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This technical project supports the Umbacarla Cultural Land Management Project implemented by traditional land managers Peter Christophersen, Violet Lawson and Sandra McGregor

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Executive summary

This report outlines preliminary findings of vegetation change analyses for Boggy Plain using remote sensing. Results are presented and discussed in two parts: (1) an assessment of contemporary changes based on remotely sensed imagery collected in 2002 and 2003; and (2) an assessment of longer-term change based on interpretation of aerial photography from 1950 and 1991.

Ground surveys showed substantial changes in vegetation-habitat cover as a result of traditional dry season burning of dense *Hymenachne* grassland in late 2002. QuickBird™ satellite imagery provided a high-resolution product suitable for detailed vegetation cover mapping and monitoring to assess the extent and form of these vegetation changes at the scale of the whole floodplain. Image analysis indicated that fire not only reduced the extent and density of *Hymenachne,* thus creating an environment more desirable for hunting, but also produced a more diverse range of vegetation habitats. In contrast to *Hymenachne*, which was reduced by some 40%, *Eleocharis sphacelata* appeared to be resilient to fire, showing no discernible change in its distribution in areas that were burnt.

Longer-term vegetation cover patterns interpreted from aerial photography exhibited a number changes. Of particular note was the increase in number and long-term persistence of Buffalo swim channels.

Acknowledgments

The authors would like to all those who have been involved with the project to date and thank them for making the field work a truly enjoyable and informative experience. In particular the Parks NRM airboat crews, Freddy Hunter and Calvin Murakami, whose patience and expertise genuinely enhanced the quality of the ground-truthing exercise. Thanks also go to Dr Penny Wurm (Cooperative Research Centre for the Sustainable Development of Tropical Savannas, Charles Darwin University) and Dr Peter Jolly (NT Department of Infrastructure, Planning and Environment) for expertise in wetland plants and hydrology respectively, and for giving their valuable time to visit the field locations and reflect upon the research issues at Boggy Plain. All have contributed to improving the general quality of remote-sensing maps and understanding of the ecology of Boggy Plain.

Vegetation change analysis on Boggy Plain, South Alligator River, using remote sensing: Report on preliminary analyses

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1 Introduction

Boggy Plain is a major freshwater wetland located on the South Alligator River Floodplain . It supports many freshwater flood plain vegetation communities typical of Kakadu National Park, and a diversity of wetland fauna. Additionally, Boggy Plain and associated wetlands to the south comprise one of the most important dry season refuges for magpie geese in the Northern Territory. In some years, up to 85% of the total Northern Territory magpie goose population have gathered to feed at Boggy Plain. Boggy Plain is also an important area for Aboriginal people who hunt geese and long-necked turtle, and collect water plants and other floodplain resources. The use and management of this important wetland by Traditional Owners represents many of the natural and cultural values of Kakadu.

The study forms part of a more comprehensive ecological risk assessment of Boggy Plain being undertaken at ***eriss*** in collaboration with Kakadu Aboriginal land managers Peter Christophersen, Violet Lawson and Sandra McGregor and Parks Australia North (PAN). In particular, the project arose out of concerns for the poor condition of natural resources on this wetland by Bininj, for example the decreased assess to hunting resources and a decline in plant and animal diversity because of a dominance of *Hymenachne* monocultures. It is thought that the high density of *Hymenachne* developed as a result of a prolonged spell, of some 10 years, without burning (Christophersen, pers com, 2003); a period also where buffalo were not present. With the plan to burn the *Hymenachne* grasslands an opportunity was presented to assess vegetation change due to fire through the timely capture of remote-sensing (RS) data.

This report presents a proposal and preliminary findings for the use of RS to assess the dynamics and extent of change in vegetation structure on Boggy Plain, South Alligator River. Additionally, this study complements the ***eriss*** ISP landscape assessment of mining impacts on the Magela Catchment by providing a comparison of change in a wetland isolated from potential mining impacts.

Floodplain vegetation responds to various environmental influences such as fire, seasonal hydrology, invasive plants and animals, season and climate. It is unknown how these factors interact and how the physical structure of Boggy Plain influences these interactions. Vegetation change occurs over different temporal and spatial scales, such as the considerable seasonal variation observed from year to year in vegetation composition and structure. In contrast change occurring over longer timeframes may be more subtle. It is therefore important to distinguish between changes due to seasonal influences and other factors such as fire, invasive species and longer-term climatic changes or cycles.

The aims of this study are to use RS in conjunction with ground based survey information to monitor major changes in floodplain vegetation composition and structure at Boggy Plain over different spatial and temporal scales. The main aim of this component of the Boggy Plain project is to assess vegetation change using:

- Historic aerial photography data over the period 1950 to 1991 using traditional interpretation techniques;
- Landsat™ satellite imagery; and
- Acquisition of real-time, high resolution, satellite data (QuickBird™ & HYMAP™) in conjunction with ground based survey information.

More specifically, the degree of vegetation change will be assessed in relation to seasonally dependent cycles and in response to fire regimes or other disturbance factors (eg hydrology, invasive species).

The results of this study will be used to develop cost-effective RS techniques to monitor and assess floodplain vegetation over entire catchments. Spatial models may then be developed to predict change in response to events such as fire, hydrology and invasive species impacts. Such models may provide a decision support framework for resource managers and is considered an important long-term spin-off from this work.

Results are presented and discussed in two parts. Part I provides an initial assessment of the capability of different RS products to discriminate between key wetland vegetation communities on Boggy Plain and the surrounding region (ie *Hymenachne* vs. *Eleocharis*). An assessment of changes in floodplain vegetation observed from September 2002 to May 2003 that may be attributed to the impact of prescribed burning and seasonal cycles is also presented. Part II presents an assessment of longer-term change interpreted from 1:25000 aerial photography from 1950 and 1991. This section also examines regional environmental trends that may have influenced vegetation change in the period 1959–1999 by providing a review of the literature, weather and oceanographic conditions, and land use history.

2 Methods

The methods referred to here relate principally to Part I, contemporary change analysis. For Part II, George Begg used traditional aerial photo interpretation techniques for the assessment of longer-term change and then observed changes were discussed in relation to available historic data.

2.1 Delineation and monitoring of floodplain fire-scars

Fire is a major factor influencing vegetation distribution in the tropics, hence it is necessary to consider how spatial information can be collected on fire frequency and intensity. Fire scars mapping using Landsat™ data is conducted by the Bush Fires Council (BFC) for PAN but is principally undertaken to monitor terrestrial landscapes in Kakadu. Further, Landsat provides only coarse resolution data (30–80 m pixel size) and no ground validation has been specifically undertaken for Boggy Plain. Nevertheless this is the only historic spatial dataset that provides a fire history on Kakadu since 1991, therefore these data will be reviewed for potential use for monitoring the extent and frequency of fires on Boggy Plain.

Methods for fire-scar mapping at Boggy Plain are still in the developmental stage. A preliminary fire-scar survey was undertaken by Rod Kennett (PAN) using aerial GPS surveying in October 2002 to determine the extent of burning prescribed in September 2002. This generalised fire-boundary, showing the overall extent of burning, is illustrated in Figures 4, 6 and 7. A peculiar characteristic of wetland fire regimes is that the same area can be burnt multiple times over the course of the dry season. This is because grasslands on wetlands continue to dry out over the dry season period allowing more fuel to become available, thus providing the potential for the same area to be burnt again. Further monitoring work to determine burn frequency and intensity patterns at established vegetation monitoring transects on the ground in 2002 was undertaken by Peter Christophersen, Violet Lawson and Sandra McGregor. These data will be essential in assessments of fine-scale differences between areas burnt a different number of times.

2.2 Ground data collection

Two vegetation surveys have been undertaken at Boggy Plain, one in the late dry season of 2002 before burning commenced and again (after burning) in the early dry season of 2003, and are used here to calibrate RS captures. The methods used to collect spatially referenced ground-based data are described in Bayliss et al (2003). The intensive acquisition of ground-based data allows an assessment of what vegetation features can be discriminated by different RS products with different spatial and radiometric resolutions. This information will be used in a cost-benefit analysis of the efficacy of different RS products in providing useful information for resource managers.

2.2.1 Image registration and integration of ground-level sampling effort

Six Ground Control Points (GCPs) were established across Boggy Plain to allow precise co-registration of future multi-temporal imagery. The geo-registration of the image to accurate ground control points also facilitates accurate cross-comparison of ground data with subsequent image interpretation, classification and accuracy assessment.

Ground control targets consisted of 2.7 m x 2.7 m sheets constructed of builders sisalation material. The reflective aluminium surface was placed facing upwards at each site and fixed to the ground using tent pegs.

Targets were placed at strategic locations (eg near to monitoring transects) and distributed evenly across Boggy Plain to ensure spatial consistency between imagery and the corresponding ground-truth data. A differential GPS, using an Omnistar™ reference satellite, was used to geo-reference GCPs to sub-meter precision. Geometric correction of the image was then obtained by assigning real coordinates to targets identified on the image.

2.2.2 Surveys of vegetation and bathymetry

Detailed vegetation surveys were undertaken at nine permanently established 200 transect lines. Data were collected at 20 intervals on these transects and methods are described in Bayliss et al (2003). A broader-scale assessment of vegetation communities was undertaken along two east-west orientated ground transects, each of approximately 7 km in length. These were chosen *a priori* from RS captures so that major plant communities were intersected. Using an airboat and GPS, vegetation was described along each transect at either 100 or 200 intervals (depending upon the uniformity of vegetation) and, at boundaries between different vegetation communities. Water depth was measured also at each sample point. A number of known locations were chosen from the satellite image to validate image interpretation, and further depth profile surveys were undertaken to improve the scope of data collected in the initial ground survey. Some depth measurements were taken at the same sites as in the April 2003 survey so that these data can be compared. Depth data were then used to generate a bathymetric map that will be used to explore relationships between vegetation distribution and depth.

2.3 Remote sensing sources

There are a variety of RS products available which provide information covering a range of spatial and temporal scales (and costs). The resolution of imagery (ability to detected specific features) is determined by spatial and spectral resolution, and the spectral range of the sensors used. These properties need to be considered when determining the usefulness of the product for monitoring. This section summarises RS data available for Boggy Plain that can be used to assess change over different temporal and spatial scales.

2.3.1 Aerial photographs (1950 /1991)

Sequential aerial photography is a reliable means of monitoring vegetation change but is also labour intensive. A record of historical vertical aerial photographs captured for Boggy Plain is provided in Appendix 1. Traditional aerial photography interpretation techniques were used to assess vegetation change of the Boggy Plain area. This initial assessment was based on a visual interpretation of 1:50 000 black and white photos taken in 1950, and 1:25 000 colour photos taken in 1991. Both sets of photographs were available and were also the earliest and latest aerial photographs.

2.3.2 HYMAP™ hyperspectral image (20th September 2002)

This image was collected opportunistically and provides an image of Boggy Plain in the late dry season of 2002, before burning occurred. Spatial resolution of the image is at 4.5 m pixel size and hyperspectral coverage is provided over the solar wavelengths (0.4–0.5 µm) using 124 spectral bands. Only a preliminary analysis of this image has been provided in this report using visual interpretation of a true-colour composite image. Geo-rectification still needs to be undertaken on data.

