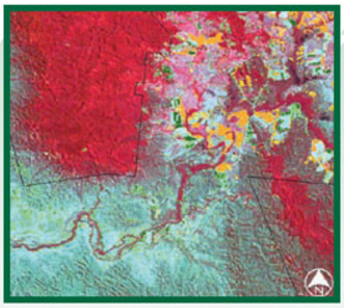

RESEARCH REPORT

Vegetation Change Within the Wet Tropics of North Queensland

Mapping Changes with Landsat TM/ETM+ Imagery from 1988 and 1999

Kasper Johansen
and Stuart R. Phinn

Rainforest CRC

Cooperative Research Centre for Tropical Rainforest Ecology and Management

VEGETATION CHANGE WITHIN THE WET TROPICS OF NORTH QUEENSLAND

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Cover Images ©
(*Top*) Extract from Figure 21 of this report. Stuart Phinn.
(*Centre*) Extract from map of Wet Tropics World Heritage Area and Bioregion. Trevor Parker, CSIRO Tropical Forest Research Centre, Atherton
(*Bottom*) Landsat Satellite Image. Stuart Phinn.

The authors wish to thank C. Bruce and D. Hilbert of CSIRO Tropical Forest Research Centre, who kindly provided Landsat image data.

Digital copies of the change images included in this report can be obtained by contacting s.phinn@uq.edu.au.

December 2005

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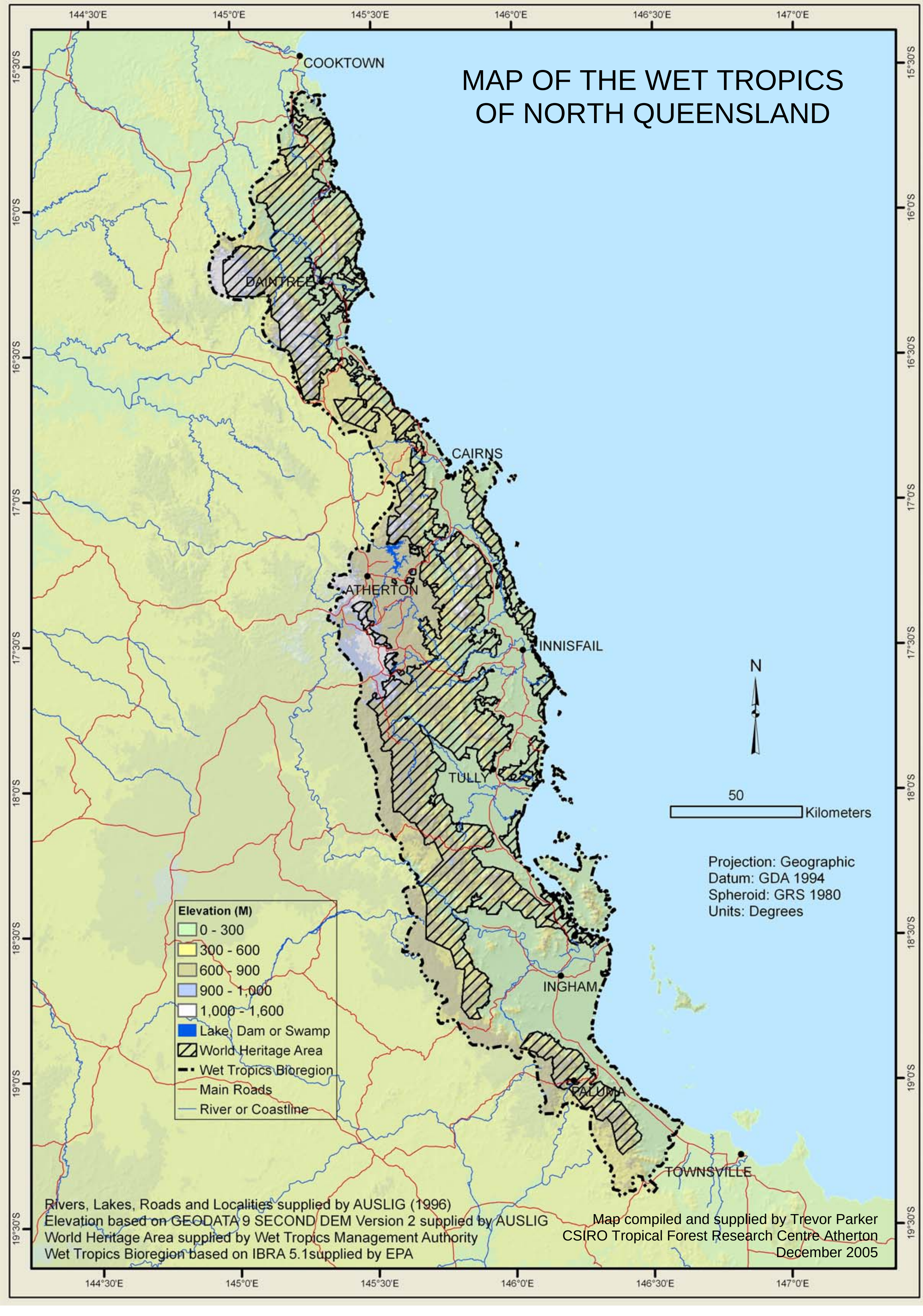
ABSTRACT

Changes in the vegetation cover of the total Wet Tropics bioregion and particularly the Wet Tropics World Heritage Area (WTWHA) of northern Queensland were mapped by comparing satellite image data from the Landsat 5 Thematic Mapper in 1988 and Landsat 7 Enhanced Thematic Mapper sensors in 1999. These image data sets had been geometrically, radiometrically and atmospherically corrected in a previous Rainforest CRC project by Bruce and Hilbert (2003). Each image data set was used to produce maps of vegetation indices that represent the amount of vegetation cover within each image pixel (Lucas *et al.* 2004).

The 1988 vegetation index image was subtracted from the 1999 vegetation index image, resulting in a *difference* image. Each pixel in the difference image represents the changes in the amount of vegetation cover present at the sampling times. The resulting map displays the vegetation cover changes over the 1988 to 1999 period, thereby identifying some areas with no significant change in vegetation cover and other areas that have experienced significant gain or loss of vegetation cover.

Of four classes of vegetation change that were identified and mapped for this study (*cleared*, *thinned*, *partial regeneration* and *regeneration*), partial regeneration was the greatest and most frequently occurring change identified within the Wet Tropics bioregion predominantly in agricultural areas around Innisfail and Tully. Within the WTWHA the main change class identified was partial regeneration of the vegetation located around drainage lines and along the boundaries between schlerophyll and wet tropical forests. Summaries are provided in this report of the vegetation index change analysis for both the entire Wet Tropics bioregion and the WTWHA. The accuracy of the vegetation cover change map was diminished by the spatial mis-registration between image data sets and insufficient topographic and radiometric correction.

The results presented in this report demonstrate that a limited amount of clearing has occurred in the Wet Tropics since the World Heritage listing of the area in 1988, however the majority of changes observed were due to regeneration of vegetation. These changes could be further monitored in cooperation with the Queensland Government's Statewide Landcover and Trees Study (SLATS) program or the MODIS SVI monitoring project established by researchers of the Rainforest CRC's Project 1.2 (Phinn *et al.* 2005).



MAP OF THE WET TROPICS
OF NORTH QUEENSLAND
COOKTOWN
DAINTREE
CAIRNS
ATHERTON
INNISFAIL
TULLY
INGHAM
PALUMA
TOWNSVILLE
N
50
Kilometers
Projection: Geographic
Datum: GDA 1994
Spheroid: GRS 1980
Units: Degrees
Elevation (M)
0 - 300
300 - 600
600 - 900
900 - 1,000
1,000 - 1,600
Lake, Dam or Swamp
World Heritage Area
Wet Tropics Bioregion
Main Roads
River or Coastline
144°30'E
145°0'E
145°30'E
146°0'E
146°30'E
147°0'E
15°30'S
16°0'S
16°30'S
17°0'S
17°30'S
18°0'S
18°30'S
19°0'S
19°30'S
Rivers, Lakes, Roads and Localities supplied by AUSLIG (1996)
Elevation based on GEODATA 9 SECOND DEM Version 2 supplied by AUSLIG
World Heritage Area supplied by Wet Tropics Management Authority
Wet Tropics Bioregion based on IBRA 5.1supplied by EPA
Map compiled and supplied by Trevor Parker
CSIRO Tropical Forest Research Centre Atherton
December 2005

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EXECUTIVE SUMMARY

Mapping Changes in Rainforest Vegetation Cover

A vegetation cover change map was generated using Spectral Vegetation Index (SVI) image mosaics of the Wet Tropics bioregion derived from Landsat 5 TM images from 1988 and Landsat 7 ETM+ images collected in 1999. These image data sets had previously been geometrically, radiometrically and atmospherically corrected by Bruce and Hilbert (2003).

Further checks of the geometric and atmospheric correction accuracy were made before applying the vegetation index transformations and classifications required to generate the SVIs. The SVIs produce maps of a continuous biophysical variable directly related to vegetation cover, biomass and Leaf Area Index (LAI) within the entire Wet Tropics bioregion in both 1988 and 1999.

The three most commonly used SVIs for tropical forests were applied in this project – the Normalised Difference Vegetation Index (NDVI), Infrared Index (IRI) and Enhanced Vegetation Index (EVI). Successive SVI image pairs were subtracted to produce SVI difference image maps in the three formats, each of these maps were then classified into six types of land cover change:

1. Cloud shadows;
2. Cleared areas;
3. Thinned areas / seasonal change;
4. No change;
5. Partial regeneration / seasonal change; and
6. Regeneration.

Analysis of the land cover change was conducted for the total Wet Tropics bioregion with particular emphasis on the Wet Tropics World Heritage Area (WTWHA). The bioregion was divided into six regions to enable an accurate and detailed description of vegetation cover change:

a) Cooktown area;
b) Daintree area;
c) Cairns area;
d) Innisfail area;
e) Tully area; and
f) Paluma area.

Observations of the differences between the 1988 and 1999 data sets revealed some changes in the vegetation cover throughout the Wet Tropics area of northern Queensland included:

- Less than five percent of the total Wet Tropics bioregion and less than one percent of the WTWHA can be classified as *cleared areas*. The cleared areas detected corresponded mainly to the expansion of agricultural land and associated agricultural activities in the Tully and Innisfail areas. Other cleared sites relate to the development of human infrastructure such as road and powerline corridors throughout the region. The clearing of vegetation within the WTWHA was concentrated around several small features; the cause of this vegetation clearance could not be established by this study.

- Extensive *partial regeneration* of vegetation throughout the entire study area could be attributed to the influence of below average rainfall in 1988 and more standard rainfall figures in 1999 (Appendix 1). The lower than average rainfall in 1988 is assumed to have caused the reduced canopy density and reduced LAI observed that year. Spatially, this partial regeneration was most prevalent along waterways and in the transitional zones between woodland, schlerophyll forests and rainforest.

- Of the three SVIs used in this study, the EVI was considered to provide the most accurate representation of vegetation cover change in the high biomass and high LAI environment of the Wet Tropics. Classification of vegetation change from the EVI enabled identification of the areas of most change in the Wet Tropics bioregion and within the WTWHA. Results obtained in this analysis support similar conclusions from past research on the use of EVI for tropical forest monitoring (Huete *et al.* 2002, Lucas *et al.* 2004).

- Due to its reliance on a red band, the NDVI was subject to saturation effects therefore low levels of increased or decreased vegetation cover at high biomass levels were unable to be detected using this method.

- The estimates of vegetation change classes used in this study should be treated with caution as the images used to perform the mapping represent two snapshots, at single points in time, of a highly dynamic system. It is possible that clearance and regrowth of different vegetation may have occurred during the ten years between each of the image mosaics. This change is not represented in these mapping results.

Future Mapping and Monitoring of Vegetation Cover Change

The findings of this project highlight the capacity of SVIs to map and monitor vegetation cover changes within the Wet Tropics of Queensland. There are two operational possibilities for continuing this monitoring on an annual or more frequent basis:

- The Statewide Landcover and Trees Study (SLATS) of the Queensland Department of Natural Resources and Mines (www.nrm.qld.gov.au/slats) is now mapping woody vegetation cover from a modified Landsat-based SVI for the entire state of Queensland on an annual basis. The SVI used by SLATS could be requested and examined for the Wet Tropics area and compared to previous years' SVIs to identify areas of change in vegetation cover.

- Researchers of the Rainforest CRC's Project 1.2 have designed a mapping and monitoring program using freely available MODIS EVI image data that are provided on a daily or weekly basis. By developing this proposed system further, weekly image data could be used for mapping and monitoring vegetation cover and its change over time (Phinn *et al.* 2005).

1. INTRODUCTION AND BACKGROUND

Remote sensing has been used extensively to map and monitor tropical rainforest environments (Lucas *et al.* 2004). In the Wet Tropics of Queensland an estimated 965,000ha were covered by tropical rainforest prior to European settlement of the area during the nineteenth and twentieth centuries. Human impacts have lead to a reduction in the area of rainforest to approximately 750,000ha. Some small areas of wet tropical rainforest are privately owned though most of the remaining rainforest areas in northern Queensland were declared the Wet Tropics World Heritage Area in 1988 (Kanowski *et al.* 2003).

Landsat TM/ETM+ has already proved useful for monitoring vegetation clearing as well as identifying the thinning and regeneration of tropical rainforests (Lucas *et al.* 2004). Some studies have found that the use of a combination of TM/ETM+ bands 3, 4 and 5 has been effective for monitoring deforestation in tropical regions (Lillesand and Kiefer 2000; Roy *et al.* 1991; Nelson 1994).

Past research has focused on developing image processing approaches related to mapping tropical rainforests using Synthetic Aperture Radar (SAR), though problems are often encountered with this method (Conway 1997; Grover *et al.* 1999; Kuntz and Siegert 1999; Luckman *et al.* 1997; Ticehurst *et al.* 2003; Van der Sander and Hoekman 1999). These problems with the use of SAR relate to the moisture content of the vegetation and soils, the landscape topography and poor signal-to-noise ratio (Kuntz and Siegert 1999; Ticehurst *et al.* 2003).

The use of optical remote sensing systems provides a spectrally precise representation of features on the Earth (Campbell 2002). However, cloud coverage can hinder some areas from being optically mapped on a regular basis (Foody and Hills 1996). This study demonstrates the utility of Landsat TM/ETM+ imagery for mapping environmental changes related to land clearing, vegetation thinning or regeneration of rainforest areas throughout the Wet Tropics bioregion of northern Queensland during the decade from 1988 to 1999. Mosaics were created from several Landsat image scenes from 1988 and 1999 to cover the entire extent of the WTWHA in northern Queensland (Bruce and Hilbert 2003). Characteristics of the Landsat TM/ETM+ sensors are depicted in Table 1.

Table 1: Characteristic dimensions of the Landsat TM/ETM+ sensors (Source: NOAA 2003).

Dimensions	Characteristics of the Landsat TM/ETM+ Sensors	
Spatial	30m x 30m pixel size for multi-spectral bands 120m x 120m pixel size for the TM thermal infrared band 60m x 60m pixel size for the ETM+ thermal infrared band 15m x 15m pixel size for the ETM+ panchromatic band 185km x 185km scene size	
Spectral	Landsat TM 0.45-0.52µm (blue) 0.52-0.60µm (green) 0.63-0.69µm (red) 0.76-0.90µm (near-infrared) 1.55-1.75µm (mid-infrared) 2.08-2.35µm (mid-infrared) 10.4-12.5µm (thermal infrared)	Landsat ETM+ **0.45-0.52µm (blue)** 0.53-0.61µm (green) 0.63-0.69µm (red) 0.78-0.90µm (near-infrared) 1.55-1.75µm (mid-infrared) 2.09-2.35µm (mid-infrared) 10.4-12.5µm (thermal infrared) **0.520-0.900µm (panchromatic)**
Radiometric	8 bits	
Temporal	Revisit time: 16 days	

Mapping the changes in vegetation cover of the WTWHA between 1988 and 1999 was conducted using a change detection analysis based on the most appropriate vegetation index. The change detection analysis was performed by subtracting the vegetation index pixel values of the 1999 mosaic from the 1988 mosaic. The vegetation indices NDVI, IRI and the EVI have been used to monitor environmental change in many different environments (Mauser *et al.* 1999; MODIS 1999; Mora *et al.* 2003).

NDVI is based on the near-infrared and the red bands. Using Landsat TM/ETM+ imagery, NDVI has been used in a variety of different environments including tropical forests (Tucker 1979). This band ratio is also used to minimise shadow and brightness effects, compensate for changing surface slope and highlight differences in vegetative cover (Barret and Curtis 1992; Lillesand and Kiefer 2000). Dawson *et al.* (2003) demonstrated that NDVI is highly sensitive to both canopy foliage and understory chlorophyll content, which can account for significant errors in remotely sensed estimates of canopy foliage parameters.

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

The IRI has been used to monitor fire effects and subsequent vegetation recovery (Bohlman *et al.* 1998). The rationale behind IRI is to combine the ability of band 4 for biomass detection with the ability of band 5 to detect vegetation moisture (Mora *et al.* 2003).

$$IRI = \frac{NIR - MIR}{NIR + MIR}$$

The EVI was developed to optimise the vegetation signal with improved sensitivity in high biomass regions while correcting for canopy background signals and reducing atmospheric influences.

The equation takes the form,

$$EVI = \frac{G\,(NIR - RED)}{NIR + (C_1\,RED) - (C_2\,BLUE) + L}$$

where G = Gain Factor
C_1 = Atmospheric Resistance Red Correction Coefficient
C_2 = Atmospheric Resistance Blue Correction Coefficient
L = Canopy Background Brightness Correction Factor

L is the canopy background adjustment term and C_1 and C_2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band. The coefficients adopted in the EVI algorithm are $L = 1$, $C_1 = 6$, $C_2 = 7.5$ and $G = 2.5$ (TBRS 2003).

The main disadvantage of ratio based indices tends to be their non-linearities resulting in asymptotic behaviour of vegetation indices in relation to the vegetation properties being examined. The main result of the non-linear response is that NDVI and IRI are susceptible to saturation at high biomass or high LAI levels, therefore their ability to detect small changes in dense tropical forests is limited (Huete *et al.* 1999). Ratios also fail to account for the spectral dependencies of additive atmospheric effects (path radiance), canopy background interactions and canopy bi-directional reflectance anisotropies (Levesque and King 2003; MODIS 1999; Sims and Gamon 2002).

2. DATA AND METHODOLOGY

2.1 DATA

The Landsat TM and ETM images used in this project were provided in a georeferenced and atmospherically corrected format by Bruce and Hilbert for the CSIRO (2003) through the Rainforest CRC (Figure 1).

