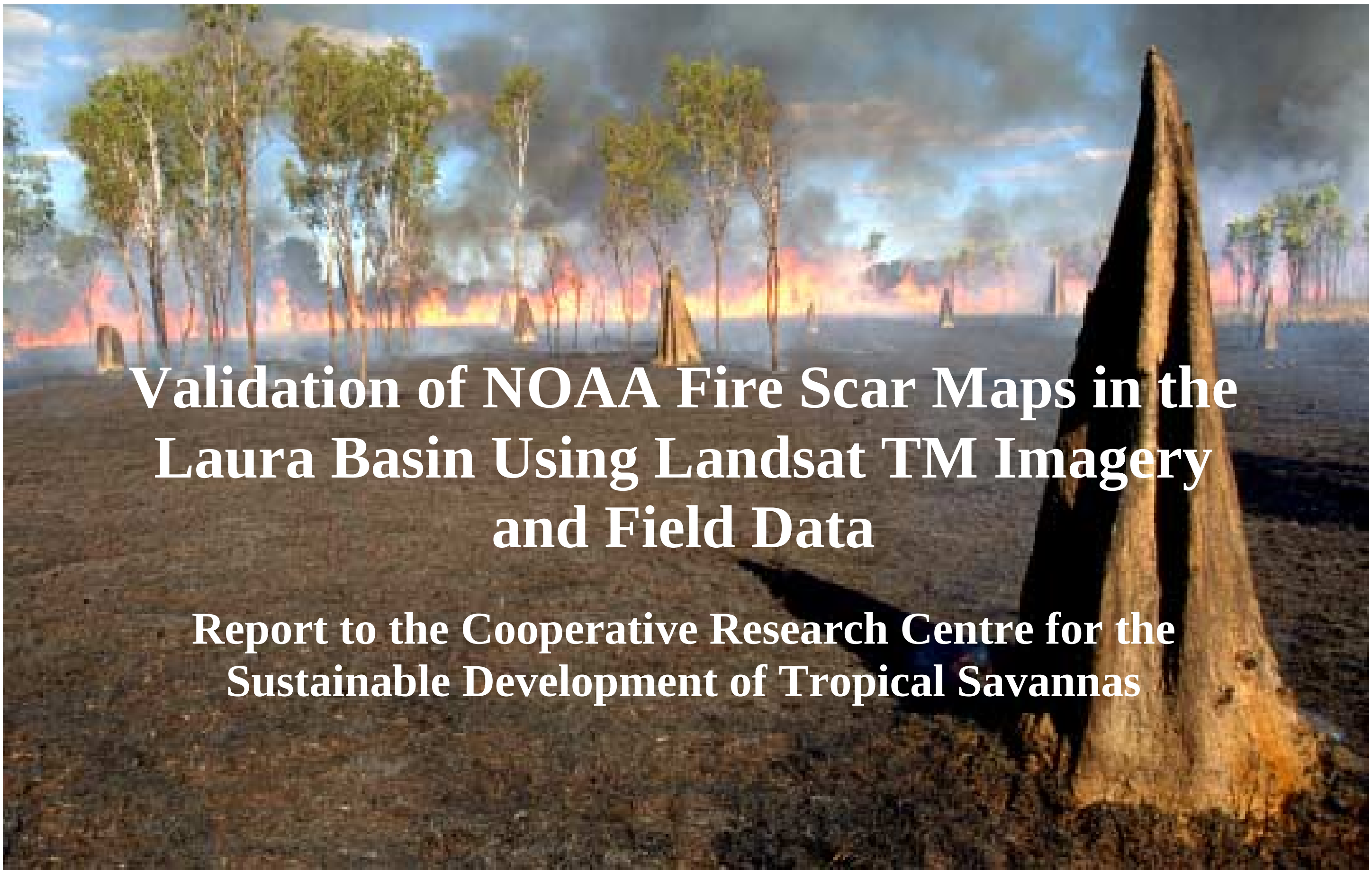
Validation of NOAA Fire Scar Maps in the Laura Basin Using Landsat TM Imagery and Field Data

Report to the Cooperative Research Centre for the Sustainable Development of Tropical Savannas



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TROPICAL SAVANNAS CRC
Cooperative Research Centre for the Sustainable Development of Tropical Savannas

Queensland Government
Natural Resources and Mines

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1. Introduction

This report summarises work conducted by the Climate Impacts and Natural Resource Systems (CINRS) group, Queensland Department of Natural Resources and Mines (NRM), as part of the CRC for Tropical Savannas - RIRDC funded Fire project. The main objective of the CINRS work was to provide an accuracy assessment of fire scar maps generated from NOAA satellite imagery for a study area on eastern Cape York Peninsula.

Spatially and temporally accurate fire scar maps are required by rangeland resource managers for various applications, including the calculation of greenhouse gas emissions, monitoring the frequency and time of year when specific vegetation communities are burnt, and for fire risk management purposes. In recent times there has been considerable work undertaken, both nationally and internationally, to develop manual, semi-automated and fully automated methods for the generation of fire scar maps from remotely sensed data. NOAA AVHRR has been the most commonly used satellite platform because of its relative cost effectiveness, resolution and frequency at which data are available, especially given that most fire scar applications have a regional or continental focus.

Whilst the validation of NOAA fire scar maps using field data was the preferred method, it was recognised at the planning stage of this work that it would be impossible to collect an adequate field data set with the resources available given the spatial resolution of NOAA imagery (0.01 degrees), the accuracy of NOAA geo-rectification (± 1 pixel), and the size of the study area. Hence a two-stage approach to validation was adopted. The first stage involved the generation of a fire scar map from Landsat TM imagery and an accuracy assessment of this map using field data from the study area. Landsat TM imagery is of a much greater resolution (30 m) than NOAA with approximately 1,300 Landsat TM pixels contained within a single NOAA pixel. The second stage involved the use of the Landsat TM fire scar map to validate the NOAA derived fire scar maps. The use of the Landsat TM fire scar map provided a spatially continuous alternative to limited field data and thus overcame the spatial sampling problems that occur in the direct application of field data to NOAA derived products.

The results of any fire scar accuracy assessment are obviously specific to the method used to produce the fire scars. For this report we have assessed fire scars produced from NOAA imagery using two methods: 1) a semi-manual technique, similar to one employed by Western Australia's Department of Land Administration's FireWatch program; and 2) an automated experimental algorithm currently under development at NRM.

2. The study area

The study area selected for this validation exercise was a region on Cape York Peninsula covered by the Kalinga Landsat TM scene (Path/Row 97/70, Figure 1). It is a region of distinct wet and dry seasons with rainfall largely controlled by the southern monsoon. In response to the rainfall seasonality there is a regular cycle of biomass fuel accumulation and curing. During the dry season, from May through to October, large areas are burnt as a result of early dry season prescribed fires and late dry season uncontrolled wildfires. These latter fires are often extremely intense and result in both ecological and pastoral management problems.

Approximately three quarters of the study area is covered by Lakefield National Park which is co-managed by Queensland National Parks and the traditional aboriginal owners. The remainder of the study area comprises mostly pastoral properties, some of which are reverting to aboriginal ownership and more traditional fire management practices. Thus there is currently a diverse range of management objectives in the region and debate over appropriate fire management strategies.

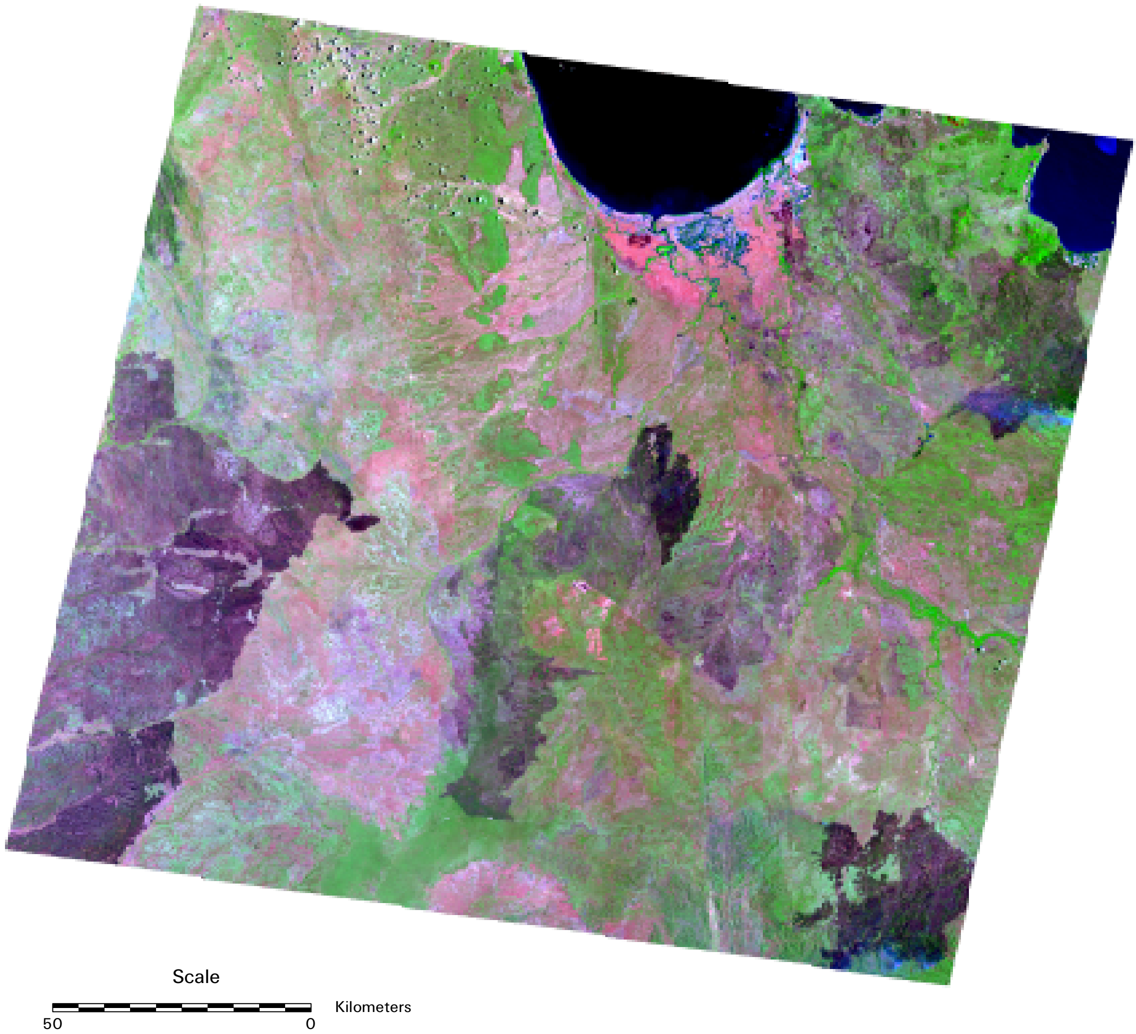

Figure 1. The study area comprising the Kalinga Landsat TM scene (bands 5, 4 and 3 in RGB).

3. Landsat TM fire scar maps

Landsat TM imagery used in this study were from two sources: 1) a single date Landsat TM scene covering the study region was purchased towards the end of the burning season (23rd October 1999); and 2) the Statewide Landcover and Trees Study (SLATS) Landsat TM database containing imagery for several other dates (Danaher *et al*. 1998).

3.1 Landsat TM pre-processing

The 23rd October 1999 Landsat TM image acquired for this analysis was pre-processed according to the methods developed by the SLATS project (Danaher *et al*. 1998, Kuhnell *et al.* 1998), including the conversion of digital radiometer counts to units of reflectance and scene to scene geometric registration accurate at the sub-pixel level. This ensured consistency with the existing SLATS archive, and enabled the testing and use of multi-temporal imagery in the Landsat TM fire scar classification (described below).

3.2 Landsat TM fire scar classification

The Landsat TM fire scar classification was undertaken in image file coordinates to preserve pixel values as much as possible. However, both the imagery and subsequent classification were also registered to field measured ground control points (positioned with Differential Global Positioning Systems (DGPS)), which were collected as part of the SLATS project (Danaher *et al*. 1998, Kuhnell *et al*. 1998).

Both supervised and unsupervised fire scar classifications were assessed with the former performing better and reported here.

3.2.1 Supervised fire scar classification

Both single date and multi-temporal imagery were assessed to determine the best approach to Landsat TM fire scar mapping.

The multi-temporal analysis used a baseline image from June 1990 to compare with the October 1999 image. Of the SLATS archive, the 1990 image was found to be the most suitable as it contained relatively few fire scars and was therefore considered better able to highlight changes in vegetation due to fire. Additionally, the more recent SLATS images were relatively greener than the October 1999 image that meant seasonal differences could have influenced the detection of change.

The supervised Landsat TM analysis involved four key steps:

1. Approximately 270 training areas were manually delineated on the October 1999 image, representing the spectral variation within the image. The spectral signatures of these training areas were analysed with ERDAS Imagine's spectral signature editor to produce 12 merged classes which represented a combination of landcover and fire activity:

    - fire affected landcover:
        - active/very recent fire;

    - fire1 – dark spectral signature;
    - fire2 – lighter spectral signature; and
    - fire3 - lighter spectral signature.

- unburnt landcover:
    - pasture;
    - coastal pasture;
    - river channel/inundated vegetation;
    - wooded vegetation;
    - rainforest;
    - claypan/salt flats; and
    - water.

2. Within the signature editor, the six bands from both the 1990 and October 1999 images, as well as three ‘difference indices’ ($NDVI_{1999}$ – $NDVI_{1990}$, $NDVI_{1999}$ – band 5_{1990}, $NDVI_{1999}$ – band 2_{1990}), were analysed to determine which bands best separated the burnt and unburnt classes. The difference indices were selected for inclusion in this stage of the analysis as a preliminary visual assessment of the two images indicated they were able to highlight changes in vegetation due to fire.

3. Through the analysis of spectral signatures and class separability, the bands selected for final classification were bands 3, 4 and 5, and the NDVI for the image being classified. The multi-temporal or difference indices proved useful for separating burnt and unburnt pasture classes but incorrectly identified more wooded areas as being burnt. This was considered a major limitation as manual editing of burnt/unburnt areas is far easier for pastures than wooded regions.

4. The October 1999 image was then classified using the four selected bands in a Maximum Likelihood Classifier based on the mean spectral values of the 12 classes.

