North Australian Fire Manager's Forum.**

State of knowledge post-project

The project had a small team but was able to draw on knowledge and expertise from across the whole tropical savanna region due to the high level of interest stemming from the requirement for useful fire related mapping products. The project has engendered further interest from stakeholders, the Bushfire and Natural Hazards Cooperative Research Centre, the North Australian Indigenous Land and Sea Management Alliance and Bushfires NT, to continue the efforts in the assessment of ecological risk. A project has been established to continue this work through the new Bushfire and Natural Hazards CRC, where the assessments previously undertaken across the broader region will be focused on key areas designated by these agencies, to reduce landscape risk and improve resilience in remote communities.

Activity 1. Fire severity mapping

The initial fire severity map product was to be produced for the whole 1.9 million km^2 area of the north Australian tropical savannas , Figure 1. The geographically extensive expectation of the fire severity mapping meant that a large dataset of waypoints describing the severity of many different fires throughout the fire season had to be sampled right across the region to first calibrate a model. This occurred throughout 2011. A similar dataset was then required to validate the model developed in the calibration phase. This was undertaken throughout 2012, whilst calibration data was collected for the rangelands. In 2013 the tropical savanna fire severity map was then assessed by a number of land managers across the region, whilst validation for the rangelands model was collected.

In each year field programs were pre-determined within the field plan mostly of Bushfires NT Research. However a number of other groups provided a lot of assistance with logistics, access, accommodation and often helicopter time: the Department of Environment and Conservation, WA; Kakadu National Park, NT; the Kimberley Land Council, WA; Cape York Sustainable Futures, QL;

The decadal fire histories provided guidance for placement and timing. However, extensive communication with end users to gain their support for the project and their assistance in the field, was a crucial component and the main reason the field datasets are so large.

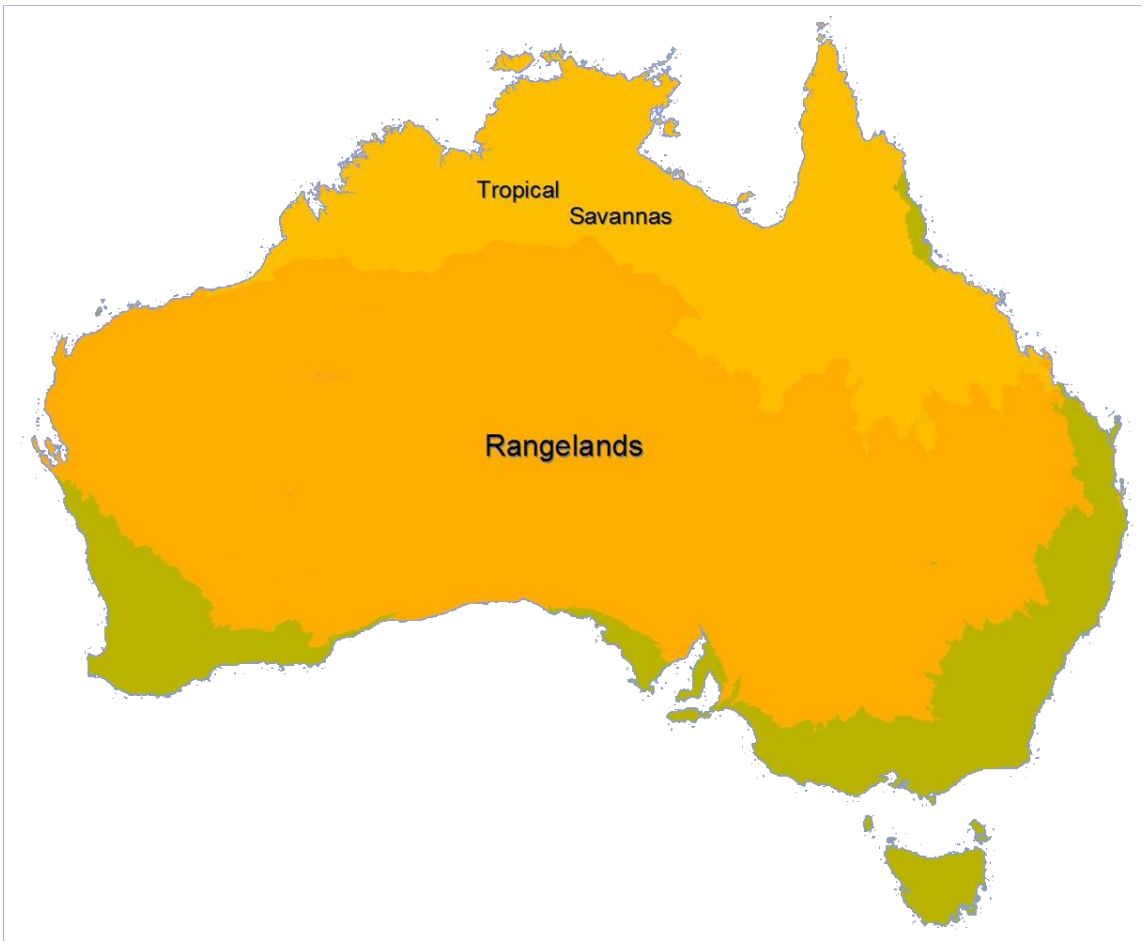


Figure 1. The extent of the north Australian tropical savannas, and rangelands.

1.1 Methods

1.1.1 Background

A PhD thesis sponsored by the Bushfire CRC, was undertaken from 2006-2010 to determine the efficacy of mapping fire severity using satellite remote sensing (Edwards 2011). The results of this thesis provided the background knowledge required to develop a methodology and produce the fire severity map. These recommendations from Dr Edwards were taken into consideration in developing the methods for the large-area sampling and model development for this project.

In Andrew's analysis he found that significant correlations occurred between reflectance spectra averaged for the optical MODIS channels 5, (R_{1240}), 6 (R_{1640}) and 7 (R_{2130}), the NDVI (Normalised Difference Vegetation Index) and the NBR (Normalised Burn Ratio). A visual assessment illustrated that the indices, NDVI and NBR, were able to separate severe from not-severe fire effects. R^2 for NBR was greater than R^2 for NDVI, therefore NBR was selected for assessment. A candidate set of MODIS channels, based on the significance of correlation and inference from the literature, was analysed through Akaike's Information Criteria (Burnham and Anderson 2002). Separation within the not-severe (low and moderate) class was not clear. The most parsimonious model, MODIS channel 6, was selected.

A result of 94% overall accuracy was obtained in the binary classification using ΔNBR. However, technical difficulties with MODIS channel 6 produced an unclear and unsatisfactory 48% overall accuracy, with considerable overlap in discriminating low from moderate severity. A revised set of candidate models was derived incorporating MODIS channels 2 (R_{860}) and 5 (R_{1240}) and 7 (R_{2130}). The overall accuracy, 57% (2+5) and 60% (2*5*7), and the class overlap improved, however KHAT statistics were still poor (+0.22 and +0.19).

The overlap in classification suggested that detecting the level of effect of fire in the lower categories was not to be simple. Unlike for severe fires which predominantly involves detecting an effect on the upper canopy. The small proportion of plant material in the lower and mid canopies suggests that the major influence on reflectance change in the lower fire severity categories derives from the ground storey. The upper storey contains the greater

proportion of photosynthetic vegetation (PV), whilst the ground storey contains the greater proportion of non-photosynthetic vegetation (NPV), and there is also a strong influence from bare soil. Generally, the field categorisation of fire severity was influenced by the assessment of scorch height and only a rough assessment of ground patchiness. To produce more accurate calibration/validation data we determined that for future characterisation of the low and moderate fire severity categories, the aerial assessment attribute data needed to include an estimate of patchiness. The aerial assessment data also required some calibration from a ground based survey, containing greater sampling intensity and accuracy.

1.1.2 Temporal applicability

Short term fire scar persistence in the tropical savannas necessitates a higher frequency of image acquisition for burnt area mapping (Edwards et al. 2001). Dr Edwards' thesis suggested this was indicative of a similar possible issue for the fire severity algorithm. The rapid change in albedo demonstrated by Beringer *et al*. (2003) and analysis of a post-fire photographic time series, suggested that the applicability of the immediate post-fire sampling in this study is brief, 5 to 6 days, as opposed to months or years for other biomes and sampling techniques. The main instruments of this rapid change are significant leaf fall and rapid vegetative re-flushing causing a quick rise in albedo to pre-fire conditions within a week to ten days at most.

1.1.3 MODIS sensor

Current small scale satellite sensor data meeting the requirement of 5 to 6 day post-fire sampling are coarse (> 250 m). There is a direct relationship between frequency of acquisition and swath width, and an inverse relationship with pixel size. Imagery from the MODIS sensor have an approximate swath of 2,400 km, therefore it was recommended to use data from the MODIS sensors, with the highest combined spectral, spatial and temporal resolution, for the least cost.

The Landsat series of satellite sensors have been used to create fire histories in many places around the globe (Chuvieco and Congalton 1988; White et al. 1996; Mitri and Gitas 2002; Alencar et al. 2006; Röder et al. 2008; Holden et al. 2009; Matricardi et al. 2010). However it is the world's tropical savannas with fire regularly recurring both annually and intra-

seasonally, where fire history mapping is extensive. Landsat derived fire histories have been developed in Africa and Brazil (Hudak and Brockett 2004; Smith et al. 2005; Alencar et al. 2006) and on a number of key estates almost exclusively in northern Australia (Hauser 1995; Russell-Smith et al. 1997; Edwards et al. 2001; Russell-Smith et al. 2002; Fisher et al. 2003; Yates and Russell-Smith 2003; Vigilante et al. 2004; Felderhof and Gillieson 2006; Edwards and Russell-Smith 2009; Elliott et al. 2009) usually back to 1990 and, for Kakadu National Park, 1980. These moderate resolution fire histories are used by land managers for detailed planning. They are used to calibrate and assess coarser AVHRR and MODIS derived fire histories, and augment these coarser mapping on sites such as NAFI.

Under the current financial circumstances, the MODIS based mapping programs become more necessary. Although lower in resolution, MODIS is also better suited to the ecosystems of the region. The free availability, high return frequency, greater spectral detail and swath, the possibility of utilising the MIR for smoke aerosol penetration, and the thermal bands already employed for active fire detection are far preferable. The MODIS geo-location approach has reduced large on-orbit geo-location errors to better than 45m (Qu 2006), a crucial factor to multi-temporal analyses.

However, the MODIS sensors had an expected 5 year life from 1999 (Terra) and 2002 (Aqua) (http://modis.gsfc.nasa.gov/: accessed 1 September 2010). The launch date of the proposed replacement program, The National Polar-orbiting Operational Environmental Satellite System (NPOESS), was originally 2005. It had been delayed till late 2013, and at the time of this report no data were yet available for assessment, however a fire severity history can be derived using the MODIS archive back to and including the year 2000.

1.1.3 Data processing

The underlying satellite data needs to be processed with respect to the existing fire mapping data from NAFI. Figure 2 represents the processing steps. The semi-automated burnt area mapping (SAM) and the automated burnt area mapping (AM) are converted to ArcInfo GRID files (Steps 1 to 6) and intersected removing all non-coincident cells (7.) and to derive a map of the omissions erros (8.) for assessment and intersection with validation data (9.) to derive an error matrix (10.). The resultant burnt area GRID (11.) has values of the reflectance change in MODIS band 2 and is classified using threshold values (12.) from the

calibration exercise in 2012. The results are intersected with validation (13.) to derive an error matrix (14.). It also provides the 3 map outputs for binary (15.), 3 class (16.) and 7 class (17.) classifications.

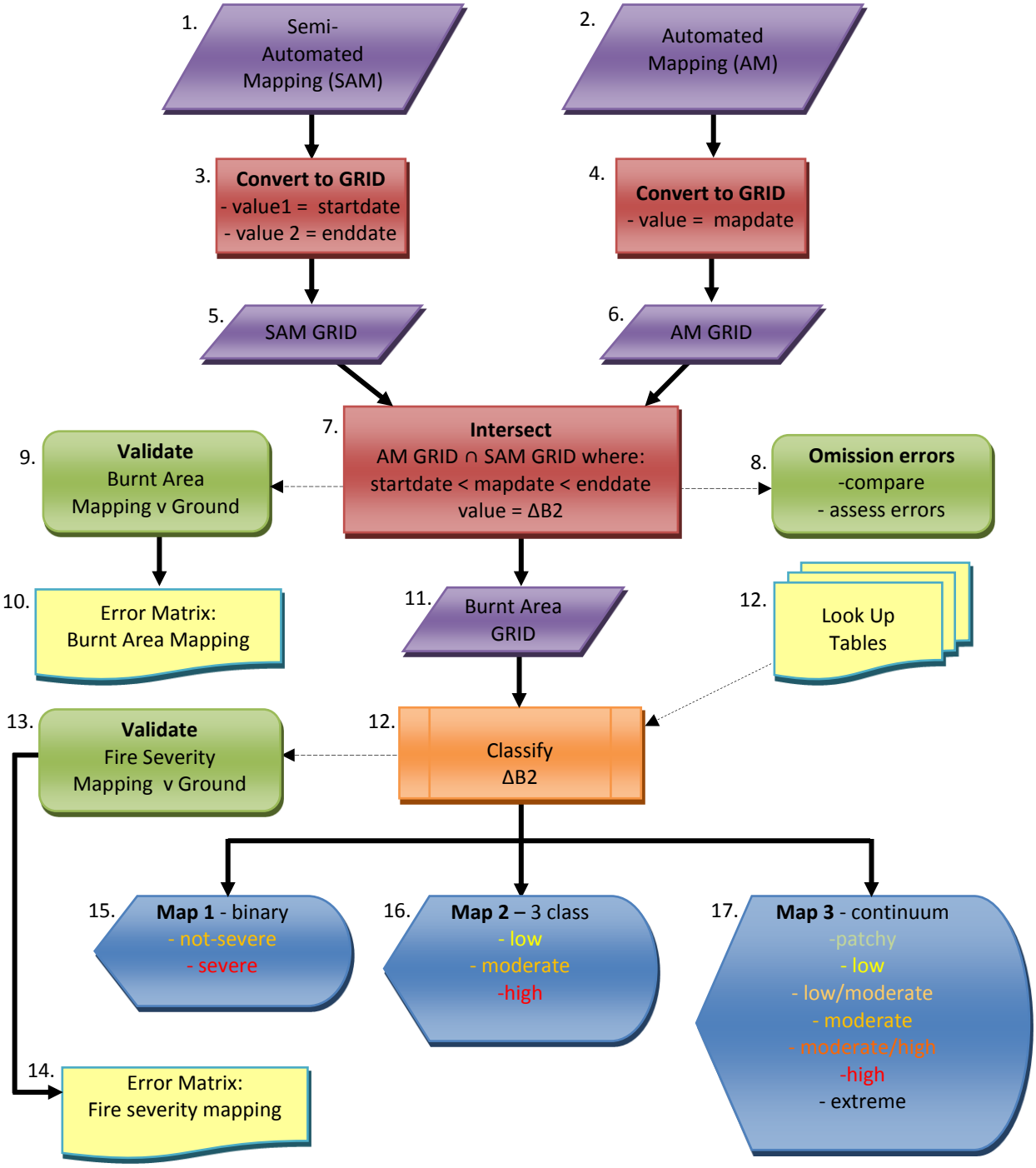


Figure 2. The spatial processing steps using MODIS satellite imagery to map fire severity. Fire extent mapping from both NAFI and Charles Darwin University are intersected to mask non-burnt areas. Calibration data in the form of lookup tables are applied to attribute severity classes and validated by a further assessment-dataset.