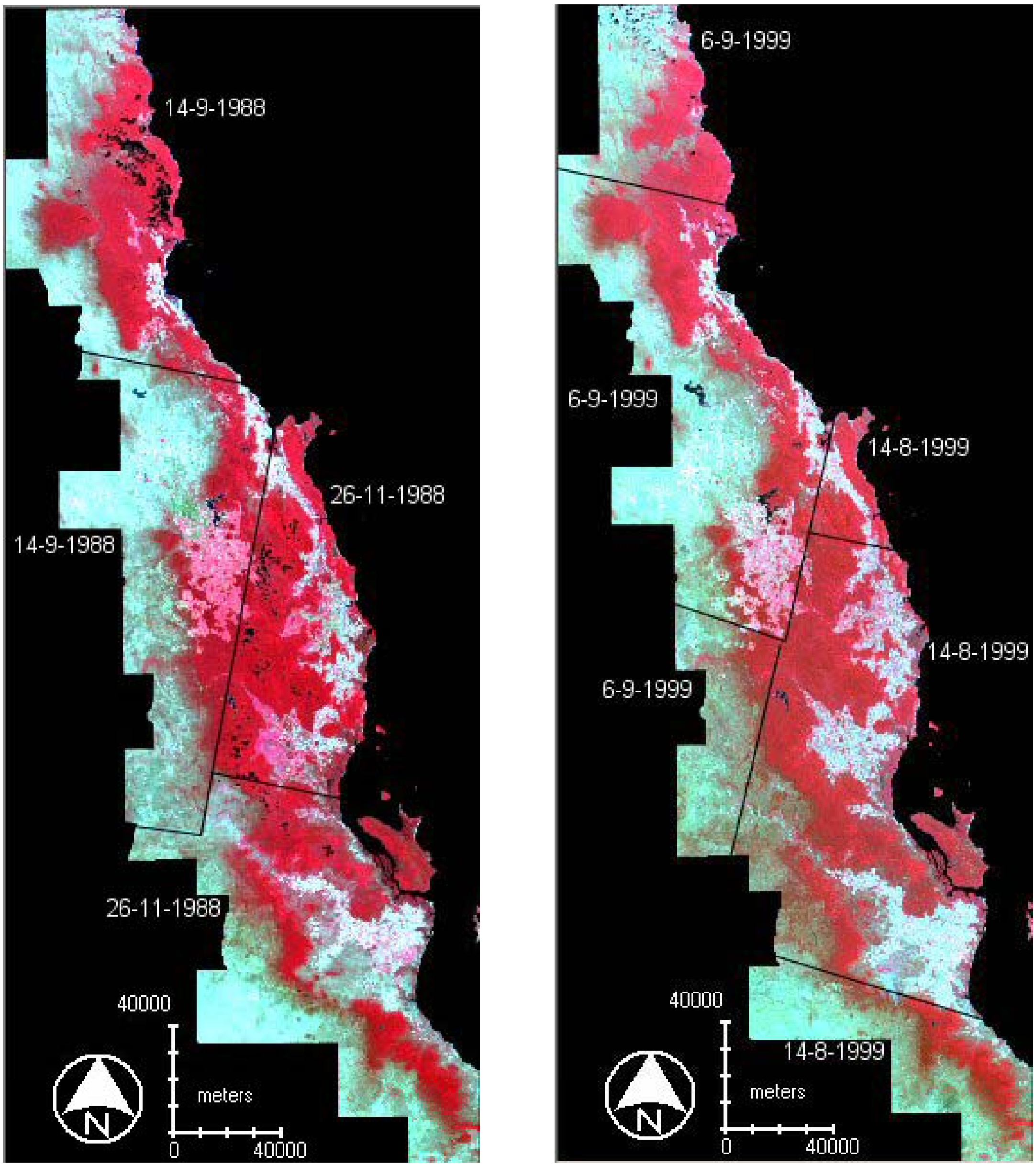


Figure 1: Landsat false colour composite mosaic from 1988 and 1999 depicting the dates the individual scenes were acquired. The black lines indicate scene boundaries. Red = NIR band, Green = red band, Red = green band.

2.2. PRE-PROCESSING

A pre-processing methodology for application to Landsat TM/ETM+ imagery of the Wet Tropics bioregion was developed and applied by Bruce and Hilbert (2003). The pre-processing procedures included:

1. Orthocorrection;
2. Correction for noise;
3. Conversion to top of atmosphere reflectance units;
4. Relative atmospheric correction;
5. Topographic normalisation; and
6. Relative radiometric correction.

Further pre-processing and quality checking was required prior to the calculation of vegetation indices and change detection operations.

2.3 CLOUD MASKING

The two Landsat image mosaics used in this project both contained some clouds that were masked out to avoid confusion in the change detection analysis (Figure 2). The development of an image mask was based on thresholds of the digital numbers for all six bands. As cleared fields and sandy exposed areas had spectral reflectance characteristics similar to the reflectance of clouds, no single cloud mask could be produced for the entire image mosaics. Hence, individual subsets of the Landsat mosaics were subjected to different image masks. The periphery areas of clouds had reflectance characteristics resembling the background reflectance. Refinement of the cloud masking process was therefore necessary to improve the exclusion of all pixels affected by clouds (Figure 2).

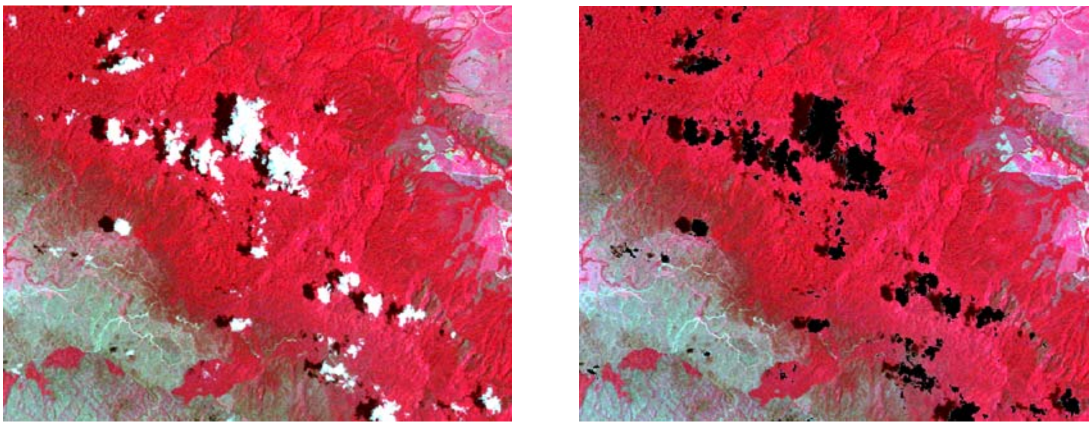
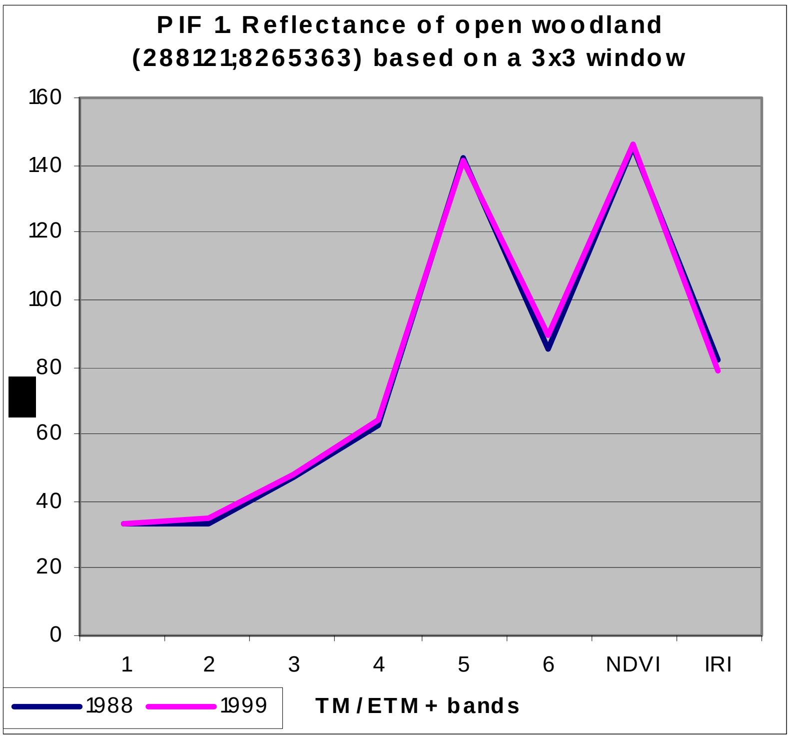


Figure 2: Subset of Landsat scene showing the result of a cloud mask.

2.4 VERIFICATION OF ATMOSPHERIC CORRECTION

A comparison of the two Landsat image mosaics was performed using pairwise observations of pixel values of Pseudo-Invariant-Features (PIFs) that exhibit minimal spectral change through time. This technique has been applied successfully in many studies (Furby and Campbell, 2001; Hall *et al.*, 1991; Hill and Sturm, 1991; Yuan and Elvidge, 1996). The relationship between the PIFs can be used to calibrate multi-temporal imagery. PIFs used were rainforest, open woodland, a lake and a grass airstrip/runway. Special care was taken to identify areas not affected by topography and not subject to anthropogenic influence. A limited number of appropriate spectrally invariant man-made targets and other urban features could be identified on the Landsat mosaics. Several rainforest areas considered to be invariant due to their remote and inaccessible location were used as PIFs. The relationships between reflectance values of each PIF between the two Landsat mosaics and their locations are depicted in Figures 3 and 4.



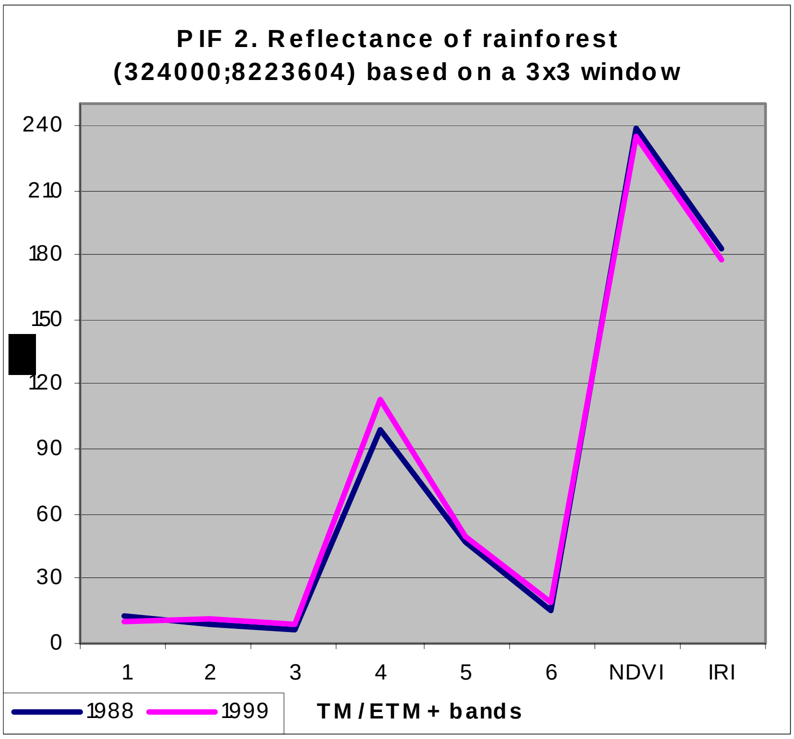
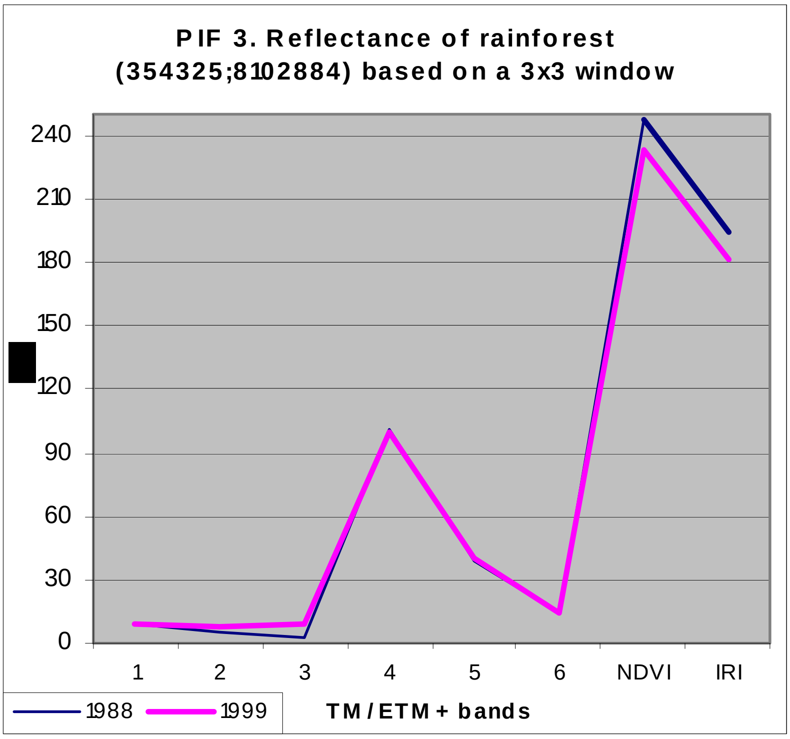


Figure 3: Spectral signature plots for individual PIF targets in 1988 and 1999 images.



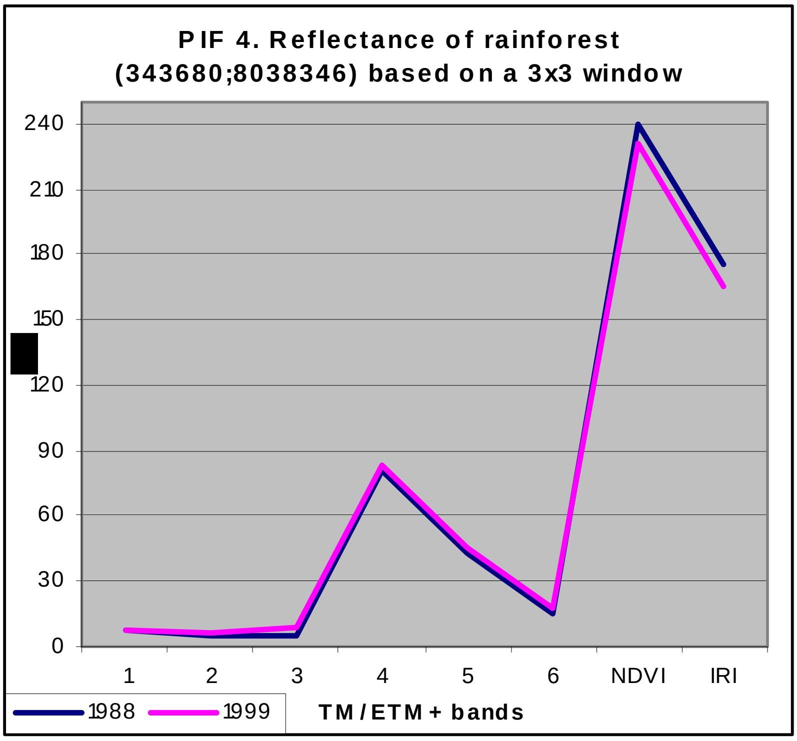
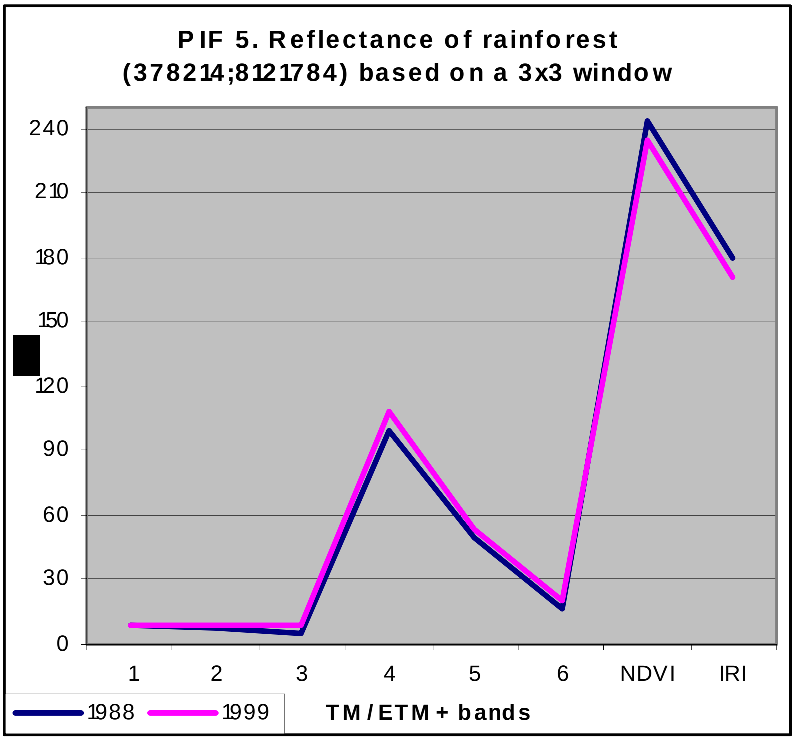


Figure 3 (cont'd): Spectral signature plots for individual PIF targets in 1988 and 1999 images.