The most difficult class to correctly classify proved to be the class labelled ‘fire3 – lighter spectral signature’. This was also the class that proved the most difficult to interpret visually as they appeared to be older burns – not current season fires. However, during the field data collection exercise, it was determined that many of these fire scars were in fact current season but occurred on very light soils and/or potentially sites of lower cover/biomass.

The 12-class fire scar classification was re-coded to a binary burnt/unburnt mask and is shown in Figure 2.

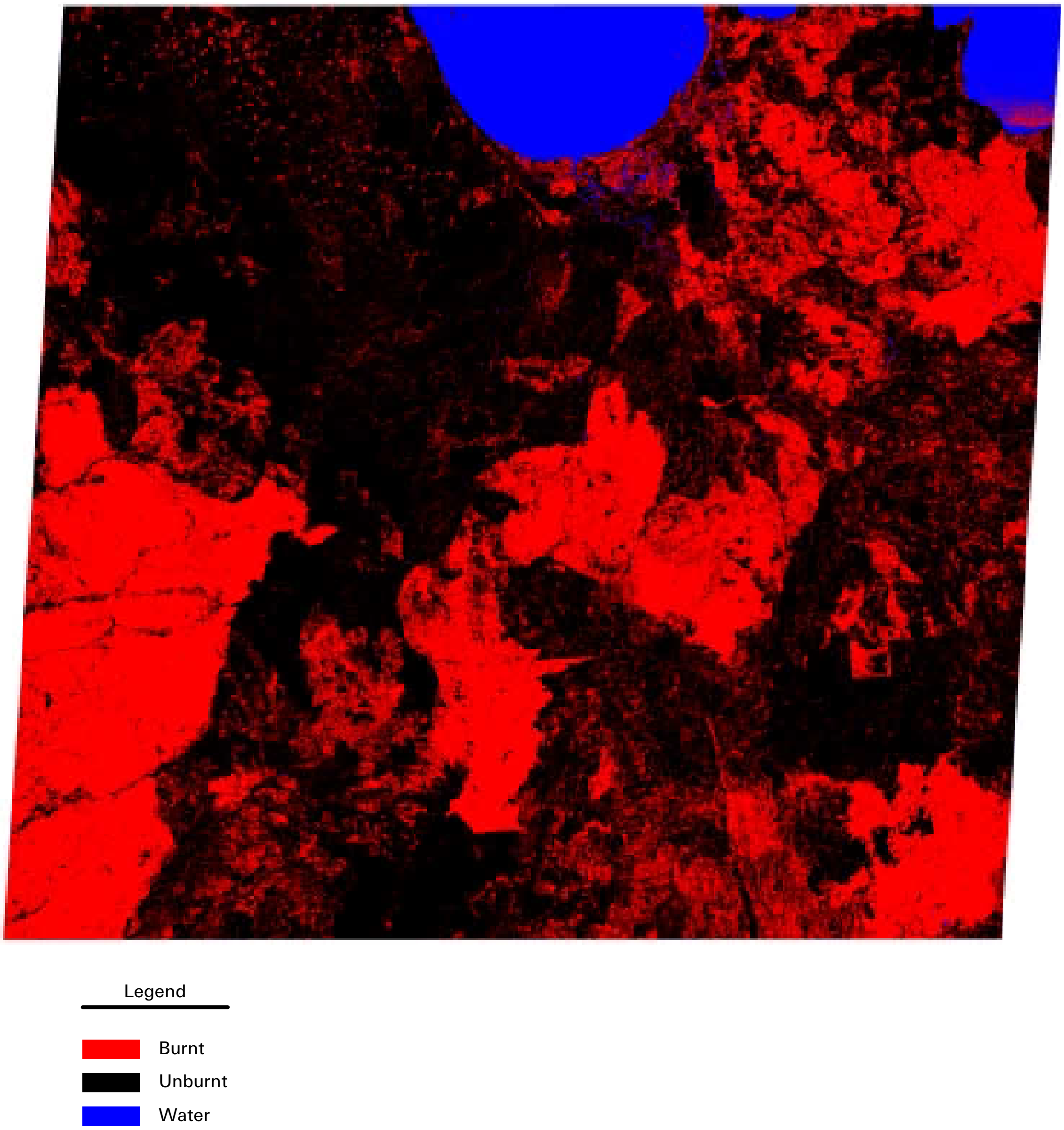

Figure 2. Landsat TM supervised binary (burnt/unburnt) fire scar classification.

3.2.2 Manual editing

Following a visual assessment of the supervised 12-class classification, manual editing of the binary image was undertaken to eliminate falsely classified burnt pixels. Visual interpretation showed that fire scar boundaries were represented well with minimal omission errors. Where omission errors did occur they were mostly scattered pixels within larger classified burnt regions. The classification traded increased errors of commission for those of omission as the latter would be harder to manually edit. Errors of commission (assessed visually) occurred mostly in unburnt pasture.

Manual editing was the most time consuming stage of the fire scar mapping process but was made less subjective with the visual aid of the four earlier SLATS Landsat TM scenes (1988, 1990, 1995, 1997). The final edited fire scar image is shown as Figure 3.

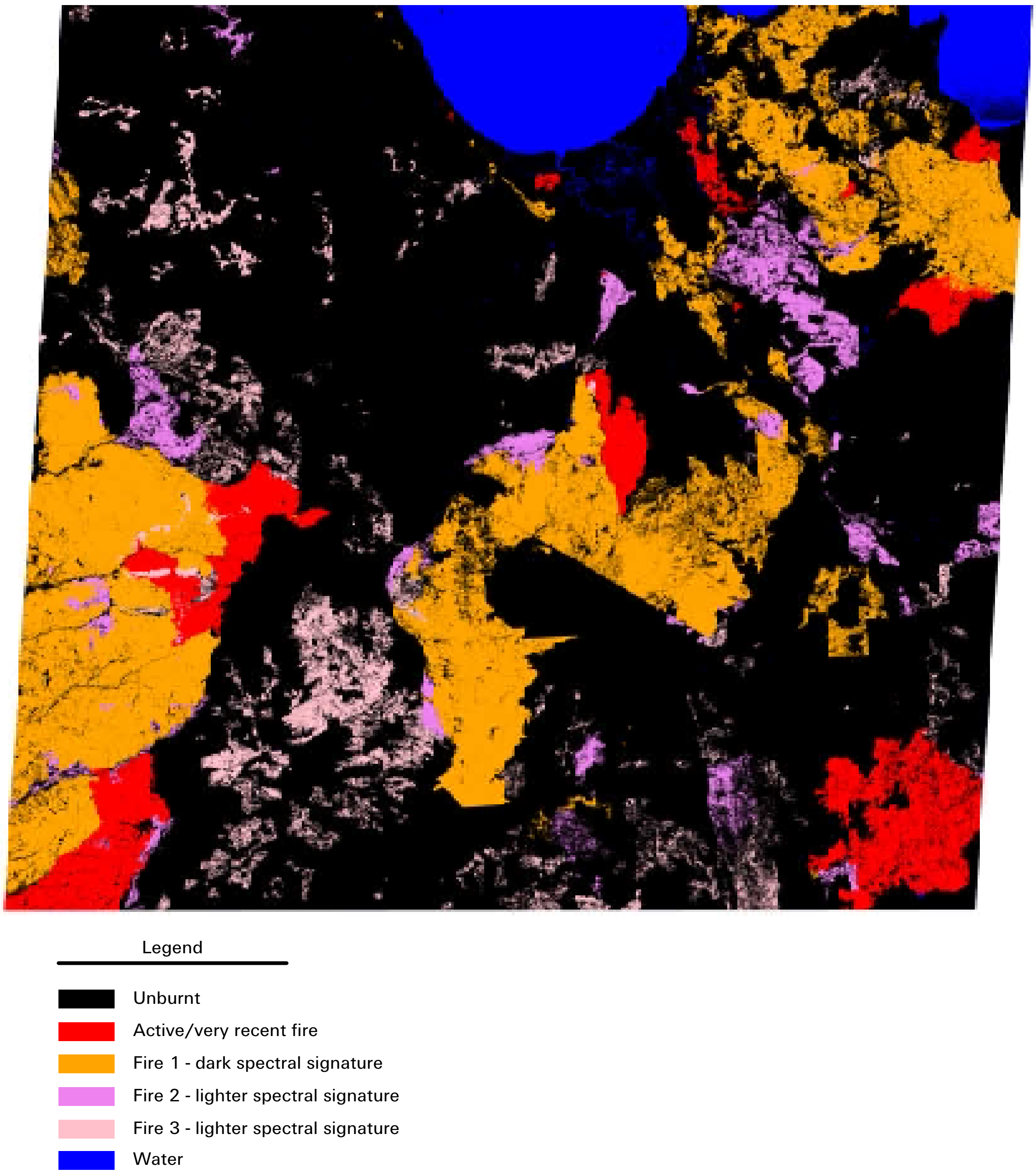

Figure 3. Landsat TM supervised fire scar classification with four burnt and one unburnt classes (plus water).

The manually edited fire scar map was then resampled from file coordinates to Geographic latitude/longitude (Figure 4), and then degraded to NOAA pixel size (0.01 degrees). For each 'NOAA pixel', the degraded image represented the proportion of that pixel classified as burnt (0-100%) according to the Landsat TM fire scar classification (Figures 5 and 6). This image was further degraded by aggregating the percentage burnt data into 11 classes: unburnt, >0 and ≤10%; >10 and ≤20% burnt; >20 and ≤30% burnt; >30 and ≤40% burnt; >40 and ≤50% burnt; >50 and ≤60% burnt; >60 and ≤70% burnt; >70 and ≤80% burnt; >80 and ≤90% burnt; and >90% burnt.

Accuracy assessment of the aggregated Landsat TM fire scar map was then undertaken using field data collected in the study area.

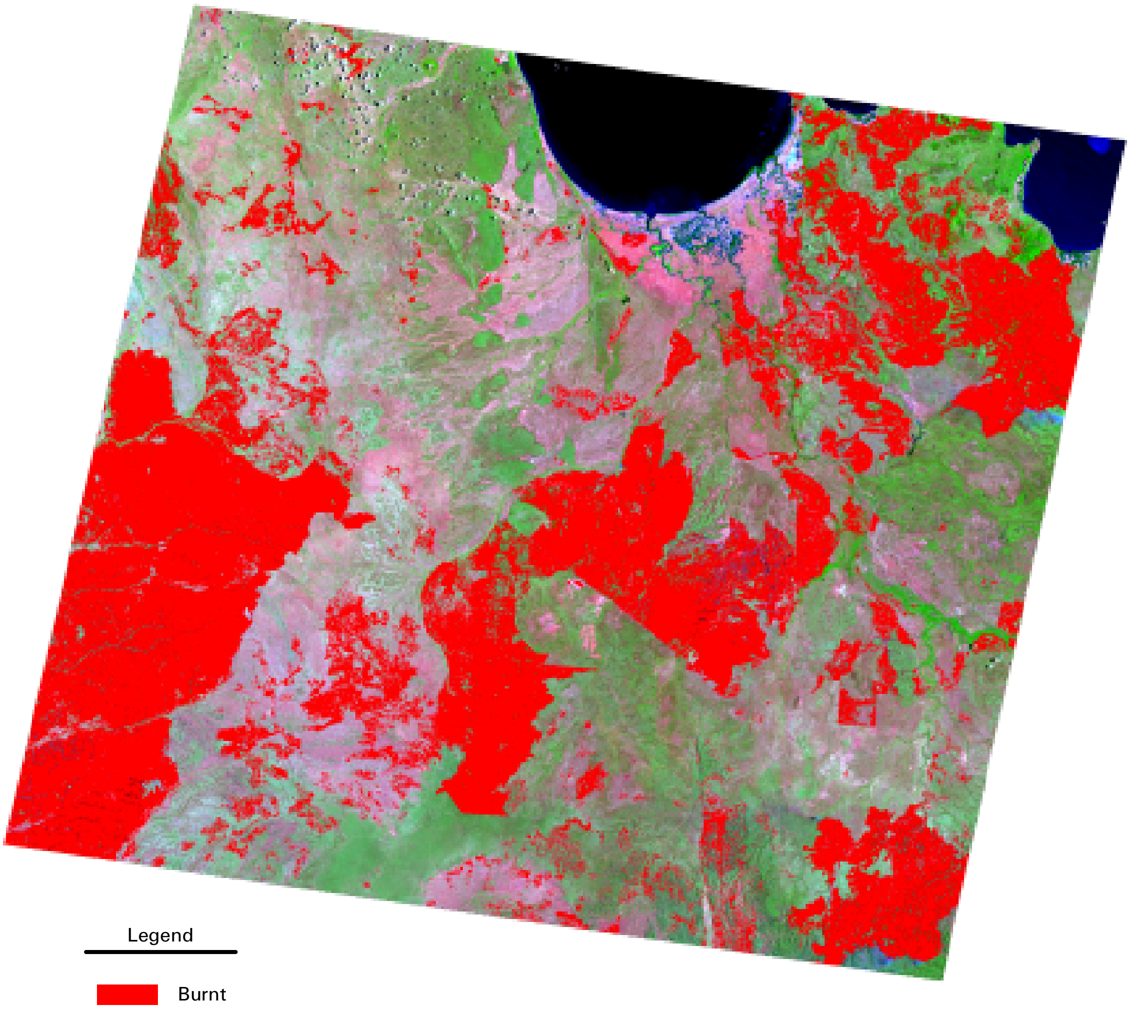

Figure 4. Fire scar map overlaid on the 29th October Kalinga Landsat TM image.