1.2 Calibration

1.2.1 Calibration data collection

An extensive calibration dataset increases the accuracy of the model and its ability to better predict the fire severity. Aerial transects were pre-determined to maximise intersection with fire affected areas mapping, provided by the North Australia Fire Information website. Transects were provided to a helicopter pilot by way of a series of waypoints. Following the

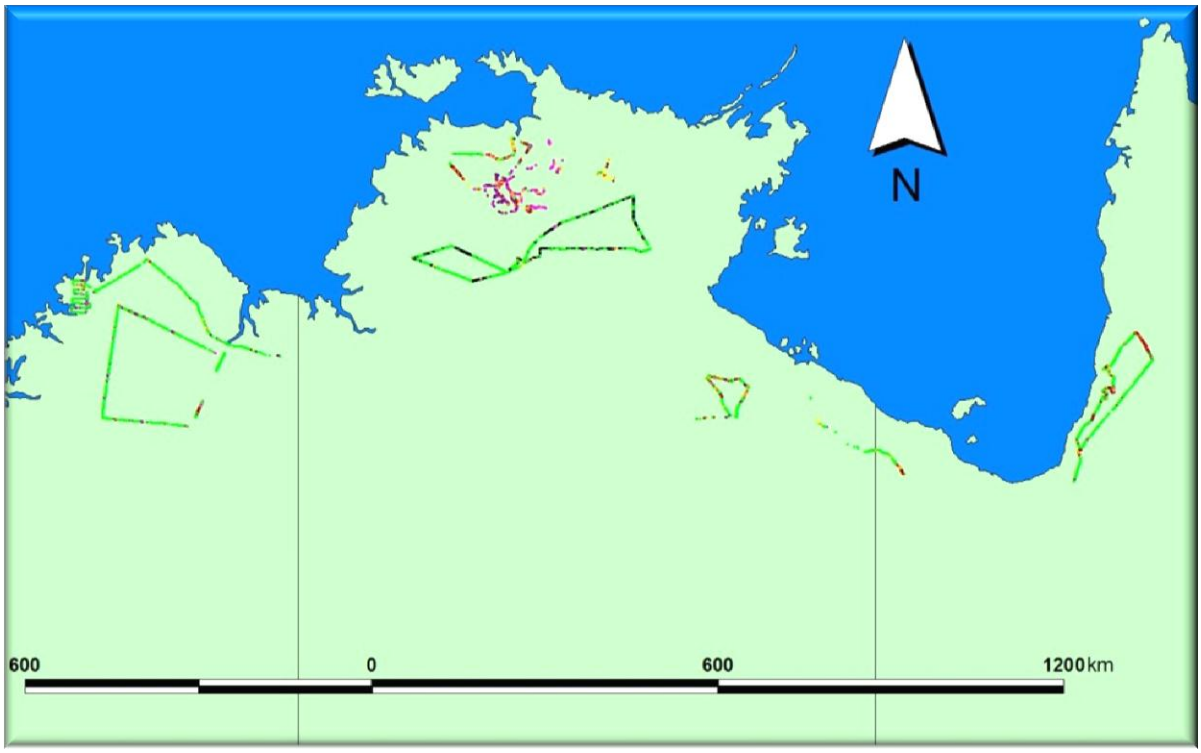


Figure 3. Distribution of fire severity calibration and burnt area validation data, 2011.

published methodology, the helicopter flew at approximately 500 feet (150 m) above ground level at an approximate velocity of 60 knots (108 km/hr) to provide maximum visibility and data point collection frequency (Edwards et al. 2001). Waypoints were collected using a GPS enabled PDA Trimble Juno. The PDA was pre-loaded with a database sequence (Cybertracker software version 3) that collected a track file and waypoints. Waypoints were attributed with categories describing the fire severity, Table 1 . The unburnt category is collected to provide an accuracy assessment of the burnt area mapping (BAM). In 2011 transects were sampled on foot, by ground vehicle and by helicopter, throughout the fire season, and across the extent of the tropical savannas, Figure 3. The

transects comprise a series of GPS waypoints each assigned a qualitative fire severity class from the set presented in **Error! Reference source not found.**. With aerial and vehicular ased transects, fire severity class only is assessed at each waypoint. With the transects assessed on foot, scorch height and basal area are also recorded.

A total of 8,097 waypoints were collected in 2011, Figure 3. Of these, 3,272 waypoints were used for fire severity calibration, while the complete dataset was used for validation of the burnt area mapping validation, . Of the 3,272 points, those assessed from the air were further filtered to remove points for which confidence in their accuracy was lower than 100%. This produced a high quality data set of 1048 points. The range of spatial and temporal variation in the dataset is extensive and covered the entire range of severity classes.

Table 1. Fire severity class descriptions, for aerial and ground based sampling.

Seven Categories	Assessment criteria	Three categories	Two categories
Low/Patchy	> 20 % unburnt patches within assessment area (~1 ha)	Low *Only ground layer vegetation affected*	Not-severe *No upper canopy effect*
Low	< 20 % unburnt patches; ground cover only affected by fire		
Low/Moderate	< 50 % of mid-storey canopy scorched by fire	Moderate *Ground and mid storey vegetation affected only*	
Moderate	> 50 % of mid-storey canopy but no upper canopy affected by fire		
Moderate/High	< 50 % of upper canopy scorched by fire	High *All strata affected*	Severe *Upper canopy affected*
High	> 50 % of upper canopy scorched by fire		
Extreme	all foliage charred		

Table 2. Temporal and spatial distribution of fire severity waypoints, 2011.

Date	Place	Type	Total Count	Count
17-18/ Apr	Kakadu NP, NT	chopper	526	282
18 Apr	Kakadu NP, NT	foot	18	18
22 May	Kakadu NP, NT	chopper	159	159
3 Jun	Kimberley, WA	chopper	1144	367
4 Jun	Karrunjie Station, WA	foot	21	21
11 Jun	Karrunjie Station, WA	foot	36	36
20 Jul	Adelaide River Region/Kakadu NP,NT	chopper	690	531
26 Jul	Delta Downs	foot	54	54
27 Jul	Normanton/SW Cape York, Qld	chopper	1430	683
28/29 Jul	Gulf (nr QLD border), NT	foot	60	60
29 Jul	Cape Crawford, NT	chopper	561	337
9 Aug	Kimberley, WA	chopper	275	38
12 Aug	Prince Regent, WA	chopper	453	251
14 Aug	Ellenbrae Station, WA	foot	39	39
15 Aug	Kalumburu Rd, WA	car	171	41
23 Aug	west Arnhem Land, NT	chopper	56	46
13-16 Sep	Robinson River station, NT	foot	92	92
16 Sep	Robinson River region, NT	chopper	112	85
20-22 Sep	Nicholson Block, NT	foot	11	11
26 Sep	Doomadgee, Qld	foot	60	60
27 Sep	Burketown, Qld to Stuart Hwy, NT	car	160	61
20 Oct	East of Katherine, NT	chopper	1159	121
21 Oct	NW of Katherine, NT	chopper	810	26

1.2.2 Calibrating the satellite imagery

The calibration dataset was intersected with the satellite imagery. The MODIS satellite images normally contain 7 bands of information representing different visible and near infrared areas of the electromagnetic spectrum reflected from the earth to the sensor. The automated burnt area algorithm (Maier and Russell-Smith 2012) continually assesses the reflectance values of an area from the time series of observations, and predicts the next value in the series. This is compared to the observed value, and if significantly different in three subsequent observations, it is assumed that a change in surface reflectance has occurred due to a change in surface properties rather than from detector noise or atmospheric corrections. Generally such a change in reflectance is the result of fire, however the presence of cloud, or smoke plumes, can also produce the effect. The latter

causes are transient, while the former is persistent, therefore the three observations is required to assign the cause of the reflectance change to fire.

When a burnt area is detected by the automated burnt area algorithm, the post-fire reflectance values and the level of reflectance change are extracted from the image for each of the 7 bands. Band 6 of the MODIS sensor on the Aqua satellite is no longer functional and is not included in the analysis. There is also a band describing the zenith angle of the observation. The zenith angle (Vz) is the angle (from vertical) at which the satellite sees the ground. The vertical view (Vz = 0) is referred to as nadir. The MODIS sensor scans from east to west and when Vz is greater than ± 20° the upper canopy of the vegetation tends to dominate the pixel. These data are, therefore, excluded from the analysis.

The calibration involves assessing the correlation between the calibration dataset and the reflectance values of the burnt area pixels. There was reasonable correlation between the calibration data and the post-fire reflectance for all 6 bands and good correlation with reflectance change. The highest correlation was observed for the reflectance change in band 2, in the near infrared, Figure 4. This band is also one of the 2 bands sampled at 250 m resolution; the remaining bands are detected at 500 m resolution.

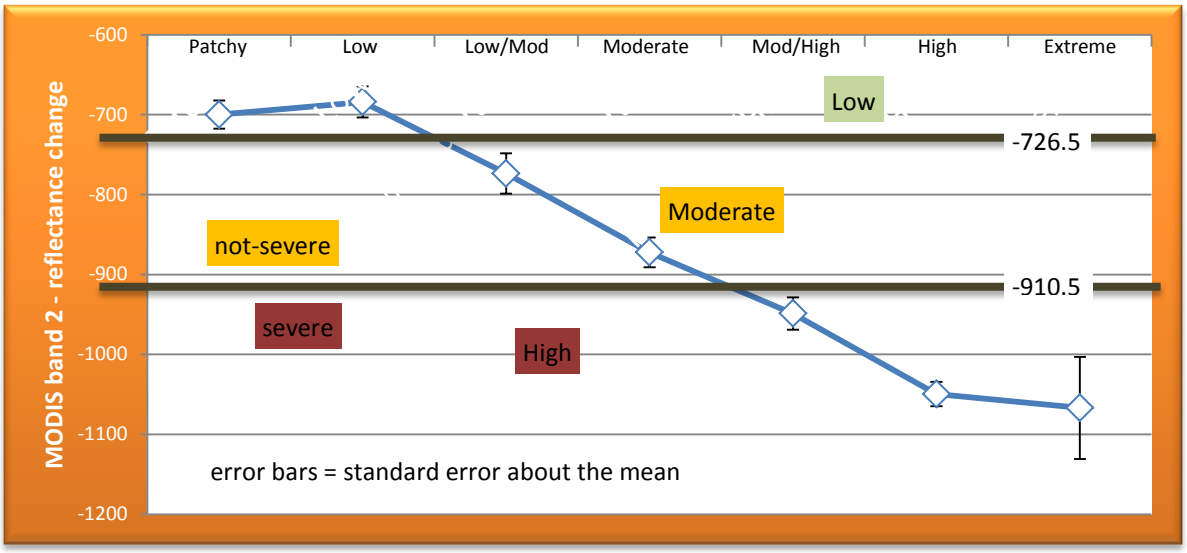


Figure 4. The correlation between the calibration dataset and MODIS band 2 reflectance change. The 7 points represent the value for the seven classes along the upper axis. The two horizontal lines represent the threshold values (-726.5 and -910.5) at which the 3 classes are separated in a trinary classification, whilst the lower horizontal line (at -910.5) separates the binary classes (severe v not-severe).

The correlation between the calibration dataset and the reflectance change allows fire severity to be classified directly from the reflectance observations. In a recent study of fire severity, Edwards (2011) found that fewer categories of fire severity produced greater accuracy in the classification. Figure 4 shows the thresholds describing a 2-class and 3-class fire severity categorisation. The 2-class classification discriminates between fire-damaged and undamaged upper-canopy. This is valuable for assessing the efficacy of fire breaks, or the effect of fire on habitat for conservation management. The 3-class classification has also been used extensively and effectively in several studies in northern Australia, in Kakadu and Nitmiluk National Parks, and is applied in the current Carbon Farming Initiative methodology for savanna burning. The 2-class thresholds were applied to the ΔB2 burnt area images to derive preliminary fire severity maps for the Kimberley, Figure 5, the Queensland Gulf region, Figure 7, and the Kakadu National Park/West Arnhem Land region, Figure 6.

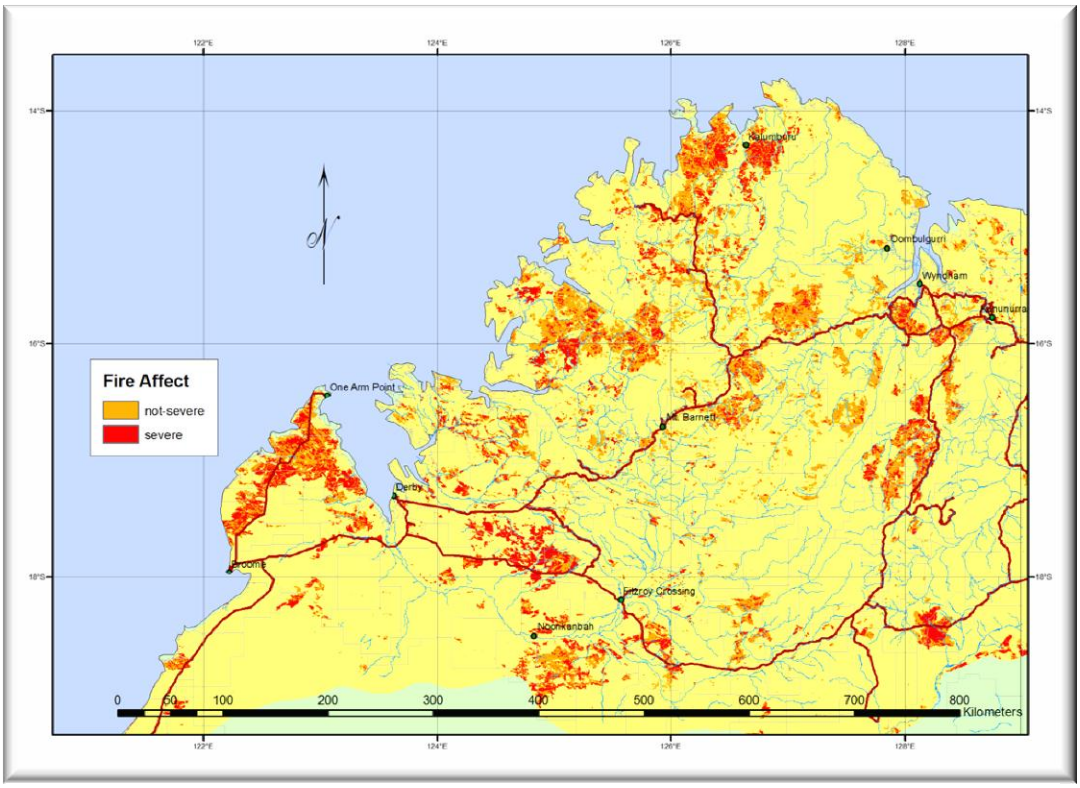


Figure 5. Binary classification of fire severity in the Kimberley region, 2011.