2.3.3 Landsat TM™ imagery

Full technical information on the Landsat program can be viewed at http://www.ga.gov.au/acres/prod_ser/landdata.htm and a summary of this has been provided in Appendix 2. Data are of a coarse spatial resolution (30 m to 80 m pixels for MS bands, depending on sensor), but provide a much wider affordable coverage than higher resolution products, so may be useful for cost-effective detection of broader-scale regional change.

The data set immediately available at ***eriss*** is that acquired by the NT Bushfire Council (BFC) annually between 1991 to 2002 (Appendix 2). Individual scenes have not been assessed for suitability. For example BFC data do not necessarily contain all band layers, some scenes do not cover Boggy Plain at all whilst others may be affected by anomalies such as cloud cover. In order to measure both inter-annual and intra-annual changes, it is suggested that data also be selected using consistent quality criteria.

A preliminary interpretation of a Landsat image of Boggy Plain captured in October 2002 was undertaken using unsupervised classification and principal components analysis.

2.3.4 QuickBird™ Imagery

The high-resolution RS product that has been chosen for ongoing monitoring is QuickBird™ Satellite imagery (multispectral/ panchromatic bundle). The initial scene for Boggy Plain was captured on 5th May 2003. It is proposed that the same area will be captured again at a similar time of year in 2005. The area purchased (87 km^2) on the first occasion constitutes only a portion of the full scene captured (225 km^2), which extends north from Boggy Plain (thumbnail JPEG image shown in Appendix 3.). The full scene has been archived by Digital Globe and will be available at a discounted rate.

The standard map-registered product that has been obtained was checked against dGPS locations taken for ground control targets in the field. All targets were identified on the image within 1 or 2-pixels (4 m) of dGPS points indicating that registration of the standard QuickBird™ product was very good. Ground control will be used in conjunction with a digital elevation model produced from 1:25 000 aerial ortho-photos to ortho-rectify image to sub-meter precision.

A comprehensive description of the specifications of these data is provided in the 'QuickBird Imagery Products: Product Guide' that can be downloaded from http://www.digitalglobe.com/products/standard.shtml.

2.4 Imagery analysis and interpretation

The following preliminary maps were derived from 2002 and 2003 imagery provided by HYMAP, Landsat, and QuickBird™ data:

- True Colour Composite images (HYMAP and QuickBird™);
- Unsupervised classification of the floodplain area (Landsat only);
- Calculation of the Normalised Difference Vegetation Index (Landsat only);
- Supervised classification (QuickBird™ only).

Interpretation and analysis of images was undertaken using available 'ground-truth' data collected between September 2002 and July 2003. Peter Bayliss took hand-held video coverage of Boggy Plain from a helicopter in September 2002 as an additional validation source.

A Normalised Difference Vegetation Index (NDVI) image was produced from the Landsat image. The NDVI is a useful index because it enhances diagnostic differences between green vegetation and senescent vegetation or bare ground (Campbell 1996), and also highlighted areas of open water on Boggy Plain

Using the 'region of interest' tool on ENVI™, the floodplain boundary was manually digitised and then used as a mask to create two independent files: one containing floodplain vegetation only and one containing terrestrial vegetation only. This separated the discrete spectral variances associated with both landscape types, thus allowing more accurate classification.

2.5 Change analysis

A pixel for pixel change analysis was undertaken by overlaying two co-registered class maps (time 1 + time 2) to produce a third image delineating areas of no change from areas where a change is observed. The type of change can then be quantified for each map classes depending on the class overlay combinations that are produced.

The basic assumption of digital change detection is that a difference exists in the spectral response of a pixel on two dates if the biophysical materials at the location have changed between dates. However, given the large seasonal change in spectral reflectance properties that are often observed for particular vegetation types, it is often necessary to first interpret and then classify the image based on this knowledge (and information on the seasonal spectral variation for key plant types if available), and produce standardised map classes before change detection is undertaken.

An initial assessment of change in response to fire was undertaken by mapping vegetation cover for area illustrated in Figure 4. Vegetation class maps were produced from the pre-burn (HYMAP) image and the post-burn (QuickBird) image and the fire-scar boundary was overlaid on both pre- and post-burn maps. Percentage cover for each vegetation type was then calculated for both the 'burnt' and 'unburnt' portions of the 'before' and 'after' images. In essence the 'unburnt' area of the test site acted as a control for assessing the impact of fire (Figures 7 & 8).

2.6 Quality control

After a land cover class map is produced for a particular time, a subset of random points is then selected for each map class to be revisited in the field as near to the time the image was captured in order to validate classification accuracy. This process is an integral part of the validation procedure once classification strategies are formalised.

3 Preliminary results

Results are presented in two sections. The first outlines results from contemporary data (2002 to 2003), while the second section outlines results from the preliminary assessment of longer-term changes based on aerial photo interpretation and an overview of the literature.

3.1 Part I: Contemporary changes

Results are presented in chronological order to help differentiate vegetation change from fire and seasonal effects (Table 1).

Table 1 Summary of image capture dates for different sensors (pan= panchromatic; MS= Multispectral)

Image	Pre-/post-fire	Season	Acquisition date	Resolution (m)
HYMAP	Pre-Fire	Late dry season	20/09/02	4.5
Landsat	Post-Fire	Late dry season	10/02	30
QuickBird	Post- Fire (after one wet season)	Early dry season	03/05/03	0.65 (pan) 2.44 (MS)

3.1.1 Late Dry Season 'Pre-burn' HYMAP image (20th September 2002)

The Hymap image (Figure 2) was captured before burning occurred where the area east of the fire boundary line was burnt. This area consisted of large homogeneous stands of *Hymenachne* grassland (extensive uniformly green areas with little texture). A large region of turbid open water coloured grey/yellow is also shown. Within this region there appears to be a gradient of change where the grey colouration becomes darker further east. This open water region is associated with *Eleocharis dulcis*, which emerges over the wet season to form dense cover. By the late dry season senescent *Eleocharis* has decomposed to leave turbid open water. Smaller areas of deep open water are show as dark regions.

3.1.2 Late Dry Season 'Post-burn' Landsat image (October 2002)

Landsat imagery clearly separated areas of 'open-water' from vegetated areas (Figure 3). The large area of open water populated by *Eleocharis* earlier in the year is evident, and is similarly demonstrated in the pre-burn HYMAP image. However, relative to the pre-burn image, open water regions have increased in areas that were burnt.

NDVIs (or greenness indices) indicate that vegetation is actively growing in recently burnt areas (Figure 3). An area of dense *Hymenachne* that did not burn (adjoining the lower south eastern boundary of the large open water area) has the highest NDVI.

Unsupervised classification of the Landsat TM image showed that there is potential to classify wetland vegetation types on Boggy Plain and other wetlands in the Alligator Rivers Region (Figure 1). The area of senescent *Eleocharis*/turbid open water (see Section 3.1.1) is associated with the blue and purple coloured classes. The mud flats, tidal areas and salt-tolerant vegetation associated with this zone appear to classify into several discrete classes. Further ground-truthing is needed to validate cover types for these image classes, nevertheless a preliminary interpretation is provided.

3.1.3 Early Dry Season 'Post-burn' QuickBird image (5th May 2003)

Major vegetation communities on Boggy Plain could be discriminated using QuickBird™ imagery. Each community type is described below with respect to its potential to be mapped by QuickBird in order to monitor and assess the effects of fire.

Hymenachne Grassland

Dense *Hymenachne* grassland (Plate 1) was typical of many areas that had not experienced fire for some ten years (Christophersen, pers com). QuickBird satellite imagery clearly resolved this grassland (Figures 4–6), which consisted of a mixture of actively growing vegetation and a build-up of dead grass. The grassland provided the main fuel source for floodplain burning. Results from the fire-scar mapping indicated that fire modified *Hymenachne* monocultures and replaced them with a more diverse range of community types. *Hymenachne* was still present in these areas but its cover was greatly reduced. Dense stands of *Hymenachne* may be a indicator that areas has not been burnt for a substantial period, and these areas often had encroaching stands of *Melaleuca* saplings, perhaps indicating successional change in the absence of fire.

Plate1 Dense *Hymenachne acutigluma* grassland, with encroaching *Melaleuca* saplings. UTM map-grid reference East 230332, North 8611187 (WGS84, zone 53). July 2003

Oryza spp *grassland*

The annual, *Oryza meridionalis* or Wild Rice (Plate 2) was clearly resolved by QuickBird satellite imagery (Figure 6). In general most of the *Oryza* observed at the time of ground-truthing (3 weeks before imagery was captured) had seeded and was in a senescent phase. This may have accounted for the high reflectance signature observed on QuickBird imagery for *Oryza*. It is difficult to assess the influence of fire on *Oryza* distribution due to lack of seasonal data. Nevertheless, *Oryza* was observed to occur in areas where *Hymenachne* density had been reduced by fire in the previous year. However, it remains uncertain where rice density has increased or decreased. The largest stand of *Oryza* occurred in the shallower water region of the Plain to the west, which remained unburnt the previous year. *Oryza* also occurred in relatively high densities at some of the monitoring sites that were dominated by *Hymenachne* before burning the previous year.

Red Lotus Lilies (Nelumbo nucifera)

Red Lotus Lilies (Plate 3) were clearly resolved by QuickBird satellite imagery (Figures 5–6) and occurred in densities generally ranging from 50-100%. They were found at the fringes of several small areas that had relatively deep water. Three sub-classes of this community could be distinguished: 1) *Nelumbo* with an ‘open water’ understorey; 2) *Nelumbo* with an understorey of low density *Hymenachne* (10–30%); and *Nelumbo* with an understorey of low density *E. dulcis* (10-30%). Gradients between these types are apparent on the satellite imagery but have not yet been classified as separate map classes. *Nelumbo* may have colonised large areas of floodplain previously inhabited by dense *Hymenachne* before burning. This increase was not apparent in areas of *Hymenachne* that were unburnt.

Plate 2 Flowering *Oryza meridionalis* grassland (Wild Rice) in foreground, with senescent *Aeschynomene* spp. visible in the background. UTM map-grid reference 235042 east, 8607380 north (WGS84, zone 53). April 2003

Plate 3 *Nelumbo nucifera* (Red Lotus Lilies) is a dominant plant community at Boggy Plain in the early dry season

Eleocharis

Eleocharis dulcis could be resolved by QuickBird satellite imagery but appeared to form two spectrally distinct groups dependent on growth-form: 1) That inhabiting deeper water in unburnt areas, characterised by dense cover and thicker stems (>4 mm) and a vertical growth-form; and 2) that inhabiting shallower water in areas that had been burnt in 2002, characterised by a dense cover of thin stems (<4 mm) often lying horizontal to the surface. The latter form expanded into areas that were dominated by *Hymenachne* previously.