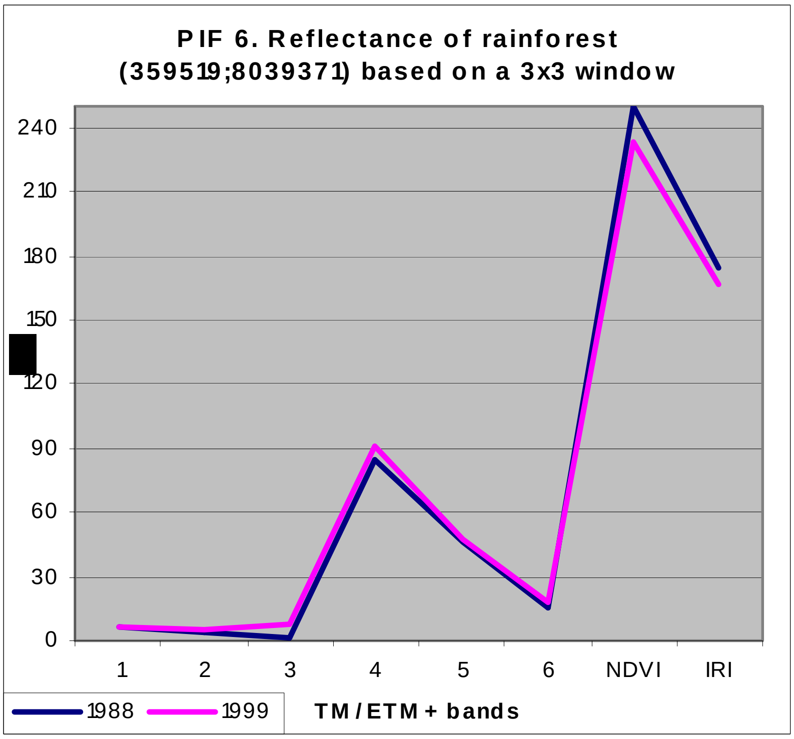
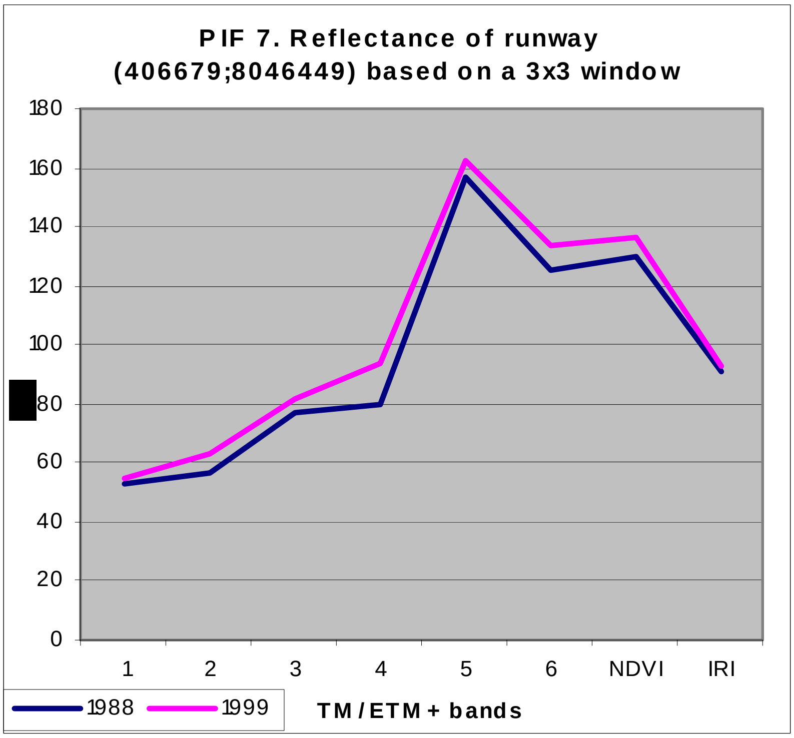


Figure 3 (cont'd): Spectral signature plots for individual PIF targets in 1988 and 1999 images.



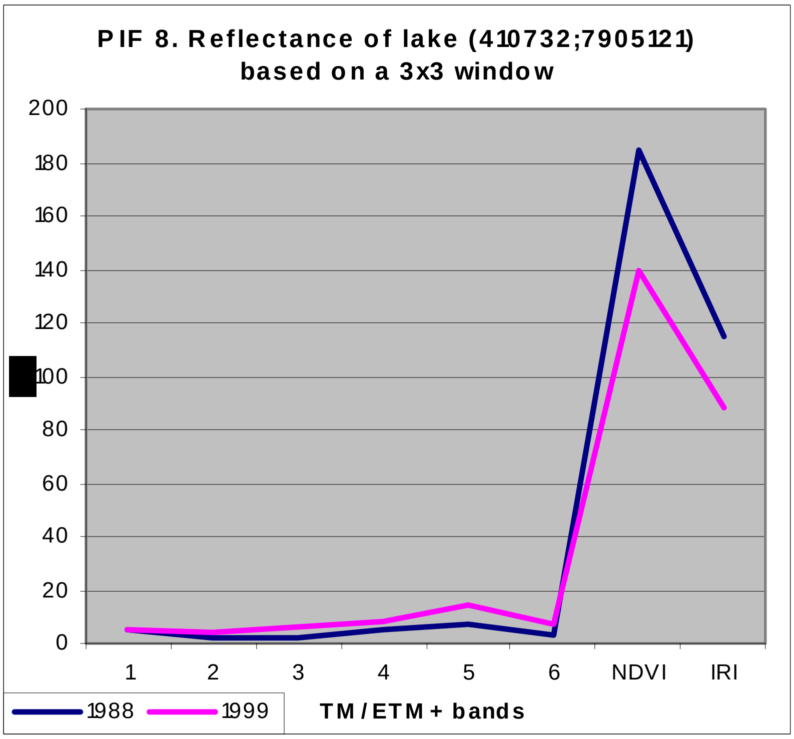


Figure 3 (cont'd): Spectral signature plots for individual PIF targets in 1988 and 1999 images.

Schott *et al.* (1988) and Hill and Sturm (1991) explained that moisture can be a profound influence on the spectral reflectance of PIFs. Schott *et al.* (1988) suggested that the PIF technique should only be used for reasonably dry surfaces. The Landsat TM/ETM+ scenes were acquired from June to November, which is the dry season in tropical Australia. Rainfall data for the six representative areas in this study of Cooktown, Cairns, Mareeba, Innisfail, Ingham and Paluma where obtained from the Australian Bureau of Meteorology (Appendix 1).

The 1988 Landsat TM mosaic comprised of four scenes, whereas the 1999 Landsat ETM+ mosaic contained six scenes. The boundaries of the individual scenes are depicted in Figure 1. The reflectance characteristics of at least one PIF from each individual scene in both Landsat mosaics were examined and related to the rainfall data for the nearest climate station. The PIFs were located in areas that had received similar but limited levels of rainfall in the month prior to image acquisition.

Due to the similarity in the spectral reflectance of the PIFs identified on both the 1988 and 1999 mosaics (Figure 3), no further normalisation of the mosaics were performed. Figure 3 shows the pixel values for bands 1-5, band 7, NDVI and IRI derived from the same location on the two Landsat mosaics. EVI was excluded from the evaluation as shaded areas caused by clouds yielded negative pixel values even in areas of dense rainforest where EVI was supposed to exhibit high positive index values.

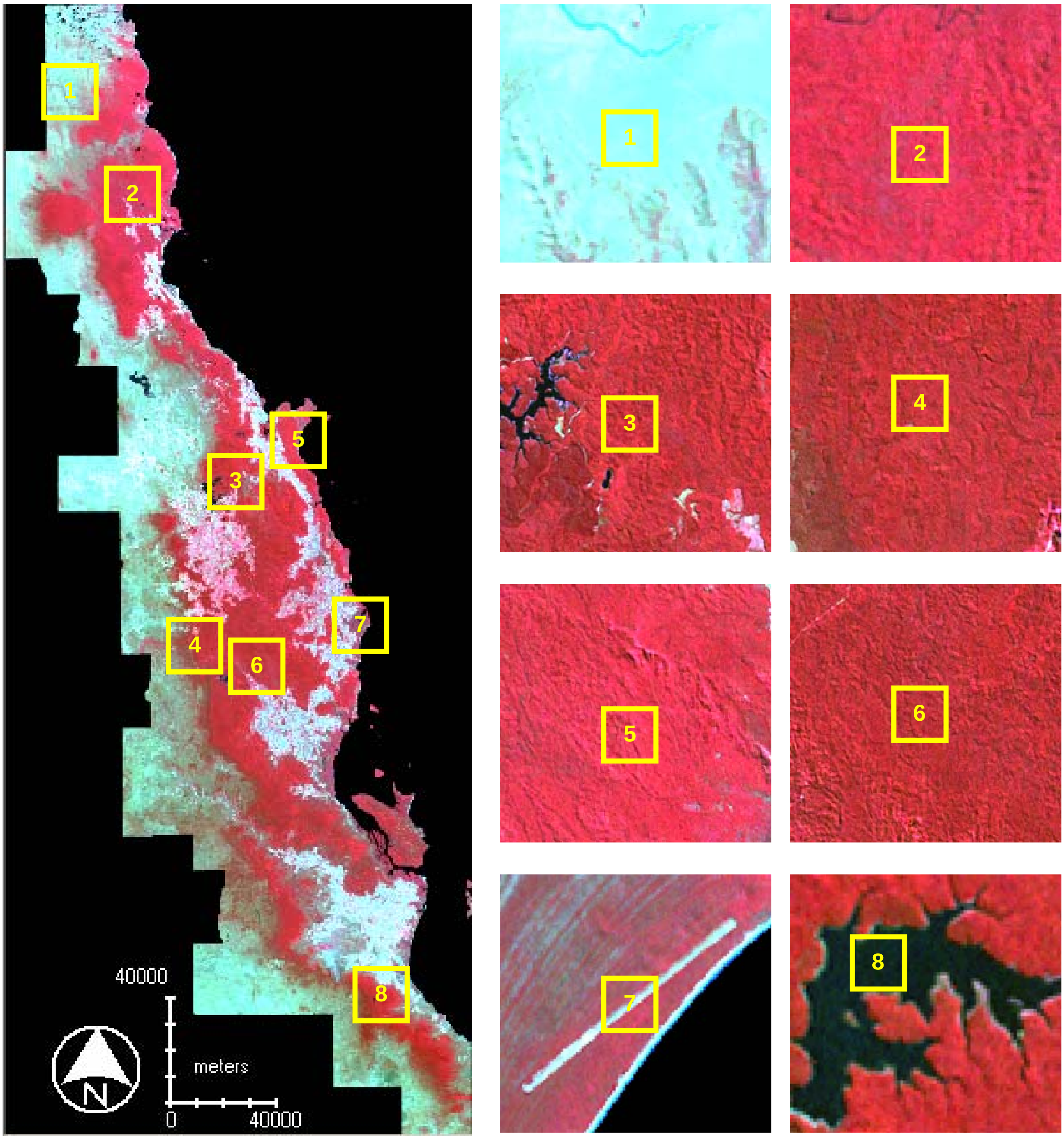


Figure 4: Location of PIFs indicated with yellow squares. Numbers correspond to PIFs presented in Figure 3.

2.5 VERIFICATION OF SATURATION EFFECTS ASSOCIATED WITH VEGETATION INDICES

Areas having an LAI of 3.0 or greater result in NDVI saturation (Gamon *et al.* 1995; Gao 1996), which was largely due to:

- the greater amount of horizontal stratification of leaves, which is difficult to identify with remote sensing instruments that operate from a vertical perspective (Sims and Gamon 2002; Wulder *et al.* 1998); and

- NDVI saturates due to the red chlorophyll absorption band causing NDVI to become insensitive to chlorophyll-a concentrations above 3-5μg/cm2 (Gitelson *et al.* 1996).

Saturation problems cause vegetation index values to remain invariant to changes in the amount, type and condition of vegetation and are normally associated with a saturated chlorophyll signal in dense vegetation canopies.

Townshend *et al.* (1991) noted that saturation is a problem as change detection and vegetation monitoring cannot be carried out in an NDVI saturated mode. Gitelson *et al.* (1996) found that maximum sensitivity to chlorophyll-a pigment absorption is at 670nm. For low and medium amounts of vegetation, the difference between red and near-infrared reflectance is a result of both red and near-infrared changes, while at higher amounts of vegetation only the near-infrared reflectance contributes to increasing the difference as the red band becomes saturated due to chlorophyll absorption (MODIS, 1999).

To test the reflectance characteristics of the red, near-infrared (NIR) and mid-infrared (MIR) Landsat bands across vegetation boundaries, a transect exhibiting different levels of vegetative cover was identified on the Landsat image mosaics and analysed. A high spatial resolution CASI (Compact Airborne Spectrographic Imager) image data set with 2.0m pixels and 19 bands was obtained for the selected area of rainforest that runs parallel to the Skyrail rainforest cableway, approximately ten kilometres northwest of Cairns (Figure 5). The CASI data was used to provide a spatial assessment of vegetation cover that is not subject to saturation effects. The reflectance characteristics of Landsat ETM bands 3 (red), 4 (NIR) and 5 (MIR) are depicted in Figure 6.

It appears that the red reflectance of dense rainforest areas along the transect shows very little variation. A slight increase in the reflectance is apparent when moving from dense rainforest into more sparsely vegetated areas. Conversely, large differences in the reflectance pixel values are identified in the NIR and MIR bands. These bands also show more reflectance variability within the densely vegetated rainforest areas along the transect line thereby providing more detailed information about the rainforest areas.

Bohlman *et al.* (1998) noted that Landsat TM bands 1, 2 and 3 had a very limited range of reflectance values when conducted upon a Brazilian rainforest area. They found that bands 4 and 5 provide more information about vegetated land surfaces as the energy in band 4 is strongly reflected by leaves due to the scattering of light by structural components within leaf tissues. Energy in band 5 is absorbed by water in the foliage. Bohlman *et al.* (1998) concluded that the low dynamic range of band 3 limited the significance of NDVI because the ratio essentially showed only variations in the band 4 reflectance. The index values of NDVI, IRI and EVI obtained along the transect are depicted in Figure 7. Despite the similarity in the vegetation index graphs, IRI and particularly the EVI, show increased variability within the rainforest areas compared to NDVI.

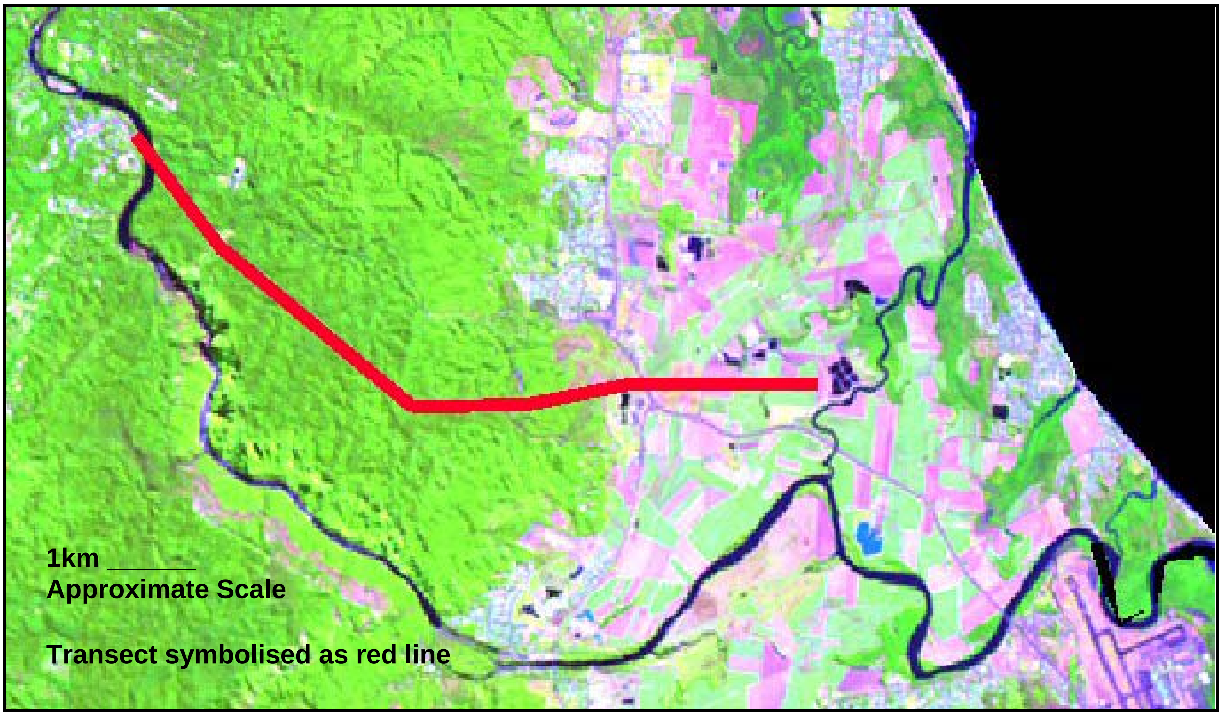


Figure 5: Landsat 7 ETM+ image (bands 5, 4 and 3) showing the location of the transect (red line) running parallel to the Skyrail, located approximately ten kilometres northwest of Cairns.

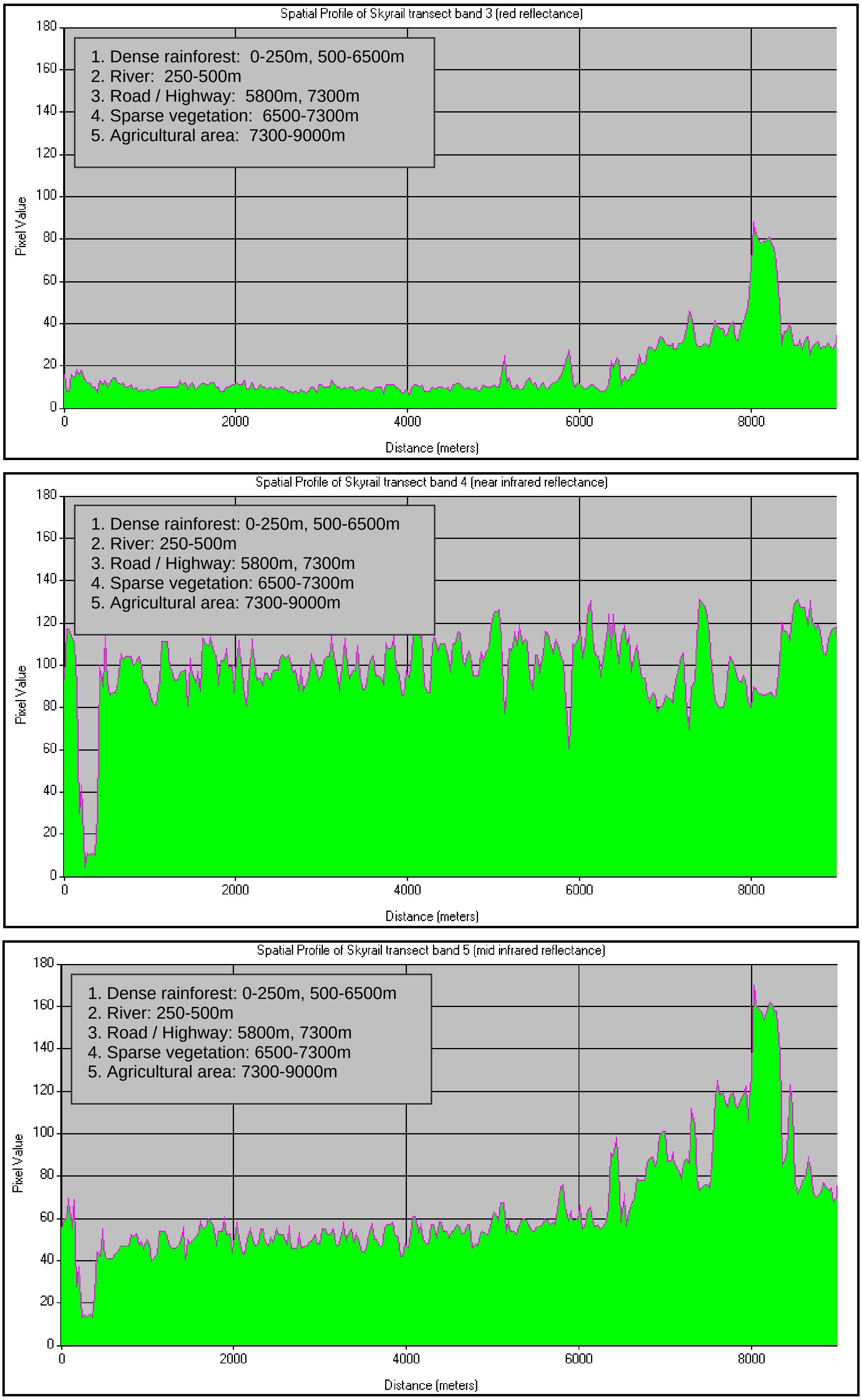


Figure 6: Profiles of Landsat 7 ETM reflectance and vegetation index values obtained from a 9,000 metre long transect running west to east from Kuranda (0m) to the Skyrail terminal north of Cairns (9,000m). The inset box lists the typical landcover along each section of the transect.