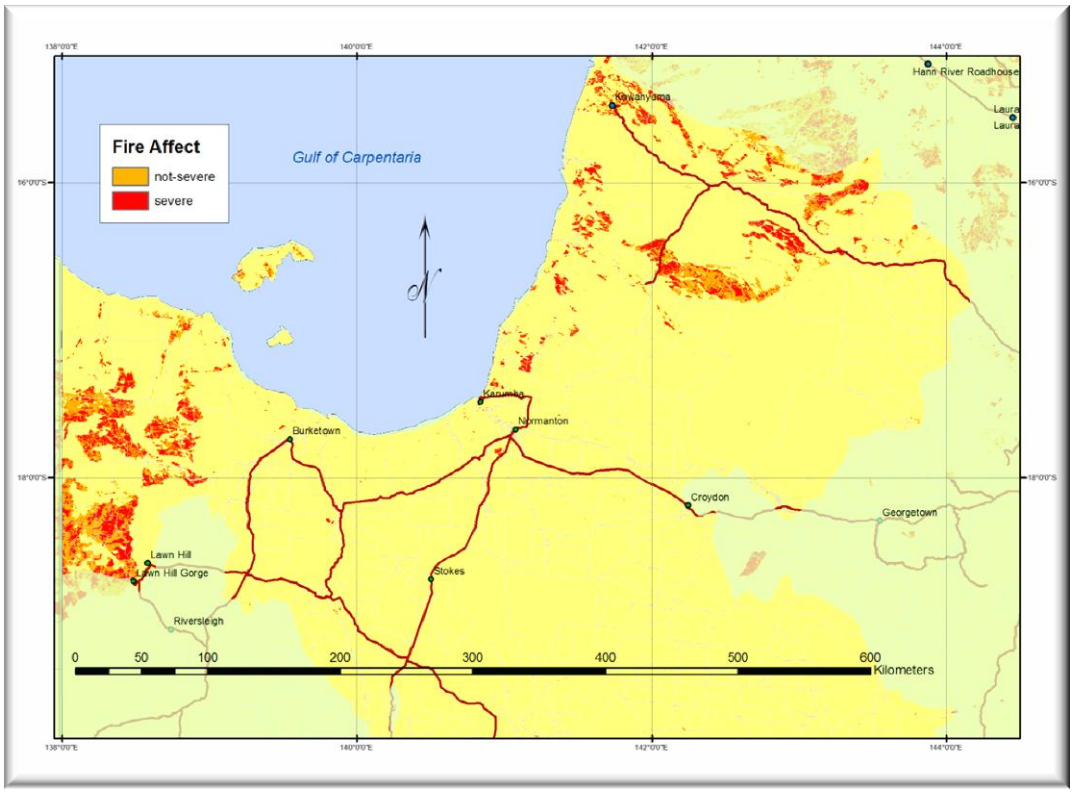


Figure 7. Binary classification of fire severity in the Gulf region of Queensland, 2011.

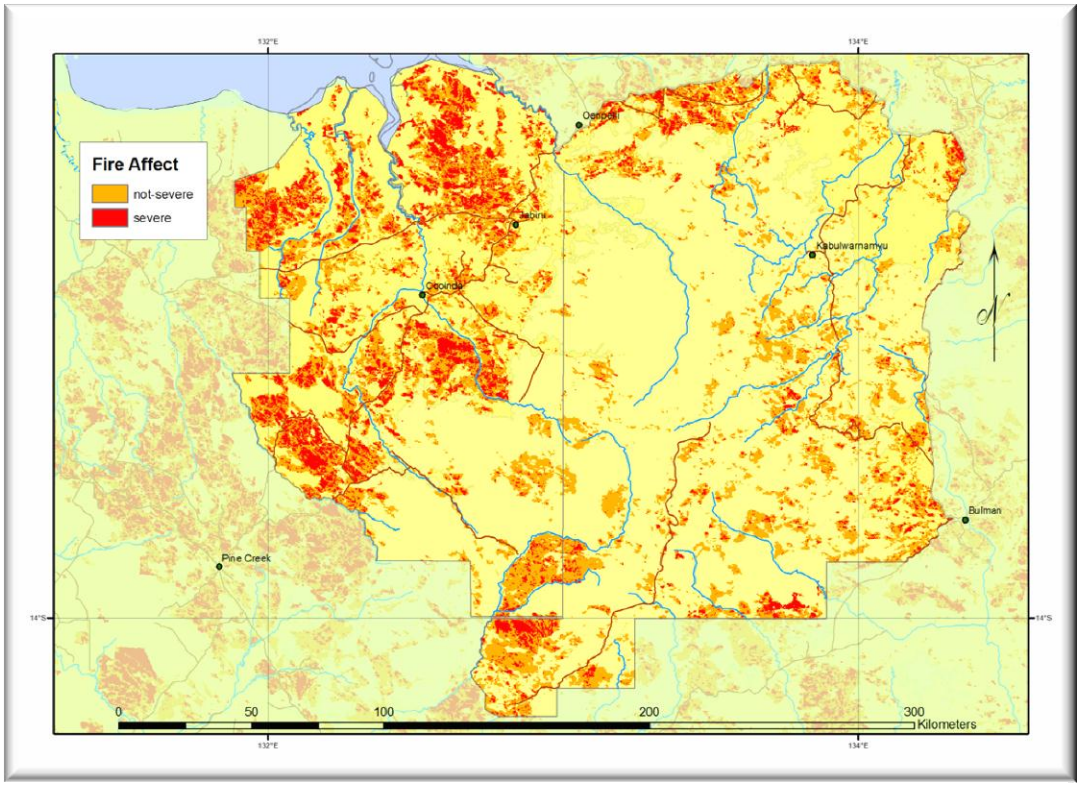


Figure 6. Binary classification of fire severity in the Kakadu National Park/west Arnhem Land region, 2011.

1.3 Validation

An extensive validation data collection program was undertaken in 2012. Four areas were assessed in the Early Dry Season (EDS), all west of longitude 135°E. Further assessments were undertaken east of longitude 135°E later in the 2012 fire season as the end of the early dry season progressed from west to east ending in the Eastern Top End and Cape York at the end of July. All areas assessed in the dry season of 2012 are mapped in Figure 8, detailed in Table 3, and summarized in Table 4.

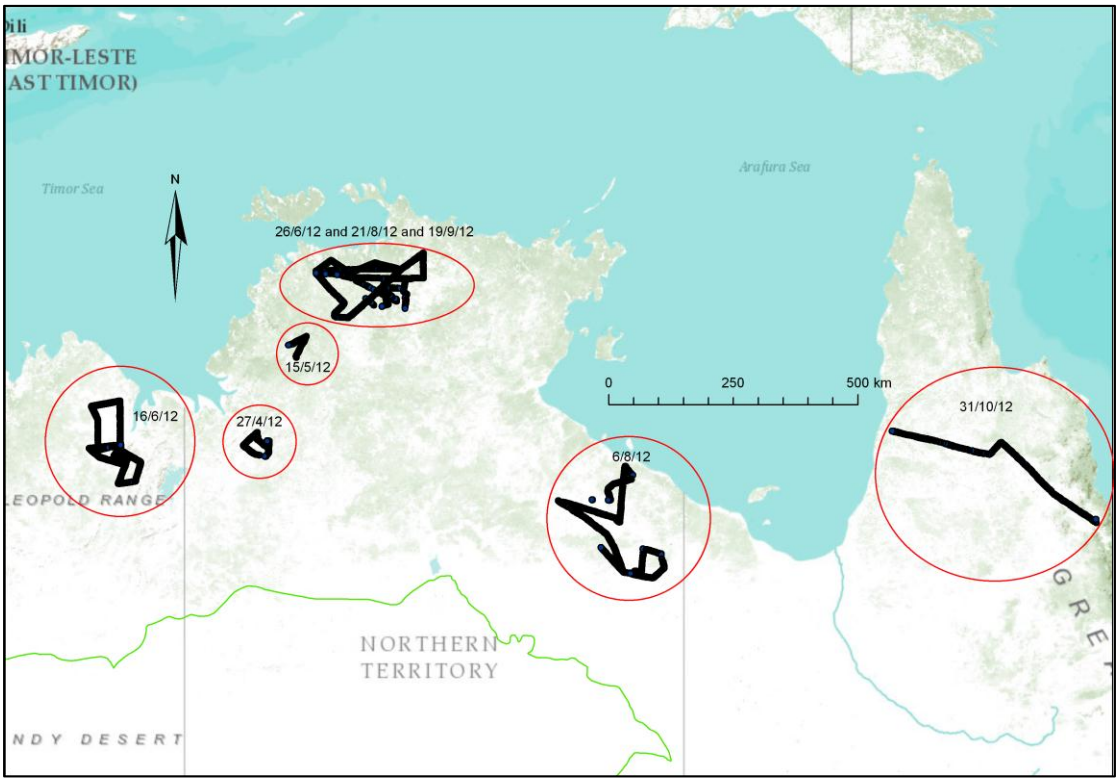


Figure 8. Locations and dates of aerial transects undertaken in north Australia for the validation component of the Bushfire CRC North Australia Fire Mapping Project, 2012.

Table 3. Aerial validation for burnt area and fire severity mapping validation, collected along aerial transects in north Australia in the fire eason, 2012.

Date	Region	Length (km)	Waypoints (severity)
27th April	Victoria River District	185	223
5th May	Fish River	84	83
16th June	East Kimberley	520	650
26th June	Kakadu National Park/west Arnhem Land	505	451
6/7th August	The NT Gulf	508	593
21st August	Adelaide, Mary and Alligator Rivers District	537	571
10th September	Home Valley Station, East Kimberley, WA	172	191
19th September	Darwin to, and including, Kakadu National Park	705	431
31st October	Cape York Peninsula (Mareeba to Kowanyama)	478	934

Table 4. Summary statistics for Late Dry Season 2012 validation data collection

Summary statistic	value
Total transect length (km)	3,694
Total number of waypoints collected for burnt area and fire severity map validation	10,310
Total number of 100% reliable waypoints for fire severity map validation	4,127

1.3.1 Validation analysis

The waypoints collected from the aerial transects, collated separately for the early and late dry seasons of 2012, were intersected with the fire severity mapping data for the respective seasons. An error matrix was then derived to determine the accuracy in terms of:

- **omission** error (the amount missing from the mapping of a category);
- **commission** error (the amount erroneously additional to the mapping of a category);
- **overall accuracy** and;
- the **Kappa statistic**, (which provides an absolute rather than relative description of the error, for each category of mapping (Congalton 1991)).

To determine the utility of each of the multi-levels of categorization, error matrices for binary, 3 class and 7 class fire severity mapping were undertaken. A table of the results of the error assessments for each classification scheme for each season are given in Table 5.

Table 5. Result of the validation assessment for the (a) early and (b) late dry seasons of 2012.

Statistic	7 Categories	3 Categories	2 Categories
Overall Accuracy	0.23	0.35	0.69
Omission error	0.14	0.37	0.72
Commission error	0.15	0.37	0.71

Statistic	7 Categories	3 Categories	2 Categories
Overall Accuracy	0.27	0.40	0.59
Omission error	0.15	0.39	0.59
Commission error	0.16	0.39	0.58

1.3.2 Validation Results

A standard error matrix was derived separately for the early and late dry seasons for 2012, Table 6. The accuracies are of a similar value to those found in experimental research to derive the initial models (Edwards 2011). The overall accuracy in the early dry season was 0.69 and 0.59 in the late dry season. The main issue highlighted in these analyses was that the models incorrectly classify a proportion of the severe fires, hence the lower accuracy in the late dry season, instead classifying these areas as not-severe, whilst misclassifying much less of the not-severe areas as severe. However, as the number of categories is reduced the accuracy improves, suggesting that it is possible for us to improve the accuracy.

Table 6. Error matrices using the 2012 validation dataset to assess the accuracy of the 2012 mapping, using the algorithm derived from the 2011 calibration for (a) the early dry season and; (b) the late dry season.

(a)

		Ground truth data				
		Not-severe	*Severe*	***Total***	*Commission accuracy*	***Average Commission Accuracy***
Mapping data	*Not-severe*	518	343	860	0.60	
	Severe	87	459	547	0.84	
	Total	605	802	1407		0.72
	Omission accuracy	0.86	0.57		**Overall Accuracy** 0.69	
	Average Omission Accuracy			0.71		

(b)

		Ground truth data				
		Not-severe	*Severe*	***Total***	*Commission accuracy*	***Average Commission Accuracy***
Mapping data	*Not-severe*	657	509	1165	0.56	
	Severe	621	934	1555	0.60	
	Total	1277	1442	2720		0.58
	Omission accuracy	0.51	0.65		**Overall Accuracy** 0.59	
	Average Omission Accuracy			0.59		

1.3.3. Discussion

At this stage of the map development we had discerned that it was possible to produce a fire severity map using the near infrared. The literature had previously suggested (Pereira 2003) that the infrared was not capable of this, and from the perspective of absolute change in photosynthetic vegetation (PV) this should be true. However, if we assess the relative change in PV, that is, infrared reflectance, before and after the fire, as in many

instances the overall pixel proportion in PV is quite low, Figure 9, especially in the latter parts of the dry season, and hence the lower in classification accuracy in the late dry season.

Figure 9. (a) Illustrates the scarcity of photosynthetically active vegetation in the latter part of the dry season, and marked increase of non-photosynthetic material in a lower rainfall zone of the tropical savannas; (b) illustrates the marked change affected by fire on photosynthetically active vegetation, and the total removal of non-photosynthetic material to reveal bare soil.

The overall accuracy in the early dry season was found to be far higher than in the late dry season. This is counter to accuracy assessments undertaken of fire extent mapping, where early dry season fires, being smaller in extent and generally patchier, consume much less of the biomass and therefore have less impact on the reflectance signal making them more difficult to detect. As opposed to late dry season fire affected areas that tend to be geographically extensive, the combustion of biomass is far more complete and their effect has a strong impact on the reflectance signal.

The fire severity mapping accuracy varies from fire extent mapping accuracy for two very different reasons: the first is that the assessments of fire severity are undertaken within already mapped fire affected areas. These areas are the union of two separate mapping techniques, both of which separately achieve total accuracies > 85%, although higher in both instances in the late dry season. Therefore the fire severity algorithm does not need to discriminate fire affected areas, but the level of effect of the fire. Overall this lowers the mapping accuracy, as the simple act of discriminating fire raises the statistical accuracy, but

it does mean that the potential omission or commission of burnt areas is removed. The second reason occurs due to the variability in intra-habitat phenological stages that occur due to climatic and edaphic conditions, particularly in the early dry season. Under this variability the fires and their effects are markedly more variable even within pixels. In the early dry season the majority of fires occur under the canopy, as opposed to the late dry season where the variation in fire severity is greater. The data from the fire monitoring plots in Kakadu National Park demonstrates this clearly (Russell-Smith and Edwards 2006), Figure 10. Ten years of plot data at 179 plots were sampled for fire effects annually. This dataset has some small bias being in National Parks, the fire regimes during this period are better than most of the rest of the Top End. Nearly 80% of plots affected by early dry season fires experienced low severity effects. However, in the late dry season the proportion of each severity class is almost equally spread, 30, 40 and 30% for low, moderate and high respectively.