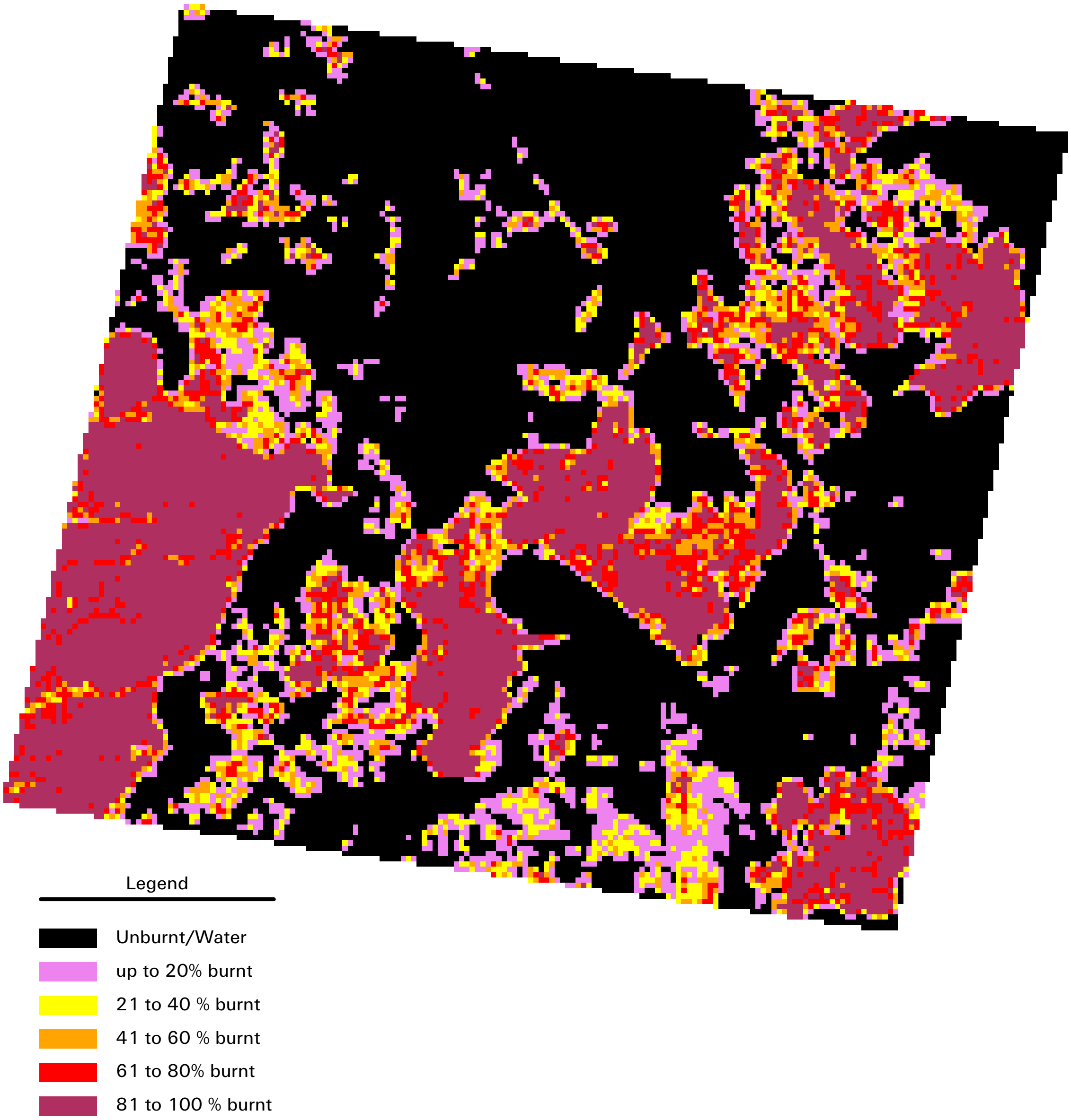

Figure 5. Landsat TM fire scar map degraded to NOAA pixel size (0.01 degrees). For each 'NOAA pixel', the degraded image represented the proportion of that pixel classified as burnt (0-100%) according to the Landsat TM fire scar classification.

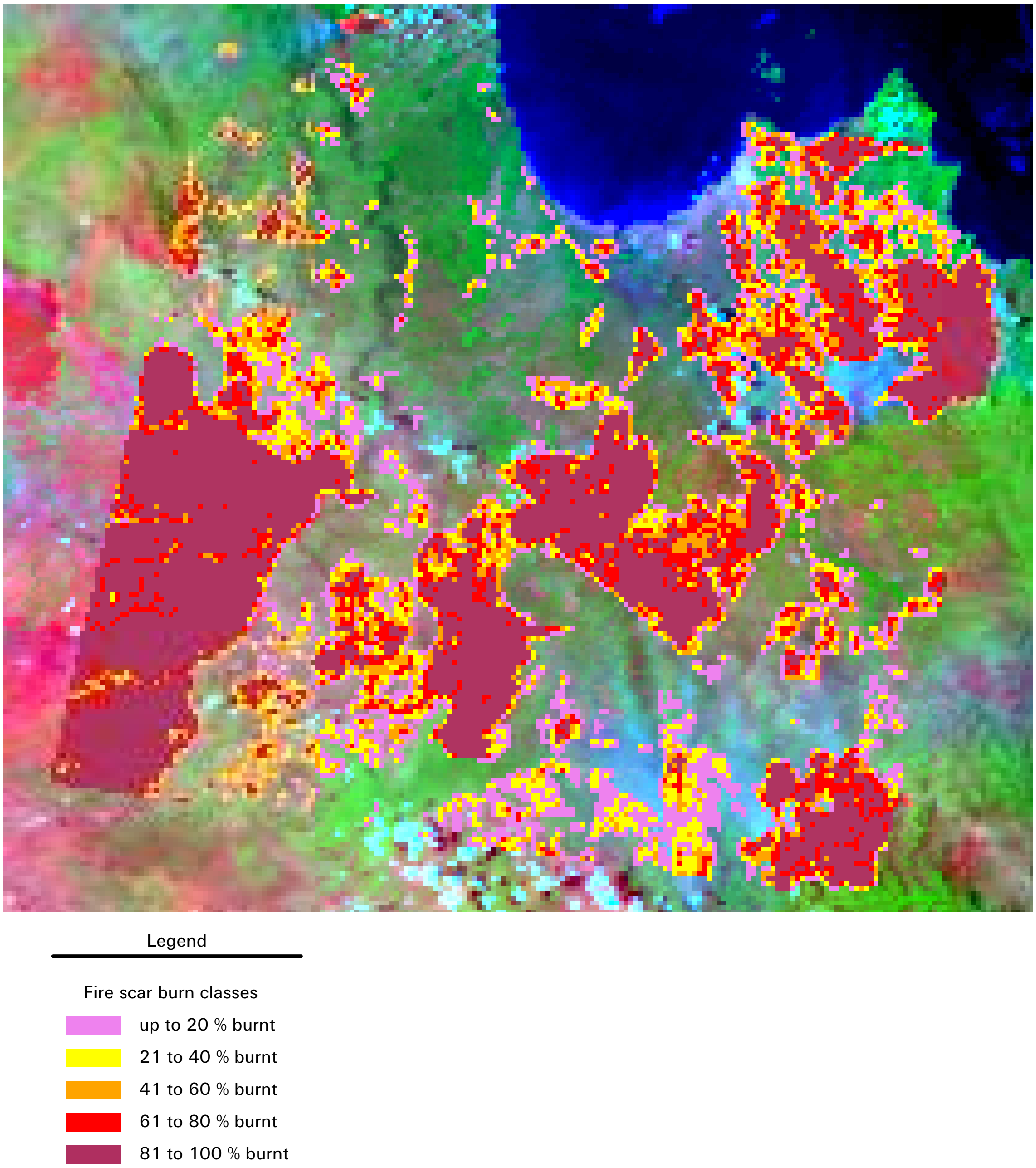

Figure 6. Degraded (0.01 degrees) Landsat TM fire scar map overlaid on NOAA imagery for the study region.

3.3 Field data

As a result of the two-staged validation approach adopted in this study, the field data component was focused on the collection of data most useful for assessing and aiding Landsat TM fire scar mapping. The field data were collected using three broad methods: 1) vehicle–based observations; 2) on-ground fire scar transect measurements; and 3) aircraft-based observations. The first two data sets were collected over a one-week period coincident with the acquisition of the 29th October Landsat TM image, and the third data set was collected on the day before the Landsat TM acquisition. At the time of the field work a number of large fires were still burning.

The field methods used were based on previous methods developed in other projects: Aussie GRASS (Hassett *et al*. 2000); Statewide Landcover and Trees Study (Danaher *et al*. 1998); and the VRD Fire History Ground Truthing Program (Allan and Ryan 1998).

3.3.1 Vehicle-based observations

The vehicle-based observations (Figures 7 and 8) were collected using a modification of the methods described by Hassett *et al*. (2000) and Kuhnell *et al*. (1998).

The method utilised a real time DGPS linked to a laptop computer in a four-wheel drive vehicle. A Fugro Omnistar demodulator receiving a differential signal from the Optus AUSSAT satellite was linked to a Garmin 12XL GPS unit fixed in the vehicle. This signal was updated every second and provided a spatial accuracy of approximately 3-10 m. Linkage of this navigation system to a laptop computer displaying a geometrically registered Landsat TM image in GeoTIFF format enabled the vehicles position to be constantly plotted on-screen. Data collection software (CIGS © 1998-2000 Geonautics International, Brisbane) allowed data to be rapidly collected and input whilst travelling. The CIGS software recorded data in a user defined format and was configured to record the presence or absence of fire, the physical effects of fire, and the associated ecological, geological, geographical and miscellaneous attributes for each observation. The position of each observation was automatically recorded via the DGPS system and represented the vehicle's position on the ground. Remotely recording the location of observations was also possible by locating the cursor over the feature on the geo-referenced image. All mobile data collected included a locality note that determined the direction from the vehicle the observation was made.

3.3.1.1 Fire observations

The majority of observations recorded were the presence or absence of fire. The software was configured to collect the following four data fields:

- burnt/unburnt/patchy/active;
- soil colour;
- tree basal area (estimated; TBA); and
- brief description of fire characteristics/site.

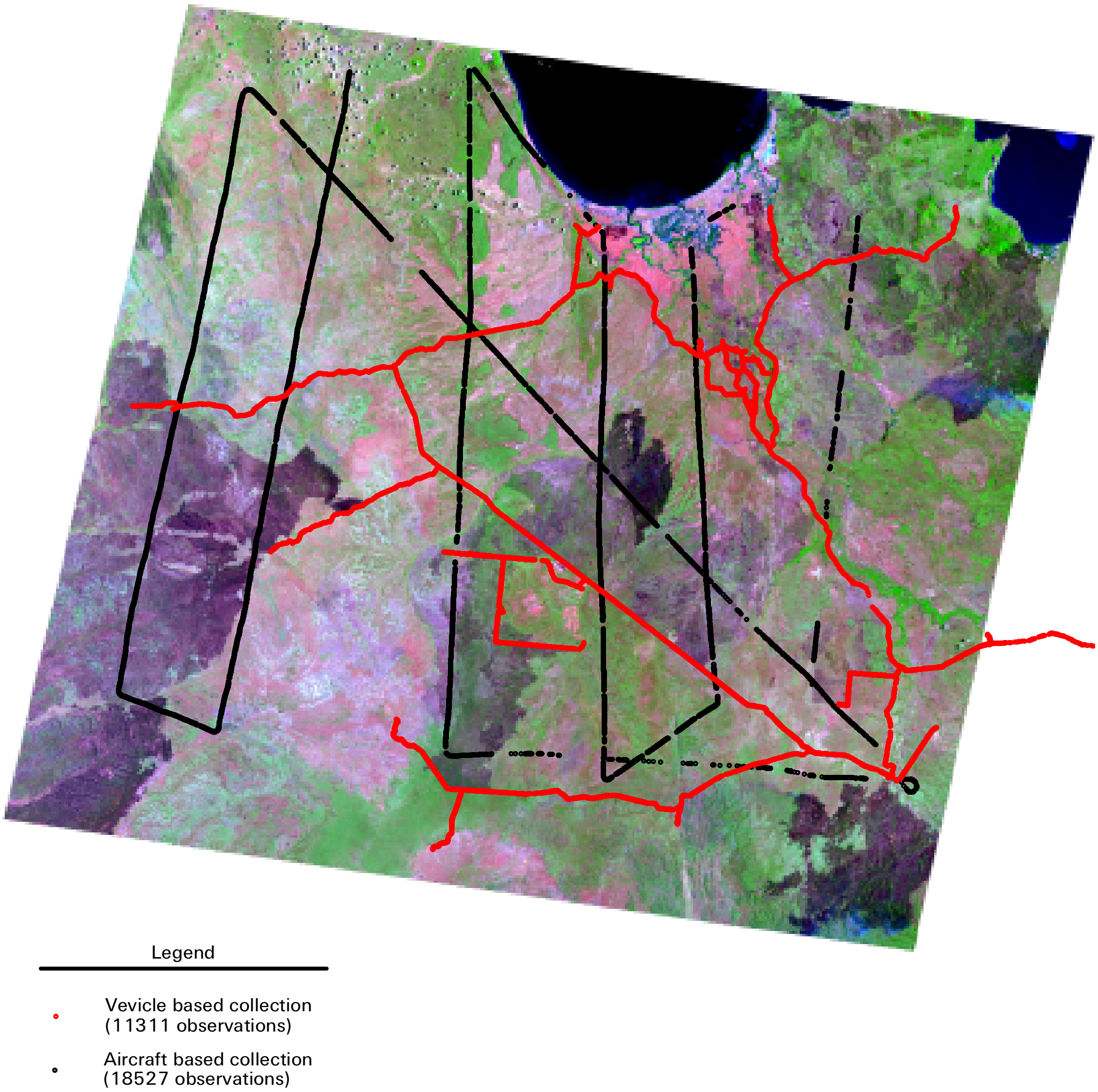

Figure 7. Vehicle and aircraft based data collection routes.