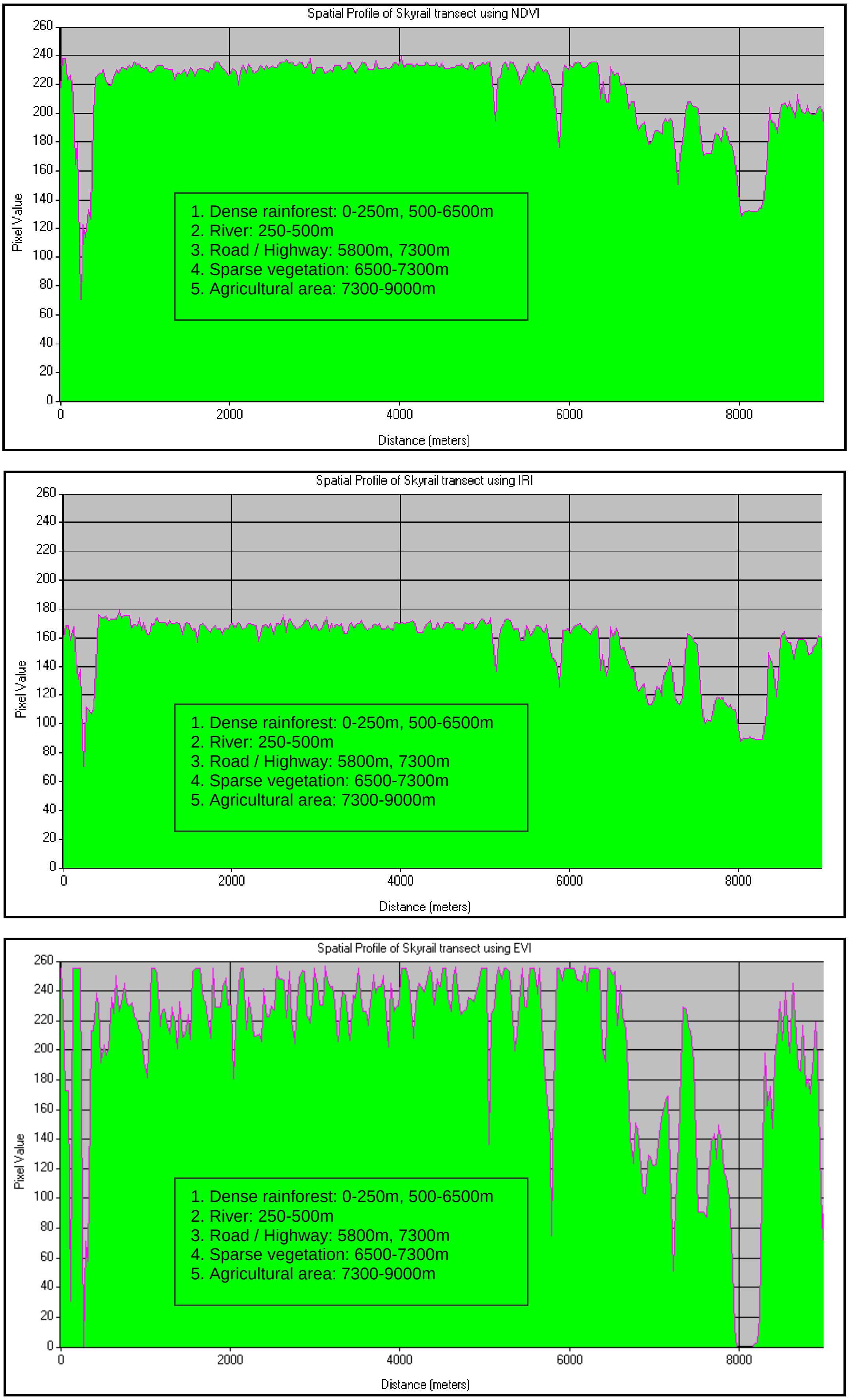


Figure 7: Reflectance characteristics of different vegetative cover for NDVI, IRI and EVI.

2.6 VEGETATION INDEX DIFFERENCING (1999 – 1988) FOR CHANGE DETECTION

Change detection through subtraction of vegetation index images creates difference images that are assumed to represent changes in vegetative cover – higher vegetation index values are assumed to represent higher vegetation cover. The suitability of the three different vegetation indices for detecting environmental change within the Wet Tropics bioregion were evaluated by differencing the vegetation indices applied to the two Landsat mosaics. The vegetation index images based on the 1988 mosaic were subtracted from the vegetation index images of the 1999 mosaic, resulting in negative values in areas with decreased vegetative cover, positive values in areas of increased vegetative cover and values of zero in areas displaying no change. As the vegetation index images had pixel values ranging from 0 to 255, the potential range of difference values was -255 to 255. Pixels in the difference images were assigned to one of the following six classes of change detected based on their difference value:

1. Clouds;
2. Cleared areas;
3. Thinned areas / seasonal change;
4. No change;
5. Partial regeneration / seasonal change; and
6. Regeneration.

The amount of change detected and recoded for this project was subjective and may have been biased. Two of the change classes, *thinned areas* and *partial regeneration*, included features and areas that are subject to minor seasonal variations such as phenological change and those changes due to the amount of rainfall prior to image acquisition. As the cleared areas and regeneration change classes do not contain any minor seasonal change influences both these change classes were assumed to represent values of true change.

Areas of shading caused by clouds in both mosaics did influence the vegetation index values, especially those of the EVI. These areas affected by cloud shadows appeared with either high negative or high positive values in the difference image. In most cases, these spurious values corresponded with areas of remote rainforest where detection of changes was not expected. The areas affected by cloud shadow that were expected to produce pixel values demonstrating *no change* were subset and recoded separately, then the individually recoded difference image subsets were subsequently joined back together. This method was time consuming but considerably reduced the possibility of misclassifications.

For ease of interpretation and the extraction of information from the three difference images based on the three vegetation indices, the difference images were divided into six subsets covering the following regions (Figure 8):

a) Cooktown area;
b) Daintree area;
c) Cairns area;
d) Innisfail area;
e) Tully area; and
f) Paluma area.

2.7 TYPES OF DETECTABLE CHANGE

Change detection is the process of identifying and evaluating land cover differences based on the comparison of remotely sensed data acquired at different times (Singh 1989; Mouat *et al.* 1993). Jensen (1996) explains that data suitable for change detection calculations should ideally be acquired by remote sensing systems that have the same temporal, spatial, spectral and radiometric resolutions. Keeping the spatial resolution constant between the mosaics used for change detection increases the ability of the mosaics to register to one another, while the use of anniversary date imagery assures seasonal sun angle and plant phenological differences are not a function of the imagery. The sensor viewing angle of the different sampling times should be approximately the same to avoid problems related to relief displacement and bidirectional reflectance caused by illumination and viewing angles (Lillesand and Kiefer, 2000).

As change detection analysis is based on the reflectance characteristics of land cover types in certain wavelength bands, each wavelength band should be the same between the dates of image acquisition to enable correct comparison of the reflectance characteristics. The radiometric resolution and radiometry should also be the same for the remotely sensed data used in change detection to avoid results that include false changes; therefore radiometric normalisation between the remotely sensed data is essential.

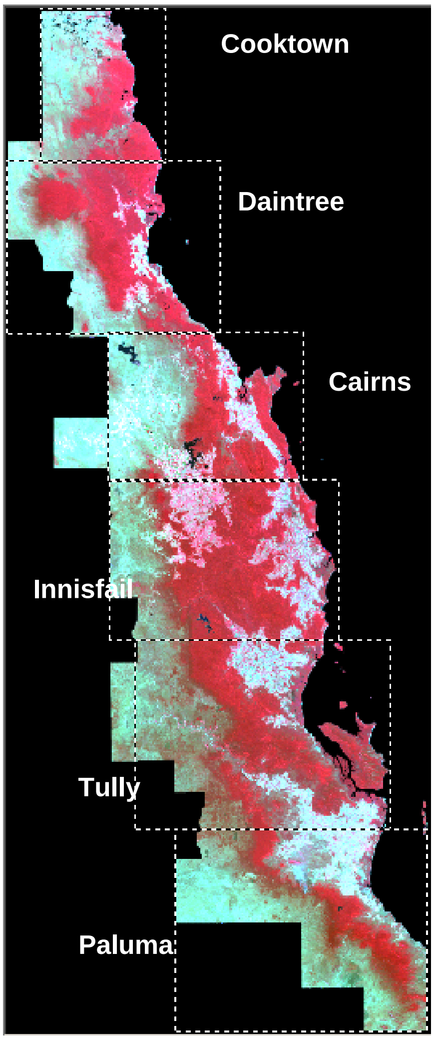


Figure 8: Image subdivisions used for the change detection analysis.

Table 2: The three kinds of change identified in the initial assessment of the vegetation index change detection.

Types of Change Identified	Causes
Image artifacts	• Insufficient radiometric correction • Insufficient topographic correction • Insufficient geometric correction
Natural	• Tides • Phenological changes • Dry period effects and fires • Soil moisture
Human induced	• Clearing • Rehabilitation/restoration • Indirect effects

2.7.1 Changes Due to Image Artifacts

The radiometry of the two Landsat mosaics was assessed using PIF and revealed that no further correction was needed. However, in some topographically complex areas within the WTWHA, the topographic correction of the 1999 mosaic caused some pixels to be assigned to erroneous pixel values (Figure 9). This would have resulted in erroneous vegetation index values that would appear as environmental changes in the change detection analysis. As the images used for the mosaics were topographically corrected prior to this project, no further correction could be performed (Table 2).

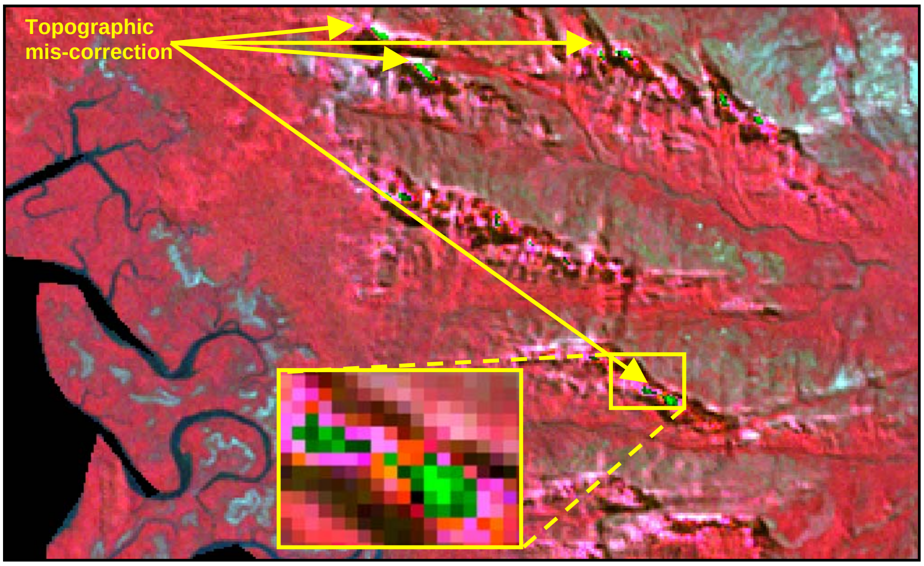


Figure 9: Topographic mis-correction of topographically complex areas on Hinchinbrook Island.

The geometric accuracy of the remotely sensed data sets influences the accuracy of environmental change detection. The importance of geometric registration of image data sets used for change detection has been identified by several authors (Furby and Campbell 2001; Phinn and Rowland 2001; Singh 1989; Stow 1999; Verbyla and Boles 2000).

A spatial offset between two image data sets will result in identification of spurious results in the changes detected (Phinn and Rowland 2001). Phinn and Rowland (2001) also noted that mis-registration effects are pronounced for urban areas and linear features such as water bodies, though land cover types occupying a relatively large and contiguous area are less affected.

Townshend *et al.* (1992) found that the mis-registration effects on image differencing are greatest for multi-temporal data sets of spatially heterogeneous regions. Some areas with contrasting reflectance such as rainforest and agricultural fields located next to each other may appear, for example, as cleared areas along the boundary between these two land cover types in the change detection analysis. In areas like this, it is very difficult to determine if the change detection result is affected by geometrical mis-registration or if the agricultural land actually has been extended into the rainforest area. To distinguish between real changes and spurious changes caused by mis-registration a thorough interpretation of the two mosaics and the change detection map was conducted.

2.7.2 Natural Changes

Natural changes will appear on change detection images and it is desirable to distinguish these kinds of changes from human induced changes. It is therefore important to understand the impact of various environmental characteristics in the remote sensing change detection analyses. Tides can have a pronounced effect on the change detection in coastal environments. A comparison of the 1988 and 1999 mosaics revealed that the tide levels were different between the individual image scenes that the two mosaics are composed of.

The WTWHA includes large areas of coastal mangroves and wetlands that are influenced by tidal movements (Figure 10). The tide levels were examined for both Lucinda Point and Cairns for the sample collection times (Figure 11).

It appears that the tide level for the coastal areas on the mosaics south of Cairns were similar around 10.00am (Landsat image acquisition time) between the dates of image acquisition in 1988 and 1999 (Table 3). The areas on the mosaics north of Cairns, however, experienced a tide level approximately one metre higher in 1988 than in 1999 at the Landsat image acquisition time. Coastal areas influenced by tides may exhibit change between the two Landsat mosaics due to the tide level difference.

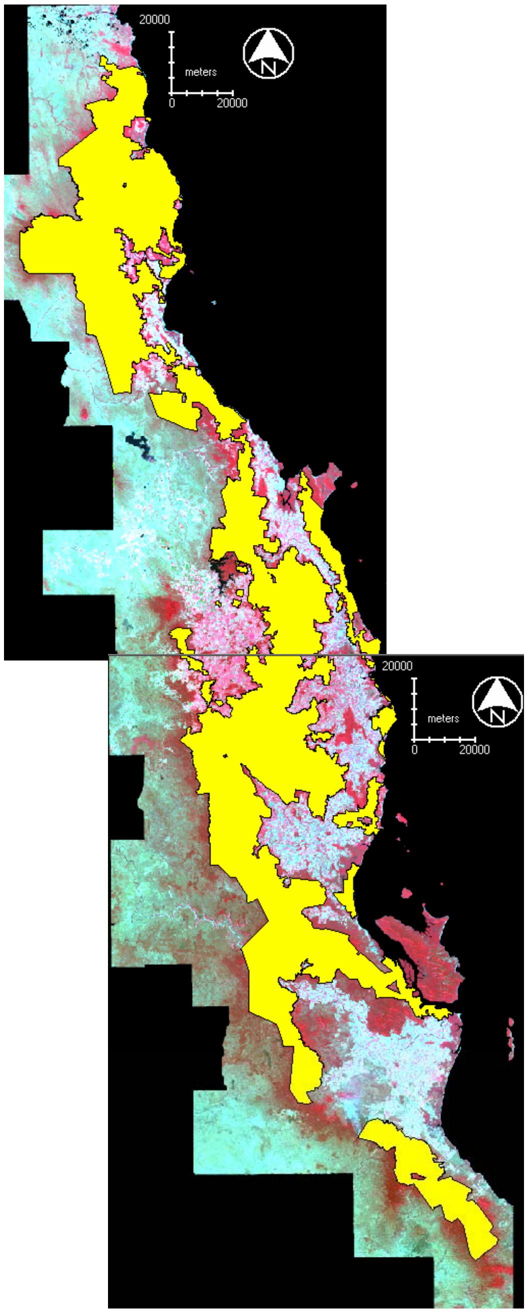


Figure 10: The Wet Tropics World Heritage Area, shown in yellow, indicating large areas of coastline.

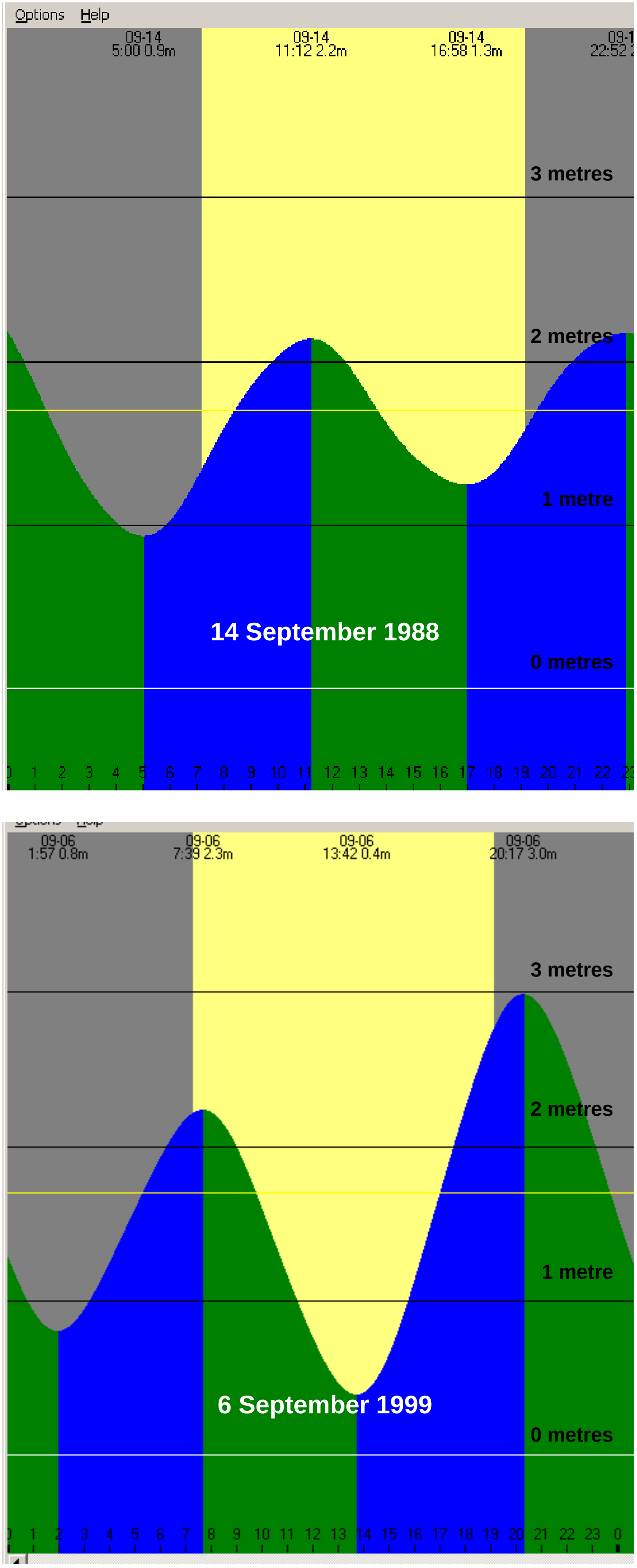


Figure 11: Tidal plots for Lucinda Point and Cairns coincident with dates and times of Landsat image acquisitions (Source: WX-tide).