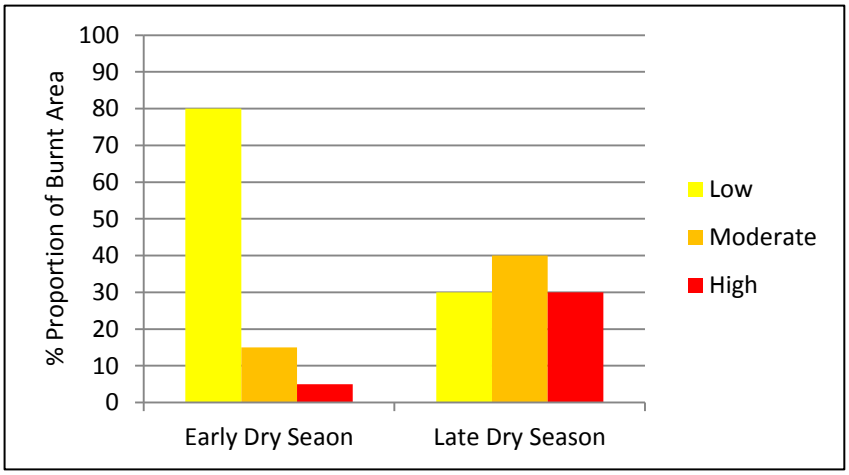


Figure 10. The proportion of each fire severity class in each season for 179 fire monitoring plots for ten years in Kakadu and Nitmiluk National Parks, NT, Australia.

The accuracy of the calibration can be improved by the addition of each years' validation data. Data collected in 2012 is collated with the 2011 calibration to expand the calibration dataset. Data collected in 2013 is being used for validation of the algorithm derived from the expanded 2011/12 calibration dataset but will be included in the expanded calibration dataset to derive the 2014 algorithm.

The original modelling was derived from a thorough and detailed spectral and statistical analysis of very high resolution spectra and field data. The theory derived from this work was initially applied to develop a fire severity mapping algorithm. Seasonally and geographically extensive transects of highly accurate field data collected annually across the breadth of the tropical savannas are providing an increase in the accuracy of our fire severity map product. Continued "truthing" of the fire severity map product, in fact any remotely sensed product, is required to maintain the user confidence, but also provides further data for improved calibration.

1.4 Implementation on the NAFI website

The underlying data on the North Australia Fire Information website has become integral in the calculations of greenhouse gas emissions abatement in the Savanna Burning methodology, having been identified in the legal Determination as the default dataset (DCCEE 2013). The fire mapping is undertaken by remote sensing specialists, employed by Cape York Sustainable Futures and, until recently, Bushfires NT in the NT government, but now with the Darwin Centre for Bushfire Research at Charles Darwin University. The mapping is derived from 250 m pixel MODIS satellite data, approximately on a weekly basis for the whole of the tropical savannas including the Kimberley in WA, the remainder of the Northern Territory and most of Queensland excluding the south eastern corner. As of early last year the northern half of SA is now also included. Concurrently an automated method of fire mapping has been developed by the Research Institute of Environment and Livelihoods (RIEL), based at Charles Darwin University. As of the fire season of 2012 the accuracy of the automated mapping product has reached the levels of the human operated mapping methodology, however this is a statistical result and NAFI users prefer the visual presentation provided by the semi-automated mapping approach.

There is major interest from fire managers in the fire map products, whereby they provide ancillary data of the locations of many of their smaller and patchier fires to guarantee that they are included in the mapping, remembering these map products are predominantly for operational purposes. Unfortunately the process of these inclusions can not be included in any automated mapping algorithm. The obvious suggestion is to use the automated mapping as a base dataset and add to it manually where required. However the automated

mapping algorithm uses every image from the twice daily overpass of the MODIS sensor on board both the Terra and Aqua satellites. It also has a delay of up to 7 days as it uses a number of assessments to reach a threshold of probability that the phenomenon detected as a burnt area is not a cloud, cloud shadow or ephemerally wet area (due to rain for instance). This also means that within a given week an part of any image may have been used to detect a burnt area. The manual approach uses a difference-image technique of approximately 1 week, using the two, or one or two more, best images. The lack of temporal alignment in both these instances is difficult for an operator to deal with satisfactorily, however there is further research being undertaken that might yet deal with this issue.

The fire severity map product is based on the result of both the automated and manual burnt area map products. Whereby the classification algorithm is applied in areas where **only both** products have determined an area to be fire affected. The product has been calibrated using data collected across the fire seasons and the breadth of the tropical savannas for the past two years. Further validation data have been collected in 2013, whereby a satisfactory accuracy will see the product displayed on NAFI by the end of the 2013 fire season. As yet the result is not yet “user-perfect” but is undergoing an iterative feedback process with a group of reliable and interested users. The accuracies previously reported in the fire severity mapping are quite acceptable from the ecological modelling view point, however mapping accuracies under 80% would not be acceptable from a fire management perspective.

The NAFI website was upgraded in 2013. Dr Peter Jacklyn who oversees the site has upgraded the display to bring it in line with other popular map display applications such as Google Earth. There have been major improvements in the background also with an upgrade of the oracle geo-databases. The MODIS derived fire histories were re-assessed and improved by a remote sensing expert, Rohan Fisher, over 2012. The financial support for the improvement came from the Australian Greenhouse Office, they will be the base datasets for the Carbon Farming Initiative’s Savanna Burning Greenhouse Gas Abatement methodology. The inclusion of the fire severity dataset will mean adaptation of the currently accepted higher rainfall methodology and integration into the development of the lower rainfall methodology. This will remove the contentious issue of the seasonal threshold date,

which currently stands at 31 July/1 August for the whole region, but will bring greater scrutiny on the fire severity mapping, where we know the levels of accuracy are not quite as high as for the burnt area mapping.

1.5 Application in the Rangelands

In 2011/12 calibration data were collected, Figure 11, in (a) parts of the northern tropical rangelands and (b) central Australia to expand the application of the algorithm into the more arid rangelands of northern Australia. The process of trialling the fire severity mapping

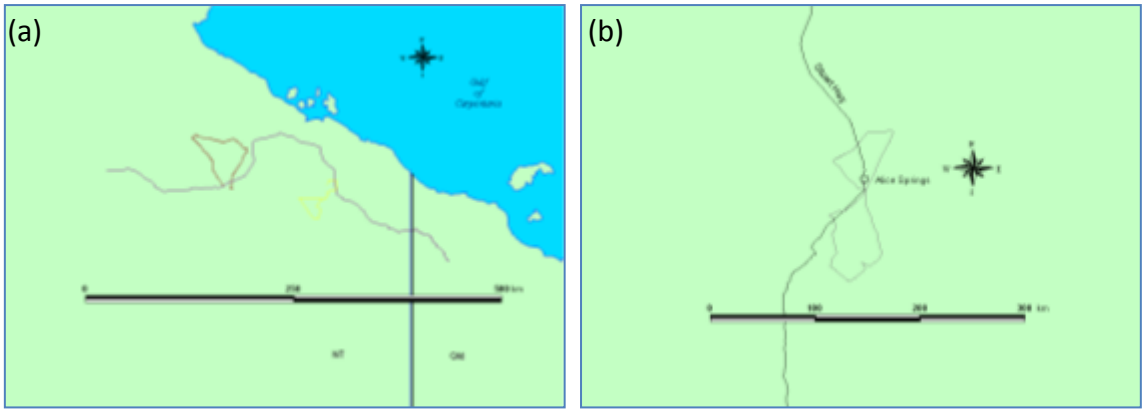


Figure 11. Calibration data collected in the Rangelands of (a) the NT Gulf region and (b) central Australia

in the rangelands commenced with end users in central Australia in early 2013, whereby a number of fire ecology researchers from Parks and Wildlife, Charles Darwin University, CSIRO and private companies, and fire managers from Bushfires NT, Parks and Wildlife and the Central Land Council.

The fire severity algorithm was developed initially for the tropical savannas as this is the region encompassed by the preliminary modelling developed in the thesis used to commence this research (Edwards 2011).

Arid landscapes present a very different spectral signature. The rangelands are vast, Figure 1, and variable (Ludwig and Tongway 2000; Fisher 2001; Whitehead 2001; Cook et al. 2010). Fire effects are far more persistent in the rangelands, they are obvious on satellite based images and aerial photography for years, even decades, unlike the tropical savannas where fire scars from early in the dry season may not be visible in the late dry season of the same fire season, and definitely not visible remotely after the proceeding wet season.

Bushfires NT colleagues based in Katherine and Alice Springs and NAFI colleagues from Darwin assisted in collecting calibration data in the NT Gulf and Alice Springs Regions. They were also involved in the assessments of the fire severity map product. These data have thus far been incorporated into the main calibration/validation dataset, as obviously it would be efficient to have a single fire severity mapping algorithm. Although the next step at the end of 2013 is to assess the accuracy separately.

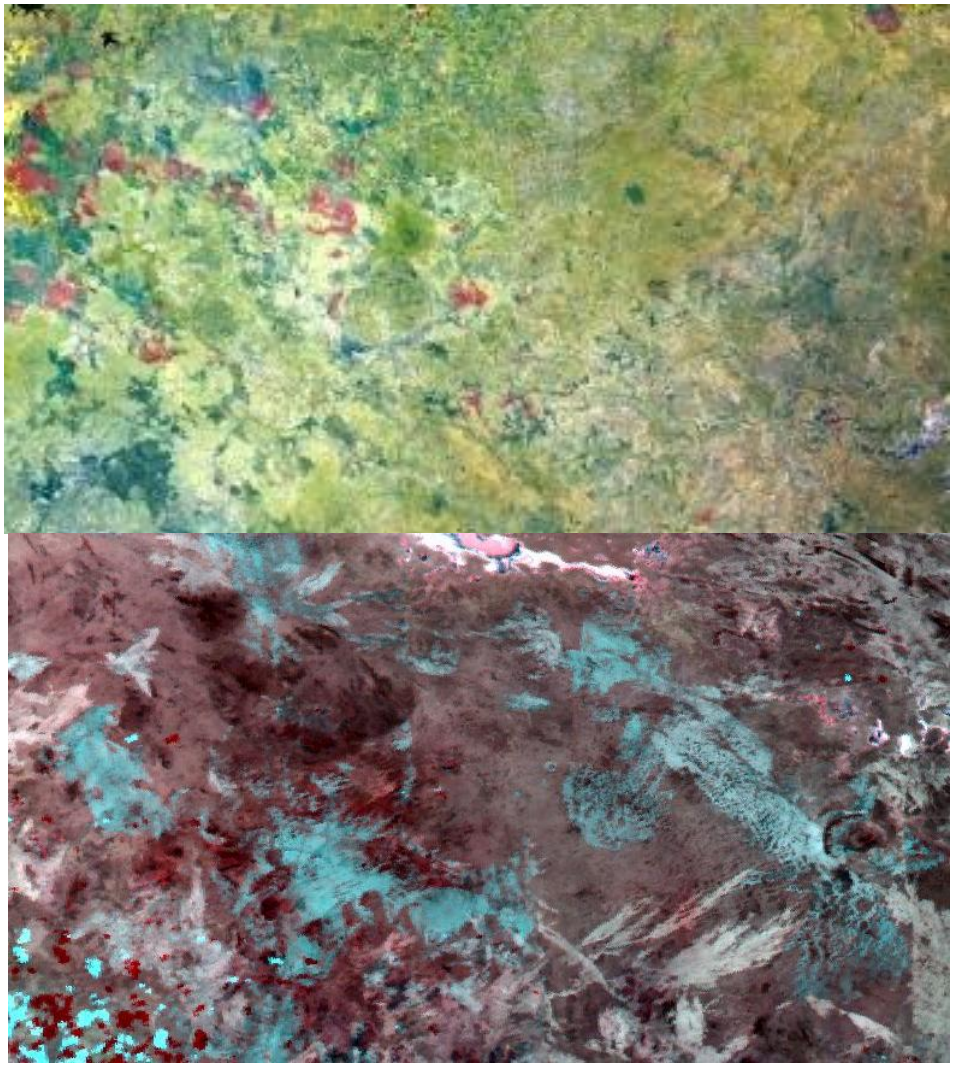


Figure 12. A spectral and fire-morphology comparison between (a) the tropical savannas (red) and (b) the central Australian rangelands (blue). Fires in the tropics are smaller and rounder due to the continuity of fuel, the scar is short lived, months at most. Fires in the rangelands are larger usually longer and thinner due to wind and scattered fuel conditions. Spectrally they are also very different due in part to combustion efficiency (the ratio of ash to char post-fire)