Eleocharis sphacelata could also be distinguished from the more common *E. dulcis* using QuickBird imagery. *E. sphacelata* occurred in fairly discreet patches with smaller patches (<50 m) forming a characteristic circular shape (Plate 4). There appears to be little change in the extent *E. sphacelata* in areas that had been exposed to fire. *E. sundaica* has a near identical growth form to *E. sphacelata* and so was not possible to distinguish. However, it was much rarer (found only one small patch across all surveys).

Plate 4 The boundary between the deep water form of *Eleocharis dulcis* (left) and *E. sphacelata* (right) could be clearly distinguished by QuickBird imagery. UTM map-grid reference 230711 east, 8607659 north (WGS84, zone 53). July 2003.

Open water and Nymphaea/ Nymphoides Lily species

Nymphaea and *Nymphoides* Lily species could be defined as a single map class by QuickBird imagery (Plate 5) and were generally associated with fringes of open water that were also differentiated. Both ‘open water’ and ‘other lilies’ increased in extent as a result of fire. Areas of ‘open water’ often had the high densities of submergent macrophytes (*Najas* spp., *Utricularia* spp., and *Hydrilla venticillata*), which were also present in other plant communities but in far lower densities. Open water areas sometimes tended to be deeper relative to areas covered by emergent vegetation.

Plate 5 Areas of open water and fringing water lilies (*Nymphaea* spp.) resolved by QuickBird imagery

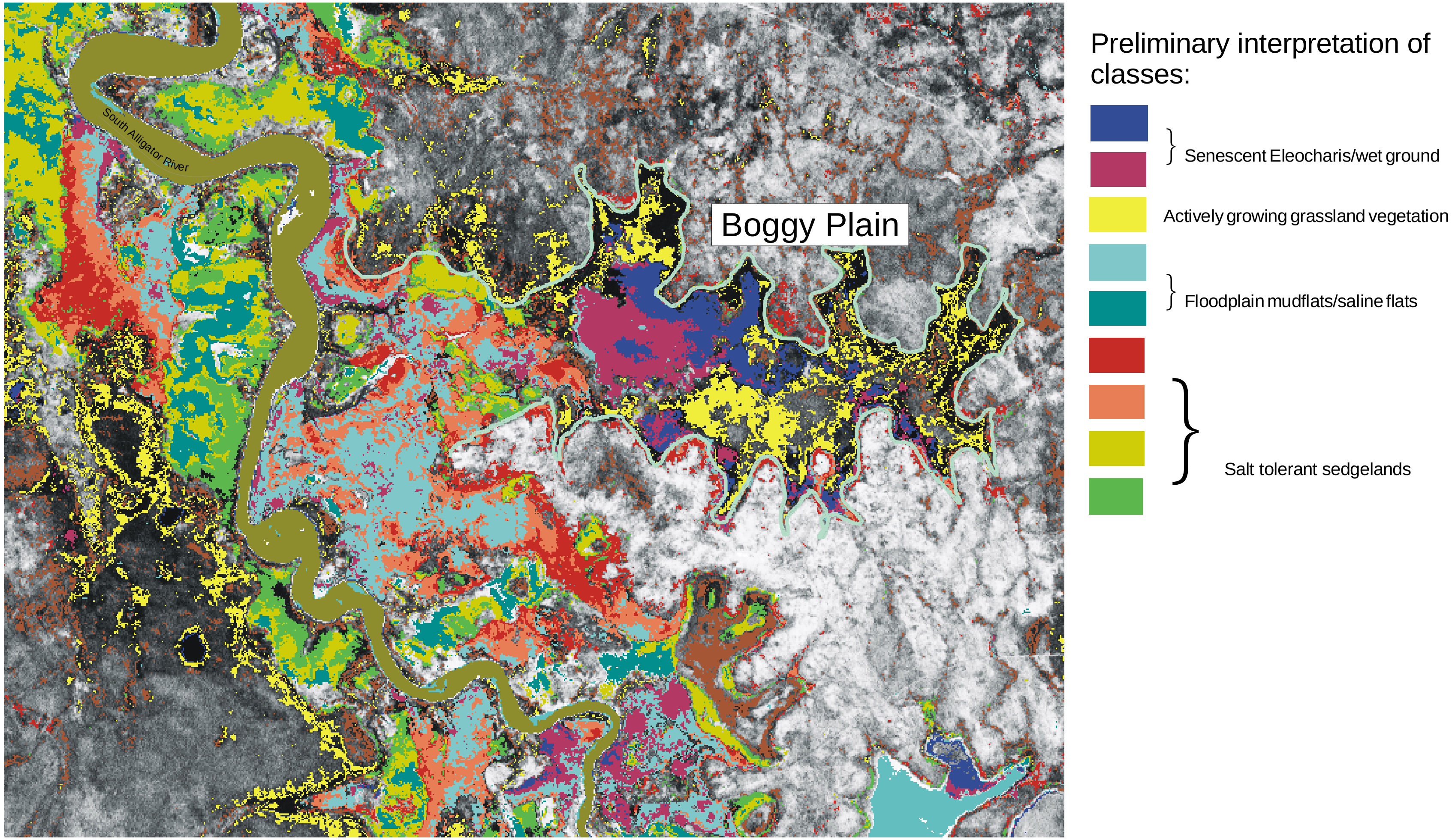


Figure 1 Overlay of map classes associated with different wetland vegetation/habitat types of the Boggy Plain-Noulangie region (South Alligator River), derived from Lands at image captured in October 2002

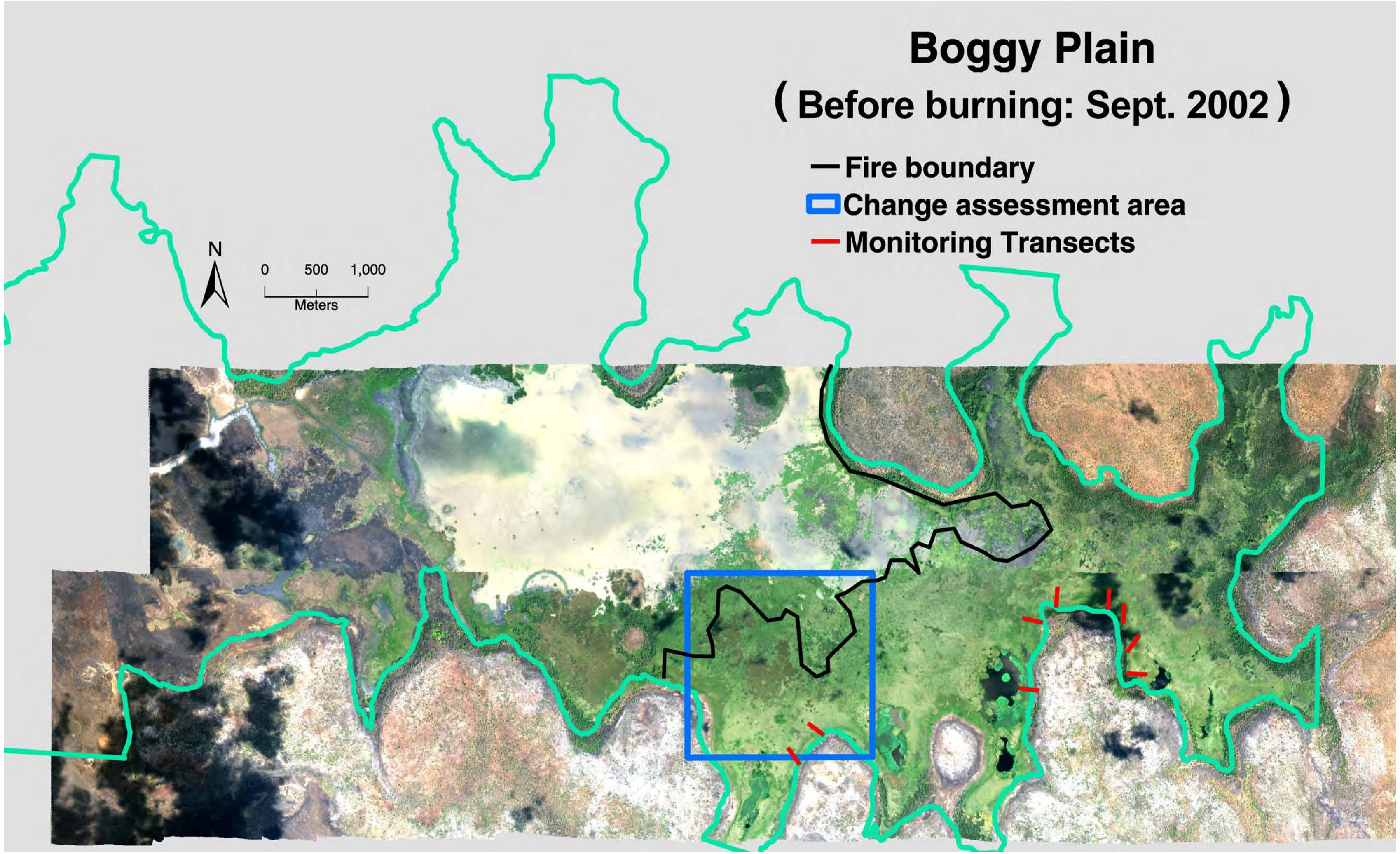


Figure 2 Pre-burn image of Boggy Plain captured in the late dry season (20th September 2002) using HYMAP. Change due to fire was determined for the area bounded in blue (see Figures 7 & 8). Red lines indicate position of vegetation monitoring transects.