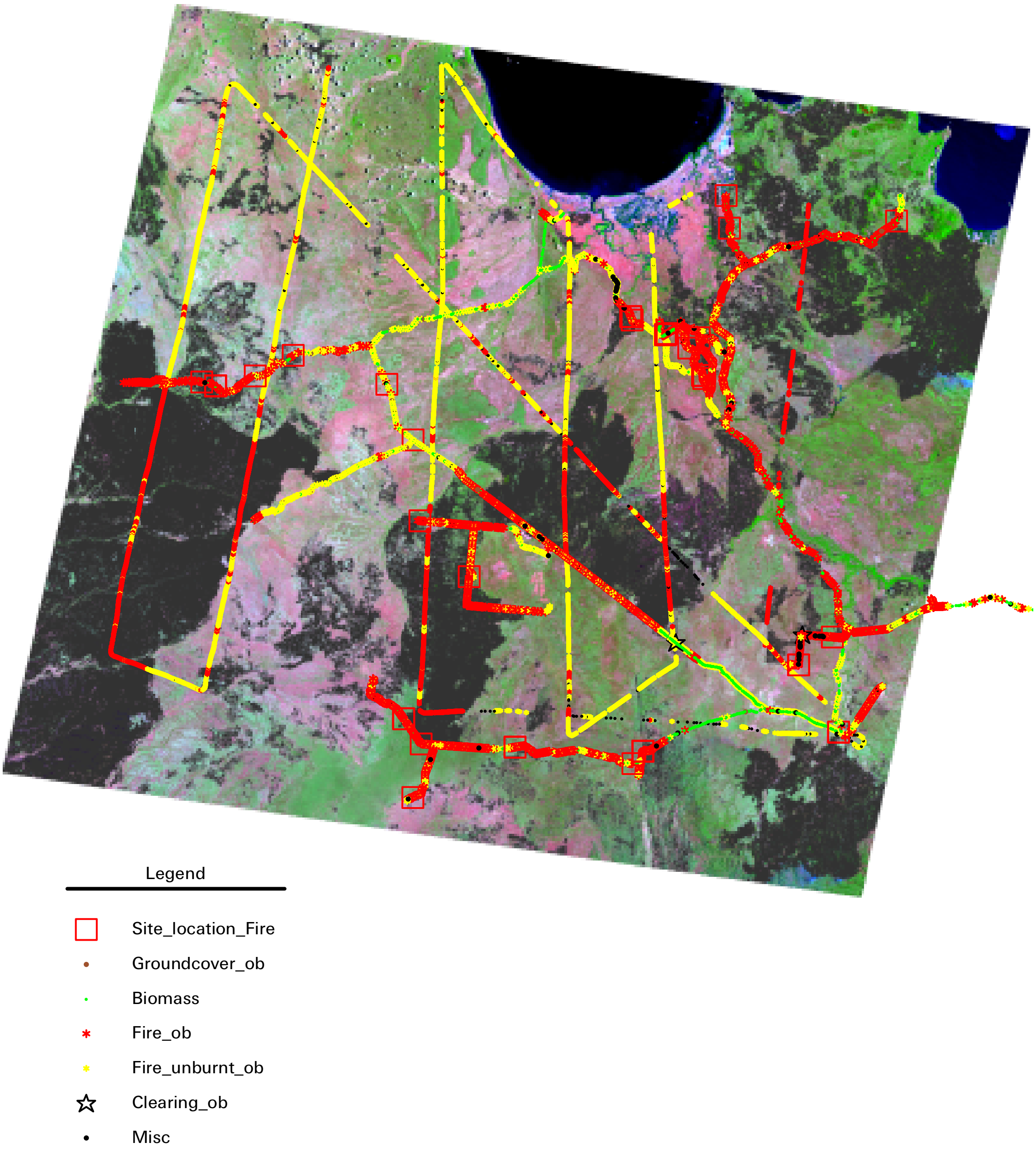

Figure 8. Location of field data observations.

Other data considered noteworthy and of possible value to this and other projects were recorded throughout the study including dominant genera (where clearly identifiable), char height, presence of new growth after fire, relative litter cover, rock cover/colour, slope, water run-on, ash residue and presence of termites.

Each vehicle-based observation, unless otherwise recorded, was for the 30 square metres (approx.) immediately to the left or right of the vehicle. The main exceptions to this were the biomass observations (described below) that represented an estimate of standing pasture biomass for a one-hectare area.

3.3.1.2 DGPS logging of fire scar boundaries

Sections of fire scars and their boundaries were recorded directly using DGPS at two locations within the study area (Figures 9 and 10). The presence of fence line tracks and recently pushed firebreaks allowed the boundaries to be recorded precisely. The vector coverages produced from these data were also used as a further check of image geo-rectification.

3.3.1.3 Biomass observations

Uncalibrated biomass estimates (kg dry matter/ha) were observed throughout all burnt and unburnt areas. The position of these observations and that of burnt or unburnt observations within the data files indicated whether the observation was made within a fire scar or not. This data was collected to build a data set of the potential fuel load burnt as well as provide indicators of fire intensity, and the subsequent biomass remaining following burning.

3.3.1.4 Miscellaneous observations

These observations included data of any nature that were considered useful to this and other studies. Frequently, these observations consisted of more detailed descriptions of landscapes observed and the ecological effects of fire.

3.3.2 Site measurements

Site measurements included but were not limited to the fire transects. Data measured/recorded at various sites included TBA, percentage biomass burnt, soil colour, photographs and ground control points. Site observations were made with the vehicle stationary and the DGPS logging an average of a minimum of 150 ‘positions’ to attain greater positional accuracy. Data recorded at each site included site name and number, description, bearing and distance from site to DGPS, and film and photograph numbers.

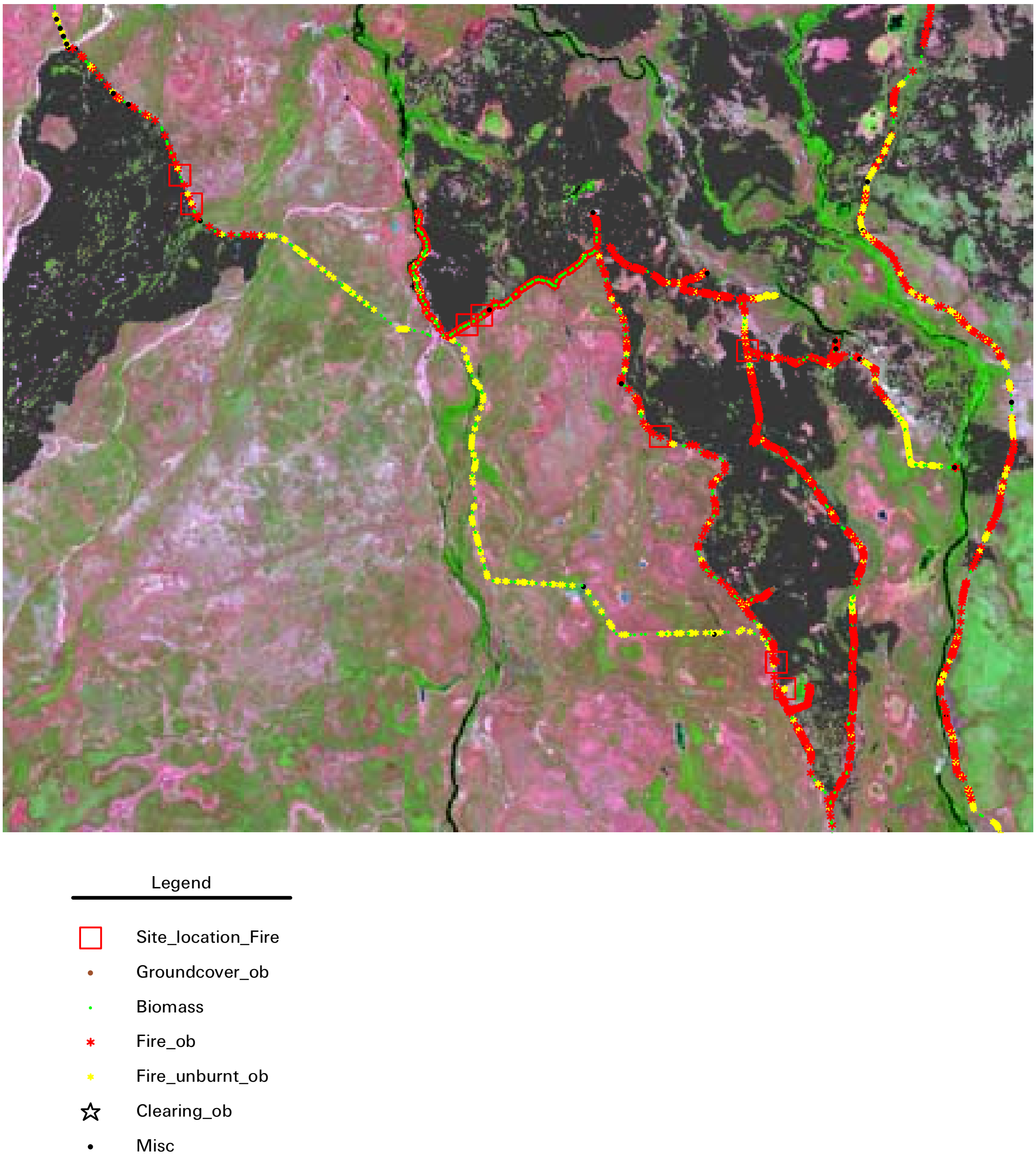

Figure 9. Data observations including DGPS logging of fire scar boundaries.

3.3.2.1 On-ground fire transects

On-ground fire transects were carried out at four representative locations throughout the study area to sample spatial variability across fire scars. The transect sites were selected opportunistically whilst traveling throughout the study area on the basis of maximal variability in the three major ground features that consistently cause spectral confusion on Landsat TM fire classification: patchiness, soils and trees. Sites were not selected where the fire scar was viewed as being uniformly 100% burnt. Each site consisted of two parallel transects (45 m apart and minimum of 300 m long).

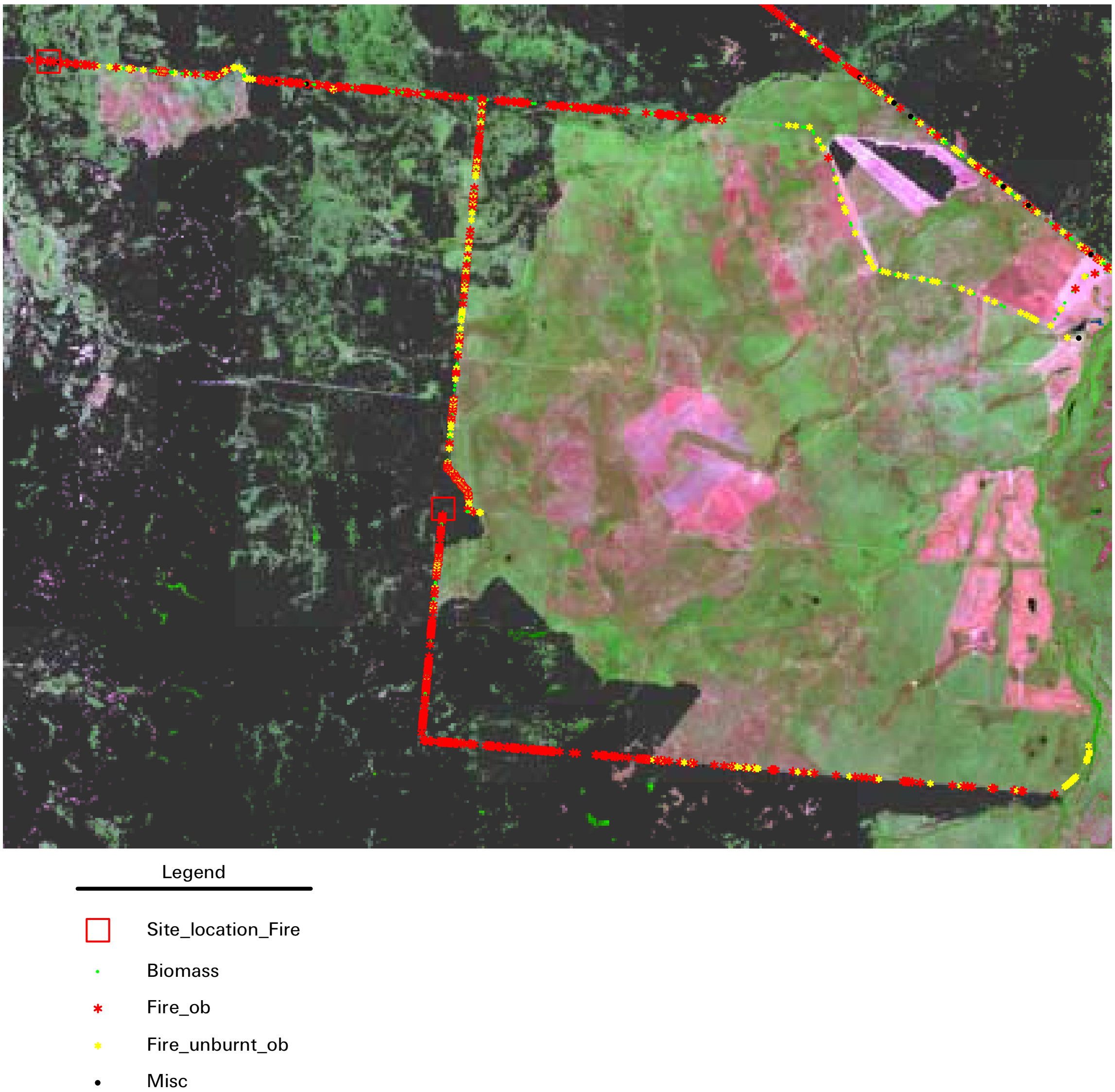

Figure 10. Data observations including DGPS logging of fire scar boundaries.

At each transect site the vehicle was positioned as close as possible to the starting points. A single compass bearing was determined for the parallel transects that would run them through the greatest variability. Starting points were located at 90 degrees from this bearing and positioned 45 m apart. Marker flags or flagging tape were positioned in the ground or in trees at the two starting points. A compass bearing and distance was taken from the starting points to the DGPS that logged and averaged the vehicle's position.

The DGPS was then used in the field to measure the position of the start and end points of the parallel transects. The two parallel transects were paced and data recorded at 1 m intervals by two field officers simultaneously. The data were recorded directly into Lotus 123 spreadsheets on Hewlett Packard 200LX palmtop's. The pre-determined bearing was checked regularly along each transect to ensure a straight-line sample. Marker flags or flagging tape was left along the transect at 50 m intervals as an aid to return navigation and as a further check of the directional accuracy using back-bearings.

At each transect data were collected on: burnt/unburnt occurrence, TBA, soil/rock colour, biomass and other miscellaneous data. Burnt/unburnt status was recorded at each 1 m interval along the transects using a point drawn on the toe of the observer's shoe as the observation point. On those occasions where the observation point was burnt but was subsequently overlain with leaves (Figure 11), or where re-sprouting had begun, the point was classified as burnt as this was believed to more accurately represent the dominant spectral response. If this occurred, actual cover was recorded as a secondary attribute. Thus this approach: 1) recorded the minimum data set of burnt/unburnt status as well as the additional cover data; and 2) minimised the necessity to collect ground data as soon as possible after the fire event in order to avoid recording post fire effects as the dominant feature.