Table 3: Tide levels for Lucinda Point and Cairns in 1988 and 1999 (Source: Australian national tide tables).

Lucinda Point (18°31'; 146°19')				Cairns (16°55'; 145°47')			
November 26, 1988		August 14,1999		September 14, 1988		September 6, 1999	
Time	**Tide level**	**Time**	**Tide level**	**Time**	**Tide level**	**Time**	**Tide level**
04:09	0.3m	05:10	1.1m	03:59	0.7m	00:56	0.9m
11:13	2.7m	10:53	2.3m	10:08	2.0m	06:50	2.2m
18:38	1.1m	16:52	0.9m	16:05	1.0m	12:46	0.4m

Vegetation grows according to diurnal, seasonal and annual phenological cycles. Obtaining anniversary images minimises the effects of seasonal phenological differences that may cause detection of spurious changes. As shown in Figure 1, the north-western section of the two Landsat mosaics were acquired on 14 September 1988 and 6 September 1999 and the south-eastern part of the Landsat mosaics was acquired on the 26 November 1988 and 14 August 1999. With over three months' difference between the capture of the image scenes used for the south-eastern part of the 1988 and 1999 mosaics, phenological changes are likely to occur due to differences in seasonal rainfall between the two image dates while the phenological differences may be minimal in the north-western sector.

Bohlman *et al.* (1998) explain that phenological changes on a stand level depend on the synchrony of phenological events such as leaf flush, expansion, aging, senescence and abscission among individual trees.

Below average rainfall in the wet season may result in significant thinning of canopies within the Wet Tropics. These dry period conditions will also influence the water levels in lakes and waterways. An examination of the 1988 and 1999 mosaics revealed that the water levels of lakes, rivers and creeks were lower in 1988 than in 1999 for the entire Wet Tropics bioregion. Figure 12 depicts the effects of the different water levels. The exposed areas of sand along the edges of the lake in the 1988 image will appear as *change* in the change detection analysis. The measurements of rainfall from 1986 to 1988 and from 1997 to 1999 (Appendix 1) support the image observations that, throughout the Wet Tropics bioregion, the years prior to image acquisition in 1988 were much drier than the years preceding 1999.

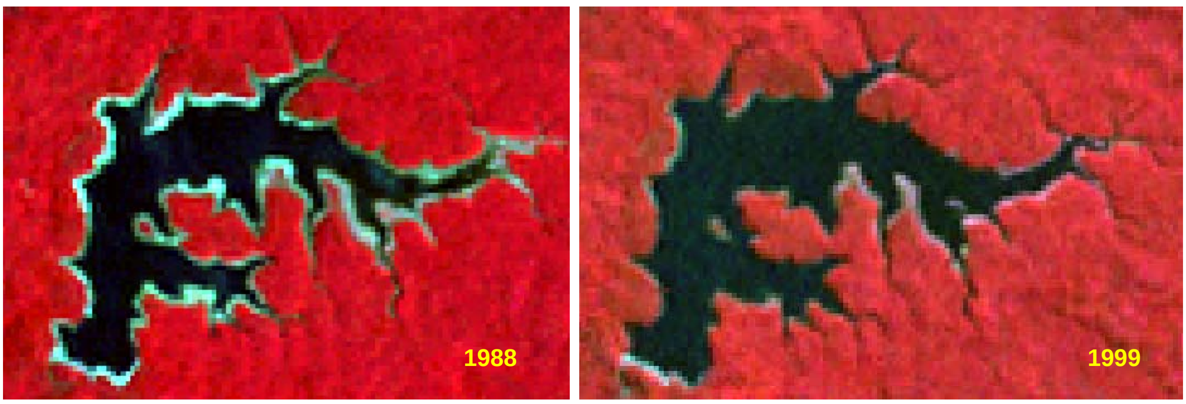


Figure 12: Water levels in Paluma Dam as depicted on the 1988 and 1999 mosaics.

Soil moisture conditions should ideally be identical for imagery used in change detection projects. Extremely wet or dry conditions at one of the dates can cause serious problems in the change detection analysis (Jensen 1996).

The north-western part of the two mosaics received a very similar and limited amount of rain in the months prior to image acquisition in both 1988 and 1999. Rainfall figures were 93 mm and 53 mm in Cooktown, 52 mm and 69 mm in Cairns and 44mm and 42mm in Mareeba respectively (Appendix 1). Despite the low water levels in lakes and waterways on the 1988 mosaic, the south-eastern part of the two mosaics received more rain in 1988 than in 1999 with 407mm and 360mm in Innisfail, 194mm and 34mm in Ingham and 128mm and 51mm in Paluma respectively (Appendix 1). It is therefore likely that soil moisture differences have influenced the change detection to some extent due to the absorption and reflectance characteristics of water.

2.7.3 Human Induced Changes

Human induced changes in the environment are often the most profound and important to recognise in change detection analyses as they can be permanent, whereas natural changes in many cases are related to year-to-year fluctuations. Urban development, expansion of agricultural areas and construction of powerline corridors are significant contributors to clearing of vegetation in Queensland.

Even though regeneration can be identified in change detection analyses, it is often difficult when using moderate spatial resolution sensors such as Landsat TM/ETM+ to determine if the regenerated area has returned to the original species composition. A regenerated area may be completely covered by weeds and still appear with similar vegetation index values as regenerated areas that have returned to their original species composition. Spectral signatures from some species may very closely match spectral signatures from other species or a spectral signature from one species may correspond closely to a mixture of spectra from other species (Price 1994). The use of radar or high spatial resolution imagery may improve the ability to determine whether or not an area has regenerated to its original structure and species composition.

It should be noted that the thresholding of the individual change detection classes was selected based on a thorough examination of the change images, hence the change maps are biased to a certain extent. The thresholds for the individual change classes were carefully selected based on several areas exhibiting the characteristics of the particular change classes. Because the two Landsat mosaics were composed of at least four difference image scenes, minor differences in the radiometry between the image scenes after the mosaicking and correction process may have resulted in overlapping between the individual change classes.

3. RESULTS AND DISCUSSION: VEGETATION CHANGE IN THE WET TROPICS 1988 – 1999

The level of vegetation change occurring between 1988 and 1999 was examined and qualitative and quantitative maps and graphs were produced for the Wet Tropics bioregion, which includes the Wet Tropics World Heritage Area (WTWHA). The entire Wet Tropics bioregion was examined under a more detailed evaluation of the six sub-regions – Cooktown, Daintree, Cairns, Innisfail, Tully and Paluma (Appendix 3).

The results, using the differencing of NDVI, IRI and EVI images, were included for a more thorough representation of the level of change and to determine which of the vegetation indices was most appropriate and suitable for monitoring change in the Wet Tropics bioregion.

3.1 CHANGES IN THE WET TROPICS BIOREGION

Based on the NDVI image differencing analyses, 85% of the Wet Tropics bioregion was not subjected to any change between 1988 and 1999 (Figure 13). Clouds covered approximately 1.15% of the Wet Tropics bioregion at the time of image acquisition in 1988 and again in 1999, though most of the cloud was positioned over the WTWHA. Fortunately, the clouds mostly obscured remote areas of dense rainforest where the level of change would be expected to be minimal.

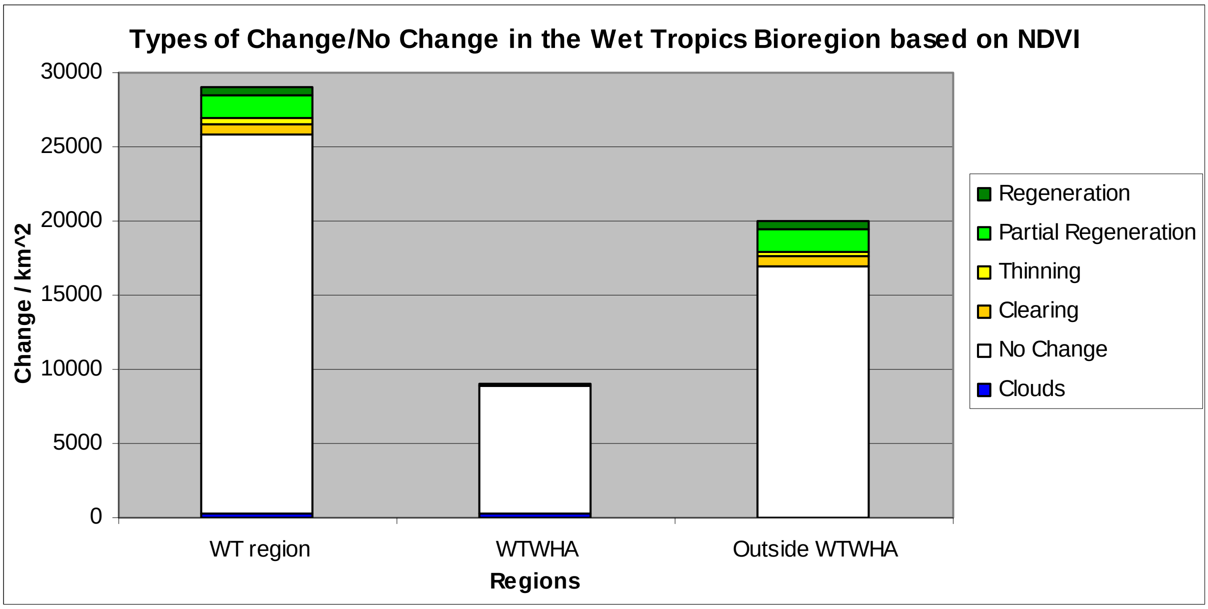


Figure 13: Changes observed between 1988 and 1999 in the Wet Tropics bioregion based on NDVI.

Areas of change were divided into four land cover change classes:

1. cleared areas;
2. thinned areas / seasonal change;
3. partial regeneration / seasonal change; and
4. regeneration.

The *partial regeneration / seasonal change* land cover class represented half of the total measured change. The majority of areas considered to have undergone change (depending on which SVI was used) were external to the WTWHA (Figure 14).

The majority of the partially regenerated areas were found in the transition zone between rainforest vegetation and woodland vegetation in remote inland areas. Increases in the vegetation index values from 1988 and 1999 may be related to dry-period effects, as the years prior to image acquisition in 1988 were considerably drier than the years preceding 1999. Canopy cover and LAI values may have been significantly reduced in the drier period, even though the same type of forest was present on both dates. Woodland areas and the sclerophyll/rainforest boundary show characteristic changes related to the amount of rainfall (Briggs *et al.* 2001; Goodall 1983). Areas not affected by dry period effects but classified as partial regeneration were located in the agricultural areas.

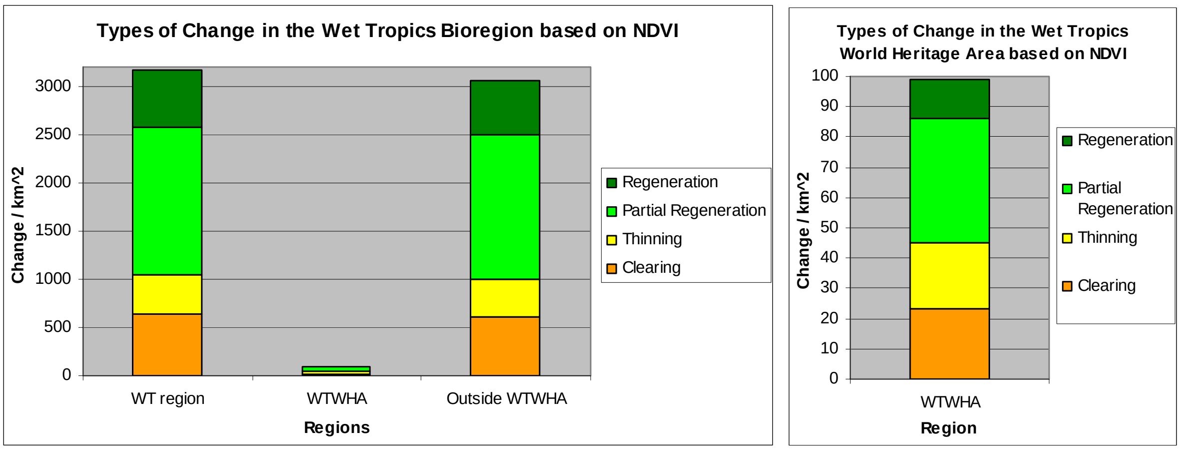


Figure 14: Areas of change between 1988 and 1999 in the Wet Tropics bioregion based on NDVI.

The *thinned areas / seasonal change* land cover class explains 13-17% of the areas of change detected within the Wet Tropics bioregion, depending on which SVI was used. More than 90% of thinned areas identified were located in agricultural areas outside the WTWHA. As the Landsat TM/ETM+ images for the south-eastern part of the mosaics were acquired in November 1988 and August 1999, the different growing stages of sugarcane crops would have contributed to their classification as either thinned or partially regenerated areas.

The *cleared areas* land cover class accounted for 10-20% of the changed areas, depending on the SVI used, while the *regeneration* land cover class explained 15-19% of the total change in the Wet Tropics bioregion. The majority of changes, being 95-98%, related to clearing and regeneration that occurred outside the WTWHA.

Examination of the change detection maps revealed that the main areas classified as cleared or regenerated were located in agricultural areas. The harvest season of sugarcane crops typically runs from mid-June to November in northern Queensland (McDonald and Lisson

2001). Fields with established sugarcane in 1988 and just-harvested fields in 1999 were classed as cleared areas, whereas sugarcane fields harvested just before image acquisition in 1988 and with established sugarcane in 1999 were classed as regeneration.

A limitation of the change detection maps and the change graphs is that they do not show which areas appear as cleared or regenerated as a result of the agricultural cycles of growth and harvesting. An area recently harvested before image acquisition in 1999 will fall under the same land cover class as an area covered by rainforest in 1988 and cleared before 1999. To determine the level of true clearing and regeneration, the change detection maps were compared to the 1988 and 1999 Landsat mosaics respectively.

3.2 REGIONAL CHANGES

The examination of change was carried out on a regional level using NDVI, IRI and EVI, however the main emphasis will be on NDVI as it appeared to be most sensitive to change across all cover types being examined (Figures 15 and 16). The IRI and EVI results are presented in Appendix 2. To evaluate the level of change that occurred between 1988 and 1999 in the Wet Tropics bioregion and within the WTWHA, the regional subsets were further divided into separate WTWHA areas (Figures 17 and 18) from non-WTWHA areas (Figures 19-20).

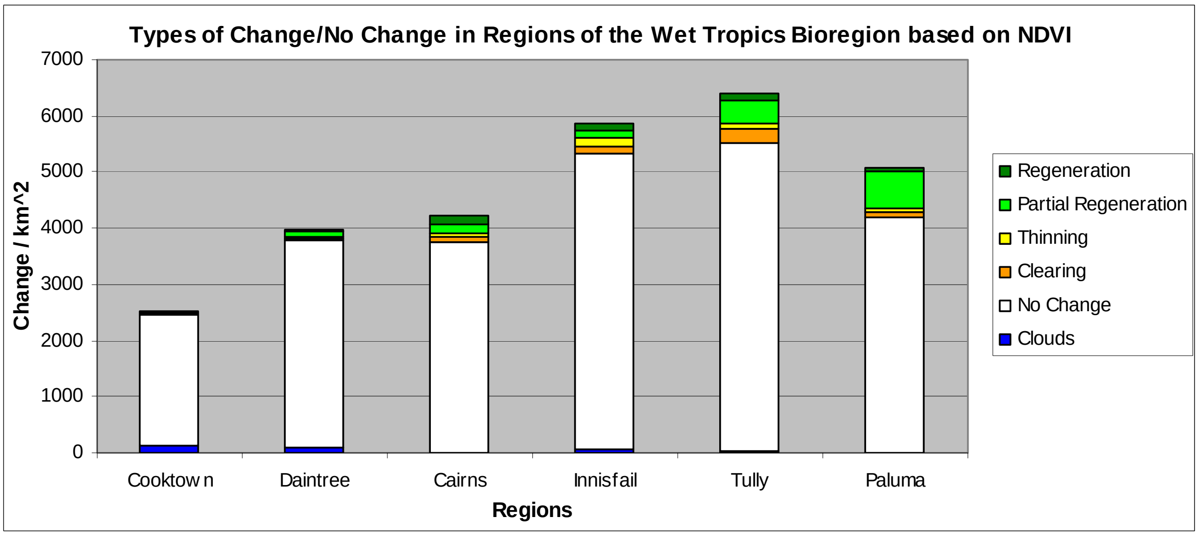


Figure 15: Level of change/no change detected in Wet Tropics sub-regions between 1988 and 1999 based on NDVI.