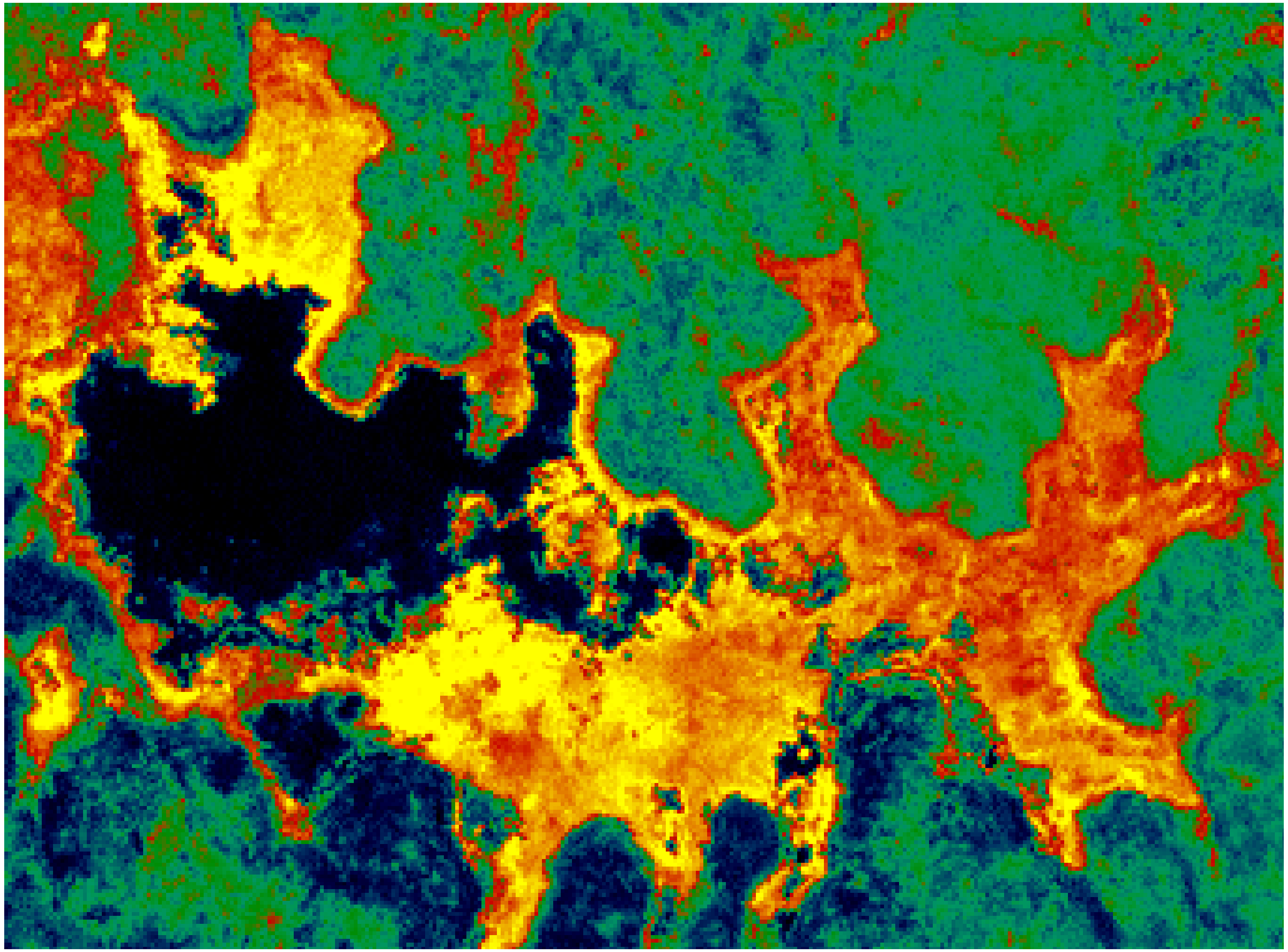


Figure 3 NDVI (greenness index) map produced from post-burn Landsat image (October 2002). Regions of no green (living) vegetation are in black and on the floodplain these areas are associated with open water; little green vegetation = green areas; moderate levels of green vegetation = red/orange areas; and high levels of green vegetation = yellow. Image is north orientated

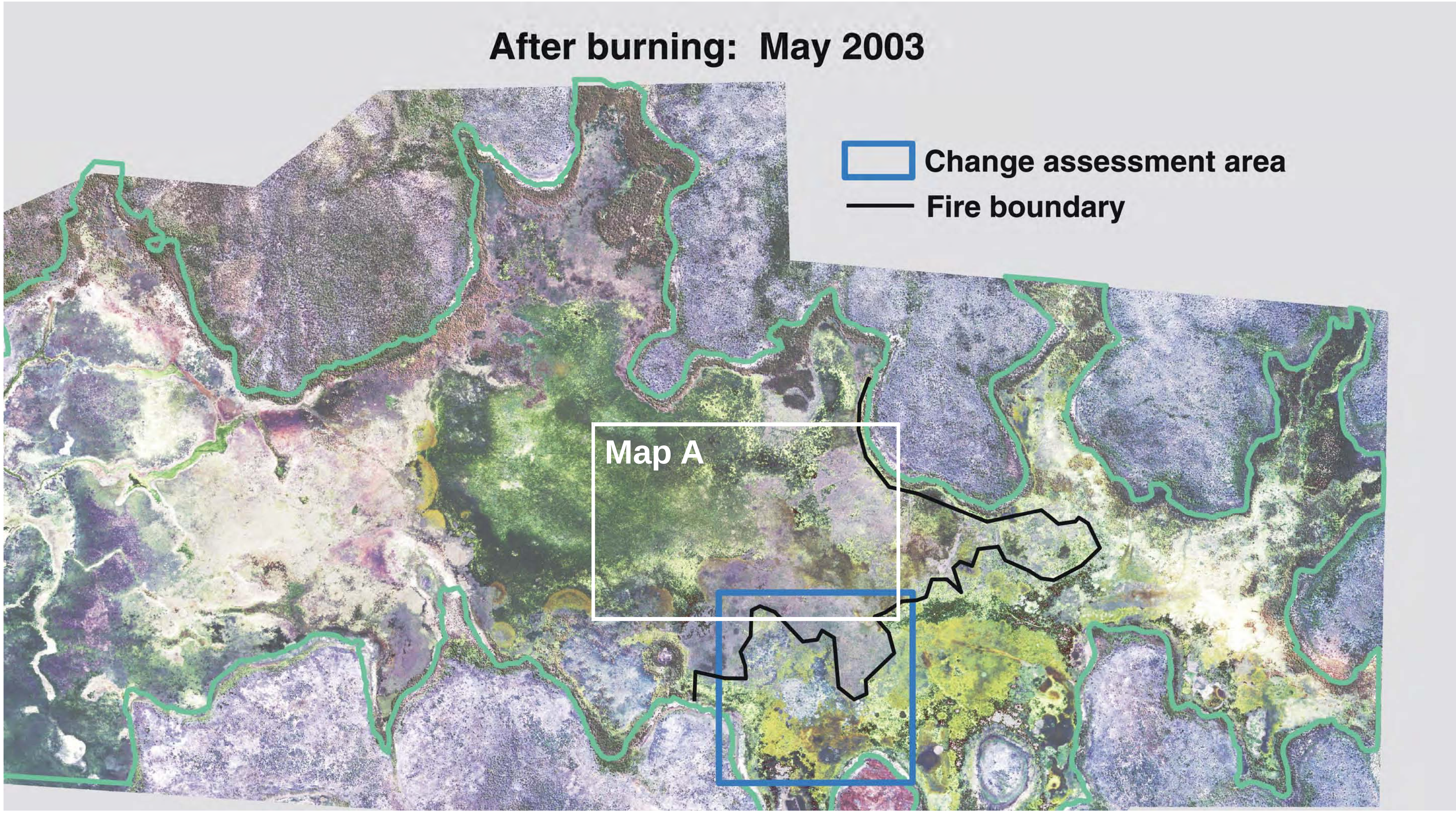


Figure 4 Post-burn QuickBird satellite image of Boggy Plain captured on the 5th of May 2003. Detail from inset Map 'A' illustrated in Figure 5. Change due to fire was determined for the area bounded in blue (see Figures 7 & 8).

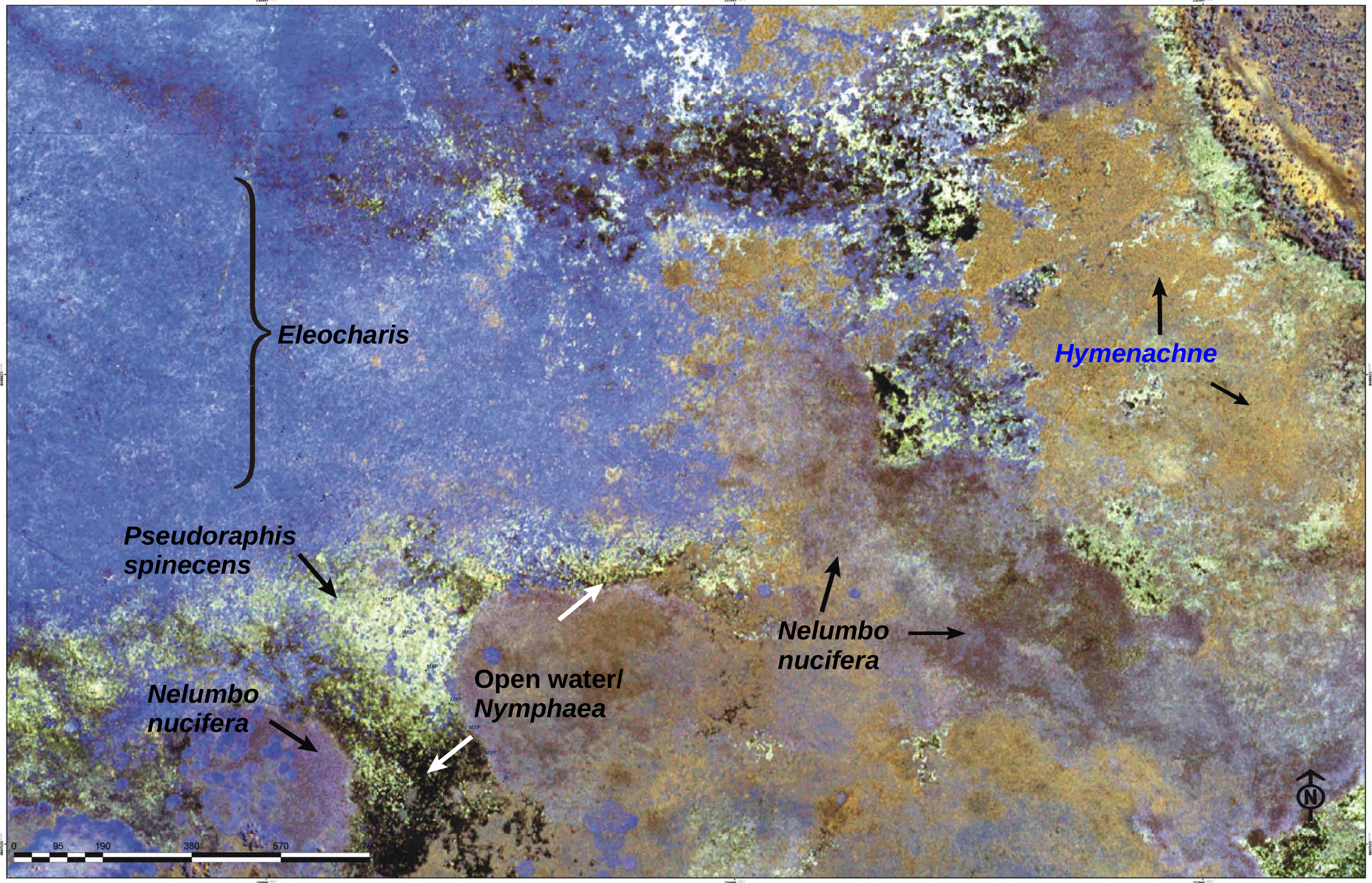


Figure 5 Detail from inset **map 'A'** (Figure 4) showing *Eleocharis dulcis*, *Hymenachne acutigluma*, *Nelumbo nucifera*, *Nymphaea* lilies, and *Pseudoraphis spinecens*. False-colour composite of red, green and Near-infrared bands.