Figure 11. Recent fire with subsequent leaf litter.

TBA (m^2/ha) and scorch height were recorded at a minimum of every 50 m including the start and end points of each transect, with the frequency of additional measurements determined by the patchiness of the trees. TBA was measured using a calibrated optical wedge with observer and prism factor recorded against counts of live, dead and killed by fire at each measuring point. The average scorch height was recorded for trees included within the TBA count.

The soil and rock colour was recorded to resolve possible spectral confusion and was not a soil/mineralogical classification. The frequency of recording along the length of each transect varied in response to the variability present, with hue, value and chroma of dry soil and rock measured using a Munsell Soil Colour handbook.

Pasture biomass (kg DM/ha) estimates were recorded at each TBA measurement or as required depending on the biomass variability. Biomass estimates were recorded in both burnt and unburnt areas in order to build a picture of the potential minimum fuel available and as a possible indicator of intensity and patchiness. The transect recording sheet is shown in Appendix 1.

On return to the vehicle, start and end point waypoint files, and the Lotus 123 files were immediately downloaded to the laptop and saved to 3½" disk. Site descriptors and photographs were recorded in the laptop for each site.

3.3.3 Aircraft-based observations

Aircraft transects were flown across the 180 km² study area to gather additional burnt/unburnt observations (Figures 7 and 8). The software and hardware used for the vehicle-based observations were removed from the vehicle and setup in the aircraft although it was not possible to utilise DGPS. As a result, the data observations from the aircraft were not believed to necessarily reflect the status of the GPS coordinates against which it was recorded. This issue was compounded by the height and speed at which the aircraft was flying, and the difficulty of maintaining a constant focal point for observations. For these reasons, the spatial accuracy of the aircraft based observations is believed to be far less than those made from the vehicle.

For the aircraft transects the software was configured to record 'simple' observations so as to maximize the total number. These were burnt, unburnt, patchy, active fire, resprout, soil colour and vegetation type as well as a miscellaneous key to record infrastructure, geological, geographical and ecological features as required.

3.3.4 Field work summary

A total of 11,311 vehicle based observations were recorded comprising:

- burnt 4,402
- patchy burnt 1,008
- active fire 8
- unburnt 3,152
- biomass 2,563
- site locations 44
- cover 33
- clearing 2
- miscellaneous 99

A total of 18,527 aircraft based observations were recorded comprising:

- burnt 5,340
- patchy burnt 357
- active fire 4
- resprout 29
- unburnt 12,648
- soil colour 8
- vegetation type 44
- miscellaneous 97

3.4 Using field data to assess Landsat TM fire scar maps

For the purposes of this report, a series of simple analyses were performed to assess the accuracy of the Landsat TM fire scar at a number of precision levels. Further, more detailed analysis using stratification by soil colour, tree density, landcover etc. is required but was not possible here due to time constraints.

Each of the three field data sets – vehicle observations, ground transects, and air transects – had a different level of precision associated with their collection. This can be summed up as the confidence with which we can position the observation on a given pixel of the Landsat TM classification, given the relative misregistration error. These are listed below:

- vehicle–based observations $\pm$ 2 pixels;
- on-ground fire transects $\pm$ 1 pixel; and
- aircraft-based observations $\pm$ 3 pixels.

These factors were determined for each data set based on the accuracy associated with the point location in the field, and the RMS error associated with registration of the Landsat TM image to map (ground) coordinates.

As the study area comprised two different AMG map zones (54 and 55), all field data were converted to geographic latitude/longitude positions to apply to the Landsat TM data in order to avoid split zone sampling.

3.4.1 On-ground fire scar transects

As the end point positions of each ground transect were measured with DGPS, and every attempt was made to ensure that observation points were evenly spaced (paced) along the transect, the position in UTM coordinates of the n^{th} point along a given transect were calculated as follows:

$$n_{t\text{-}east} = start_{east} + n_t/N\ (start_{east} - finish_{east})$$
$$n_{t\text{-}north} = start_{north} + n_t/N\ (start_{north} - finish_{north})$$

where:
$start_{east}$ and $start_{north}$ were the start of the transect, as measured with DGPS;
$finish_{east}$ and $finish_{north}$ were the end of the transect, as measured with DGPS; and
N was the total number of points along the transect.

Once the points along each transect were calculated, ARC/INFO point vector coverages were generated and overlayed on the Landsat TM binary fire scar map. The 300 - 400 points along each transect were aggregated into 30 m (Landsat TM pixel sized) ‘sections’ and the central point of each section labelled with the percentage of points burnt within that section.

A threshold was then set in order to label each central point as burnt or unburnt. This would usually be dictated by the user’s requirements of the satellite fire scar mapping, e.g. whether their interest was in the representation of ‘patchiness’ or perhaps, the representation of total area burnt. For this analysis two series of tests were run using different thresholds:

1. If ≥ 30% of the section was burnt, then whole section was labelled burnt; and
2. If ≥ 50% of the section was burnt, then whole section was labelled burnt.

Every pixel in a 3∗3 window (representing ± one pixel precision) around each transect 'section' was then assessed to determine whether or not there was a match between the field data and the Landsat TM classification. If at least one pixel in the window matched the label (burnt/unburnt) of the transect section, then the pixel was considered correctly classified, otherwise it was incorrectly classified.

Preliminary analysis showed that a significant level of bias existed in one of the transect sites (site no 2), located in an older burn on very light soil. The tests were therefore run both including and excluding this site. Results for both tests are shown in Tables 1 and 2 respectively.

Table 1. Results from the comparison of on-ground fire observations for all transect locations and the Landsat TM fire scar map using two thresholds (30 and 50%) and the 3∗3-pixel window. The thresholds determined the percentage of on-ground burnt observations within each 30 m section (or pixel) at which point the section was classified as burnt. A pixel was considered correctly classified in the Landsat TM fire scar map if any of the 9 pixels in a 3∗3-pixel window centred on the observation section had the same classification.

		On-ground classification of Landsat TM pixels			
		30% threshold		*50% threshold*	
		Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)
Landsat TM fire scar classification of pixels	Burnt (%)	**84**	16	**74**	26
	Unburnt (%)	0	**100**	0	**100**

Table 2. Results from the comparison of on-ground fire observations for transects locations 1, 3 and 4 and the Landsat TM fire scar map using two thresholds (30 and 50%) and the 3∗3-pixel window. The thresholds determined the percentage of on-ground burnt observations within each 30 m section (or pixel) at which point the section was classified as burnt. A pixel was considered correctly classified in the Landsat TM fire scar map if any of the 9 pixels in a 3∗3-pixel window centred on the observation section had the same classification.

		On-ground classification of Landsat TM pixels			
		30% threshold		*50% threshold*	
		Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)
Landsat TM fire scar classification of pixels	Burnt (%)	**96**	4	**86**	14
	Unburnt (%)	0	**100**	0	**100**

The ground transect assessment shows an overall accuracy of 92% with all sites included and 98% with site number 2 excluded from the analysis. The transect observations are shown against the 'raw' Landsat TM in Figure 12.

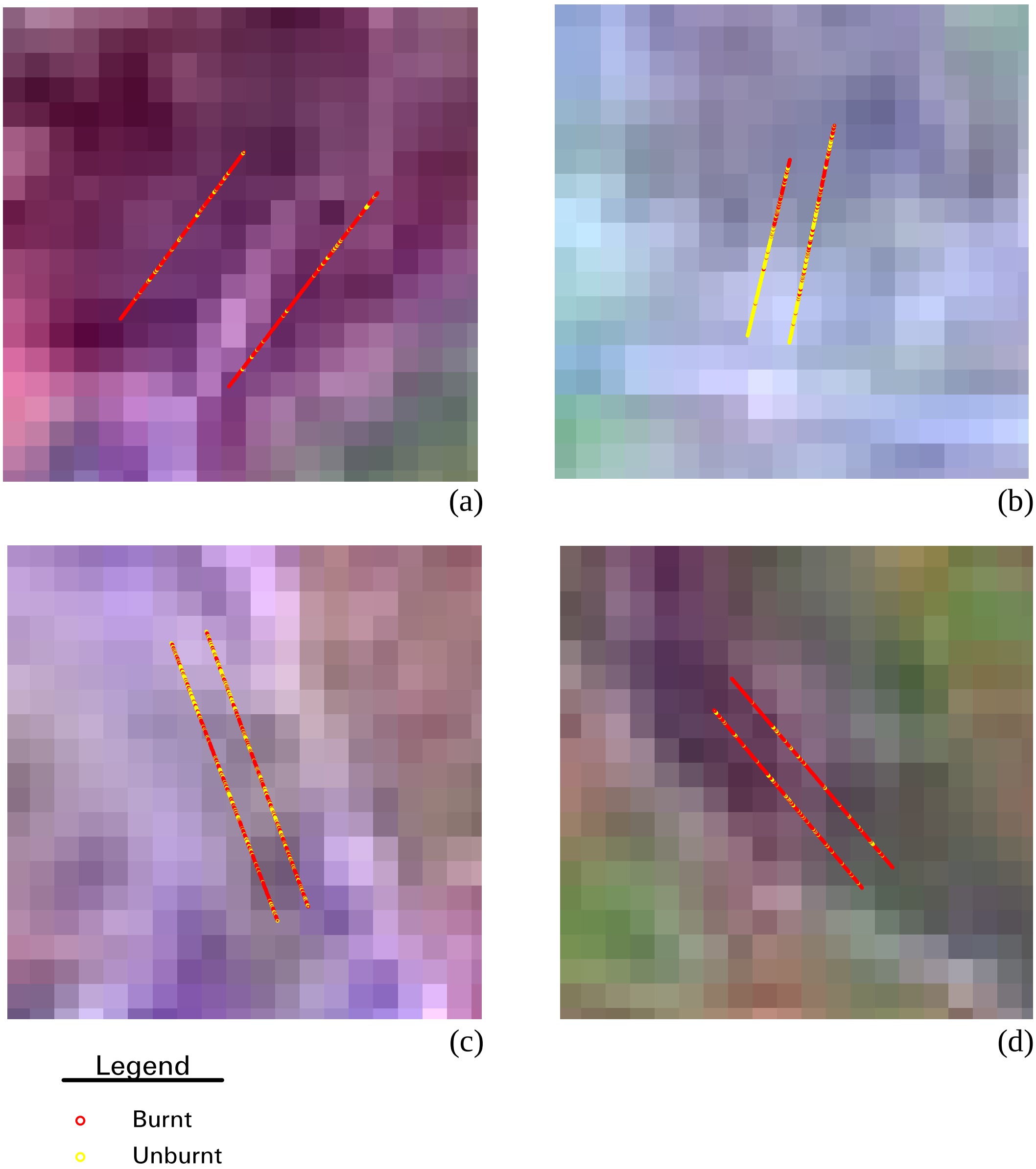

Figure 12. Transect observations against the 'raw' Landsat TM image for: a) site 1; b) site 2; c) site 3; and d) site 4.

3.4.2 Vehicle-based observations

An ARC/INFO point vector coverage was generated using all of the vehicle-based burnt, unburnt and active fire observations and overlayed on the Landsat TM binary fire scar map. For this data set, a single observation represented approximately one Landsat TM pixel on the ground so no aggregation of the vehicle-based observations was necessary. Patchy burn observations were excluded from this analysis as the field data set was being used itself as a binary data set. Each pixel in a 5*5 window around the burnt or unburnt observation point (representing the ± 2 pixels precision) was assessed, as for the on-ground observations, to determine whether a match existed or not.

The results of the vehicle-based observations (Table 3) show a lower overall accuracy of 77.5%. This is biased heavily by large numbers of omission errors in the southern more densely wooded part of the scene. In this region, it was observed in the field that the understorey was predominantly 100% burnt with the dense canopy largely unaffected by fire. No fire scar is evident at all on the Landsat TM image in this region.

Table 3. Results from the comparison of vehicle-based individual burnt/unburnt observations and the Landsat TM fire scar map and a 5∗5-pixel window. A pixel was considered correctly classified in the Landsat TM fire scar map if any of the 25 pixels in the 5∗5-pixel window centred on the observation point had the same classification.

		Vehicle-based classification of Landsat TM pixels	
		Burnt (%)	Unburnt (%)
Landsat TM fire scar classification of pixels	Burnt (%)	**90**	10
	Unburnt (%)	35	**65**

3.4.3 Aircraft-based transects

An ARC/INFO point coverage of the plane transects were also generated and a similar method used to compare this data set to the Landsat TM binary fire scar classification. In this case the precise location of an observation point on the ground was considered to have an error of ± 3 pixels (this may be a conservative estimate of the positional error) and therefore a window of 7∗7 pixels around a given observation point was used. Once again, a pixel was labelled as correctly classified if at least one of the pixels in the window matched the observation. Table 4 shows the comparison of the Landsat TM fire scar classification with the aircraft based observations. These results are again very high with an overall accuracy of 98%.

Table 4. Results from the comparison of aircraft-based individual burnt/unburnt observations and the Landsat TM fire scar map and a 7∗7-pixel window. A pixel was considered correctly classified in the Landsat TM fire scar map if any of the 49 pixels in the 7∗7 pixel window centred on the ‘observation point had the same classification.

		Aircraft-based classification of Landsat TM pixels	
		Burnt (%)	Unburnt (%)
Landsat TM fire scar classification of pixels	Burnt (%)	**99**	1
	Unburnt (%)	3	**97**

3.4.4 Summary of Landsat TM accuracy assessment

Based on the results above, we believe the Landsat TM derived fire scar classification has an accuracy in the range of 77 – 98%. Whilst there may be some bias in the accuracy of the classification in different regions, it is considered to be suitable for the application to the assessment of NOAA derived fire scar mapping.

4. NOAA fire scar maps

4.1 NOAA pre-processing

Pre-processing of NOAA-14 data received at QDNR was achieved using the CSIRO Common AVHRR Processing Software (CAPS) (Turner and Davies 1998, http://www.dar.csiro.au/rs/capshome.html) which:

1. read in the HRPT data;
2. geo-located each pixel; and
3. converted radiometer data to counts of radiance and then physical units of 'top-of-atmosphere' reflectance (bands 1 and 2), or brightness temperature (bands 3, 4, and 5).