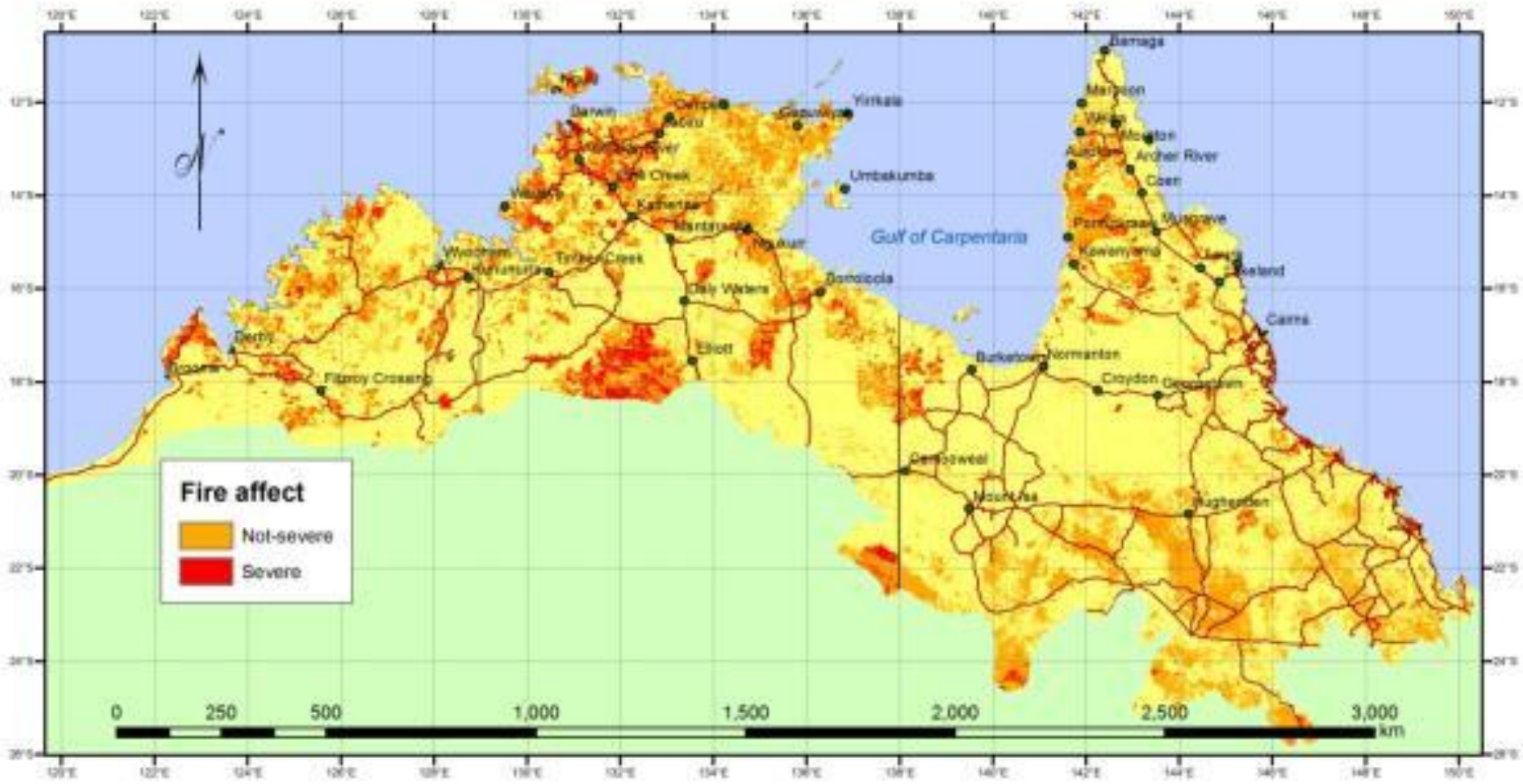


Figure 13. Fire severity mapping, tropical savannas, Australia, 2011

Activity 2: Ecological Risk assessment

In this research we applied spatial information layers, describing the extent and effect of fire across the higher rainfall region (> 1,000 mm mean annual rainfall), Figure 14, and other topographical and vegetation mapping, in a geographical information systems analysis to characterise the effects of fire regimes to key ecological-risk models. Four regimes were compared, the first being recent time (RT, 2008-2012), the second an improved regime (IR) being for the same period but equivalent to the improved regime imposed by indigenous land managers in west Arnhem Land already funded for their emissions abatement. Then, by surmising potential climate change effects (CSIRO & Bureau of Meteorology 2007), instigating a change to fire regime variables in both the RT and IR scenarios, Table 7 (a). The results of this study have been summarised in a paper, currently submitted to the Journal ***Ecography***. A draft is attached to this report: Appendix A.

2.1 Data collation

The primary base datasets for derivation of spatially explicit fire metrics were the monthly mapping of fire affected (burnt) areas, and the annual mapping of fire severity available for the whole tropical savannas region and the period 2008-2012. Fire mapping was derived using difference-image techniques of red and near infrared 250m pixel satellite-borne MODIS sensor imagery, detailed mapping methods are outlined in (Fisher et al. *unpublished*), and operational utility for north Australian land managers given in (Jacklyn et al. in press). The theoretical derivation of the fire severity satellite-derived mapping model is given in (Edwards et al. 2013) whilst the operational model is given in Activity 1 of this report.

A global digital elevation model was derived from the Shuttle Radar Topography Mission (SRTM) (http://www2.jpl.nasa.gov/srtm/) and supplied with 3” pixels. In a 3 x 3 pixel window slope was calculated in degrees of rise, from 0 to 90°, and the topographic index (Riley et al. 1999), being the root of the sum of the squares of the difference between the central pixel elevation and the elevation value of all other pixels in the 3 x 3 window. Areas with slope > 5% and area > 56 ha (i.e. 3 x 3 pixels) were selected as representative for soil movement

modelling (Russell-Smith et al. 2006), whilst a maximum elevation difference of 15 m was selected to define the threshold of topographic roughness representing the occurrence of obligate seeder taxa (Edwards and Russell-Smith 2009). Vegetation mapping was re-classified into 4 classes from (Fox et al. 2001) to match the Carbon Farming Initiative (CFI) "Fuels" classification given in (Russell-Smith et al. 2009) for savanna burning emissions calculations and into two classes (lowlands and uplands) for Carbon sequestration models (Murphy et al. 2009).

2.2 Methods

2.2.1 Study Area

The Interim Biogeographic Regionalisation of Australia (Environment Australia 2000) defines an area approximately 1.9 million km^2 referred to as the tropical savannas of northern Australia. Analyses were undertaken with GIS mapping, bounded within the north of the tropical savannas by a 1,000 mm rainfall isohyet (Russell-Smith et al. 2012). The 1,000 mm isohyet provides delineation for the application of the Australian Government's Carbon Farming Initiative's Savanna Burning methodology (http://www.climatechange.gov.au/reducing-carbon/carbon-farming-initiative/methodologies/methodology-determinations/savanna-burning), in turn determined from the geographical extent of empirical data for development of the models within the methodology. *Eucalyptus* dominated habitats ranging from closed forest to grassland (Specht 1981) cover the 444, 550 km^2 of this area, referred to as the higher rainfall (HR) region, Figure 14. Rainfall, by definition, in the tropical savannas is highly seasonal (Scholes and Archer 1997; Pereira 2003) (Edwards et al. 2013) with over 90% of mean annual rainfall falling in the southern hemisphere's summer/autumn months (Williams et al. 1996). The remaining months, referred to as the dry season, are further divided into two distinct fire management periods in response to climate driven fire effects. The early dry season (EDS) is characterised by higher humidity and soil moisture with the greatest potential to manage the outcome of prescribed burning activities to mitigate wildfires in the late dry season (LDS), from approximately 1 August.

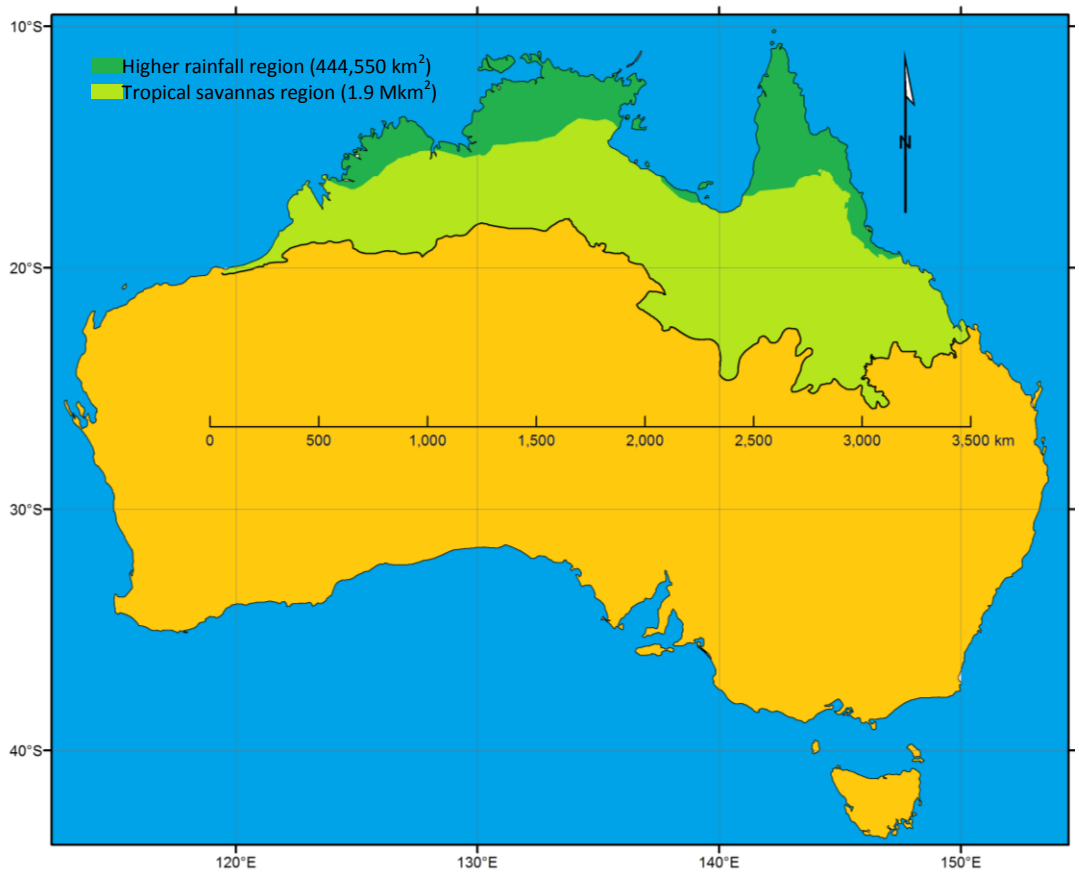


Figure 14. The extent of the tropical savannas and higher rainfall region in northern Australia

2.2.2 Scenario Building

The first assessment was undertaken to determine the longer term effects of wildfire dominated contemporary fire regimes. The second assessment was to determine the effects of an enhanced fire regime, already demonstrably possible in parts of the Top End. In both assessments we changed the proportions of the landscape affected by various seasonality and severity fire effects attributes, such that the overall proportion of the landscape burnt, the incidence of wildfire and the proportion of severe fires is increased by 10% due to the impacts of climate change, Table 7 (a).

Scenarios were developed to determine the effects of various fire regimes. We firstly assessed the ambient condition, applying the conditions from recent fire history information from 2008-2012, and secondly a condition consistent with improved fire management as demonstrated in west Arnhem Land, a large (28,000 km^2) indigenous estate in the centre of

the region. In addition we applied the potential effects of climate change to both the ambient and improved fire management scenarios, Table 7 (a).

Commensurate with the scale of the analyses, five broad fire-related ecological impacts to tropical savanna ecosystems were surmised based on the evidential literature to date, Table 9, including: 1. Accountable (methane, nitrous oxide) greenhouse gas (GHG) emissions abatement, derived using the formally approved (Australian Government's Carbon Farming Initiative) methodology for "Savanna burning emissions abatement" given in (Russell-Smith et al. 2009) and (CSIRO & Bureau of Meteorology 2007); 2. Bio-carbon sequestration, using generalised models derived from long term plots to estimate tree growth against the frequency of various fire severities (Murphy et al. 2010); 3. Applying fire severity models on the recruitment of the long lived obligate seeder species, also an indicator of landscape health, *Callitris intratropica*, found primarily in regions of the most highly variable topography, given in (Russell-Smith et al. 2012). 4. The effect of fire frequency on long-maturing obligate seeder shrub taxa, given in ; 5. The effects of fire on hill-slope erosion using figures relating erosion volume, slope and fire type, by seasonality, from (Russell-Smith et al. 2006);

Table 7. The risk categories and (a) fire metrics for each category and; (b) descriptions for associated scenarios for the risk categories.

Parameters / variables	**Business as usual (BAU)**	**BAU with climate change (BAU + CCI)**	**Improved fire management (IFM)**	**IFM with climate change (IFM + CCI)**
(a)				
Fire seasonality the proportion of the region affected by Early (EDS) and late (LDS) dry season fires.	EDS = 0.19 LDS = 0.34	EDS = 0.19 LDS = 0.44	EDS = 0.29 LDS = 0.17	EDS = 0.29 LDS = 0.22
Fire severity proportion of burnt area affected by the frequency of a fire severity class	mild = 0.25 moderate = 0.17 severe = 0.11	mild = 0.28 moderate = 0.21 severe = 0.14	mild = 0.28 moderate = 0.12 severe = 0.06	mild = 0.30 moderate = 0.14 severe = 0.07
(b)				
Savanna burning emissions abatement applying formal CFI methodological approach	Baseline scenario effectively no change	Baseline scenario with worsening fire-weather conditions	Reduced GHG emissions through strategic burning	Attempted reduced GHG emissions, but with worsening fire weather conditions

Parameters / variables	Business as usual (BAU)	BAU with climate change (BAU + CCI)	Improved fire management (IFM)	IFM with climate change (IFM + CCI)
Savanna burning Biosequestration applying modelling approach as per (Murphy et al. 2010) (Murphy and Russell-Smith 2010)	Baseline scenario effectively no change	Baseline scenario with worsening fire-weather conditions	Increased bio-sequestration associated with milder fire regime	Attempted increased bio-sequestration, but encountering worsening fire-weather conditions
Biodiversity effect: (1) small mammal fauna—applying fire frequency models as per (Woinarski et al. 2010)	Ongoing precipitous decline	Ongoing precipitous decline, exacerbated by climate change	Attempt to impose (slightly) more sustainable fire regime	Attempt to impose (slightly) more sustainable fire regime, but encountering worsening fire-weather conditions
Biodiversity effect: (2) fire-vulnerable obligate seeder vegetation—applying fire frequency models as per (Russell-Smith et al. 2012)	Ongoing decline, especially in more rugged terrain	Ongoing decline, exacerbated by climate change	Attempt to impose (slightly) more sustainable fire regime	Attempt to impose (slightly) more sustainable fire regime, but encountering worsening fire-weather conditions
Erosion effect—applying erosivity relationships as per Russell-Smith et al. (2006)	Ongoing high erosion rate, especially in rugged terrain	Ongoing high erosion rate, exacerbated by climate change	Attempt to impose (slightly) more sustainable fire regime	Attempt to impose (slightly) more sustainable fire regime, but encountering worsening fire-weather conditions
Ecosystem services generally	Deteriorating	Deteriorating, exacerbated by climate change	Positive intervention	Positive intervention, but encountering worsening fire-weather conditions
Ecosystem services, on Indigenous lands specifically	Deteriorating, likely at greater rate than for north Australia generally	Deteriorating, exacerbated by climate change	Positive intervention, with potential for enhanced benefits relative to north Australia generally	Positive intervention, but encountering worsening fire-weather conditions

2.3 Spatial Analyses

Spatial analyses were undertaken as raster using the Spatial Analyst extension of ESRI® Arcmap™ 10.0 (ESRI 2011). Spatial data, Table 8, were projected into the Australian Albers equal area projection (central meridian: 132°, 1st standard parallel: -18°, 2nd standard parallel: -36°, false easting: 0.0, false northing: 0.0, latitude of origin: 0.0, linear unit: metre, datum: GDA94) with 250m pixels, being the maximum pixel size of all non-categorical data. Attributes of the four scenarios, , were determined primarily from the literature (Russell-Smith and Edwards 2006; Murphy and Russell-Smith 2010), however the estimates of the

improvement to fire regimes were taken from analyses of the recent (7 year) fire history of the West Arnhem Land Fire Abatement (WALFA) project, being the only longer term fire management project in the north Australian tropical savannas, meeting the requirements of the scenario *sensu* (Edwards and Russell-Smith 2009).

Table 8. Source of primary spatial data. All data were rescaled to 250 m pixels prior to analysis to reflect the maximum pixel size of non-categorical data.