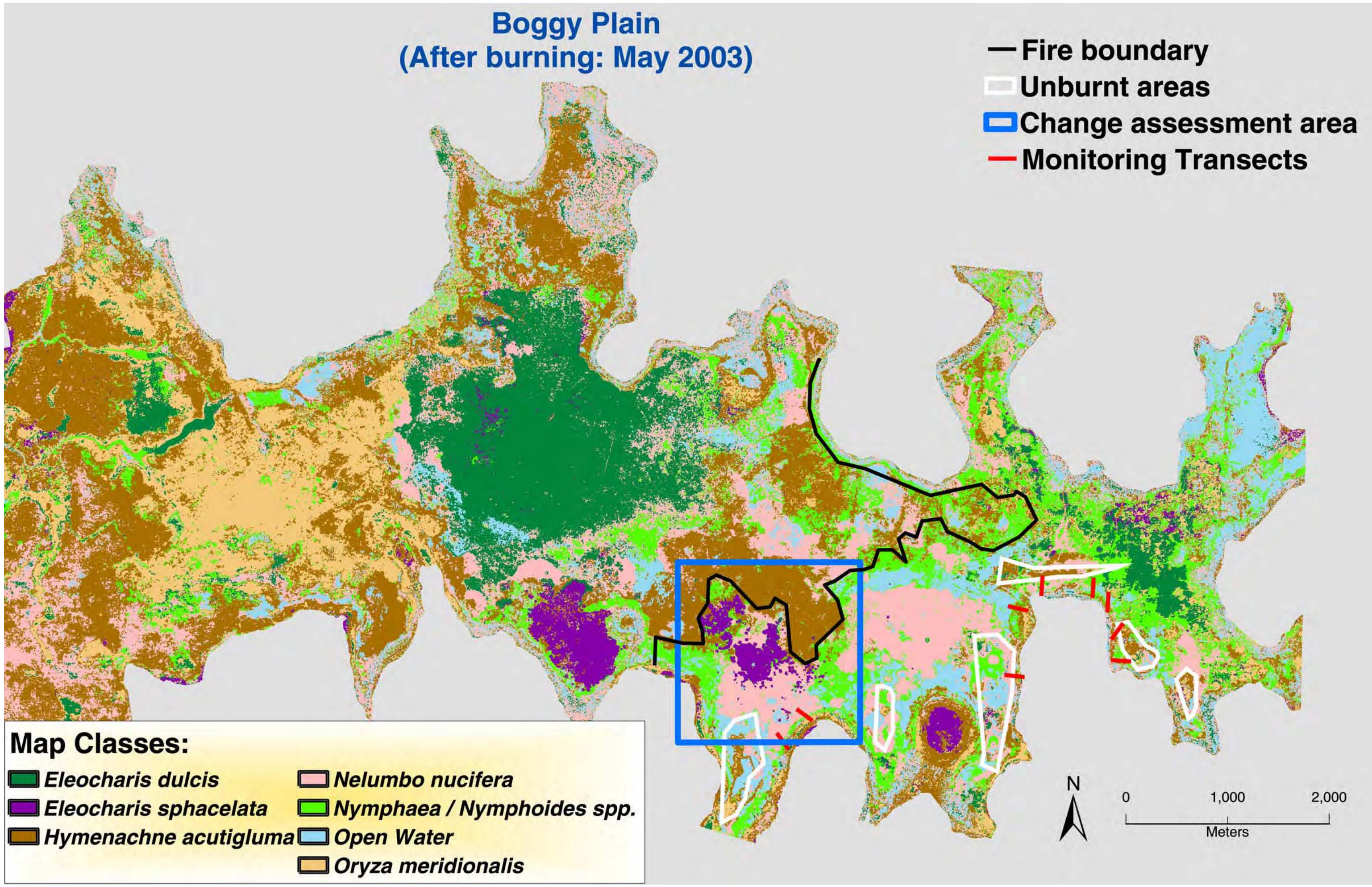


Figure 6 Post-burn vegetation-habitat map for 5th May 2003 generated using supervised classification approach with the Maximum Likelihood classifier algorithm on ENVI™. Note that trees were omitted from classification and as such have been misclassified. Areas to the far west (including *Fimbristylus* sedgeland and *Ischaemum australe* grassland) were also omitted from classification.

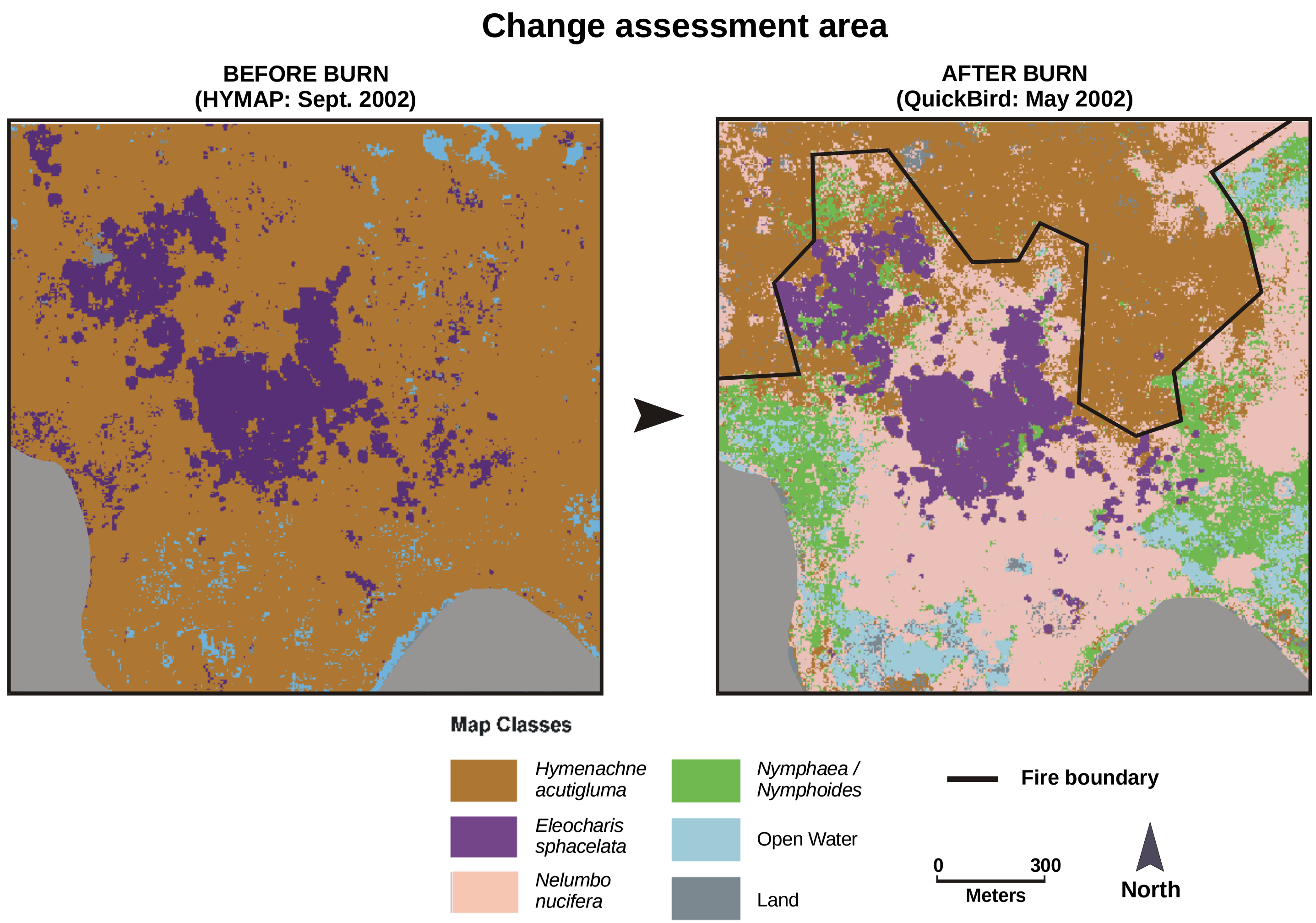


Figure 7 Vegetation cover observed before (Sept 2002) and after fire (May 2003) from the change assessment area (Figures 2 & 4). The burnt region lies south of the fire boundary line (black). The percentage change in different cover classes was compared for both the burnt and unburnt area in this diagram and results are presented in **Figure 8**.

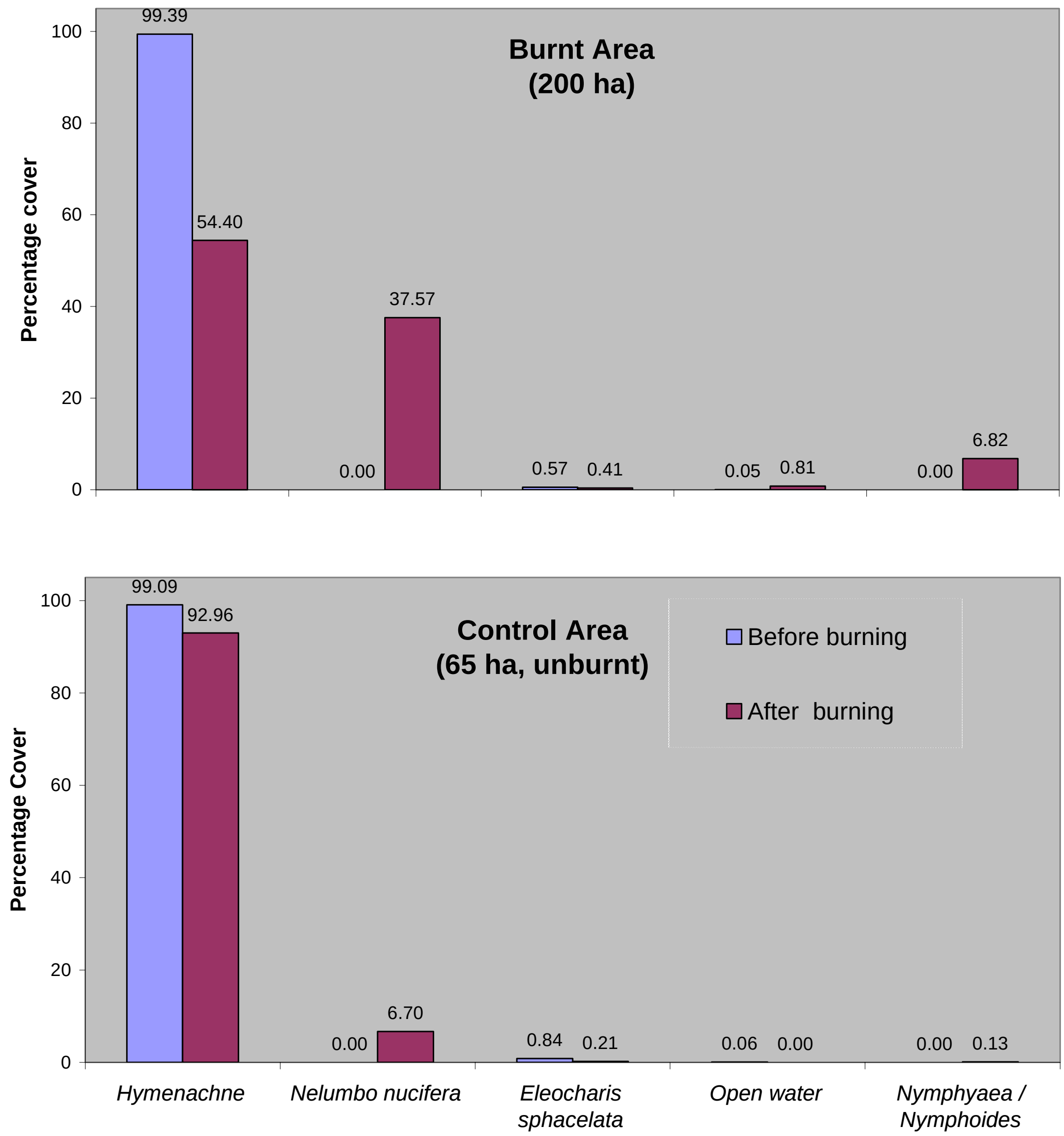


Figure 8 Vegetation cover compared between burnt and adjacent unburnt areas, at September 2002 (before burning) and at May 2003 (after burning) calculated for the area illustrated in Figures 2 & 4. Vegetation cover characteristics of the burnt area (200 ha), before and after burning are indicated on the top graph, while the bottom graph shows percentage cover observed in the *unburnt* 'control' region (65 ha) at the same times.