Geo-registration was performed using the 'Clift' navigation algorithm developed by CSIRO Marine Laboratories, Hobart. This algorithm offered the best available accuracy (± 1 km of ground position) of any of the navigation algorithms available in CAPS. Conversion from radiometer data to reflectance followed methods recommended by Mitchell (1999).

A cloud mask for every pass was generated using the CLAVR algorithm (Stowe *et al.* 1998). Whilst CINRS has found this algorithm performed better than others documented it still did not produce cloud masks of sufficient accuracy to eliminate problems in both automated active fire and automated fire scar mapping procedures.

Some of the NOAA passes used in this study were also manually geo-registered to the Landsat TM scene to minimise misregistration errors and hence any possible bias in the analysis. However, automated methods where large numbers of images were required did not use manually registered NOAA images.

4.2 CINRS prototype NOAA fire scar mapping techniques

Research into methods of automated fire scar mapping by CINRS is still under development and the algorithm used to produce the automated NOAA fire scar for this study is pre-operational. This algorithm, described in more detail below, is known as FireMD3 (multi-date testing with three indices), and has been developed through testing in a number of key regions in Queensland which cover a diverse range of soil types, landscapes, and fire regimes: Normanton, Charters Towers, Monto, and Arrabury. The following section outlines briefly some of the main findings of previous fire scar research, and some of the key stages in the evolution of the FireMD3 algorithm.

The CINRS automated fire scar program has drawn much from research into automated NOAA fire scar mapping conducted in Africa on similar savanna landscapes by Barbosa *et al.* (1998, 1999). These studies tested an algorithm called the Burnt Area Algorithm (BAA) that was based upon the principals of relative spectral changes in certain wavebands immediately after fire. Post-fire NOAA data response is characterised, in most biomes, by short-term increases in surface temperature and hence brightness temperature in all three thermal bands, and decreases in both of the reflective bands. The latter changes also result in decreases in response after fire of a number of commonly used remote sensing indicators for resource monitoring, such as NDVI and GEMI (Pinty and Verstraete 1992), and surface albedo.

In a comparative evaluation of remotely sensed indicators, Pereira (1999) found that indices based on AVHRR reflective band 2 and mid-infrared/thermal band 3 rated more highly in terms of burnt and unburnt class separability than others. In particular, a new index called the VI3T (described below), together with GEMI and band 3 showed the highest separability in most biomes. CINRS research has confirmed that these indices performed better than others in a number of Queensland test areas (Normanton, Charters Towers, Monto and Arrabury).

Although a number of single-date, multi-date (two dates only), and time-series criteria were initially trialed, the multi-date method based on the three indices above with additional allowances for seasonal and background variability (i.e. the FireMD3 algorithm), performed considerably better than any combination of single pass indices. At the time of testing, the NRM archive of NOAA passes was limited and therefore limited the performance of the longer-term time-series methods.

A pixel was classified as a fire scar in FireMD3 if the following set of criteria were all satisfied:

$GEMI_t - GEMI_{t-1} <$ GEMI relative mean background difference + 0.02

and

$VI3T_t - VI3T_{t-1} <$ VI3T relative mean background difference + 0.05

and

$BT3_t - BT3_{t-1} >$ BT3 relative mean background difference + 1.8

where:

$$GEMI = \eta\,(1 - 0.25\eta) - (\rho_1 - 0.125) / (1 - \rho_1)$$
$$VI3T = (\rho_2 - BT3 / 1000) / (\rho_2 + BT3 / 1000)$$

$$\eta = [2(\rho_2^2 - \rho_1^2) + 1.5\rho^2] / (\rho_2 + \rho_1 + 0.5)$$

ρ1 is normalised reflectance in band 1
ρ2 is normalised reflectance in band 2
BT3 is brightness temperature in band 3

The constants in the above equations were calibrated for the Normanton, Charters Towers, and Monto test areas.

The relative mean background difference between dates for each index was calculated using an 81 ∗ 81 pixel ‘context window’ centred on each pixel being evaluated. The 29 ∗ 29-pixel window immediately surrounding that pixel were ignored in order to reduce the number of burnt pixels in the calculation of the mean relative background difference, and thus reduce bias in the statistics. The change due to post-fire response was then calculated as a constant threshold above this mean background variation. Adding ‘context’ to the ‘per pixel change’ classification has been found to reduce the reliance of the multi-date change analysis on threshold stratification for different regions and seasons.

Four different NOAA fire scar classification methods incorporating the FireMD3 algorithm were tested against the Landsat TM fire scar map. Each method differed in the combination of images used as inputs.

In addition, a fifth semi-manual method based on an unsupervised classification followed by manual editing was also tested against the Landsat TM fire scar map.

4.2.1 Generation of NOAA fire scar maps

NOAA fire scar maps for the Kalinga Landsat TM scene were generated using suitable NOAA imagery between June and October 1999. Imagery not considered suitable were those where: 1) there was incomplete coverage of the study area; 2) there was excess cloud cover; and 3) satellite zenith (scan angle) was greater than 40 degrees. This resulted in a variable number of images per month, many of which were partially clouded:

- June 1999 - 12 images;
- July 1999 - 8 images;
- August 1999 - 3 images (due to problems in receiving NOAA data);
- September 1999 - 8 images; and
- October 1999 - 10 images.

The key 'cloud free' image, i.e. that closest to the Landsat TM acquisition date, was received on the 15th October 1999.

4.2.1.1 Test 1: Two dates, manual choice of images and automatic classification

The first test used two input images: 1) the key NOAA image from the 15th October 1999; and 2) an earlier 'reference' image. A series of less cloudy images from earlier dates were trailed as the reference image and thus scars were produced using FireMD3 for the following periods:

- *test 1a*: 8th September 1999 - 15th October 1999;
- *test 1b*: 20th June 1999 – 15th October 1999;
- *test 1c*: 10th July 1999 - 15th October 1999; and
- *test 1d*: 26th July 1999 - 15th October 1999.

No test was conducted with an August reference image as all three images were very cloudy. The results for Test 1 are shown in Table 5, and the resultant image for Test 1a in Figure 13.

Table 5. Test 1 NOAA burnt/unburnt classification findings relative to Landsat TM classification of NOAA pixels. (the pixel counts in brackets in the table are the number of NOAA pixels within each of the Landsat TM classification groups)

Landsat TM classification		Completely unburnt (14,928 pixels)		>0 and ≤20% burnt (2,492 pixels)		>20 and ≤50% burnt (2,240 pixels)		>50% burnt (6,551 pixels)	
	Test	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)
NOAA classification	1a	99.9	0.1	99.2	0.8	98.3	1.7	63.3	36.7
	1b	99.9	0.1	99.2	0.8	97.5	2.5	72.4	27.6
	1c	99.9	0.1	99.3	0.7	98.0	2.0	65.0	35.0
	1d	99.7	0.3	99.2	0.8	96.8	3.2	62.6	37.4

Tests 1a-d all had similar classification of the NOAA pixels as burnt/unburnt apart from Test 1b which was affected by a relatively large patch of cloud in the 20th June reference image. Overall the results were relatively disappointing, especially in terms of the classification of those NOAA pixels where greater than 50% of the Landsat TM pixels were classified as burnt, with only 27.6 – 37.4% of NOAA pixels classified as burnt using the FireMD3 algorithm.

4.2.1.2 Test 2: Many dates, manual choice of image and automatic classification

This test used the sum of a number of two-date FireMD3 fire scar maps (such as those tested individually in Test 1) to produce a more comprehensive fire scar classification. Each of the following 'minimal cloud' images was used in combination with the other images in the list to produce a total of 21 fire scar maps:

- 20th June 1999;
- 10th July 1999;
- 26th July 1999;
- 8th September 1999;
- 16th September 1999;
- 13th October 1999; and
- 15th October 1999.

Two of the 21 fire scar maps which covered a period of greater than three months were not considered in the subsequent analysis: 1) 20th June 1999 - 13th October 1999; and 2) 20th June 1999 - 15th October 1999. The remaining 19 images were processed to produce a 'count' image that recorded the frequency of classification of each pixel as burnt. Following a preliminary analysis of the count image a threshold frequency count of one was selected to classify NOAA pixels as burnt or unburnt in the final fire scar classification, i.e. any pixels that were classified as burnt in any of the 19 fire scar maps were classified as burnt in the final fire scar map.

The results for Test 2 are shown in Table 6 and Figure 14.

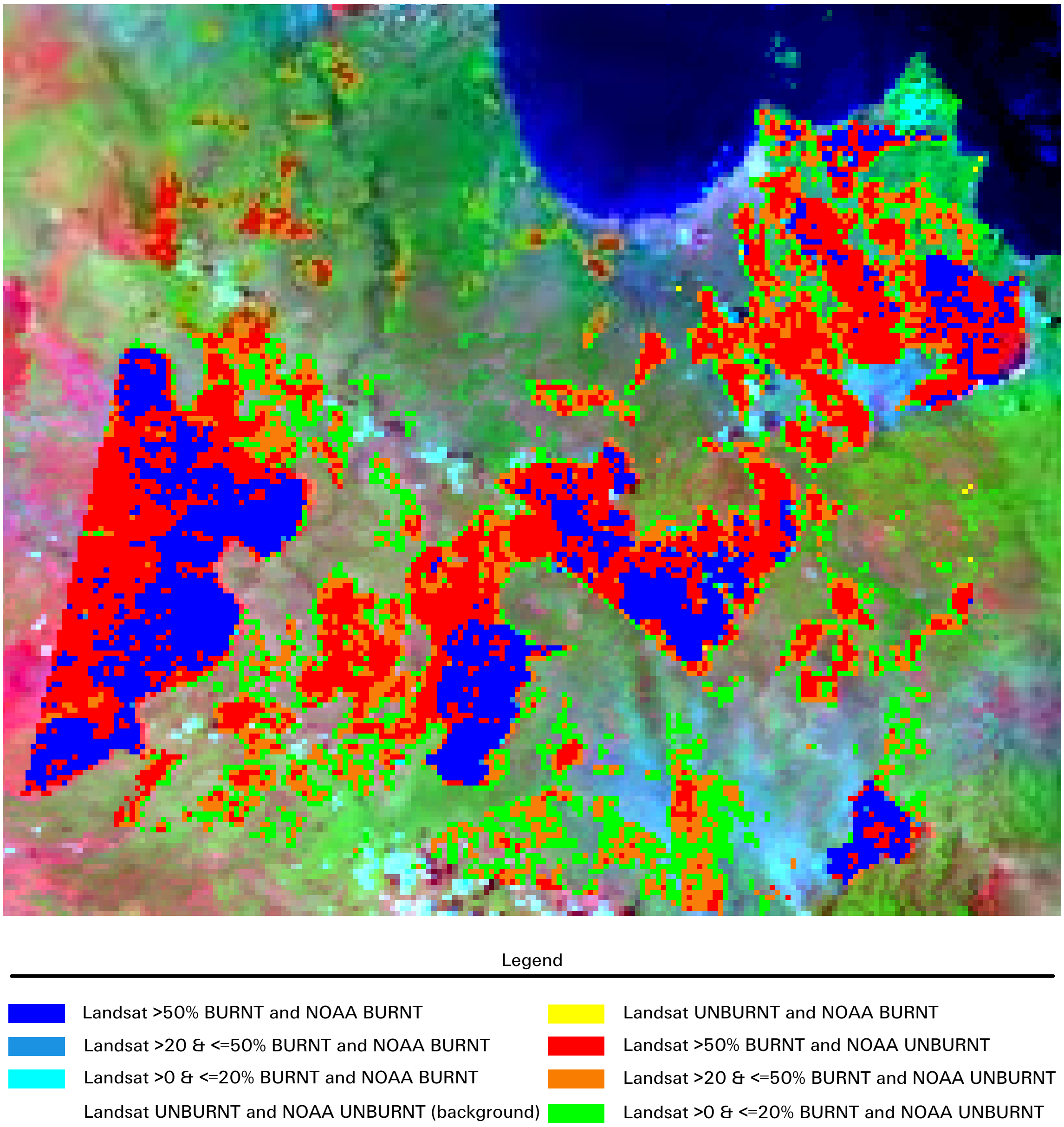

Figure 13. Test 1a spatial results.