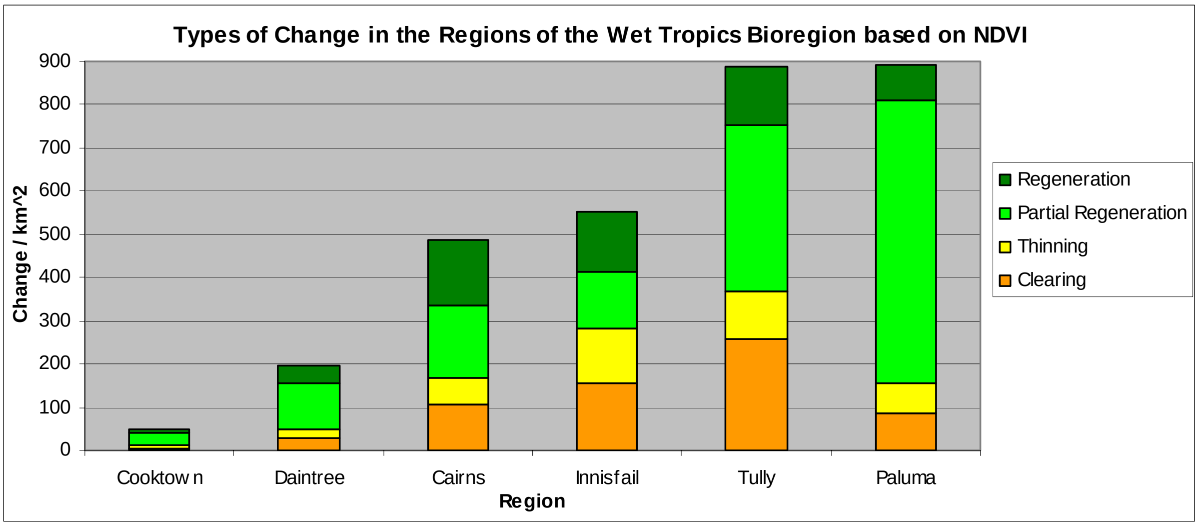


Figure 16: Change detected in Wet Tropics sub-regions between 1988 and 1999 based on NDVI.

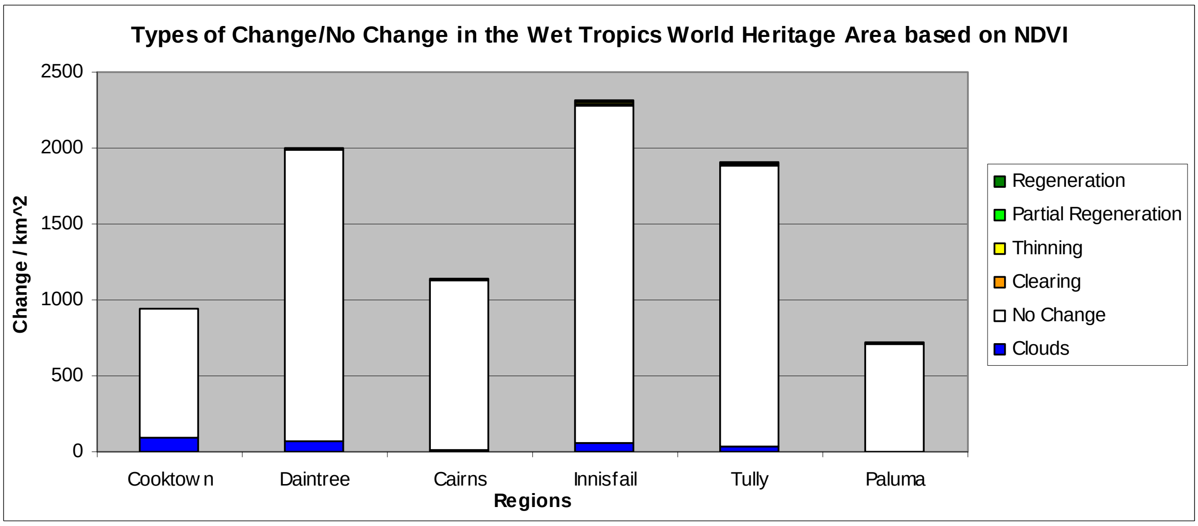


Figure 17: Change detected in WTWHA sub-regions between 1988 and 1999 based on NDVI.

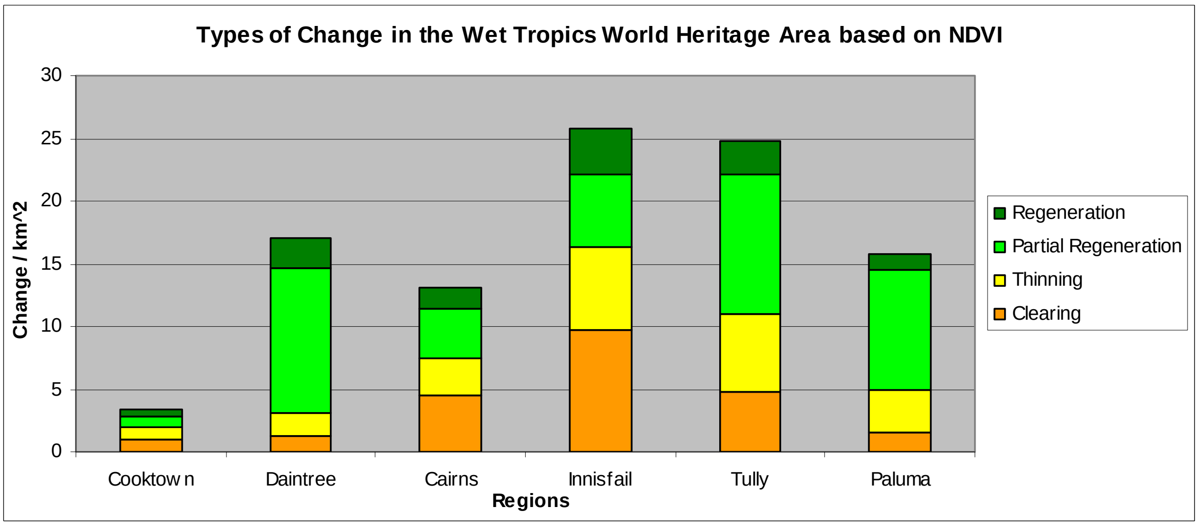


Figure 18: Change detected in WTWHA sub-regions between 1988 and 1999 based on NDVI.

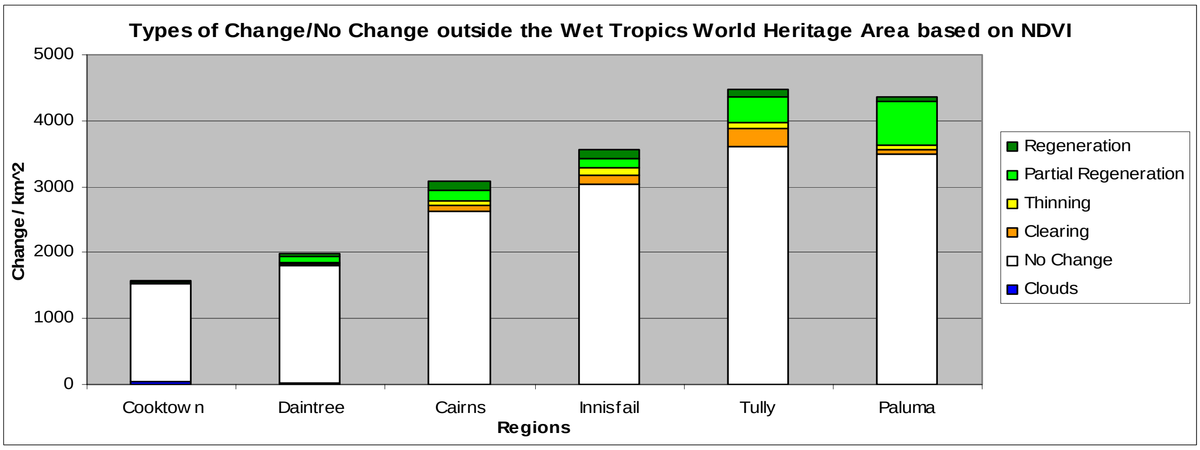


Figure 19: Change and no-change detected outside WTWHA between 1988 and 1999based on NDVI.

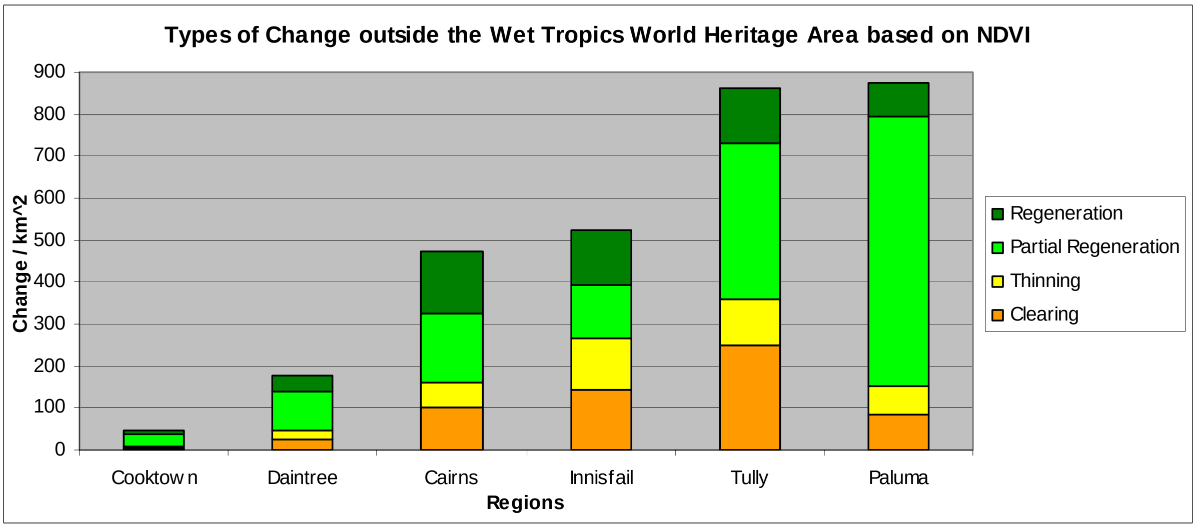


Figure 20: Change detected outside WTWHA between 1988 and 1999 based on NDVI.

3.2.1 Changes Identified Within the Cooktown Area

The lowest percentage of change was detected in the Cooktown area using NDVI (Figures 15 and 16), which was found to have experienced only 2% of land cover change between 1988 and 1999. The Cooktown sector also had the greatest area covered by clouds with 130km² obscured in both the 1988 and 1999 images. The *partial regeneration* land cover class covered 29km² and was responsible for the most change detected in this area. Of the change detected in the Cooktown area, 86% occurred outside of the WTWHA.

Examination of the change detection map based on NDVI difference images revealed that most of the partially regenerated areas were located within the riparian vegetation of the creeks and rivers in the area. The regeneration of vegetation in these areas is most likely a result of the dry-period effects prior to 1988 that resulted in the low water levels in most of the water bodies. The increased availability of water in 1999 may have increased the amount of green vegetation present, yielding higher vegetation index values than in 1988. IRI and EVI also displayed partial regeneration in areas outside the WTWHA, mainly in the transition zones between rainforest vegetation and woodlands. This may also be attributed to the dry period effects in the years preceding 1988.

The *regeneration* land cover class was identified mainly in coastal areas affected by tides. Table 3 indicates that the tide level was about one metre higher at the time of image acquisition in 1988 than it was in 1999. As water strongly absorbs near-infrared light, the vegetation indices would have displayed lower values in the 1988 image scene than in the 1999 image as tide-affected beaches and other low-lying coastal areas would have been covered by water in 1988. Areas affected by the tides would appear as regeneration in the change detection image. Only small areas were classified as regeneration within the WTWHA. Most of the thinned areas were located adjacent to zones classified as *cleared areas*. Cleared areas were most often located along linear features such as roads, creeks and rivers. Where roads were identified and classified as cleared areas on both the 1988 and 1999 subsets of the Cooktown area, the geometric correction of the imagery may not have been sufficient.

A spatial offset of one pixel will result in a thirty metre-wide road being classified as either a cleared or regenerated area, though roads constructed between 1988 and 1999 appeared correctly as cleared areas on the change detection map.

Several areas towards the mouths of the Annan and Bloomfield Rivers were classified as cleared, which could have been a result of spatial offsets between the two mosaics. As rivers are dynamic systems, especially in areas affected by tidal currents, natural change may have been the main reason for the classification of cleared areas in these regions.

The boundary areas between the beaches and the rainforest have been classified as either *cleared* or *regenerated*. These changes may have occurred because of spatial offsets between the mosaics or the dynamic nature of beaches, though a combination of both is most likely.

An area of about 0.5km^2 outside the WTWHA (lat 323376; long 8247113) was identified as cleared, while >4ha appeared as cleared within the WTWHA. Generally, very little change occurred within the WTWHA between 1988 and 1999 in the Cooktown area.

3.2.2 Changes Identified Within the Daintree Area

Using NDVI, approximately five percent of the Daintree area was found to have undergone change when comparing the 1988 and 1999 mosaics. Just over eleven percent of the change identified occurred within the WTWHA. Clouds obscured 83.5km^2 of the Daintree area in this study.

Most of the changes observed throughout the Daintree section of the Wet Tropics bioregion were found to be *partial regeneration*. This partial regeneration occurred mainly along riparian areas of creeks and rivers or in the transition areas of rainforest and woodlands (Figure 21). In transition areas with topographic variations, partial regeneration was found in the low-lying areas that have the ability to retain water for longer periods of time.

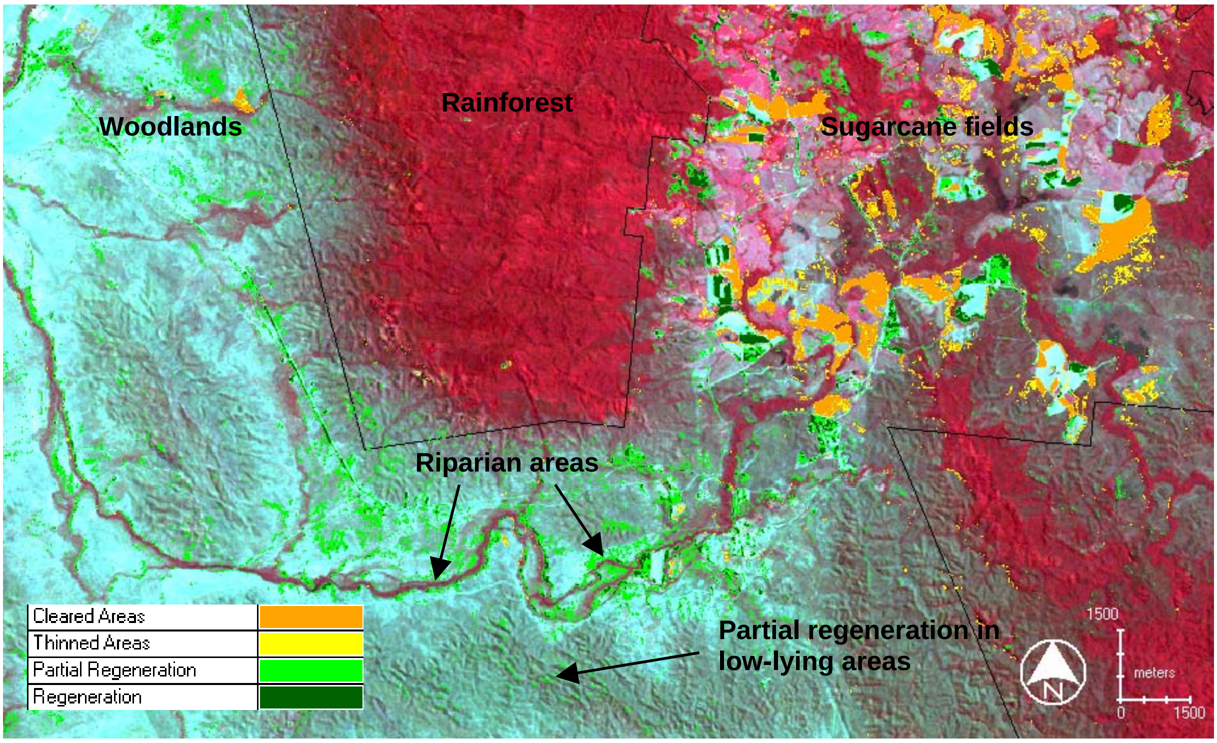


Figure 21: Change detection classes overlaid on the Landsat 7 ETM+ false colour composite (band 2, 3 and 4) located approximately 20km southeast of Port Douglas.

Large areas along the coastline were classified as *regeneration* due to the tide level differences between the dates of image acquisition in 1988 and 1999. A regenerated area of 3 to 4km^2 was identified in the south-eastern part of the Daintree area just outside the WTWHA. Within the WTWHA an abandoned road with an area of approximately 0.5km^2 had regenerated but the majority of the areas classified as regeneration were located in agricultural areas outside of the WTWHA.

Due to different growing and harvest patterns between the image acquisition dates of the Landsat TM/ETM+ scene in 1988 and 1999, most agricultural areas were classified as either *regenerated* or *cleared* in this study. Most of the thinned or cleared areas within the WTWHA were found along creeks and rivers as well as along the WTWHA boundaries with adjacent agricultural fields.

A remote area of 0.1km^2 within the WTWHA appeared to have been cleared. The majority of the cleared areas identified could be related to agricultural land outside the Daintree within the WTWHA. A comparison between the 1988 mosaic and the change detection map revealed that some areas covered by dense rainforest vegetation in 1988 had been converted to sugarcane fields. Figure 21 shows an area of approximately 4km^2 situated within a five-kilometre radius of the area marked as sugarcane fields, which was converted from rainforest vegetation to sugarcane fields between 1988 and 1999.

3.2.3 Changes Identified Within the Cairns Area

The NDVI of the Cairns region revealed that approximately 11.5% of the area was subjected to change when comparing the 1988 and 1999 mosaics. A total of 2.7%, or 13.15km^2, of the changes in the Cairns area occurred within the WTWHA. The Cairns area displayed more change than the Cooktown and Daintree areas due to the large amount of the Cairns sector under cultivation as sugarcane fields.

Cloud cover obscured a relatively small area of approximately 12.2km^2 within the Cairns area. The majority of these clouds were situated in remote areas of the WTWHA where anthropogenic changes would not be expected to have occurred.

Contiguous areas of *partial regeneration* and *regeneration* were located outside the WTWHA. Areas of partial regeneration found within the WTWHA were located along the WTWHA boundaries. Areas of regeneration within the WTWHA were identified along the Barron River north of Cairns and other smaller creeks.

The majority of areas classified as *partial regeneration* were found along rivers and creeks as well as in low-lying, transition areas between rainforest and woodland areas. Large areas classified as *regeneration* outside of the WTWHA were mostly related to cultivated land.

In 1988 in the Lake Mitchell area, water level differences and possibly higher turbidity levels, along with the availability of floating algae, resulted in large areas of Lake Mitchell originally being classified as regeneration. Some parts of Lake Mitchell were completely dry in 1988 but contained water in 1999. These areas were classified as clearing in the vegetation change maps due to the lower reflectance values of water in the 1999 image.

The perimeters of other lakes such as Lake Morris, Lake Barrine and Lake Eacham, all located within the WTWHA, were also classified as cleared in this study possibly due to the lower water levels recorded in 1988.

Beaches with fringing rainforest were in most cases classified as *cleared* even though the tide levels were similar south of Cairns between the two mosaics. This could have been due to mis-registration of the imagery or due to natural changes within the area. A comparison of the two mosaics revealed that they had not been subset identically, which resulted in the mis-classification.