3.2 Part II Results: assessment of long-term change using aerial photography (1950 & 1991)

This section of the report was written by George Begg.

3.2.1 Overview of past research

Cobb 1988 and Cobb et al 2000

Using historical aerial photos from the years 1950, 1975, 1984 & 1991, Stephanie Cobb's main focus was tidal creek / mangrove expansion as evidence for saltwater intrusion in the South Alligator estuary. Field sites at Munmarlary (6 km downstream of Boggy Plain) and Kapalga creek (6 km upstream of Boggy Plain) were given special attention. She found that over the period 1950–1975 there was significant growth / expansion in the extent of the tidal creek network along the South Alligator estuary. Growth of the tidal creek network was particularly evident within the confines of pre-existing palaeochannels / palaeomeanders and the most rapid period of mangrove growth was post-1985.

Wurm 1998

Penny Wurm's study of wild rice (*Oryza meridionalis*) on Boggy Plain was undertaken between December 1992 and May 1994. It was an autecological study, which investigated the attributes of the life cycle of Oryza that determine and regulate its distribution and abundance. A 'fate of seed' approach was adopted (ie particular emphasis was given to the weight of seeds produced, seed loss, seed predation, soil seed banks, seed counts, seed longevity, influence of inundation and population modelling).

3.2.2 Geomorphological influences

From a geomorphological point of view Boggy Plain, which is approximately 64 km^2 in size, may comprise two distinct units that appear to be separated by a fault line (or possibly a sub-surface sill). This feature runs in a NW-SE direction through the Plain, approximately 5 km east of the South Alligator estuary (Figure 10). To the west of this feature, which appears to act as a natural divide, the Plain is influenced by the flood-flows and tidal-flows associated with the lower reaches of the South Alligator river system. Lying adjacent to the South Alligator estuary, the soils of the western unit are salinised.

To the east of the fault line the Plain comprises a freshwater-influenced, self-contained basin supplied by water from several unnamed tributaries draining a 420 km^2 watershed. According to Wurm (1998) the pH of the dark cracking clays (vertisols) on Boggy Plain is as low as 3.5 in the dry season, more typically 4.5, and neutral in the wet season when fully inundated. There are a large number of small depressions (old buffalo wallows?) scattered throughout the Plain as well as several, fairly large (10–20 ha), low-lying depressions that in periods of above average rainfall can retain water throughout the year. However, under normal circumstances most of the waterholes dry out towards the end of each Dry. The two most conspicuous of these waterholes, named Nembargoo and Coolaboo, lie on the southern margins of Boggy Plain (Figure 10).

3.2.3 Meteorological influences / interannual variation in rainfall

Over the period 1966–1997 there were two distinct rainfall periods in Kakadu (Figure 9). The years 1974–1985 were characterised by above average rainfall whereas the years 1986–1996 were characterised by below average rainfall. The rainfall records from Kapalga confirm this situation in that the 1992/93/94 wet season rainfall was approx. 125–400 mm below average (Wurm 2001).

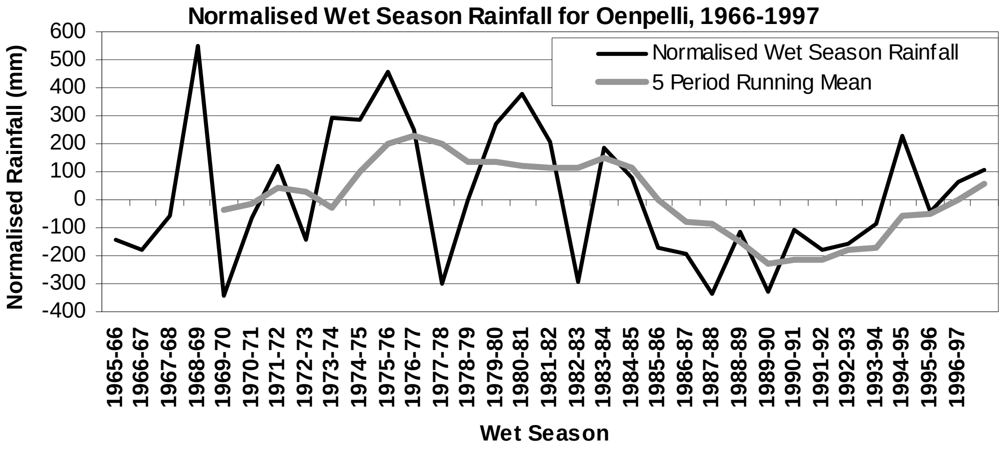


Figure 9 Normalised wet season rainfall for Oenpelli, 1966–1997 (from Winn 2001)

3.2.4 Oceanographic processes in the Van Diemen Gulf

The general lack of data on the oceanographic processes operative in the Van Diemen Gulf (eg tides, sea level variation and water circulation) means that surrogate datasets for Darwin have to be used (Eliot et al 2000). Nevertheless, the large (7 m) tidal range in Van Diemen Gulf is known to induce strong bi-directional currents along the South Alligator estuary with velocities capable of channel scouring (Cobb 1988). It is also suspected that in the wet season cyclone-induced storm surges in the Gulf can give rise to the extension / expansion of tidal creeks alongside the South Alligator estuary.

As a result of large scale El Nino events in 1962, 1976 and 1999 sea-water levels for Darwin were unusually high, some 12–15 cm above average. It is probable that similar conditions occurred in the Van Diemen Gulf, noting that periods when water levels remain below the norm can also occur and extend for periods as long as six years. The period 1990 to 1996 serves as a case in point.

The main tidal / mangrove creeks present in the western, saline-influenced, component of Boggy Plain lie within a number of ancient, low-lying, palaeochannel formations on the eastern flank of the South Alligator estuary. With the exception of the southernmost of these palaeochannels, where some noticeable expansion occurred, the tidal creeks of Boggy Plain have shown little change over the period 1950 to 1991. This is probably a result of the relatively straight (non-sinuous) nature of estuary channel opposite Boggy Plain and the resulting reduction of the incising processes normally associated with tidal scour. Although there is little evidence of saltwater intrusion invading the freshwater basin, it is worth noting that in 1992 a cyclonic event of similar intensity to cyclone ‘Tracy’ occurred (Winn 2001). Under these circumstances it is possible that tidal creeks in the palaeochannels of the South Alligator underwent another period of extension and expansion. However, the lack of any post-1991 aerial photographs makes this difficult to prove.

3.2.5 Hydrological influences

There is no information about the hydrological characteristics of the creeks that supply Boggy Plain. However, judging from the size of the larger creeks and the response of the vegetation at the outflow points of the streams in question (ie the proliferation of closed *Melaleuca* forest), the main water sources (springs?) appear to lie north east of the Plain. Floodwater discharges from the South Alligator river (estimated to be in the order of 400–700 m^3/s) are also important as these are not only likely to spread eastwards from the South Alligator into Boggy Plain, but also impede the outflow of locally derived run-off.

Water depths were recorded manually by Wurm (1998) during site visits to Boggy Plain. The maximum depth recorded in February 1994 was 70 cm. Otherwise many areas of the Plain can dry out completely during the dry season.

3.2.6 Influence of feral buffalo

Water buffalo were first introduced to northern Australia in the 1820s (Stocker 1970, Roberts 1996). By 1981 the total buffalo population in northern Australia was estimated to exceed 280 000. Exactly when, or how many, water buffalo became established in Boggy Plain is unknown but the presence of what appear to be 'swim-channels' suggests that water buffalo were present long before 1950. Along with the rest of the buffalo in Kakadu that were removed under the BTEC (Brucellosis and Tuberculosis Eradication Campaign) scheme, the Boggy Plain population was eradicated in the late 1980s. Between 1979 and 1987 a total of 50 000 buffalo are said to have been removed from Stages 1 and 2 of Kakadu National Park (Spiers 2000). Due to the higher than average rainfall in the 1970s (Figure 9) it may have been possible that the water buffalo population peaked in 1975/76.

Aerial photographs confirm that several of the 'swim channels' that are evident today date back to pre-1950. Having been used repeatedly for 30–40 years some of the larger, more heavily-tracked channels became sufficiently incised during this time to have altered both the surface hydrology and the vegetation. Over the period 1950–1990 the cumulative length of 'swim channels' in Boggy Plain increased threefold from 11.2 km to 31.5 km (Table 2).

Table 2 Abundance and extent of water buffalo 'swim channels' in Boggy Plain, 1950–1991

	1950	1991
Number of 'swim channels'	14	61
Total length (km)	11.2	31.5

Some people consider that the net result of eradicating water buffalo was an increase in plant (graminoid and cyperaceous) biomass, changes in floodplain fuel load and availability, and an inevitable change in the pattern/incidence of floodplain burning (Corbett 1988, Roberts 1996, Wurm 1998). Such an increase in plant biomass would have included native *Hymenachne*, which until then was not common and may have been suppressed by grazing.

3.2.7 Influence of fire

Neither the 1950 nor the 1991 aerial photos reveal much about the influence of fire on Boggy Plain. Nevertheless, fire-scars on the southern margin of Boggy Plain are evident in the 1991 aerial photos. However, the effect of this particular fire was very localised and confined largely to the fringes of the wetland on the periphery of the system near the Coolaboo waterhole.

Wurm (1998) reports that during the dry season of 1992 an unplanned fire burnt the Boggy Plain study sites, leaving the soil surface bare until the onset of the 1993 Wet. The standing crop of *Pseudoraphis* did not completely recover during the ensuing two years of the study, but *Oryza* seedlings continued to emerge.