Table 6. Test 2 NOAA burnt/unburnt classification findings relative to Landsat TM classification of NOAA pixels. (the pixel counts in brackets in the table are the number of NOAA pixels within each of the Landsat TM classification groups)

Landsat TM classification	Completely unburnt (14,928 pixels)		>0 and ≤20% burnt (2,492 pixels)		>20 and ≤50% burnt (2,240 pixels)		>50% burnt (6,551 pixels)	
NOAA classification	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)
	97.1	2.9	86.2	13.8	70.4	29.6	23.8	76.2

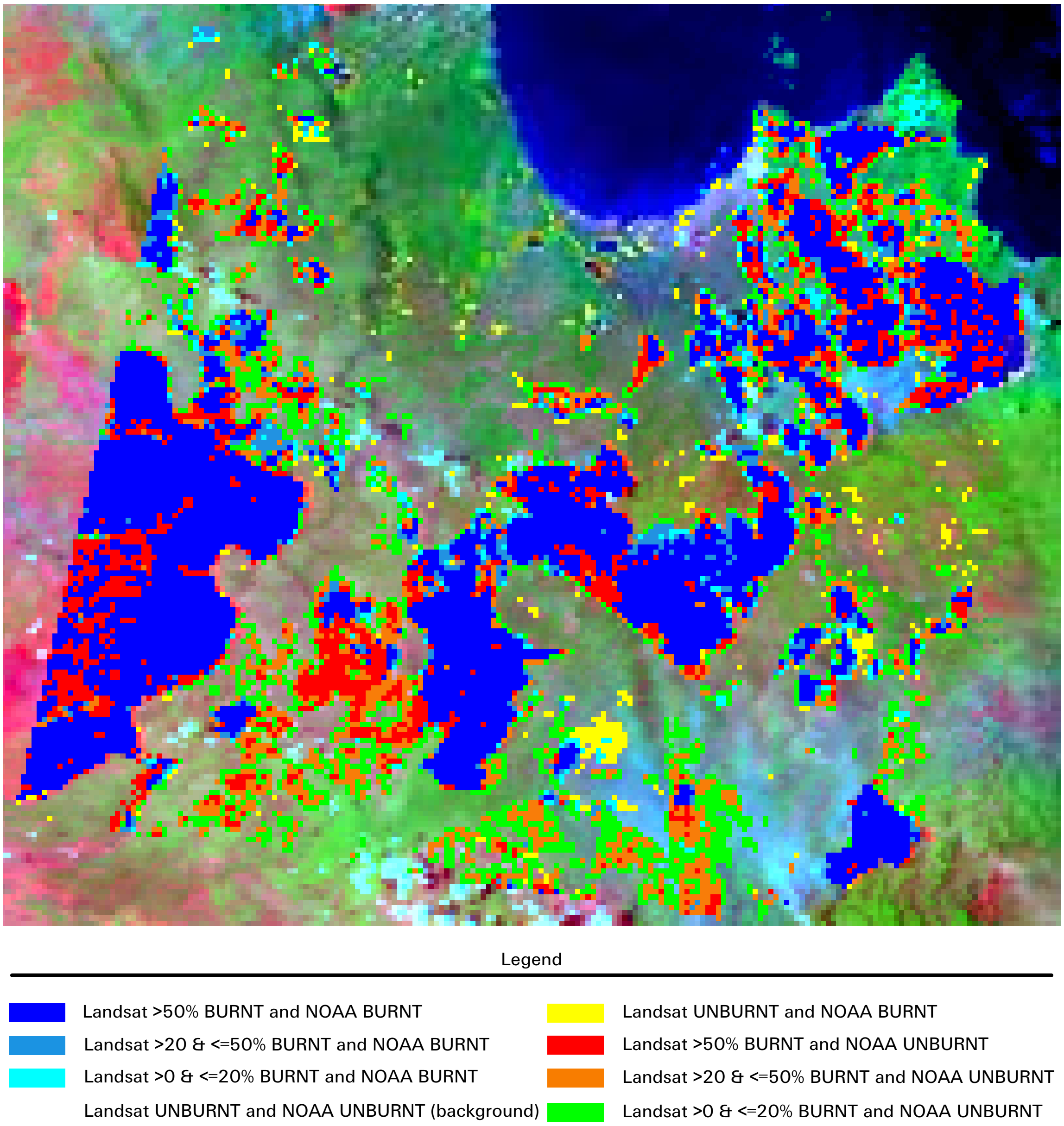

Figure 14. Test 2 spatial results.

4.2.1.3 Test 3: Bi-monthly composite and automatic classification

This method required the production of two 'per-pixel composites' each month for June through to October on the following basis:

- composite 1 – produced using imagery for using days 1-14 of each month; and
- composite 2 – produced using imagery for day 15 through to the last day of each month.

The number of input images for each composite was:

- June 1999 #1 – 7;
- June 1999 #2 – 5;
- July 1999 #1 – 2;
- July 1999 #2 – 6;
- August 1999 #1 – 1;
- August 1999 #2 – 2;
- September 1999 #1 – 4;
- September 1999 #2 – 4;
- October 1999 #1 – 4; and
- October 1999 #2 – 6.

Previous work by Barbosa *et al.* (1998) showed that the identification of fire scar pixels can be maximised if, during the creation of multi-temporal composites for each pixel, the four images with the minimum albedo value are chosen. From those, the composite is generated using the image with the maximum brightness temperature in band 4 (BT4). However, due to the limited number of images available to produce each bi-monthly composite, the following modified procedure was adopted for each pixel:

1. choose the two images with minimum albedo values; and of those,
2. select the one with the maximum BT4 value.

Obviously, the August #1 'composite image' was not a true composite, and the August #2 image (only two images) used only the second stage of the compositing procedure.

The resulting composites were characterised by reduced cloud effects compared to choosing a reference image on the basis of minimum albedo values alone, although areas of cloud shadow and cloud still occurred in most composites.

Each of the ten 'composites' described above was used in combination with each of the other composites from the previous month to produce 20 fire scar images. Thus reference images were no more than two months earlier than the original image. The 20 fire scars were then processed as in Test 2 to produce a 'count' image. A threshold count of ≥ 2 was selected for production of the final scar map following a preliminary visual assessment.

The results for Test 3 are shown in Table 7 and Figure 15.

Table 7. Test 3 NOAA burnt/unburnt classification findings relative to Landsat TM classification of NOAA pixels. (the pixel counts in brackets in the table are the number of NOAA pixels within each of the Landsat TM classification groups)

Landsat TM classification	Completely unburnt (14,928 pixels)		>0 and ≤20% burnt (2,492 pixels)		>20 and ≤50% burnt (2,240 pixels)		>50% burnt (6,551 pixels)	
NOAA classification	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)
	95.6	4.4	87.3	12.7	78.1	21.9	45.2	54.8

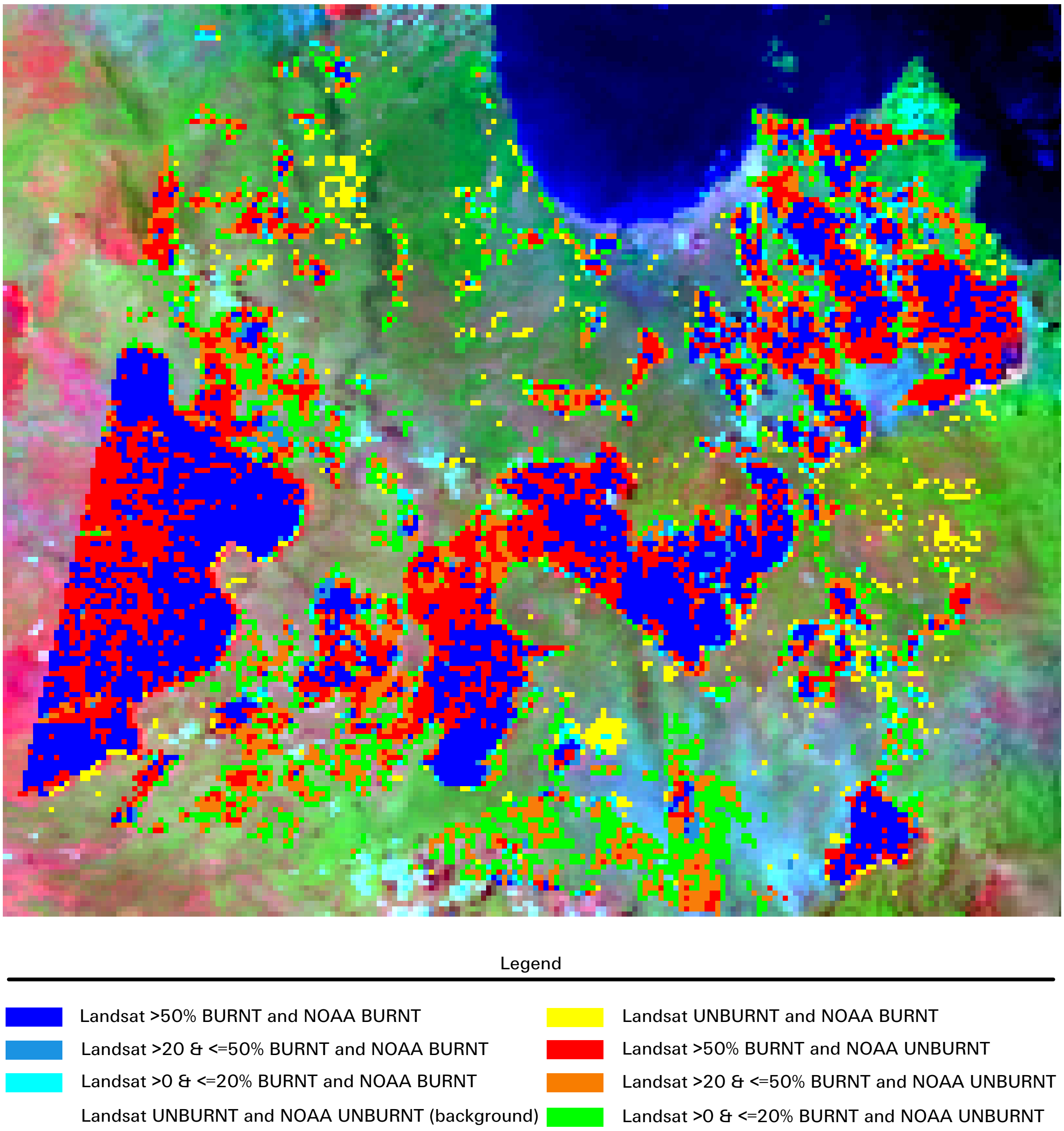

Figure 15. Test 3 spatial results.

4.2.1.4 Test 4: All dates, automatic choice of images and automatic classification

Test 4 was based on the Test 2 method but with an increased level of automation, and thus was considered a prototype method for automated production of fire scar maps on a monthly basis for the entire State.

This test required that the three index layers (VI3T, BT3 and GEMI) were calculated for each NOAA image with areas of missing data, cloud, or high satellite zenith recoded to zero to reduce file size. The FireMD3 algorithm was then applied to all non-zero overlap areas of every image using each previous image within the current month and the previous month as reference images for the period June to October 1999. The resultant preliminary fire scar images were processed on a monthly basis to produce monthly 'count' images.

The count threshold for classifying pixels as burnt or unburnt in each monthly count image was initially determined based on the number of input images and a visual assessment of each count image. From this manual determination a set of rules were produced for the automated production of count thresholds. These rules are currently undergoing further testing:

> If number of input files = 1, then count threshold = 1;
> If number of input files >1 and ≤25, then count threshold = 2;
> If number of input files >25 and ≤40, then count threshold = 3; and
> If number of input files >40, then count threshold = number of input files / 10 (rounded to the nearest integer).

A final fire scar map was produced using the monthly count images and the appropriate count threshold – each pixel with a fire count greater than or equal to the threshold count was classified as burnt.

The results for Test 4 are shown in Table 8 and Figure 16.

Table 8. Test 4 NOAA burnt/unburnt classification findings relative to Landsat TM classification of NOAA pixels. (the pixel counts in brackets in the table are the number of NOAA pixels within each of the Landsat TM classification groups)

Landsat TM classification	Completely unburnt (14,928 pixels)		>0 and ≤20% burnt (2,492 pixels)		>20 and ≤50% burnt (2,240 pixels)		>50% burnt (6,551 pixels)	
NOAA classification	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)
	97.0	3.0	84.5	15.5	69.6	30.4	21.8	78.2

The Test 4 results were very similar to those from Test 2 and thus demonstrate that it is possible to fully automate a fire scar algorithm producing the above classification results.

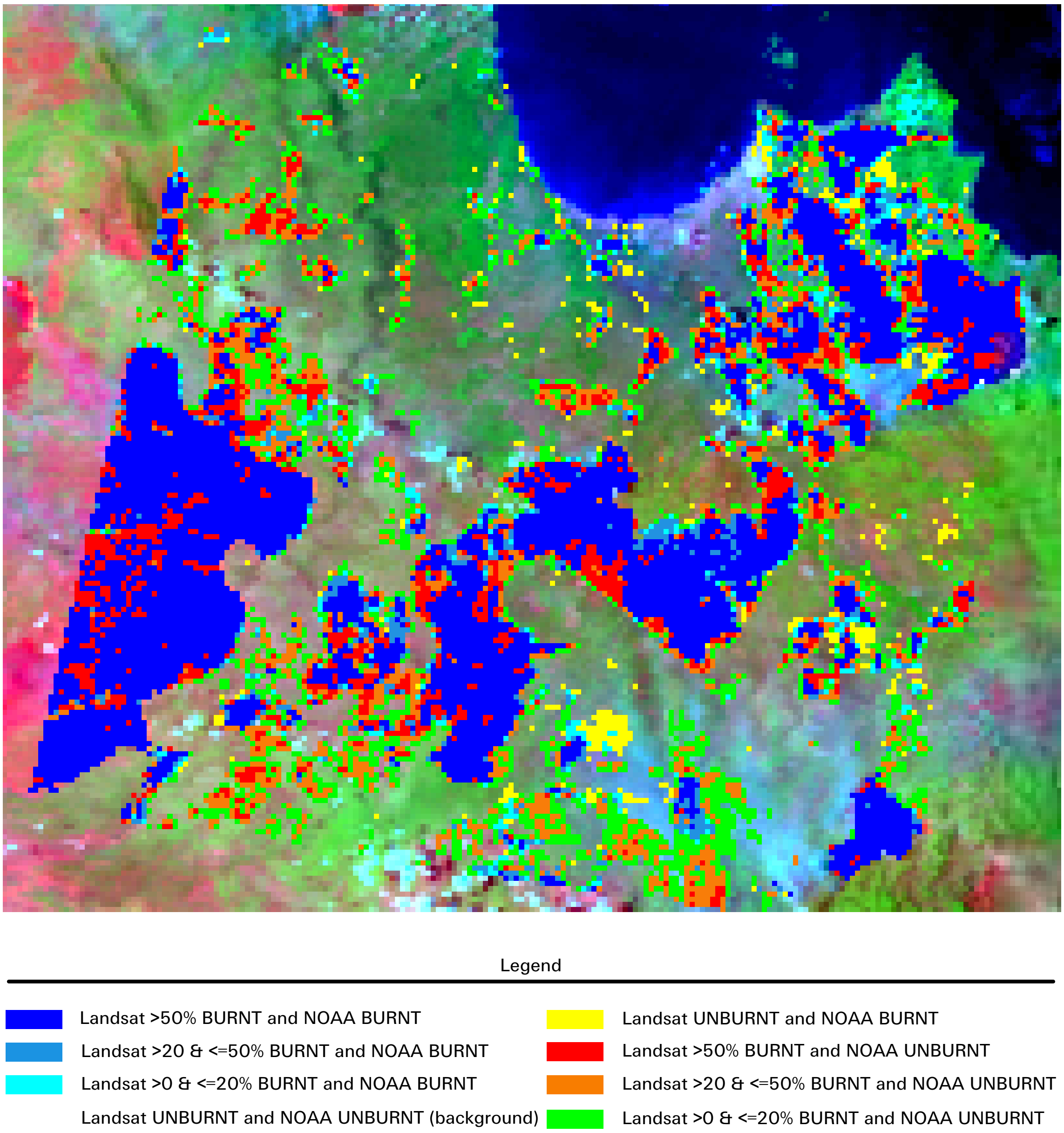

Figure 16. Test 4 spatial results.