Dataset	**Source**	**Derivation**	**Original pixel size**
Vegetation	Vegetation of the Australian tropical savannas (Fox et al. 2001)	Classification based on Meyer *et al.* 2008, as applied to the National Greenhouse Gas Inventory (NGGI).	1 km
Fire History	North Australia Fire Information (NAFI) www.firenorth.org.au	Mapped using difference-image techniques of red and near infrared 250m pixel satellite-borne MODIS sensor imagery (R Fisher *et al.*, unpublished).	250 m
Fire Severity	North Australia Fire Information (NAFI) www.firenorth.org.au	Mapped using a multiple difference-image technique and applying threshold values to a pre v post-fire proportional change in the near infrared (Edwards *et al.* 2013).	250 m
Digital Elevation Model	The Shuttle Radar Topography Mission (SRTM) (http://www2.jpl.nasa.gov/srtm/)	Processed from raw radar signals at 3 arc-second intervals for global distribution (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/SRTM)	9" (~250 m)
Land Use	Australian Bureau of Agricultural and Resource Economics – Bureau of Rural Sciences (ABARE-BRS) (http://adl.brs.gov.au)	Based on the Australian Land Use and Management Classification. Catchment scale mapping is produced by combining land tenure and other types of land use information, fine-scale satellite data and field information. (ABARE-BRS 2010)	50 m
Mean Annual Rainfall	Australian Bureau of Meteorology (BOM)	30 year mean of monthly rainfall data	500m

Table 9. Key risk attribute table.

Key risk attribute model	Reliability	References
(a) Greenhouse gas emissions abatement		
Applying the nationally accepted Australian model, savanna burning emissions (*E*) are calculated as the product of the mass of fuel pyrolised (*FP*) and the emission factor (*EF*) of respective accountable GHG (*g*) species: *E = FP * EF(g)* where *FP* is the product of the area exposed to fire (*A*) taking into account spatial patchiness, the fuel load (*FL*) in respective fuel classes, and the burning efficiency (*BEF*) defined as the mass of fuel exposed to fire that is pyrolised. *EF(g)* is defined relative to the fuel elemental content where, for carbon species, *EF(g)* is expressed relative to fuel carbon, and nitrogen species are expressed relative to fuel nitrogen. Fuel carbon mass is determined from fuel mass by the fuel carbon content, while fuel nitrogen is derived from the fuel mass by the product of carbon content and the fuel nitrogen to carbon ratio. Units of emissions (*E*) are given as Mt CO_2-e, taking into account the enhanced respective warming potential of accountable gases (CH_4, N_2O) relative to CO_2.	Based on a formal uncertainty assessment for a 24,000 km^2 fire-prone region, domain emissions were found to be accurate at the 95% confidence level to within a factor of 30–35% of the mean, with an overall CV = 0.16	(Russell-Smith et al. 2009; DCCEE 2013)
(b) Savanna burning biosequestration		
Based on assessment of 10 years of long-term monitoring data for 135 plots, the annual proportional change in tree biomass carbon stocks for both lowland and upland woodland savannas can be given as: *New C Biomass (t.ha^{-1}) = C biomass * ((1.45 - 0.11 * ln(C biomass) + b)^(1/6))* Where (1) if fire severity = mild, moderate, severe, then b = -0.1, -0.15, -0.53 respectively, and (2) assuming an initial tree carbon biomass of 25.8 t.ha^{-1}	Best linear mixed effects model (determined using Akaike's Information Criterion) assessing importance of 7 variables (e.g. annual rainfall; plot basal area; stem increment; fire severity variables) on stem DBH increment: $p < 0.005$; $R^2 = 0.11$	(Murphy et al. 2009; Murphy et al. 2010)
(c) Fire-sensitive obligate seeder plants		
(i) *Callitris intratropica*		
Based on assessment of 15 years fire regime observations at 18 long-term monitoring plots, change in stem (> 5 cm DBH) density in topographically variable terrain can be given as: Stem density = 1.33 – 1.15 * frq_sev where (1) frq_sev = the frequency of moderately severe and severe fires over the assessment period, and (2) assuming an initial stem density of 99.8 stems.km-^{2}	Simple linear regression, *Callitris* stem density vs. frq_sev: $p = 0.002$, $R^2 = 0.45$	(Edwards and Russell-Smith 2009; Russell-Smith et al. 2012)

(ii) *Longer-maturing (LOS) shrub taxa*		
Based on assessment of 15 years fire regime observations at 34 long-term monitoring plots, change in numbers of longer-maturing (>3 yr) obligate seeder shrub taxa in topographically variable terrain can be given as: Number of LOS taxa = 0.89 – 0.26 * fire frq where (1) fire frq = frequency of fires over the assessment period, and (2) assuming an initial complement of 2.27 LOS taxa.0.01 ha^{-1}	Simple linear regression, LOS vs. fire frq: p = 0.0015, R^2= 0.27	(Russell-Smith et al. 2012)
(d) Erosion effects		
Based on replicated assessment of the effects of LDS burning on soil movement at two hillslope sites, the effects of LDS fires on soil movement in topographically variable terrain can be given as: Soil movement ($t.ha^{-1}$) = (2.0 * frq_nonLDS + 4.21 * frq_LDS) * 22.8 where (1) frq_nonLDS is the mean frequency of UNB and EDS fires combined, frq_LDS is the mean frequency of LDS fires, and (2) assuming each 1 mm of soil movement results in movement of 22.8 $t.ha^{-1}$ of fine earth and coarse fragments	Non-parametric ANOVA comparison of soil movement on unburnt vs. LDS-burnt treatment plots; p < 0.0001	(Russell-Smith et al. 2006)

2.3 Outcomes

The deleterious effect of frequent wildfire to all ecosystems is well known, whilst the occurrence of a relatively high proportion of the landscape burnt under all management scenarios has been demonstrated many times in northern Australia (Russell-Smith et al. 2003; Williams et al. 2004; Russell-Smith and Edwards 2006; Price et al. 2007; Russell-Smith and Yates 2007; Yates et al. 2008; Edwards and Russell-Smith 2009; Murphy et al. 2009; Russell-Smith et al. 2009; Russell-Smith et al. 2009; Russell-Smith et al. 2012), hence the widely acknowledged requirement and continued effort in the undertaking of prescribed burning. It is not unexpected that with the international comprehension of the threat of climate change and the need to reduce greenhouse gas emissions and sequester carbon to mitigate its effects, that payments for ecosystem services (PES) that reduce biomass burnt have become sought after as a sustainable means of offsetting emissions and carbon pool reductions from mining and clearing due to urban/agricultural expansion. Not to mention the additional benefits

to health, livelihoods and indigenous employment, where increased pyro-diversity provides improved landscape health and therefore biodiversity and agricultural/pastoral capacities. In light of this the results of these analyses, Table 10, demonstrate that PES is completely undervalued and will become a very valuable commodity. At the time of writing this report Australian Carbon Credit Units are guaranteed by the Australian Government at $24/tonne (although this is expected to be markedly reduced within a year under the stewardship of the conservative Abbott government). The change from the current region-wide regime to those demonstrated, in the past by Kakadu National Park (Edwards et al. 2003) and, currently in west Arnhem Land, costs approximately $71/km^2, this equates to a meagre $31.5 M for the whole 444,550 km^2 higher rainfall region. Our results suggest that by implementing such a regime, savanna burning emissions abatement would produce > $24 M, and carbon sequestration approximately 4 times this. An outstanding result, making these analyses very important.

Table 10. Effects on key risk attributes under BAU, and respective scenario conditions over analogous 5-year periods, applying statistical models as described in Methods and Table 9. Percentages describe proportional change relative to BAU.

Effects on key risk attributes	**Business as usual (BAU) benchmark (2008-2012)**	**Scenarios**		
		BAU+CCI	**IFM**	**IFM+CCI**
Savanna Burning (Mt CO_2-e.y-^{1})	5.7 + 0.9	7.0 + 1.1 (+23%)	4.3 + 0.7 (-25%)	4.9 + 0.8 (-14%)
Biosequestration (Mt C.y-^{1})	-0.641 + 0.002	-6.86 + 0.02 (-1078%)	5.51 + 0.01 (+959%)	2.75 + 0.006 (+538%)
Obligate seeders – Callitris (Increase in Stems > 5 cm DBH.km-^{2})*	100.25 + 0.04	99.93 + 0.05 (-0.32%)	100.44 + 0.03 (+0.19%)	100.28 + 0.04 (+0.03%)
Obligate seeders - Longer-maturing shrubs (Species.0.1 ha^{-1})*	2.75 + 0.02	2.66 + 0.02 (-3.3%)	3.08 + 0.02 (+12%)	2.77 + 0.02 (+0.7%)
Erosion effects - soil movement (t.ha^{-1})	50	63 (+26%)	28 (-44%)	34 (-32%)

Activity 3: Communications

3.1 Presentations

A number of presentations regarding related aspects to the project were given by Dr Edwards over the three years:

2010/2011

i. North Australia Fire Manager's forum, Darwin, June 2011;
ii. Results of PhD thesis, AFAC conference, Darwin, September 2010;
iii. Fire in north Australia, Nature Conservation Council of NSW, Sydney, June 2011;
iv. Remote Sensing of fire severity, Int. Soc. Of Remote Sensing of Environment conference, Sydney, April 2011
v. Fire mapping and management in the sandstone of Kakadu National Park, Kakadu National Park Science Advisory seminar, Jabiru, April 2011

2011/2012

i. Northern Fire Mapping Project, AFAC conference, Sydney, 1st September 2011;
ii. North Australian Indigenous Land and Sea Management Alliance carbon seminar series, Darwin, 7 to 11 November 2011;
iii. North Australia Fire Manager's forum, Darwin, 7th March 2012;
iv. Fire ecology and remote sensing, Environmental Science students, Charles Darwin University, 17th August 2011;
v. The remote sensing of fire severity mapping, NT Spatial conference, Darwin 22nd February 2012;
vi. The remote sensing of fire severity mapping, the Forum on Advanced Satellite Technology Applications at the University of NSW, Sydney, November 2011.

2012/2013

i. Fire ecology and remote sensing, Environmental Science students, Charles Darwin University, 28th August 2012;
ii. Northern Fire Mapping Project, AFAC conference, Perth, 29th August 2012;
iii. Fire ecology and effects on local biota, Casuarina Coastal Reserve Committee, 20th September 2012;
iv. Fire severity, DERM staff Brisbane, 28th September 2012;
v. Bushfire research, Bushfires Council and Chief Minister of the NT, Alice Springs, 9th November 2012;
vi. Fire severity and tropical savanna ecology, Dept. of Environment, Brasilia, Brazil, 10-14 December 2012;
vii. Remote Sensing seminar, Kakadu National Park, 5th February, 2013;
viii. Fire severity in the rangelands, Alice Springs Ecological Society, Alice Springs, NT, 10th May 2013;
ix. Project update, CRC Research Advisory Forum, Perth, WA, 14-15 May 2013;
x. Savanna Burning Abatement on-line calculation tool (SavBAT), North Australia Fire Manager's Forum, 19th June 2013;
xi. The risk of fire to ecosystem services in north Australia, 2-5 September, 2013.

3.2 Publications and other media

Copies of publications are given in Appendix B. The following is a list of those publications.

Dr Edwards attended the ISRSE conference where the following paper was published in the proceedings of the International Society of Remote Sensing of the Environment conference in Sydney, April 2011, it is attached to this report as "Northern Fire Mapping – final project report – Dec 2013 – Appendix B:

Edwards, A., S. Maier, L. Hutley, R. Williams and J. Russell-Smith (2011) "***Mapping fire severity from satellite imagery for greenhouse gas emissions calculations, conservation management and operational use*"**.** Proceedings of the International Society of the Remote Sensing of the Environment.

The following was published in the proceedings of the AFAC conference in Sydney in August 2011:

Edwards, A., S. Maier, L. Hutley, R. Williams and J. Russell-Smith (2011) "***The development of an automated algorithm to map fire severity from satellite imagery: tropical savannas northern Australia***". Proceedings of Bushfire CRC & AFAC 2011 Conference Science Day 1 September, 2011, Sydney Convention Centre, Darling Harbour.

The following Fire note was published in the second quarter of 2011-12:

Edwards, A.C. (2011) "***Fire Severity Mapping: mapping the effects of fire on savanna vegetation in northern Australia from satellite imagery***". Bushfire CRC FIRE NOTE, Melbourne, Australia.

The following paper was published in 2013:

Edwards, Andrew C., Stefan W. Maier, Lindsay B. Hutley, Richard J. Williams and Jeremy Russell-Smith (2013). "***Spectral Analysis of Fire Severity in North Australian Tropical Savannas***." Remote Sensing of Environment **136**: pp.56-65.

Analyses undertaken in Activity 2 of this report have been submitted for publication in 2014:

Edwards, A., J. Russell-Smith and C.M. Meyer (2014) "***Assessing fire regime risks to ecological assets and processes in north Australian savannas***." Ecography *in press*.

3.3 Annual AFAC posters

The first poster in 2010 was the summary of Dr Edwards' thesis providing the basis of the methodological approach for the project.

Remote Sensing of Fire Severity in north Australia

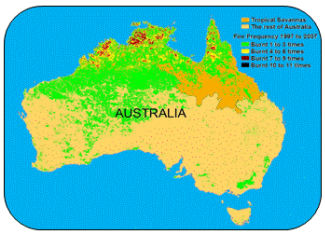
Andrew Edwards
Charles Darwin University Darwin Northern Territory Australia
Bushfires NT PO Box 37346 Winnellie NT 0810 Australia

Tropical Savannas

Tropical savanna grasslands and woodlands:

- globally constitute the largest annually recurring source of pyrogenic emissions;
- the world's most heavily grazed biome;
- cover 12% of the earth's landmass.

Australia's tropical savanna grasslands and woodlands cover 25% of the Australian landmass, and with over 90% of mean annual fires occurring in the north, information on fires that can assist the land manager is vital.

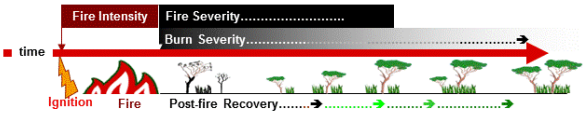


Current Information

Current fire mapping provides land managers with the knowledge of the occurrence, extent, and frequency of fires. It has not yet provided information on the affect of various types of fire, referred to as Fire Severity.

Fire severity is useful for determining the effectiveness of prescribed or hazard reduction burning, the effect of wildfires & for calculating Greenhouse Gas Emissions.

The Fire Continuum



Fire Severity

We define the fire severity to be the measureable post-fire affect of the fire on the vegetation. The definitions of the classes of fire severity are taken from the paper by Russell-Smith & Edwards (2006):

Fire Severity	Leaf Scorch Height (m)	Ground Patchiness (%affected)	Fire Line Intensity (MWm^{-1})
Low	< 2 m	> 20%	<< 1
Moderate	> 2 m	> 80%	< 1 - 2
High	> 5 m		< 1 - 10+
Extreme	Total charring		> 10

Results

The ground sampled data provides a measure of the fire severity from the parameters in the table above. The categories are correlated first with the ground parameters to determine the drivers of fire severity, then with the spectra to create a model for remote sensing.