Of the large area of sugarcane fields classified as cleared areas in the Cairns region, some sites had been converted from rainforest and wetlands into agricultural fields between 1988 and 1999.

3.2.4 Changes Identified Within the Innisfail Area

Comparing the 1988 and 1999 mosaics of the Innisfail area using NDVI found that approximately 9.4% of this region was subject to vegetation change. A total of 25.8km^2 or 4.7% of the total changes occurred within the WTWHA. Clouds covered an area of 69km^2 though 91.5% of the clouds were situated over the WTWHA.

The areas of change within the Innisfail area were equally divided between the four land cover classes. Most of the *partially regenerated* and *regenerated* areas within the WTWHA were found either along the boundaries of the WTWHA or along rivers and creeks.

The north-western part of Lake Koomboolooma was classified as *regeneration* because deep water is expected to absorb more light than shallow water. When considering the lower water levels and lower NDVI recorded in 1988 compared to the higher NDVI values found in 1999 it is possible that this part of the lake may have been affected by floating algae in the 1999 samples.

The majority of areas classified as *regeneration* were located in agricultural areas outside the WTWHA. Some areas of regeneration not related to agriculture were identified as riparian vegetation located west of Atherton and at a wetland area half way between Cairns and Port Douglas. Abandoned roads and a likely spatial offset between the mosaics caused linear features to be classified as *regeneration* or *clearing* in this sector.

The main areas classified as *thinning* and *clearing* within the Innisfail section of the WTWHA were identified along rivers, creeks and at Lake Koombooloома. Some of the rivers and creeks had exposed sandy stream banks in 1988 but these areas were covered by water in 1999, thereby yielding higher vegetation index values in 1988 than in 1999.

As the reflectance from water bodies is very low in visible and infrared bands, small reflectance differences can cause large proportional differences between the individual bands, influencing the vegetation index values considerably.

Outside the WTWHA the majority of cleared sites were located in agricultural areas. At least ten areas measuring between 0.3-1km^2 that had been covered by rainforest vegetation in 1988 had been cleared for agricultural purposes by 1999.

Some wetland areas and boundary areas between the beaches and the adjacent forested were classified as *cleared*.

3.2.5 Change Identified Within the Tully Area

The study of the Tully area using NDVI found that approximately 13.9% of the area experienced vegetation change when comparing the 1988 and 1999 mosaics. A total of 24.7km^2 or 2.8% of the total changes occurred within the WTWHA. Clouds obscured an area of 41km^2 though 96.4% of the clouds were positioned over remote areas within the WTWHA where anthropogenic changes would not be expected to occur.

Areas of *regeneration* and *partial regeneration* within the Tully section of the WTWHA were located along rivers, creeks and areas with topographic variation and less dense vegetation. Transitional areas between rainforest and woodlands extending into the WTWHA also exhibited *partial regeneration*. Some cultivated areas located on WTWHA property on the 1988 mosaic had regenerated by the time the 1999 images were generated. Most of the areas classified as regeneration were related to agricultural areas that where harvested prior to the image acquisition in 1988. Two large areas outside the WTWHA, approximately 6-7km^2 and 10km^2 respectively, were identified as *regenerated* but were not found to be related to agricultural activities.

Thinning and clearing within the WTWHA in the Tully area was identified along the Herbert River and its tributaries. These changes could be a result of either dry-period effects or the dynamic nature of river systems. Mis-registration between the two mosaics may also have influenced the mis-classification of linear features.

Thinned and cleared areas were also identified in the wetland areas north of Cardwell, again the majority of clearing was found to be associated with sugarcane farming. Some clearing has also occurred in the wetland areas west of Dunk Island where at least ten sites of over 1km^2 in area, situated outside the WTWHA, have been changed from rainforest cover in 1988 to cultivated areas in the 1999 samples. Areas along the tidal streams within the wetlands west and south of Hinchinbrook Island were classified as *cleared*, possibly due to the dynamic characteristic of these environments.

3.2.6 Changes Identified Within the Paluma Area

Approximately 17.5% (using NDVI) of the Paluma area was subject to change when comparing the 1988 and 1999 mosaics. A total of 15.8km^2 or 1.8% of the changes occurred within the WTWHA. Areas classified as *partial regeneration* accounted for 73.5% of the change within the Paluma region. Clouds covered an area of 2.3km^2, of which only 0.02km^2 was located over the WTWHA. The cloud shadows obscured only remote locations where anthropogenic changes would not be expected.

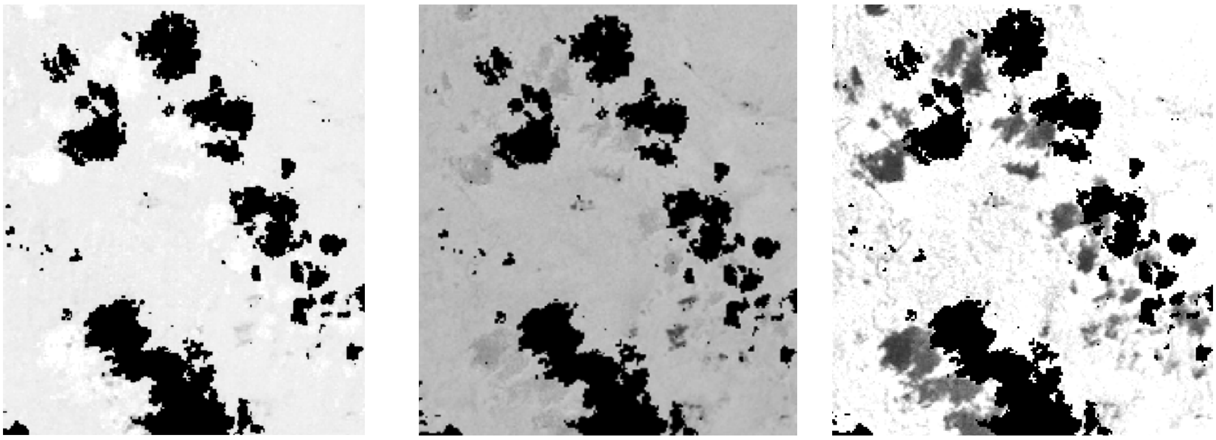
Partially regenerated areas within the Paluma section of the WTWHA were located along the boundaries of the WTWHA in topographically variable areas with sparse vegetation cover. Regeneration of 0.8-1km^2 within the WTWHA was located in one main area west-southwest of Ingham, while large areas of partially regenerated woodland were located west of the Paluma region of the WTWHA. Partial regeneration in these areas was attributed to the higher amount of rainfall in the year preceding image acquisition in 1999 compared to rainfall during the twelve months prior to 1988.

Areas of *partial regeneration* and *regeneration* were also identified in some coastal wetlands along the northern part of Halifax Bay, while *partial regeneration* could be identified in a sparsely vegetated area approximately 14km southwest of Ingham. The majority of regeneration occurred in agricultural areas where growing and harvesting patterns deviated between the dates of image acquisition in 1988 and 1999. Two areas of 3-4km^2 and 2-3km^2 respectively were identified as *regeneration* but are not located in agricultural areas.

Thinned and *cleared* areas within the WTWHA were located around creeks and a lake in the Paluma area. Cleared sites were identified along Crystal Creek however the majority of cleared sites were located in agricultural areas. The main section of clearing in the Paluma region between 1988 and 1999 occurred along the coastal areas east of the WTWHA.

3.3 COMPARISON OF CHANGE DETECTED FROM DIFFERENT VEGETATION INDICES (NDVI, IRI AND EVI)

To evaluate the performance of NDVI, IRI and EVI the extent and location of areas classified to individual land cover change classes by the vegetation indices were compared. During the classification of the land cover change classes, it became apparent that shaded areas caused by clouds had significantly affected the vegetation index values. Shaded areas caused EVI to yield lower than expected index values, even in areas of dense rainforest vegetation (Figure 22). The NDVI and IRI index values were not affected to the same extent as EVI in shaded areas caused by clouds (Figure 22).



Pixel values of shaded areas:	NDVI:	254	IRI:	196	EVI:	48
Pixel values of adjacent non-shaded areas:	NDVI:	246	IRI:	177	EVI:	227

Figure 22: Influence of shadows caused by clouds on the NDVI, IRI and EVI images. Black areas on the subsets indicate clouds that have been masked out. Shaded areas can be identified to the left of the clouds.

Figures 23 and 24 demonstrate that analysis of land cover changes mapped by the NDVI, IRI and EVI difference images did not produce identical results for the *cleared*, *thinned* and *partial regeneration* change classes. About the same areas of the regeneration class where mapped by each SVI. The graphs (Figure 23 and 24) do not demonstrate the spatial correspondence of the mapped changes but they do provide a means for assessing the sensitivity of each SVI for change detection.

Discrepancies were observed in the extent of land cover change mapped by each SVI at both the Wet Tropics bioregion and WTWHA scales. In all cases of land cover change, the EVI detected the most amount of change. In analysing just the tropical forest areas, NDVI detected the least amount of change and EVI the most. This was expected as the saturation of NDVI at high biomass levels reduces its ability to detect all but the largest changes within tropical forests. For the *cleared*, *thinned* and *partial regeneration* change classes, estimates of the aerial extent of change differed between the NDVI, IRI and EVI by within $\pm$100km^2 or $\pm$15%, with similar results found at both bioregion and WTWHA scales. The largest discrepancies between mapped land cover changes were for the *partial regeneration* class.

Previous work comparing NDVI and EVI for change detection in the Wet Tropics (Simpson and Phinn 2003) and other tropical forests (Huete *et al*. 2002) indicates that EVI should be the most accurate index, with NDVI and IRI expected to underestimate the extent of change. To provide more detail and a spatial component to the assessment, the land cover changes that were mapped using the three different SVIs in each individual sub-region were evaluated.

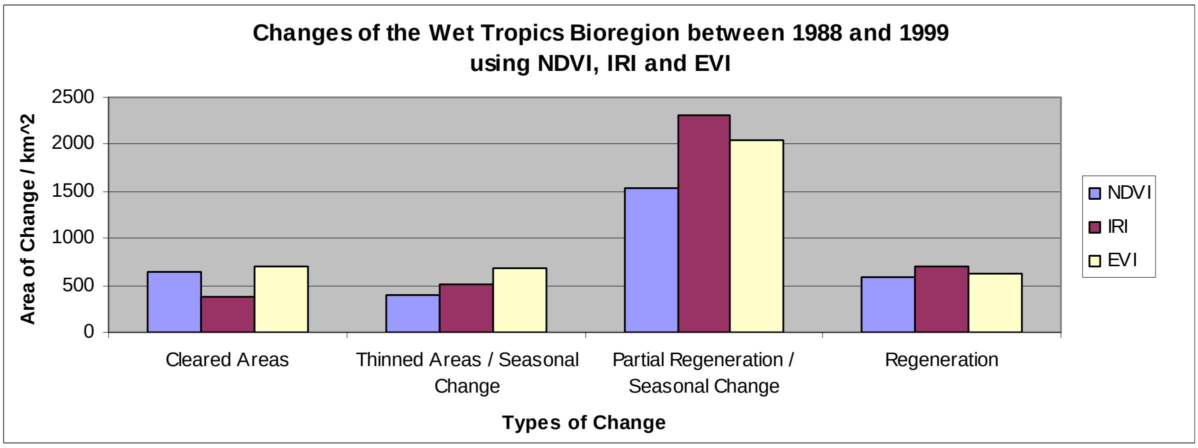


Figure 23: Area of land cover change classes for the Wet Tropics bioregion as mapped from NDVI, IRI and EVI difference images.

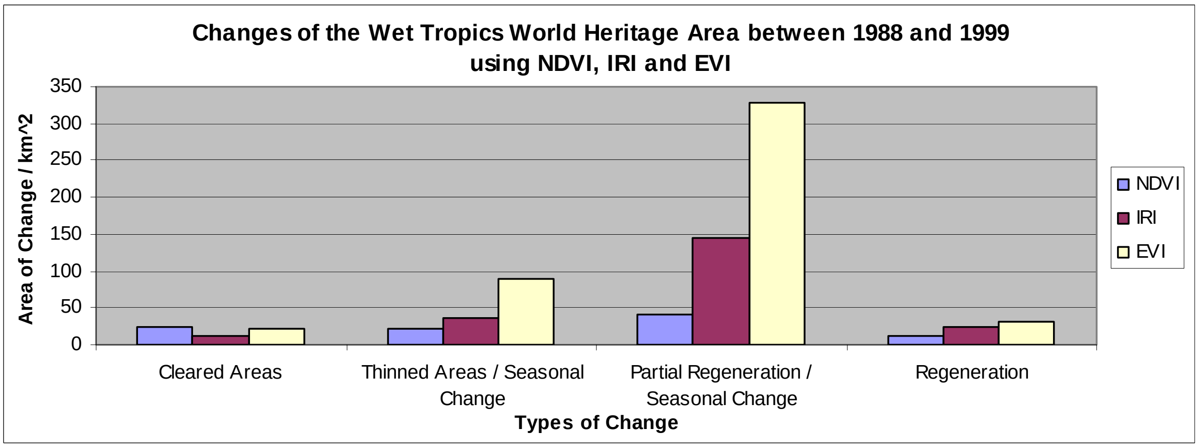


Figure 24: Area of land cover change classes for the WTWHA as mapped from NDVI, IRI and EVI difference images.

3.3.1 The Cooktown Area

A comparison of the NDVI, IRI and EVI change detection maps showed that *cleared*, *thinned* and *regenerated* areas were identified similarly by the three vegetation indices, except for one area located within the WTWHA (Easting 310140m; Northing 8266770m, UTM Zone 55S, WGS'84). The NDVI change detection map classified this area as *cleared*, whereas the IRI classified the area as *regenerated* and the EVI detected *no change*. The pixel values for this area produced different vegetation index values depicting different levels of change (Table 4). According to the Web and Tracey map, this area appears to be deciduous microphyll vine forest, which may explain the changes seen.

Table 4: Pixel and index values of an area (Easting 310140m; Northing 8266770m, UTM Zone 55S, WGS'84) within the WTWHA.

TM / TEM+ bands	Pixel values from 1988 mosaic	Pixel values from 1999 mosaic
1	16	69
2	7	57
3	2	74
4	30	87
5	132	145
7	96	105
NDVI (cleared)	0.429	0.081
IRI (regenerated)	-0.630	-0.25
EVI (no change)	0.190	0.121

A large difference between the NDVI, IRI and EVI land cover change maps was observed for the partially regenerated areas. IRI and EVI mapped more areas as *partial regeneration* than the NDVI. Partially regenerated areas were located along rivers and creeks and in the transition zones between rainforest vegetation and woodlands, especially in low-lying areas within topographically variable landscapes. As low-lying areas retain water over longer periods of time, it would be expected that IRI, including band 5 with the ability to detect vegetation moisture, identified differences between the two Landsat mosaics, (Lillesand and Kiefer 2000; Mora *et al.* 2003). Figure 25 confirms the extent of mapping differences of the partial regeneration land cover class.

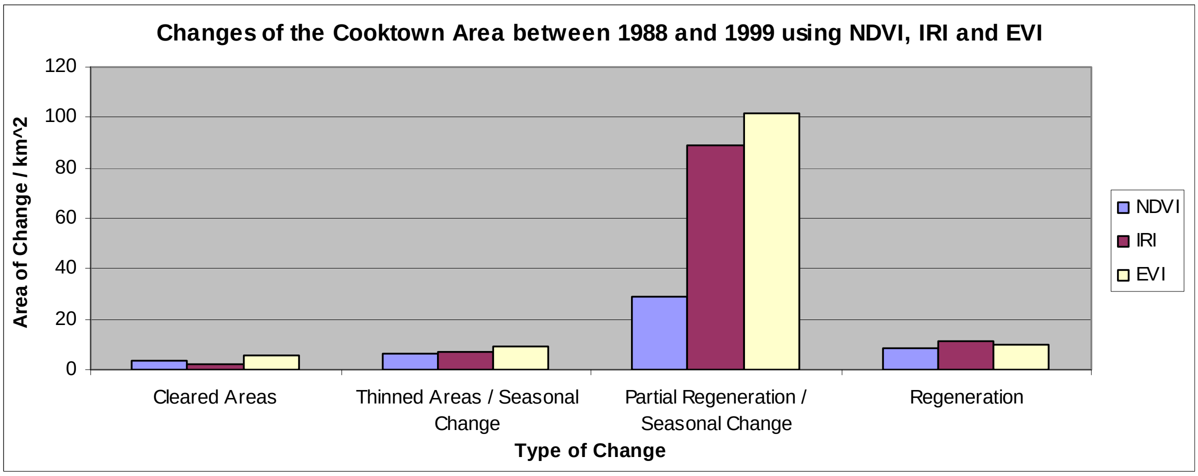


Figure 25: Area of land cover change classes for the Cooktown area as mapped from NDVI, IRI and EVI difference images.

3.3.2 The Daintree Area

The change detection maps of the Daintree area based on NDVI, IRI and EVI depicted similar characteristics as those of the Cooktown area (Figures 25 and 26). The areas classified as *cleared*, *thinned* and *regenerated* were similar between the three vegetation indices. The partially regenerated areas would have been either underestimated by NDVI or overestimated by IRI and EVI (Figure 26). As NDVI, IRI and EVI are all based on different spectral bands, the information extracted from them will vary. The thresholding of the individual land cover classes could also have influenced the extent of areas included in each land cover class.

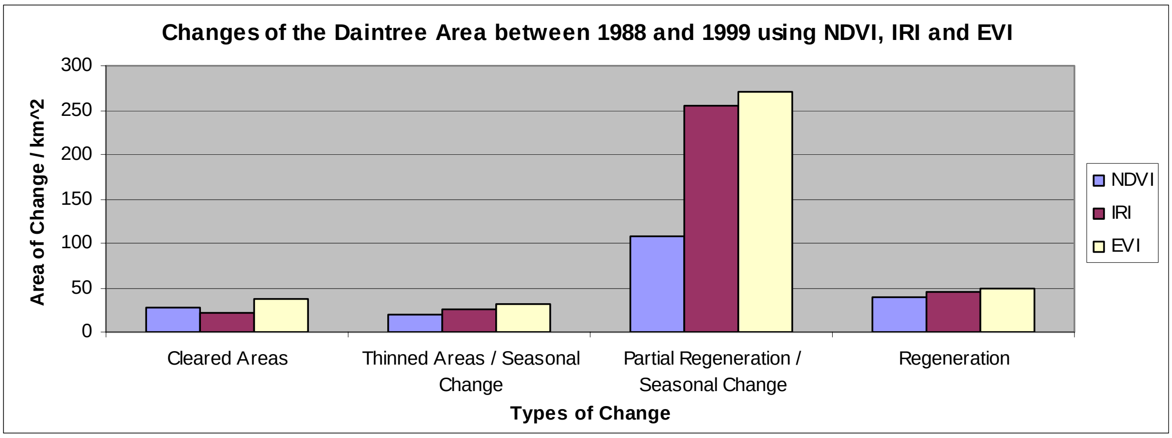


Figure 26: Area of land cover change classes for the Daintree area as mapped from NDVI, IRI and EVI difference images.