4.2.1.5 Test 5: Single date and semi-manual classification.

Test 5 involved an unsupervised classification of bands 5, 8 and 9 from the 15th October 1999 NOAA image followed by manual editing to produce a single date fire scar map comparable to those produced in Test 1. The results for Test 5 are shown in Table 9 and Figure 17.

Table 9. Test 5 NOAA burnt/unburnt classification findings relative to Landsat TM classification of NOAA pixels. (the pixel counts in brackets in the table are the number of NOAA pixels within each of the Landsat TM classification groups)

Landsat TM classification	Completely unburnt (14,928 pixels)		>0 and ≤20% burnt (2,492 pixels)		>20 and ≤50% burnt (2,240 pixels)		>50% burnt (6,551 pixels)	
NOAA classification	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)
	96.0	4.0	85.1	14.9	68.3	31.7	15.4	84.6

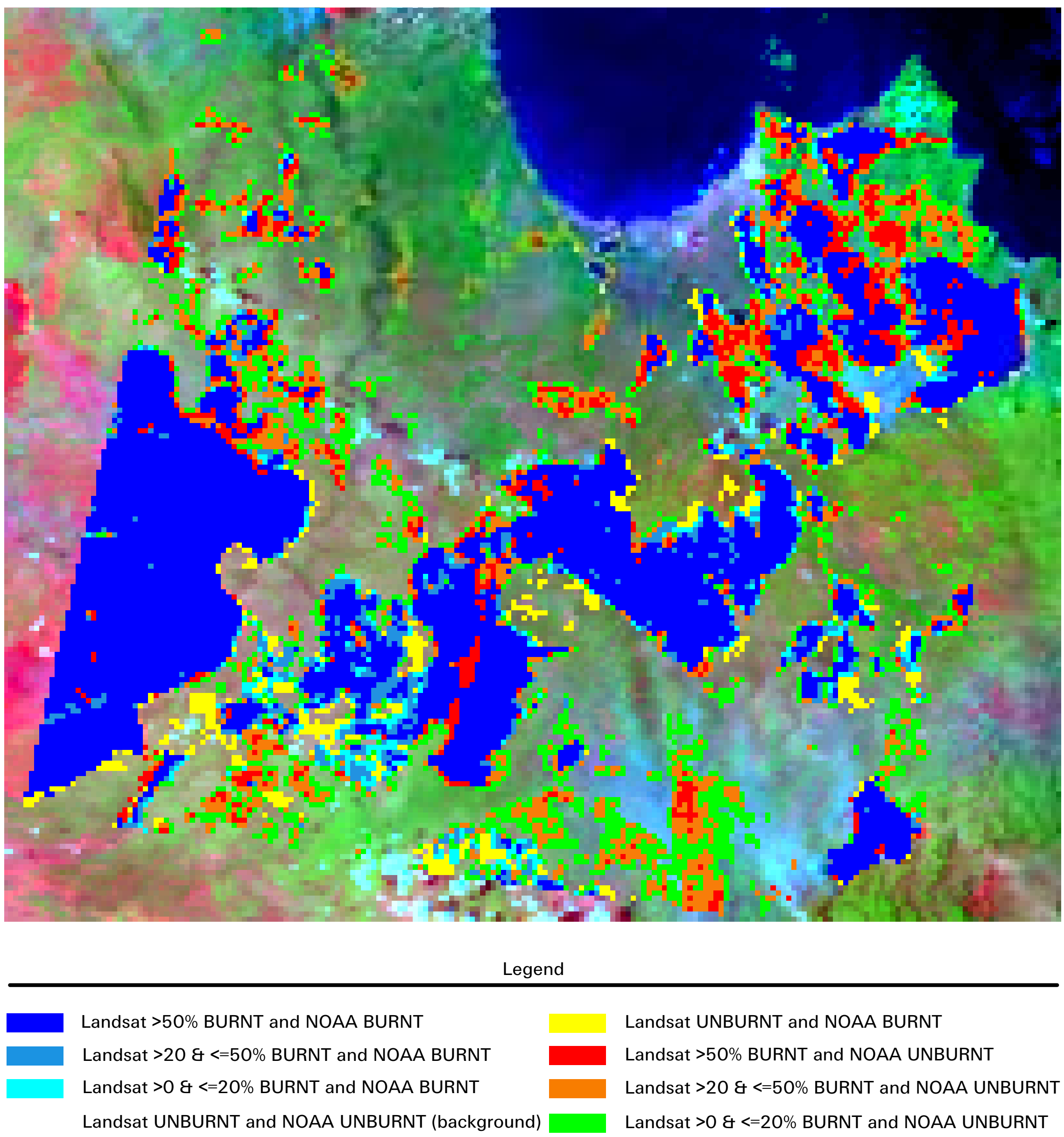

Figure 17. Test 5 spatial results.

4.2.2 Overall results

The combined results for Tests 1 – 5 are shown in Table 10. The distribution of percentage NOAA pixel burnt (according to the number of burnt Landsat TM pixels contributing to one NOAA pixel) and the proportion of these classified as burnt for Tests 1a, 2, 3, 4 and 5 are shown in Figure 18.

Table 10. Results for Tests 1 – 5 for NOAA burnt/unburnt classification relative to Landsat TM classification of NOAA pixels. (the pixel counts in brackets in the table are the number of NOAA pixels within each of the Landsat TM classification groups)

Landsat TM classification		Completely unburnt (14,928 pixels)		>0 and ≤20% burnt (2,492 pixels)		>20 and ≤50% burnt (2,240 pixels)		>50% burnt (6,551 pixels)	
	Test	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)	Unburnt (%)	Burnt (%)
NOAA classification	1a	99.9	0.1	99.2	0.8	98.3	1.7	63.3	36.7
	1b	99.9	0.1	99.2	0.8	97.5	2.5	72.4	27.6
	1c	99.9	0.1	99.3	0.7	98.0	2.0	65.0	35.0
	1d	99.7	0.3	99.2	0.8	96.8	3.2	62.6	37.4
	2	97.1	2.9	86.2	13.8	70.4	29.6	23.8	76.2
	3	95.6	4.4	87.3	12.7	78.1	21.9	45.2	54.8
	4	97.0	3.0	84.5	15.5	69.6	30.4	21.8	78.2
	5	96.0	4.0	85.1	14.9	68.3	31.7	15.4	84.6

5. Discussion

The results have been presented to allow the user to interpret the ‘usefulness’ of NOAA for their specific application. The results for all the NOAA methods (Figure 18) show that a partially burnt NOAA pixel really only started to be detectable as burnt, or fire influenced, when quite a high percentage of the given pixel was burnt. At these higher percentages, however, the results show that NOAA fire scar maps have a high degree of reliability.

The range in results across different classification methods indicate that the reliability of NOAA mapping is very much dependant on the algorithms used for mapping. The algorithms that performed best at the higher percentage end (≥ 50% burnt), the semi-manual classification (Test 5) and the fully automated FireMD3 (Test 4), also appeared more sensitive to the detection of partially burnt pixels.

The results of the NOAA fire scar mapping assessment are generally very promising. The performance of the fully automated FireMD3 algorithm shows comparable results with the semi-manual classification. More development and testing in different regions are necessary before this method could be adopted operationally. It must be recognised that the performance of the FireMD3 algorithm was not tested in an operational sense and results may be significantly different if the algorithm was run on a regular time-step basis, e.g. monthly or quarterly. In such cases only the fires that occurred between time-

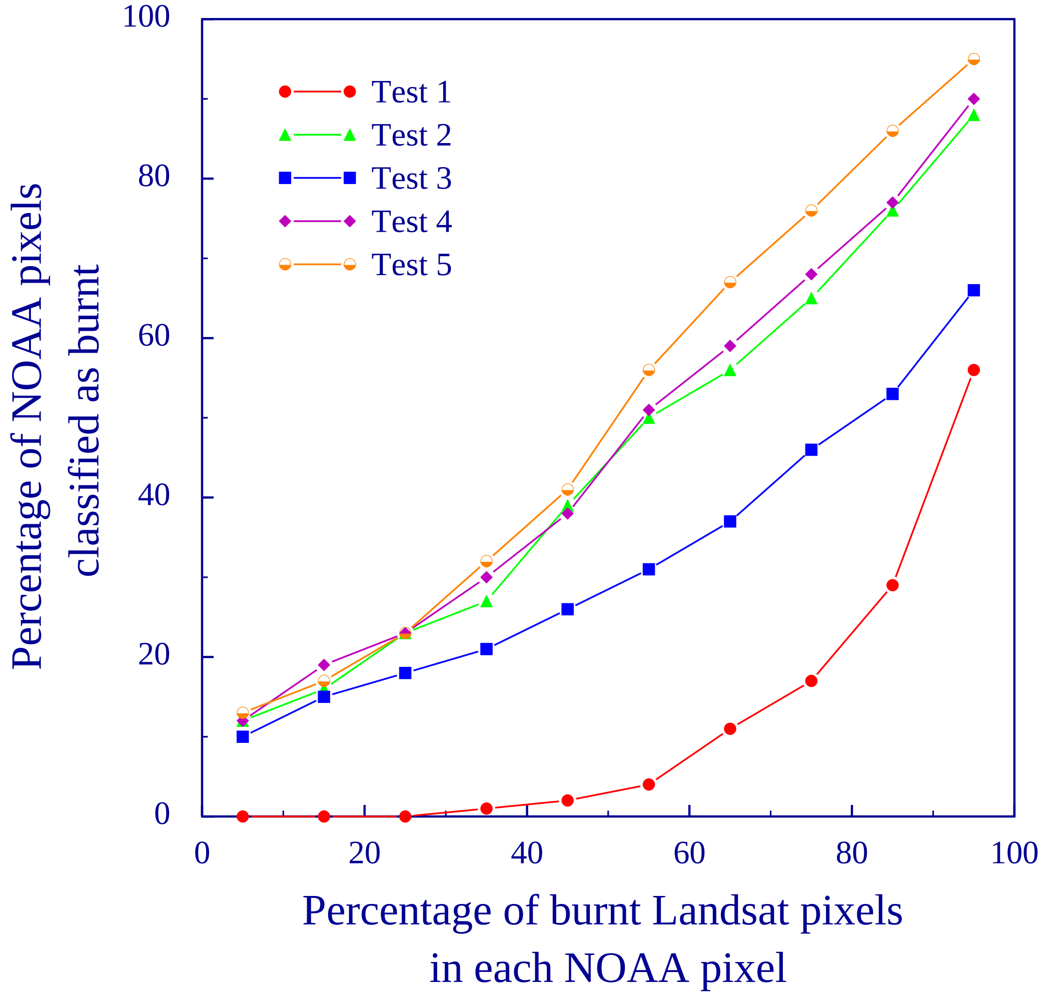

Figure 18. Relationships between the percentage of each NOAA pixel burnt (according to the number of burnt Landsat TM pixels contributing to one NOAA pixel) and the proportion of these classified as burnt using Tests 1a, 2, 3, 4 and 5. The above relationships were plotted by pooling NOAA pixels based on the Landsat TM derived percentage burnt into 10 groups: >0 and ≤10%; >10 and ≤20%; >20 and ≤30%; >30 and ≤40%; >40 and ≤50%; >50 and ≤60%; >60 and ≤70%; >70 and ≤80%; >80 and ≤90%; and >90%.

steps of the algorithm would need to be detected. The FireMD3, as it was run for this analysis, did not have a baseline starting point from which to run a cumulative time-step classification, rather it was run retrospectively over imagery acquired over several months.

It was also difficult to interpret the age of fire scars on the Landsat TM imagery, therefore, all fire scars that were spectrally evident were mapped. However, the retention of fire scars on NOAA and those on Landsat TM are not necessarily comparable, and a more detailed assessment may have been possible with a second Landsat TM scene acquired earlier in the season to use as a baseline, especially for the assessment of fire scar age. The use of several different types of field data of varying precision appears to be a good approach to assessing Landsat TM fire scar maps. However, it is recommended that for similar work in the future the Landsat TM image be acquired immediately before the field trip and a preliminary classification undertaken. This would enable better targeting of areas that represent the variability within the image (and within the classification), as well as variability on the ground. In this study, the ground transects were selected on their degree of patchiness of burn on the ground – from unburnt cover through to 100% burnt. However, the corresponding pixels on the Landsat TM imagery were almost all classified as burnt, therefore few pixels classified as unburnt were sampled.

The Landsat TM classification results, and visual comparison with overlayed field data, indicated that the classification could possibly be improved by stratification for both soil colour and tree basal area. Older fire scars on light soils (Figure 19), where initial ground cover was possibly low were very difficult to interpret on the Landsat TM image, as were areas of densely wooded vegetation.

Figure 19. Older fire scars on lighter soils.

6. Conclusions

The results presented in this report show that NOAA fire scar mapping is very useful but highly dependant on the methods used to produce the fire scar maps. The performance of the automated FireMD3 algorithm shows particular promise for future operational use. However, it was also evident in this analysis (and from other work not presented here) that more rigorous testing in different landscapes is necessary before it can be employed operationally.

We believe that the two stage approach to validation of NOAA fire scar maps provides a good indication of the usefulness of NOAA products and the accuracy at a range of levels. However, further analysis of NOAA fire scar maps needs to be more in line with the type of products that would be produced by an operational system, e.g. monthly fire scar maps.

Future work using both Landsat TM and NOAA fire scar mapping would benefit greatly from stratification by soil colour and vegetation density.

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Appendix 1: Recording sheet for on-ground fire transect data

Site No	Date	Time	Recorder	Car E	Car N	Brg	Dist	Datum	Zone	GPSFile	Start E	Start N	Mid E	Mid N	End E	End N	
TBrg	TDist	Water RO	Termites	Fire Age	Film	Photo	Desc										
Slope	Aspect																

	BURNT		RESPR.	UNBURNT					TBA					SOIL/ROCK				BIOMASS	OTHER
	Ash (Black)	Ash (White)	Vegetation	Vegetation (Attatched)	Grass/Forbs /Leaf Litter	Woody Litter	Bare	Rock	Live	Dead	Killed by Fire	Prism	Scorch Height	S/R	Hue	Value	Chroma	kg/ha	
1																			
2																			
3																			
4																			
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