Ground variables:
DOES NOT indicate Fire Severity
The amount of Charred material (blackened)
The amount of Green material (photosynthetic vegetation)
DOES indicate Fire severity
The amount of White Ash
The amount of non-Green plant material (non-photosynthetic vegetation)
Remote Sensing: Mapping Fire Severity
Severe v not-Severe Fires accuracy = 89%
Low v Moderate Severity Fires accuracy = 75%

Methods

A coupled top-down/bottom-up sampling methodology was developed for the project.

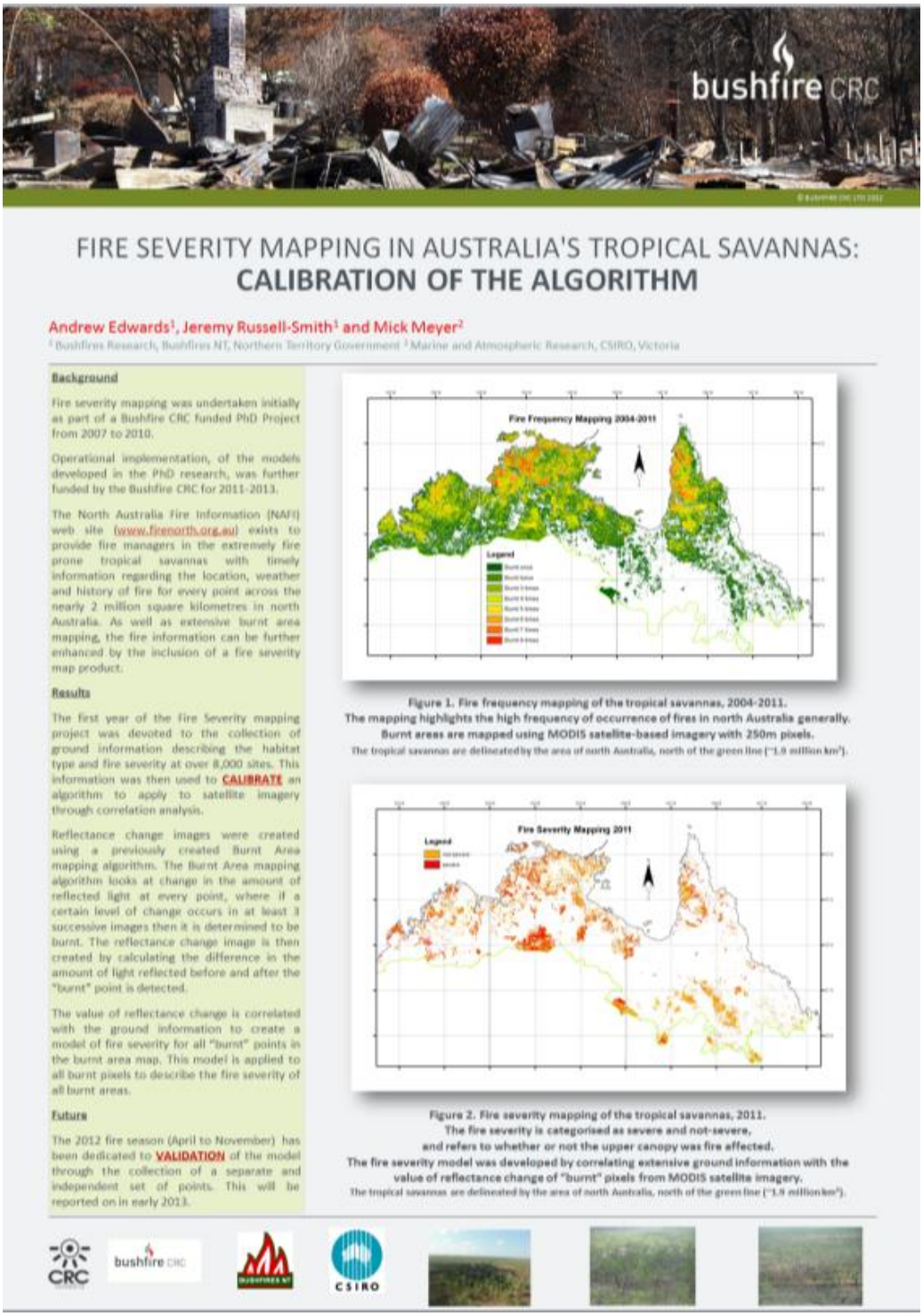
Top Down

Using a helicopter and a hand-held spectrometer, light (spectra) reflected from recently burnt areas is measured for each wavelength in the optical portion of the electromagnetic spectrum (450 - 2400 nm) including the visible, near infrared and short wave infrared.

Bottom Up

Ground sampling in the same area is undertaken. Measures such as the vegetation structure, proportions of various components, scorch height, and ground patchiness characterise the affect of the fire.

The following poster was provided to the Bushfire Conference in Perth in August 2012, the intention was to provide a clear and simple overview of the main component of the project.



bushfire CRC

FIRE SEVERITY MAPPING IN AUSTRALIA'S TROPICAL SAVANNAS:
CALIBRATION OF THE ALGORITHM

Andrew Edwards[1], Jeremy Russell-Smith[1] and Mick Meyer[2]
[1] Bushfires Research, Bushfires NT, Northern Territory Government [2] Marine and Atmospheric Research, CSIRO, Victoria

Background

Fire severity mapping was undertaken initially as part of a Bushfire CRC funded PhD Project from 2007 to 2010.

Operational implementation, of the models developed in the PhD research, was further funded by the Bushfire CRC for 2011-2013.

The North Australia Fire Information (NAFI) web site (www.firenorth.org.au) exists to provide fire managers in the extremely fire prone tropical savannas with timely information regarding the location, weather and history of fire for every point across the nearly 2 million square kilometres in north Australia. As well as extensive burnt area mapping, the fire information can be further enhanced by the inclusion of a fire severity map product.

Results

The first year of the Fire Severity mapping project was devoted to the collection of ground information describing the habitat type and fire severity at over 8,000 sites. This information was then used to **CALIBRATE** an algorithm to apply to satellite imagery through correlation analysis.

Reflectance change images were created using a previously created Burnt Area mapping algorithm. The Burnt Area mapping algorithm looks at change in the amount of reflected light at every point, where if a certain level of change occurs in at least 3 successive images then it is determined to be burnt. The reflectance change image is then created by calculating the difference in the amount of light reflected before and after the "burnt" point is detected.

The value of reflectance change is correlated with the ground information to create a model of fire severity for all "burnt" points in the burnt area map. This model is applied to all burnt pixels to describe the fire severity of all burnt areas.

Future

The 2012 fire season (April to November) has been dedicated to **VALIDATION** of the model through the collection of a separate and independent set of points. This will be reported on in early 2013.

Fire Frequency Mapping 2004-2011

Legend

Figure 1. Fire frequency mapping of the tropical savannas, 2004-2011.
The mapping highlights the high frequency of occurrence of fires in north Australia generally.
Burnt areas are mapped using MODIS satellite-based imagery with 250m pixels.
The tropical savannas are delineated by the area of north Australia, north of the green line (~1.9 million km²).

Fire Severity Mapping 2011

Legend

Figure 2. Fire severity mapping of the tropical savannas, 2011.
The fire severity is categorised as severe and not-severe,
and refers to whether or not the upper canopy was fire affected.
The fire severity model was developed by correlating extensive ground information with the value of reflectance change of "burnt" pixels from MODIS satellite imagery.
The tropical savannas are delineated by the area of north Australia, north of the green line (~1.9 million km²).

3.3 Feedback

The number of presentations Dr Edwards has given over the past few years regarding the project has resulted in many requests for further presentation of the project data and related fire ecological information.

Key groups making these requests have included:

- the Casuarina Coastal Reserve Management Committee;
- the Fire Ecology undergraduate course at Charles Darwin University;
- the Bushfires Council of the NT who also invited the Chief Minister, the honourable Terry Mills MP;
- Dr Anja Hoffman of the German equivalent of AUSAID known as Deutsche Gesellschaft fur Internationale Zusammenarbeit, to present to the Brazilian Dept. of Environment regarding our studies and mapping of fire severity in tropical savanna habitats, of which they have an Australian equivalent of nearly 2 million km^2.
- Kakadu National Park managers also requested a presentation on the latest available data and techniques for the extensive work undertaken by the Bushfire Research in to remote sensing, burnt area and fire severity mapping.
- The North Australia Fire Manager's forum,regular updates on the progress of the project and finally to present on the inclusion of the new Savanna Burning Abatement Tool (SavBAT) for calculating greenhouse gas emissions abatement using the Determination from the Australian Greenhouse Office. This also included interviews with the National ABC News channel and the Country Hour which is broadcast right across north Australia accessing the greatest network for north Australian land managers.
- The Nature Conservation Council of NSW, to provide information regarding fire management through the use of prescribed burning techniques and this effects the occurrence and severity of fire.

3.3.1 The Research Advisory Forum

The Research Advisory Forum (RAF) offered useful feedback to presenters from a range of end users. This was a unique opportunity rarely provided to Dr Edwards as his Lead End-User did not provide any interest in nor support to the project, and did not attend the RAF which was held in his building. Dr Edwards presented the research to date from the project to the RAF and received the following comments:

"*This is clearly a technical project so it was very pleasing to note that most respondents felt they could explain it to others. It was also pleasing to see that everyone thought the project would achieve its planned outcomes and was giving high quality applied outcomes. There were a number of comments which said the slides were difficult to read due to the dark background, so this is something to watch in the future. It was also noted that you may be able to get some useful data from the QFRS Cairns Rural Operations Office which have an annual burning project – this may be worth following up*".

3.3.2 Assistance of Indigenous agencies

The exceptional involvement of the Land Councils and indigenous rangers has occurred primarily through strong support from the North Australian Indigenous Land and Sea Management Alliance (NAILSMA – see extract from "NAILSMA Science Component Report 2010/11" below). Their focus, in the development of the fire severity mapping product, is to assist with fire management activities for indigenous people and to improve data for greenhouse gas (GHG) emissions calculations for the implementation of the Federal Government Department of Climate Change and Energy Efficiency's (DCCEE) Carbon Farming Initiative (CFI). The CFI projects offer land owners the opportunity to trade GHG emissions abatement, through improved fire management, and through the provision of additional resources and employment opportunities. As a requirement of the CFI methodology tracts of project land must be > 10, 000 km^2, most indigenous land holdings in northern Australia are large and contiguous and so can find inclusion in this scheme. The larger representative bodies such as the Land Councils are the only organisations with the legislative ability to combine the smaller contiguous pieces of tenure. NAILSMA attempts to be a coordinating body in northern Australia for the Land Councils with respect to land management activities.

Extract from NAILSMA Science Component Report 2010/11 (page 1 paragraph 3):

- *Fire severity mapping*—as reported on in the previous Milestone report, work on developing automated fire extent and severity mapping has continued, with funding made available through the Bushfire CRC for the appointment of a post-doctoral researcher, Andrew Edwards, based at Bushfires NT. A demonstrational model of fire severity mapping is already up and running on the NAFI website. This year, Andrew's work is focusing on the field collection of fire severity data in all regional project areas, in association with the MODIS fire mapping validation exercise reported on in the previous dot-point

3.3.3 North Australian Fire Manager's Forum

Useful communication occurred at the annual North Australia Fire Manager's Forum. The meetings were attended by the regional manager's representing the National Parks and Rural Fire Services from north Queensland, Western Australia and the Northern Territory as well rep's from the Australian Wildlife Conservancy, the Bureau of Meteorology, the Land Councils and the Bushfire CRC representatives. Dr Edwards was asked to provide updates on the project at each meeting of their findings. The presentations were always well received with many offers of further assistance from across the region.

References

ABARE-BRS (2010). "Catchment Scale Land Use Mapping of Australia Update March 2010 (Clum Update 03/10) Dataset". Australian Bureau of Agricultural and Resource Economics - Bureau of Rural Sciences, Canberra, Australia.

Alencar, A., D. Nepstad and M. d. C. V. Diaz (2006). "Forest Understory Fire in the Brazilian Amazon in Enso and Non-Enso Years: Area Burned and Committed Carbon Emissions." Earth Interactions **10**(Paper no. 6).

Bowman, D. M. J. S., O. Price, P. J. Whitehead and A. Walsh (2001). "The "Wilderness Effect" and the Decline of *Callitris Intratropica* on the Arnhem Land Plateau, Northern Australia." Australian Journal of Botany **49**: 665-672.

Burnham, K. P. and D. R. Anderson (2002). Model Selection and Multi-Model Inference: A Practical Information Theoretic Approach. New York, USA, Springer-Verlag.

Chuvieco, E. and R. G. Congalton (1988). "Mapping and Inventory of Forest Fires from Digital Processing of Tm Data." Geocarto International **3**(4): 41-53.

Cook, G. D., R. J. Williams, C. J. Stokes, L. B. Hutley, A. J. Ash and A. E. Richards (2010). "Managing Sources and Sinks of Greenhouse Gases in Australia's Rangelands and Tropical Savannas." Rangeland Ecology and Management **63**(1): 137-146.

CSIRO & Bureau of Meteorology (2007). "Climate Change in Australia: Technical Report 2007". CSIRO Australia. http://www.climatecghangeinaustralia.gov.au/

DCCEE (2013). Carbon Credits (Carbon Farming Initiative) (Reduction of Greenhouse Gas Emissions through Early Dry Season Savanna Burning—1.1) Methodology Determination 2013. Carbon Credits (Carbon Farming Initiative) Act 2011. Parliamentary Secretary for Climate Change Industry and Innovation. Australian Government, Canberra, Australia. **Federal Register of Legislative Instruments F2013L01165:** pp. 41.

Edwards, A., P. Hauser, M. Anderson, J. McCartney, M. Armstrong, R. Thackway, G. Allan, C. Hempel and J. Russell-Smith (2001). "A Tale of Two Parks: Contemporary Fire Regimes of Litchfield and Nitmiluk National Parks, Monsoonal Northern Australia." International Journal of Wildland Fire **10**: 79 - 89.

Edwards, A., R. Kennett, O. Price, J. Russell-Smith, G. Spiers and J. Woinarski (2003). "Monitoring the Impacts of Fire Regimes on Vegetation in Northern Australia: An Example from Kakadu National Park." International Journal of Wildland Fire **12**(3-4): 427-440.

Edwards, A. and J. Russell-Smith (2009). "Ecological Thresholds and the Status of Fire-Sensitive Vegetation in Western Arnhem Land, Northern Australia: Implications for Management." International Journal of Wildland Fire **18**(2): 127-146.

Edwards, A. C. (2011). I Spy with My Little Eye Something Beginning With...Fire. Faculty of Engineering, Health, Science and the Environment. Darwin, Northern Territory, Charles Darwin University. **PhD**.

Edwards, A. C., S. W. Maier, L. B. Hutley, R. J. Williams and J. Russell-Smith (2013). "Spectral Analysis of Fire Severity in North Australian Tropical Savannas." Remote Sensing of Environment **136**(0): 56-65.