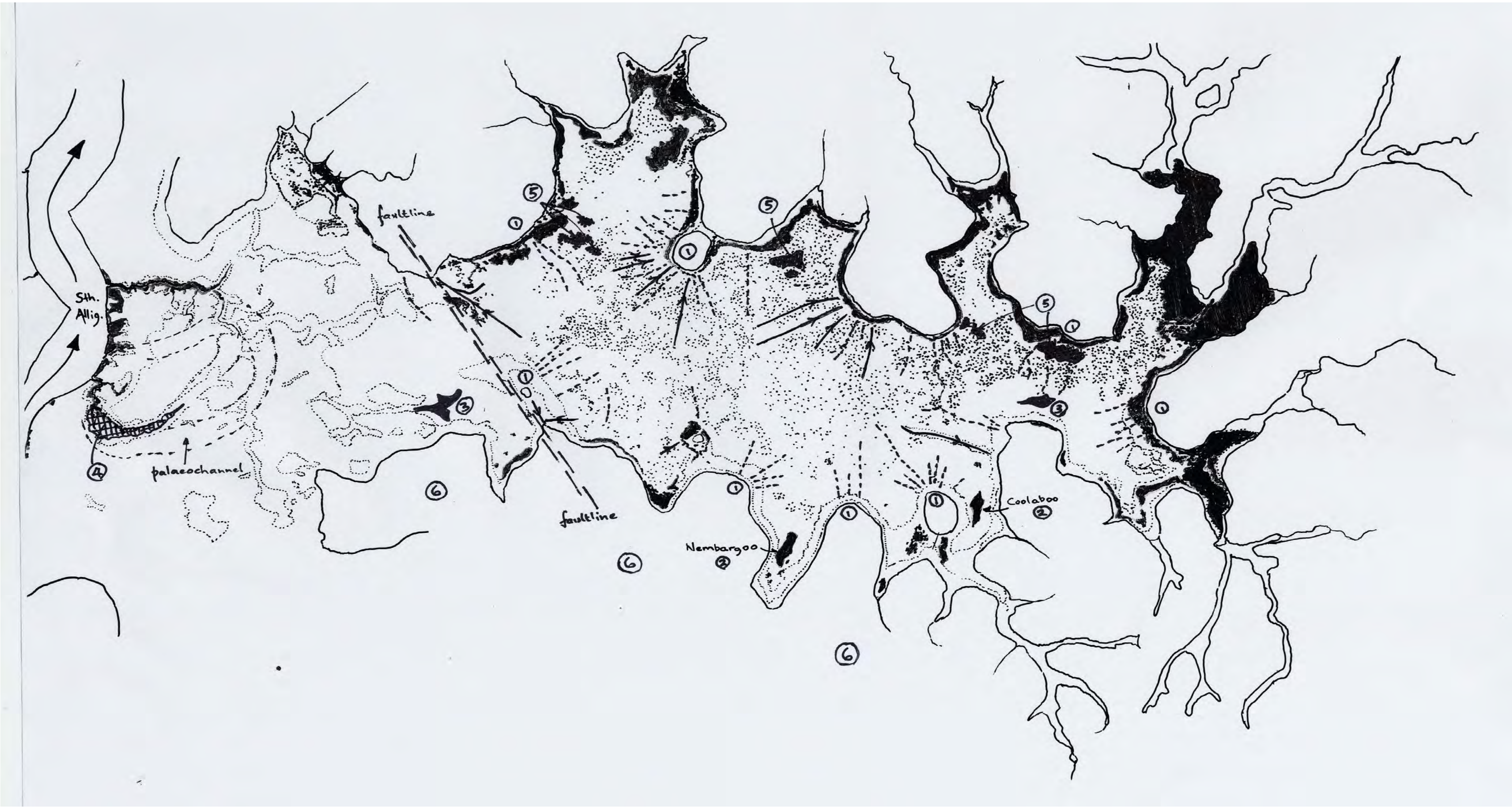


Figure 10 A sketch map of Boggy Plain (not to scale) showing the principle changes evident from a comparison of the 1950 / 1991 aerial photos. (See conclusions for explanation of numbers 1–6; ⟶ = swim channels in 1950; - - - - swim channels in 1991; dotted area - *Eleocharis dulcis* distribution in 1950)

3.2.8 Vegetation distribution

Other than in the case of *Eleocharis dulcis* (water chestnut) the distribution of the major vegetation types on Boggy Plain does not seem to have changed significantly over the period 1950–1991. In 1950 *Eleocharis* was widespread, but patchily distributed throughout the Plain. By 1991, large monospecific stands of the plant were confined to the northern margins, but since then, *Eleocharis* has become dominant at the western end of the freshwater basin (J Boyden, pers. obs.). However, seasonal differences in the extent of *Eleocharis* may confound any interpretation of longer-term change given as aerial photographs were taken in different months, and this possibility is currently being investigated. The amount of *Melaleuca* woodland also increased slightly along the northern margin of the Plain over the period 1950–1991.

As expected, mangroves spread landwards along the tidal creeks and gutters on the edge the South Alligator estuary, but the most noticeable zone of mangrove encroachment over the 40-year period was in the southernmost palaeochannel of Boggy Plain.

3.2.9 Land use

Although buffalo hunters had occupied Munmarlary since the late 1940s (Spiers 2000) the Munmarlary lease for 1010 km^2 for the exploitation of feral buffalo meat was issued only in 1969 (Christian 1973). Whether or not the lease incorporated Boggy Plain is uncertain. However, in 1978 the Federal Government resumed the Munmarlary pastoral lease and Kakadu National Park (Stage 2), which included Boggy Plain, was proclaimed in 1984 (Environment Australia 1999).

There is little evidence that usage of the area for cattle had any noticeable impact on the condition of Boggy Plain, although the near treeless condition of the Nembargoo peninsula in 1950 is noteworthy. Land clearing to promote grazing is a possible cause for the low tree numbers, but this remains unsubstantiated. There is evidence of land scraping (using mechanical plant?) in 1991 at the end of the Coolaboo peninsula.

4 Conclusions

QuickBird™ imagery discriminated between major vegetation communities observed on Boggy Plain in the early dry season 2002.This enabled a map of suitable accuracy to be produced using image classification and traditional interpretation techniques. The imagery is of high resolution (2.7 m pixel) and proved to be geometrically precise, therefore providing a product suitable for detecting fine-scale spatial changes in vegetation community structure over time.

Of the map classes produced, the *Nelumbo* map class presented the greatest range of variation in plant community structure. This variation was associated with distinct spatial gradients observed on the original image that related to the degree of understorey of 'open water', *Eleocharis* or *Hymenachne*. Further classification of the '*Nelumbo*' class could probably produce sub-classes related to these differences.

A number of relatively minor plant communities were omitted from the preliminary classification of QuickBird imagery (Figure 6) as they contributed to misclassification: *Melaleuca* woodland, *Fimbristylis* sedge-land, *Cyperus* spp. and *Actinoscirpus grossus* and *Ischaemum australe* grassland. These communities generally had spatially distinct distributions, and can be visually interpreted from original images. In future they will be independently mapped.

A comparative analysis between QuickBird™ and Landsat™ data still needs to be undertaken to assess suitability of Landsat data for detecting seasonal changes in vegetation. Preliminary analysis shows that Landsat imagery differentiated areas of open water and actively growing vegetation. The large area of open water central to the Plain that was revealed by the late dry season image may be used as a surrogate to indicate *E. dulcis* distribution in this area. However, this may depend on the consistency of observed patterns of *Eleocharis* distribution in the early dry season.

A distinct east-west gradient of change in plant communities, that is likely to be associated with environmental gradients related to hydrology and salinity, is also apparent over the full extent of Boggy Plain. These changes are illustrated in Table 3.

Table 3 Major plant community zones (east, central, west, and far west) observed on Boggy Plain along the east-west axis

Zone	Dominant community types	Impacted by fire (2002)	Relative depth range
East	*Hymenachne* grassland (dominant pre-fire) *Nelumbo* swamp (expanded post-fire) *Eleocharis dulcis* swamp (expanded post-fire) Cyperus/Actinoscerpus swamp Open water/ Nymphaea swamp (expanded post-burn)	Yes	Shallow to very deep
Central	*Eleocharis dulcis* swampland	No	Deep
West	Oryza Grassland	No	Shallow
Far West	Mangroves along out-flowing channels Areas of ‘salt-tolerant’ sedge-land abounding mangrove channels *Ischaemum australe* grassland	No	Very shallow

A number of detectable changes in vegetation composition, distribution and structure occurred between September of 2002 and May of 2003. These changes can be attributed to both seasonal cycles and the impact of floodplain burning in the previous dry season as discussed below.

4.1 Vegetation distribution in relation to season

An assessment of the influence of seasonality on vegetation distribution is incomplete. Nevertheless, a number of seasonal changes in vegetation patterns were detectable. The most obvious change was the re-emergence of dense *Eleocharis dulcis* in the large region of turbid water observed in the late dry season, indicating that this plant remains dormant until the wet season when it again begins its growth cycle. This is the largest area of *E. dulcis* and is a major nesting area for magpie geese. Given that *E. dulcis* consistently colonises this particular region, it may be possible to use this ‘open water’ trait as a surrogate to map *E. dulcis* distribution using Landsat satellite imagery. Flowering annual Wild Rice (*Oryza* spp.), which is absent in the late dry season, was also mapped effectively from early dry season QuickBird imagery.

4.2 Vegetation distribution in relation to recent fire

Vegetation change analysis using RS images suggests strongly that the extent and density of *Hymenachne* grassland was greatly reduced as a result of fire and produced a more diverse and less dense vegetation cover (an environment more favourable for hunting). A major question that can be addressed by monitoring is how long a period does it take for dense *Hymenachne* monocultures to return after a fire event (assuming this grass can be viewed as a climax species in the absence of fire).

In summary dense *Hymenachne* grassland dominated the eastern half of Boggy Plain in 2002 after a long period of some ten years without fire (Christophersen pers com 2003). The grassland provided most of the fuel for prescribed burning in the late September 2002, allowing a large portion of the Plain to be burnt. This region changed to a more heterogeneous vegetation structure. In order of descending magnitude, several vegetation communities expanded their range into the burnt region: 1) *Nelumbo* dominated areas, 2) Open water and *Nymphaea* lilies; 3) mixed *Eleocharis*/*Oryza* grassland; and 4) *Oryza* (Wild Rice).

Hymenachne remained present in the burnt region, but at far lower density. With respect to *Oryza*, it is unclear whether this change is due to fire or seasonal changes, as this grass is an annual and was not growing when initial vegetation surveys were undertaken in September 2002. Remaining areas of dense *Hymenachne* on the Plain all corresponded to unburnt regions, providing evidence that the decrease in cover observed in burnt areas can be attributed to fire and not simply a seasonal change.

Change due to fire was quantified for a 200 ha area (Figures 7 & 8), where it was found that *Hymenachne* cover was reduced by 40%, relative to unburnt areas where *Hymenachne* cover was reduced by only 5% (presumably by seasonal effects). Interestingly the distribution and extent of *Eleocharis sphacelata* remained relatively unchanged after being exposed to fire.

Calculation of the NDVI (greenness index) from the post-burn Landsat image (October 2002) indicate that vegetation was actively growing in recently burnt areas of the Plain (Figure 3) only weeks after the Plain had been burnt. The density and array of plant species germinating or regrowing from rootstock is presently unknown due to lack of quantitative data. However, burn surveys undertaken at the 200 m permanent transect lines noted regrowth of *Hymenachne* from rootstock (in areas only burnt once), as well as growth of Wild Rice, *Aeschynomene* spp., herbs and vines.