Elliott, L. P., D. C. Franklin and D. M. J. S. Bowman (2009). "Frequency and Season of Fires Varies with Distance from Settlement and Grass Composition in Eucalyptus Miniata Savannas of the Darwin Region of Northern Australia." International Journal of Wildland Fire **18**(1): 61-70.

Environment Australia (2000). "Revision of the Interim Biogeographic Regionalisation of Australia (Ibra) and the Development of Version 5.1. - Summary Report". Department of Environment and Heritage, Canberra.

ESRI (2011). Arcgis Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.

Felderhof, L. and D. Gillieson (2006). "Comparison of Fire Patterns and Fire Frequency in Two Tropical Savanna Bioregions." Austral Ecology **31**(6): 736-746.

Fisher, A. (2001). Maintaining and Monitoring Biodiversity in the Northern Australian Rangelands. in Proceedings of the Northern Australia Beef Industry Conference (NABIC), Department of Agriculture Western Australia, Kununurra, 8 - 9 November.

Fisher, R., T. Vigilante, C. Yates and J. Russell-Smith (2003). "Patterns of Landscape Fire and Predicted Vegetation Response in the North Kimberley Region of Western Australia." International Journal of Wildland Fire **12**(3-4): 369-379.

Fisher, R., A. C. Edwards, S. W. Maier and C. P. Meyer (*unpublished*). "*North Australia Fire Information: Fire Mapping Methods and Assessment*" in Carbon in North Australia: Scientific Methods. Ed's: J. Russell-Smith, C. P. Meyer, B. P. Murphy and A. C. Edwards. CSIRO Publishing, Melbourne.

Fox, I. D., V. J. Neldner, G. W. Wilson, P. J. Bannink, B. A. Wilson, P. S. Brocklehurst, M. J. Clark, K. J. M. Dickinson, J. S. Beard, A. J. M. Hopkins, G. R. Beeston, J. M. Harvey, E. J. Thompson, T. S. Ryan, S. L. Thompson, D. W. Butler, H. Cartan, E. P. Addicott, L. P. Bailey, R. J. Cumming, D. C. Johnson, M. Schmeider, K. M. Stephens and A. R. Bean (2001). The Vegetation of the Australian Tropical Savannas. Queensland Herbarium, Environmental Protection Agency, Brisbane and the Cooperative Research Centre for the Sustainable Development of Tropical Savannas, Darwin.

Garde, M., L. B. Nadjamerrek, M. Kolkkiwarra, J. Kalarriya, J. Djandjomerr, B. Birriyabirriya, R. Bilindja, M. Kubarkku and P. Biless (2009). "*The Language of Fire: Seasonality, Resources*

and Landscape Burning on the Arnhem Land Plateau." in Managing Fire Regimes in North Australian Savannas – Ecology, Culture, Economy. Ed's: J. Russell-Smith and P. Whitehead. CSIRO Publishing, Canberra, Australia.

Hauser, P. M. (1995). "Long-Term Monitoring of the Effects of Management-Imposed Fire Regimes across Three National Parks in the Top End: Phase 1". Parks and Wildlife Commission.

Holden, Z. A., P. Morgan and J. S. Evans (2009). "A Predictive Model of Burn Severity Based on 20-Year Satellite-Inferred Burn Severity Data in a Large Southwestern Us Wilderness Area." Forest Ecology and Management **258**(11): 2399-2406.

Hudak, A. and B. Brockett (2004). "Mapping Fire Scars in a Southern African Savannah Using Landsat Imagery." International Journal of Remote Sensing **25**(16): 3231-3243.

Jacklyn, P., A. Edwards, C. Devonport, O. Franzen, B. Lewis, M. Trueman, B. Lynch, H. Eeley, P. Thompson, G. Crowley, P. Cooke and J. Russell-Smith (in press). "North Australia Fire Information: Methods for the Development of a Web Based Tool for Fire Management.".

Ludwig, J. A. and D. J. Tongway (2000). "*Viewing Rangelands as Landscape Systems*" in Rangeland Desertification. Ed's: O. Arnalds and S. Archer. Advances in Vegetation Sciences Vol. 19 Kluwer Academic Publishers The Hague. pp.39 - 52.

Maier, S. W. and J. Russell-Smith (2012). "*Chapter 4. Measuring and Monitoring of Contemporary Fire Regimes in Australia Using Satellite Remote Sensing*" in Flammable Australia. Fire Regimes, Biodiversity and Ecosystems in a Changing World. Ed's: R. A. Bradstock, A. M. Gill and R. J. Williams. CSIRO Publishing, Melbourne, Australia.

Matricardi, E. A. T., D. L. Skole, M. A. Pedlowski, W. Chomentowski and L. C. Fernandes (2010). "Assessment of Tropical Forest Degradation by Selective Logging and Fire Using Landsat Imagery." Remote Sensing of Environment **114**(5): 1117-1129.

Mitri, G. H. and I. Z. Gitas (2002). "The Development of an Object Oriented Classification Model for Operational Burned Area Mapping on the Mediterranean Island of Thasos Using Landsat Tm Images." Forest Fire Research & Wildland Fire Safety, Viegas (ed.) **ISBN 90-77017-72-0**.

Murphy, B. P., J. Russell-Smith, F. A. Watt and G. D. Cook (2009). "*Fire Management and Woody Biomass Carbon Stocks in Mesic Savannas*" in Managing Fire Regimes in North Australian Savannas – Ecology, Culture, Economy. Ed's: J. Russell-Smith and P. Whitehead. CSIRO Publishing, Canberra, Australia.

Murphy, B. P. and J. Russell-Smith (2010). "Fire Severity in a Northern Australian Savanna Landscape: The Importance of Time since Previous Fire." International Journal of Wildland Fire **19**(1): 46-51.

Murphy, B. P., J. Russell-Smith and L. D. Prior (2010). "Frequent Fires Reduce Tree Growth in North Australian Savannas: Implications for Tree Demography and Carbon Sequestration." Global Change Biology **16**: 331-343.

Murphy, B. P., J. Russell-Smith and L. D. Prior (2010). "Frequent Fires Reduce Tree Growth in Northern Australian Savannas: Implications for Tree Demography and Carbon Sequestration." Global Change Biology **16**(1): 331-343.

Pereira, J. M. C. (2003). "Remote Sensing of Burned Areas in Tropical Savannas." International Journal of Wildland Fire **12**(4): 259-270.

Price, O., A. Edwards, G. Connors, J. Woinarski, G. Ryan, A. Turner and J. Russell-Smith (2005). "Fire Heterogeneity in Kakadu National Park, 1980-2000." Wildlife Research **32**(5): 425-433.

Price, O. F., A. C. Edwards and J. Russell-Smith (2007). "Efficacy of Permanent Firebreaks and Aerial Prescribed Burning in Western Arnhem Land, Northern Territory, Australia." International Journal of Wildland Fire **16**(3): 295-307.

Qu, J. J. (2006). "*Chapter 4. Modis Geolocation*" in Earth Science Satellite Remote Sensing: Science and Instruments. Ed's: W. G. John J. Qu, Menas Kafatos, Robert E. Murphy and Vincent V. Salomonson. Tsihnghua University Press, Beijing and Springer-Verlag GmbH Berlin Heidelberg. **1**. pp.414.

Riley, S. J., S. D. DeGloria and R. Elliot (1999). "A Terrain Ruggedness Index That Quantifies Topographic Heterogeneity." International Journal of Sciences **5**(1-4): 183-191.

Ritchie, D. (2009). "*Things Fall Apart: The End of an Era of Systematic Indigenous Fire Management*" in Culture, Ecology and Economy of Savanna Fire Management in Northern Australia: Rekindling the Wurrk Tradition. Ed's: J. Russell-Smith, P. J. Whitehead and P.M.Cooke. CSIRO Publications, Melbourne.

Röder, A., J. Hill, B. Duguy, J. A. Alloza and R. Vallejo (2008). "Using Long Time Series of Landsat Data to Monitor Fire Events and Post-Fire Dynamics and Identify Driving Factors. A Case Study in the Ayora Region (Eastern Spain)." Remote Sensing of Environment **112**(1): 259-273.

Russell-Smith, J., P. G. Ryan and R. Durieu (1997). "A Landsat Mss-Derived Fire History of Kakadu National Park, Monsoonal Northern Australia, 1980-94: Seasonal Extent, Frequency and Patchiness." Journal of Applied Ecology **34**: 748-766.

Russell-Smith, J., P. G. Ryan and D. C. Cheal (2002). "Fire Regimes and the Conservation of Sandstone Heath in Monsoonal Northern Australia: Frequency, Interval, Patchiness." Biological Conservation **104**(1): 91-106.

Russell-Smith, J., A. C. Edwards and G. D. Cook (2003). "Reliability of Biomass Burning Estimates from Savanna Fires: Biomass Burning in Northern Australia During the 1999 Biomass Burning and Lightning Experiment B Field Campaign." Journal of Geophysical Research-Atmospheres **108**(D3): 9-1 - 9-12.

Russell-Smith, J., C. Yates, A. Edwards, G. E. Allan, G. D. Cook, P. Cooke, R. Craig, B. Heath and R. Smith (2003). "Contemporary Fire Regimes of Northern Australia, 1997-2001: Change since Aboriginal Occupancy, Challenges for Sustainable Management." International Journal of Wildland Fire **12**(3-4): 283-297.

Russell-Smith, J. and A. C. Edwards (2006). "Seasonality and Fire Severity in Savanna Landscapes of Monsoonal Northern Australia." International Journal of Wildland Fire **15**(4): 541-550.

Russell-Smith, J., C. Yates and B. Lynch (2006). "Fire Regimes and Soil Erosion in North Australian Hilly Savannas." International Journal of Wildland Fire **15**: 551-556.

Russell-Smith, J. and C. P. Yates (2007). "Australian Savanna Fire Regimes: Context, Scales, Patchiness." Fire Ecology (Special Issue) **3**(1): 48-63.

Russell-Smith, J., B. P. Murphy, C. P. Meyer, G. D. Cook, S. Maier, A. C. Edwards, J. Schatz and P. Brocklehurst (2009). "Improving Estimates of Savanna Burning Emissions for Greenhouse Accounting in Northern Australia: Limitations, Challenges, Applications." International Journal of Wildland Fire **18**(1): 1-18.

Russell-Smith, J., P. Whitehead and P. Cooke (2009). Managing Fire Regimes in North Australian Savannas – Ecology, Culture, Economy. Rekindling the Wurrk Tradition. Canberra, Australia, CSIRO Publishing.

Russell-Smith, J., A. C. Edwards and O. F. Price (2012). "Simplifying the Savanna: The Trajectory of Fire-Sensitive Vegetation Mosaics in Northern Australia." Journal of Biogeography **39**: 1303-1317.

Scholes, R. J. and S. R. Archer (1997). "Tree-Grass Interactions in Savannas." Annual Review of Ecology and Systematics **28**: 517-544.

Smith, A. M. S., M. J. Wooster, N. A. Drake, F. M. Dipotso, M. J. Falkowski and A. T. Hudak (2005). "Testing the Potential of Multi-Spectral Remote Sensing for Retrospectively Estimating Fire Severity in African Savannahs." Remote Sensing of Environment **97**(1): 92-115.

Specht, R. L. (1981). "*Foliage Cover and Standing Biomass*" in Vegetation Classification in Australia. Ed's: A. Gillison and D. Anderson. CSIRO Publishing, Canberra, Australia. pp.10-21.

Townsend, S. and M. M. Douglas (2000). "The Effect of 3 Fire Regimes on Stream Water Quality, Water Yield and Export Coefficients in a Tropical Savanna (Northern Australia)." Journal of Hydrology **229**: 118-137.

Vigilante, T., D. Bowman, R. Fisher, J. Russell-Smith and C. Yates (2004). "Contemporary Landscape Burning Patterns in the Far North Kimberley Region of North-West Australia: Human Influences and Environmental Determinants." Journal of Biogeography **31**(8): 1317-1333.

White, J. D., K. C. Ryan, C. C. Key and S. W. Running (1996). "Remote Sensing of Forest Fire Severity and Vegetation Recovery." International Journal of Wildland Fire **6**(3): 125-136.

Whitehead, P. J. W. J. C. Z. F. A. B. K. C. G. H. A. W. I. (2001). "Developing an Analytical Framework for Monitoring Biodiversity, in Australia's Rangelands, Report to the National Land and Water Resources Audit". Tropical Savannas CRC Darwin.

Williams, R. J., G. A. Duff, D. M. J. S. Bowman and G. D. Cook (1996). "Variation in the Composition and Structure of Tropical Savannas as a Function of Rainfall and Soil Texture Along a Large-Scale Climatic Gradient in the Northern Territory, Australia." Journal of Biogeography **23**: 747-756.

Williams, R. J., L. B. Hutley, G. D. Cook, J. Russell-Smith, A. Edwards and X. Y. Chen (2004). "Assessing the Carbon Sequestration Potential of Mesic Savannas in the Northern Territory, Australia: Approaches, Uncertainties and Potential Impacts of Fire." Functional Plant Biology **31**(5): 415-422.

Woinarski, J. C. Z., R. J. Williams, O. Price and B. Rankmore (2005). "Landscapes without Boundaries: Wildlife and Their Environments in Northern Australia." Wildlife Research **32**: 377-388.

Woinarski, J. C. Z., M. Armstrong, K. Brennan, A. Fisher, A. D. Griffiths, B. Hill, D. J. Milne, C. Palmer, S. Ward, M. Watson, S. Winderlich and S. Young (2010). "Monitoring Indicates Rapid and Severe Decline of Native Small Mammals in Kakadu National Park, Northern Australia." Wildlife Research **37**(2): 116-126.

Woinarski, J. C. Z., S. Legge, J. A. Fitzsimons, B. J. Traill, A. A. Burbidge, A. Fisher, R. S. C. Firth, I. J. Gordon, A. D. Griffith, C. N. Johnson, N. L. McKenzie, C. Palmer, I. Radford, B. Rankmore, E. G. Ritchie, S. Ward and M. Ziembecki (2011). "The Disappearing Mammal Fauna of Australia: Context, Cause, and Response." Conservation Letters **4**: 192-201.

Yates, C. and J. Russell-Smith (2003). "Fire Regimes and Vegetation Sensitivity Analysis: An Example from Bradshaw Station, Monsoonal Northern Australia." International Journal of Wildland Fire **12**(3-4): 349-358.

Yates, C. P., A. C. Edwards and J. Russell-Smith (2008). "Big Fires and Their Ecological Impacts in Australian Savannas: Size and Frequency Matters." International Journal of Wildland Fire **17**: 768-781.

Yibarbuk, D., P. J. Whitehead, J. Russell-Smith, D. Jackson, C. Godjuwa, A. Fisher, P. Cooke, D. Choquenot and D. Bowman (2001). "Fire Ecology and Aboriginal Land Management in Central Arnhem Land, Northern Australia: A Tradition of Ecosystem Management." Journal of Biogeography **28**(3): 325-343.