Of the several remaining unburnt regions of dense *Hymenachne*, two of these regions (those adjoining the lower south eastern boundary of the Plain) are associated with deeper water areas, which may have prevented them from being burnt. A large area of *Hymenachne* adjoining the far northern shores of Boggy Plain and not associated with deeper water also remained unburnt, suggesting this area was not burnt because of other factors. For example, this region was isolated from fires started in the main body of *Hymenachne* to the east because of a large region of open water with decaying *Eleocharis*. These unburnt regions also had the highest NDVI values. Extreme NDVI values can indicate areas of high biomass of actively growing vegetation with low amounts of senescent vegetation. This would also reduce burning potential, as such vegetation is generally less flammable. Alternatively, the higher NDVI values observed in the October 2002 Landsat image may simply indicate higher biomass relative to unburnt areas. It will be necessary to calculate NDVI for Landsat imagery taken immediately before burning to validate which hypothesis is correct.

4.3 Assessment of long-term changes

The most obvious changes, annotated 1–6 in Figure 11, include:

1 A three-fold increase in the extent of water buffalo ‘swim channels’ from 1950 to 1991;

2 The desiccated condition of the Coolaboo and Nembargoo waterholes in 1991 This almost certainly is a result of the wet season rainfall having been below normal for the previous four years;

3 The presence of water (in 1991) in two depressions which, in 1950 were scarcely detectable. One at the eastern end of the freshwater basin (centrally positioned), the other 1.5 km west of the fault line. Both are a possible result of wallowing by water buffalo and subsequent deepening of the depressions, but why they remained flooded when Coolaboo and Nembargoo were dry (see point 2) requires explanation;

4 The landward expansion of mangroves in the southernmost palaeochannel;

5 The expansion of woody vegetation (mainly paperbarks?) on the northern margin of the freshwater basin; and

6 A marked increase (by 1991) in tree density (eucalypt woodland) on the Nembargoo peninsula.

Bibliography

Bayliss P, Boyden JM, Kennett R, Christophersen P, Lawson V & McGregor S 2003. Internal report 429, Supervising Scientist for the Alligator Rivers Region, Darwin. Unpublished paper.

Breen C 1999. Change : a strategic leadership issue for river management. In Proceedings of Integrated Management of River Ecosystems Conference, 10–11 August 1999, Kruger National Park, South Africa.

Campbell JB 1996. *Introduction to Remote Sensing*. Guilford Press.

Christian CS 1973. *A review report of the Alligator Rivers Region Environmental Fact Finding Study*: Department of the Northern Territory, Darwin.

Cobb SM 1998. Channel extension and the geomorphology of tidal creeks in Kakadu National Park, Northern Territory. Internal report 280, Supervising Scientist, Canberra. Unpublished paper.

Cobb SM, Saynor MJ, Eliot I & Hall R 2000. Saltwater intrusion in the Alligator Rivers Region, northern Australia. In *Assessment and monitoring of coastal change in the Alligator Rivers Region, northern Australia*. eds Eliot I, Saynor M, Eliot M & Finlayson CM, Supervising Scientist Report 157, Supervising Scientist, Darwin.

Corbett LK 1988. Fluctuations in yearly numbers of Magpie Goose (*Anseranus semipalmata*) nests at Kapalga in Kakadu National Park with emphasis on the effects of feral buffalo and rainfall.

Eliot I, Saynor M, Eliot M & Finlayson CM 2000. *Assessment and monitoring of coastal change in the Alligator Rivers Region, northern Australia*. Supervising Scientist Report 157, Supervising Scientist, Darwin.

Environment Australia 1999. Kakadu National Park Tour Operators Handbook. 1–85.

Roberts SJ 1996. Fire on the Gapalg (floodplain): contemporary Aboriginal and other burning patterns in KNP, Northern Australia. In *Fire in the Wetlands: a management perspective*. Proceedings of the Tall Timbers Conference, No 19, eds Cerulean SI & Engstrom RT, Tall Timbers Research Station, Tallahassee, Florida.

Stocker GC 1970. The effects of water buffaloes on paperbark forest in the Northern Territory. *Australian Forest Research* 5, 29–34.

Spiers AG 2000. History of land use and resultant environmental change in the Alligator Rivers Region. In *Assessment and monitoring of coastal change in the Alligator Rivers Region, northern Australia*. eds Eliot I, Saynor M, Eliot M & Finlayson CM, Supervising Scientist Report 157, Supervising Scientist, Darwin.

Winn KO 2001. Saltwater intrusion and morphological change at Point Farewell, Alligator Rivers Region. Internal Report 387, Supervising Scientist, Darwin. Unpublished paper.

Wurm PAS 1998. The population ecology of *Oryza meridionalis* Ng on the South Alligator floodplain, Kakadu National Park, monsoonal Australia Darwin. PhD thesis, University of Northern Territory, Darwin NT.

http://www.ga.gov.au/acres/prod_ser/landdata.htm

http://www.digitalglobe.com/products/standard.shtml.

Appendices

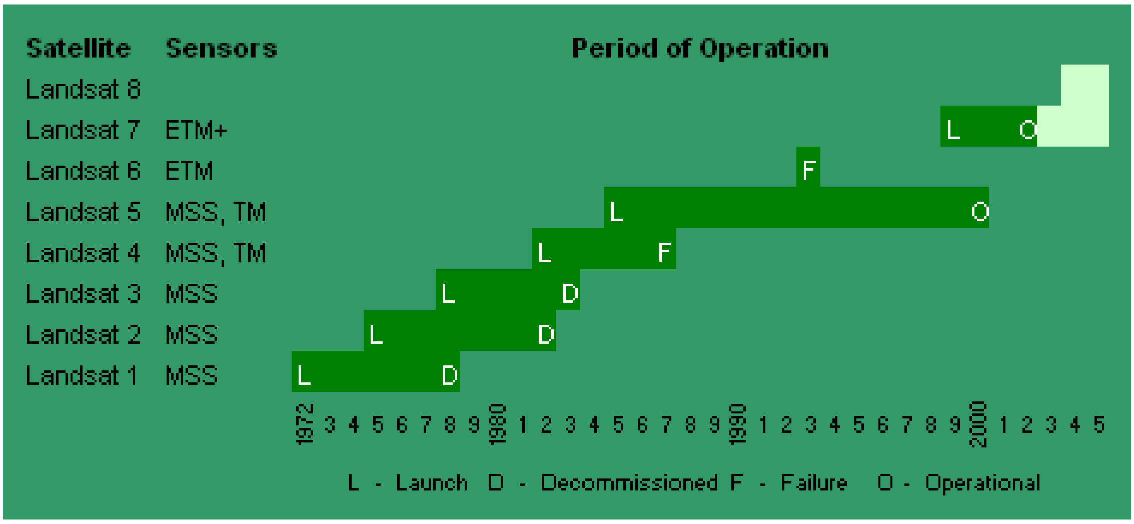
Appendix 1: Boggy Plain – air photo coverage

Year	Day/month	Run	Photo #	Scale	Medium	Comments
1950	16 May	9	5097 - 99	1: 50 000	B & W	Rainfall data needed
1964	… ??July ?	24 25 26	5142 – 52 5160 – 69 5140 – 50	1: 16 000	B & W	Largest scale / best resolution photos available. Correlation with rainfall data needed.
1975	… June			1: 25 000	B & W	wet season rainfall was well <u>above</u> average. Buffalo density possibly at an all time peak?
1979	27 July			1: 50 000	B & W	Munmarlary lease resumed by Federal Govt. in 1978. Only southern region visible as site is obscured by smoke.
1981	5 June 7 June	14 13 E 13 W	022– 029 191– 197 059– 062	1: 25 000	Colour and / or B & W	Middle of the 1974 - 1986 Wet cycle (a period of above normal rainfall).
1984	…. May			1: 25 000		wet season rainfall was ~150mm <u>above</u> normal. Colour slides (in possession of P Bayliss) taken from the air by T Hertog (CSIRO)
1987	19 August 27 August	? ?	190– 195 065– 070	1: 60 000		The buffalo era was either nearing an end or was already over.
1991	… May	13 14	081– 090 150– 159	1: 25 000	Colour	Middle of the 1986 - 1996 dry cycle. wet season rainfall was ~ 200mm <u>below</u> normal.

Appendix 2 : Landsat specifications and coverage for Boggy Plain (*)

The first Landsat satellite was launched in July 1972. Of the sensors carried, the Multispectral Scanner (MSS) with 80 metre pixels and four spectral bands was found to provide information of unforeseen value. In July 1982, the launch of Landsat 4 saw the inclusion of the Thematic Mapper (TM) sensor with a 30 metre resolution and 7 spectral bands. Both sensors are on Landsat 5.

The newest in this series of remote-sensing satellites is Landsat 7. Launched on 15 April 1999, Landsat 7 has the new Enhanced Thematic Mapper Plus (ETM+) sensor. This sensor has the same 7 spectral bands as its predecessor, TM, but has an added panchromatic band with 15 metre resolution and a higher resolution thermal band of 60 metres.



NT Bushfire Council Landsat Imagery acquired by *eriss*

.(*) see also list of satellite imagery held by PAN in SSR 123 (pgs. 109 – 114)

<table>
<tr><th>Year</th><th>day/month</th><th>Data type</th><th>Raw / geo-coded</th><th>Spatial resolution</th></tr>
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<tr><td>1992</td><td>16 July</td><td>Raw</td><td>80m</td></tr>
<tr><td>1993</td><td>3 July</td><td>Raw</td><td>80m</td></tr>
<tr><td>1994</td><td></td><td>Raw</td><td>80m</td></tr>
<tr><td>1995</td><td></td><td>Raw</td><td>80m</td></tr>
<tr><td>1996</td><td></td><td>Raw</td><td>80m</td></tr>
<tr><td>1997</td><td>25 April
2 October
18 Oct</td><td>Raw
Raw
Raw</td><td>80m (both 3 & 4 bands)
as above</td></tr>
<tr><td>1998</td><td>1 July
18 Aug</td><td rowspan="2">Landsat 5 TM</td><td>Raw & geo-coded
Raw & geo-coded</td><td>Bands 1-5 & 7 (30m) ; Band 6 (120m) ;</td></tr>
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21 Aug</td><td>Geo-coded
Geo-coded</td><td></td></tr>
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15 Aug
3 Nov</td><td>Geo-coded
Geo-coded
Raw & geo-coded</td><td></td></tr>
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30 May
1 July
24 July
2 Aug
26 Sept</td><td>Landsat 5 TM</td><td>Geo-coded
Geo-coded
Geo-coded
Geo-coded
Geo-coded
Geo-coded</td><td>Band 6 (120m) & Band 8 (15m)</td></tr>
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2 Aug
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Raw & geo-coded
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9 June
15 Oct</td><td>Landsat 5 TM</td><td>Geo-coded
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Bands 1-5 & 7 (30m)</td></tr>
<tr><td>2 June
9 June</td><td>Landsat 7 ETM</td><td>Raw & geo-coded
Raw</td><td>Band 6 (60m) ; Band 8 (15m)</td></tr>
</table>

Appendix 3: Full scene coverage of QuickBird 05/05/03 capture