3.3.3 The Cairns Area

The same characteristics for the *partial regeneration* land cover class were identified for the Cairns area. The lakes in the Cairns region were classified differently by the three vegetation indices. NDVI classified most of Lake Barrine as *cleared*, whereas the IRI classified most of the lake as *regenerated*. The EVI detected *no change* in the vegetation cover (Table 5) except for the edges of the lake that displayed dry period effects in the results (Figure 12).

The classification of the lake as *no change* by EVI is due to the inclusion of the background brightness correction factor (L). As the blue, red and near-infrared spectral reflectance was very low, the brightness correction factor caused EVI to yield very low negative or positive index values that demonstrated little change between 1988 and 1999. The pixel values are very low due to the absorption of light by the water. Areas with very low pixel values are likely to show a large variation in vegetation index values due to the greater proportional differences between the pixel values of the spectral bands. Only small differences in the spectral reflectance caused by turbidity, for example, will have a major influence on the vegetation indices.

Shaded areas caused by clouds resulted in mis-classification when using EVI. Similar effects were identified in areas with topographic variation. Shaded areas were classified as either *thinned* or *cleared areas* by EVI (Figure 27). The differences between the observed land cover classes in Figure 28 are therefore a product of the different information provided by the three vegetation indices.

Table 5: Pixel and index values of an area at Lake Barrine within the WTWHA.

TM/ETM+ bands	Pixel values from 1988 mosaic	Pixel values from 1999 mosaic
1	9	7
2	0	1
3	0	3
4	2	7
5	9	13
7	4	7
NDVI	1	0.4
IRI	-0.636	-0.3
EVI	0.026	0.044

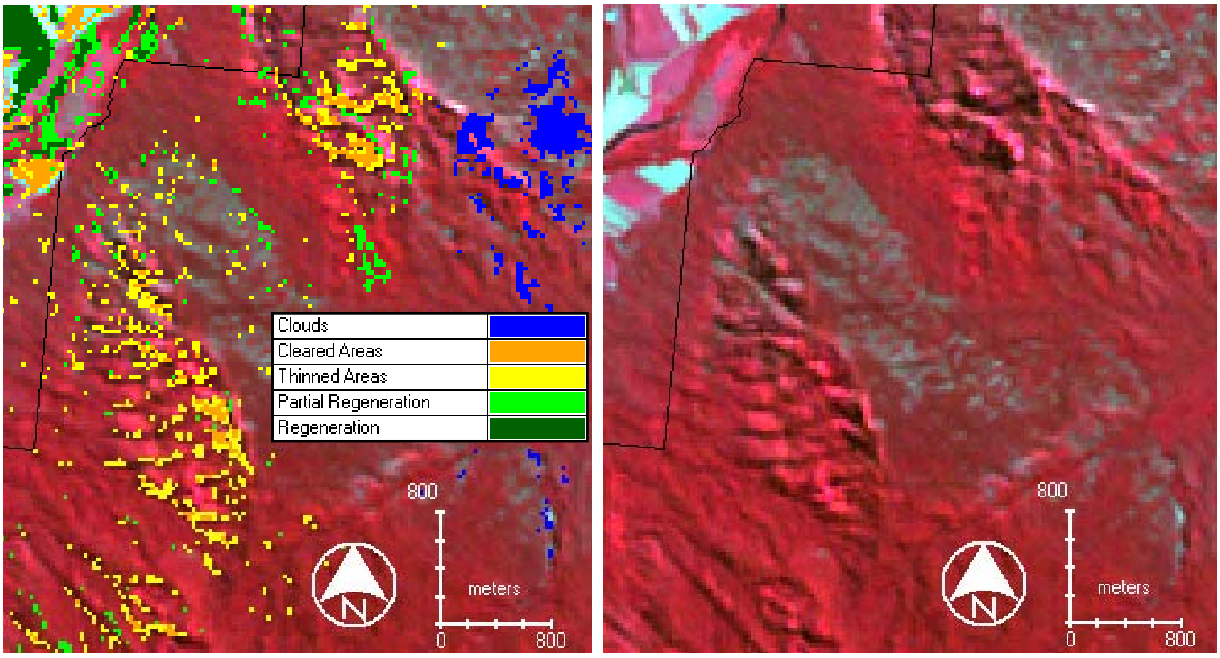


Figure 27: False colour composite (band 2, 3 and 4) with and without the EVI change detection map overlaid. Image is located approximately 6.5km south of Gordonvale.

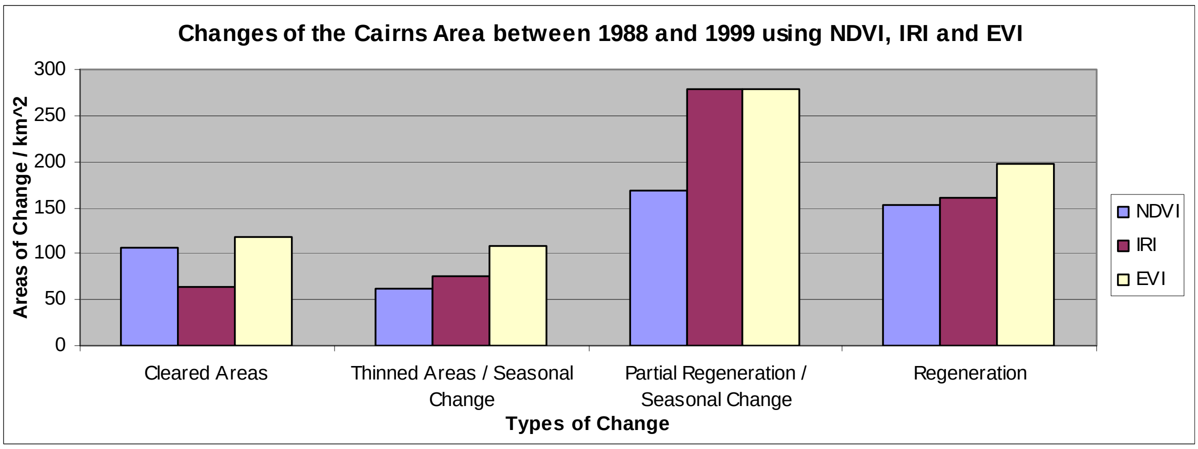


Figure 28: Area of land cover change classes for the Cairns area as mapped from NDVI, IRI and EVI difference images.

Figure 27 demonstrates how the shaded areas were mis-classified using EVI. A comparison of the original Landsat mosaics revealed that the topographical correction of the 1988 mosaic was more successful than for the 1999 mosaic in limiting the effects caused by topographic variation in the landscape. Shaded areas in the 1999 mosaic had therefore considerably lower pixel values than the corresponding areas on the 1988 mosaic. The mis-classification of shaded areas was not identified using NDVI and IRI. An example of typical pixel values from shaded and sunlit rainforest areas within the WTWHA is provided in Table 6.

Despite the large difference in pixel values between the shaded and sunlit areas, NDVI results are similar in both, while the IRI shows a small increase in pixel values in sunlit areas. The EVI yielded distinctly different index values in the shaded and sunlit rainforest areas. It was found that the larger difference between the near-infrared and red reflectance in conjunction with the multiplication of the gain factor (2.5) result in large differences between EVI values for shaded and sunlit areas.

Table 6: Pixel and index values of a shaded area within the WTWHA covered by rainforest.

TM/ETM+ bands	Shaded rainforest area	Sunlit rainforest area
1	6	12
3	2	12
4	23	122
5	13	52
NDVI	0.84	0.82
IRI	0.28	0.40
EVI	0.21	0.77

3.3.4 The Innisfail Area

The extent of cleared and regenerated areas identified by IRI was smaller than when using NDVI and EVI (Figure 29). Both IRI and EVI mapped greater *thinned* and *partially regenerated* areas than the NDVI, resulting in EVI mapping a much larger area of vegetation change in the Innisfail area than NDVI and IRI.

The larger area identified as *cleared*, together with the thinned areas mapped by EVI, was partly due to the mis-classification of shaded areas. Large agricultural areas classified as *no change* by NDVI and IRI were in some cases classified as *thinned* or *partially regenerated* areas by EVI. This was found to be partly due to the thresholding of the individual land cover classes and particularly due to the correction terms included in EVI.

Some partially regenerated areas were found along the woodland riparian zones as well as in low-lying transitional areas between rainforest and woodlands throughout the Innisfail region, IRI identified the largest extent of partial regeneration in these areas.

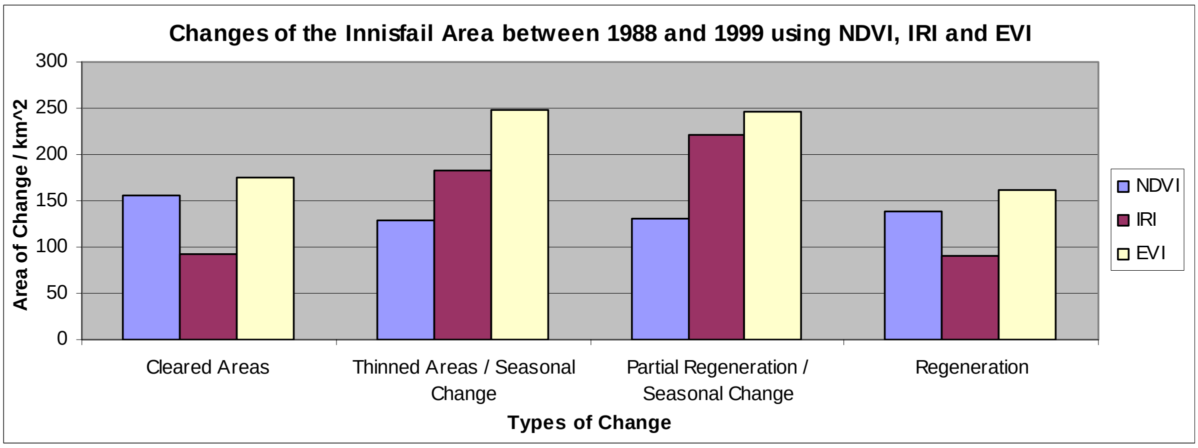


Figure 29: Area of land cover change classes for the Innisfail area as mapped from NDVI, IRI and EVI difference images.

3.3.5 The Tully Area

The proportional distribution of *cleared* and *thinned* areas between NDVI, IRI and EVI was similar to results from the other areas in this study, though IRI identified more *partially regenerated* and *regenerated* areas than EVI (Figure 30). EVI mis-classified some areas as *thinned* due to topographic shadowing effects. NDVI, and particularly IRI, identified more areas of *partial regeneration* than EVI in the woodlands west of the WTWHA.

Another difference between the change detection maps using the three vegetation indices was the classification of *partial regeneration* detected by EVI in the mangrove wetland areas of Hinchinbrook Island and the coastal wetlands south and to the west of the Island (Table 7). The pixel values for these areas were evaluated to determine the reason for this difference. It can be seen that near-infrared reflectance was higher in 1999 than in 1988. The proportional differences between the red and near-infrared reflectance, as well as the near-infrared and mid-infrared, were approximately the same. The main reason for the increase in EVI in 1999 is related to the larger difference between the red and near-infrared reflectance and the multiplication with the gain factor.

The tide level was similar in this area at the time of image acquisition in 1988 and 1999 (Table 3) but water levels could have been influenced by wind patterns and atmospheric pressure. A slight increase in the water level at the time of image acquisition in 1988, caused by wind or atmospheric factors, may have lowered the reflectance values in the wetland areas due to the absorption of light by water.

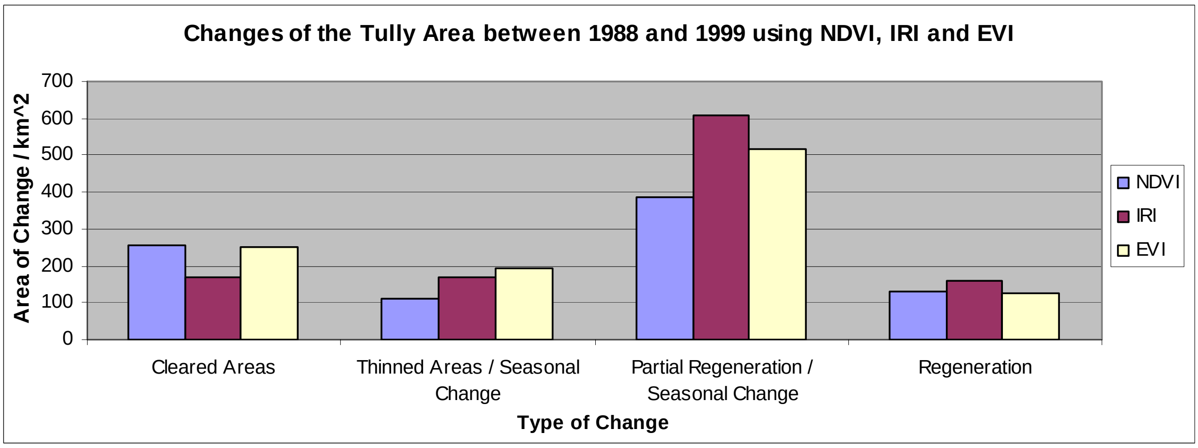


Figure 30: Changes in vegetation cover of the Tully area mapped by NDVI, IRI and EVI.

Table 7: Pixel and index values of an area on Hinchinbrook Island.

TM/ETM+ bands	Pixel values from 1988 mosaic	Pixel values from 1999 mosaic
1	9	11
2	5	11
3	5	10
4	66	98
5	21	30
7	10	12
NDVI (cleared)	0.859	0.815
IRI (regenerated)	0.517	0.531
EVI (no change)	0.538	0.666

3.3.6 The Paluma Area

Small areas were classified as *cleared*, *thinned* and *regeneration*. A much larger area was identified as *partial regeneration* using NDVI, IRI and EVI. IRI classified a regeneration area twice as large as NDVI and EVI (Figure 31).

Large woodland areas were classified as *partial regeneration* using NDVI and IRI. The main section of these partially regenerated woodlands (mapped by IRI) were located just west of the WTWHA, whereas NDVI also identified woodlands further inland as *partially regenerated*. Some of the woodland areas were even classified as *regeneration* using IRI. This was the main reason for the differences between IRI, NDVI and EVI in this land cover class. Some of the wetland areas along Halifax Bay were also classified as *partial regeneration* using EVI, though most areas within the Paluma region, except for the woodland and wetland areas, produced similar results for the NDVI, IRI and EVI methods of differencing.

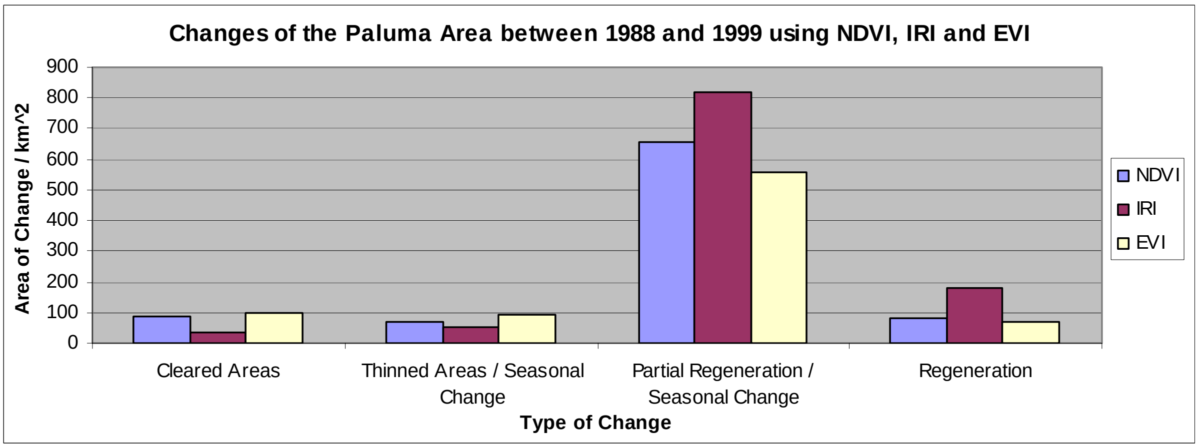


Figure 31: Change of the Paluma area mapped by NDVI, IRI and EVI.

4. CONCLUSIONS AND IMPLICATIONS FOR RAINFOREST MAPPING

4.1 MAPPING CHANGES IN RAINFOREST VEGETATION COVER

Vegetation cover change was mapped using Spectral Vegetation Index (SVI) image mosaics of the Wet Tropics bioregion derived from Landsat 5 TM and Landsat 7 ETM+ images collected in 1988 and in 1999. The image data sets had previously been geometrically, radiometrically and atmospherically corrected by Bruce and Hilbert (2003). Processing in this project conducted further checks of geometric and atmospheric correction accuracy before applying vegetation index transformations and classification.

The SVIs produced maps of a continuous biophysical variable directly related to vegetation cover, biomass and LAI for the entire Wet Tropics bioregion in both 1988 and 1999. The three most commonly used SVIs for tropical forests; NDVI, IRI and the EVI were applied in this work.

Successive SVI image pairs were subtracted to produce three SVI difference images (1988 minus 1999) and each image was then classified into six types of land cover change:

1. Clouds;
2. Cleared areas;
3. Thinned areas / seasonal change;
4. No change;
5. Partial regeneration / seasonal change; and
6. Regeneration.

Analysis of land cover change was then conducted within the Wet Tropics bioregion, generally, and the WTWHA particularly. To enable accurate and complete description of vegetation cover change the region was divided into six zones for analysis:

a) Cooktown area;
b) Daintree area;
c) Cairns area;
d) Innisfail area;
e) Tully area; and
f) Paluma area.

Observations of the differences between the 1988 and 1999 data sets revealed some changes in the vegetation cover throughout the Wet Tropics area of northern Queensland, including:

- Less than five percent of the total Wet Tropics bioregion and less than one percent of the WTWHA can be classified as *cleared areas*. The cleared areas detected corresponded mainly to the expansion of agricultural land and associated agricultural activities in the Tully and Innisfail areas. Other cleared sites relate to the development of human infrastructure such as road and powerline corridors throughout the region. The clearing of vegetation within the WTWHA was concentrated around several small features; the cause of this vegetation clearance could not be established by this study.

- Extensive *partial regeneration* of vegetation throughout the entire study area could be attributed to the influence of below average rainfall in 1988 and more standard rainfall figures in 1999 (Appendix 1). The lower than average rainfall in 1988 is assumed to have caused the reduced canopy density and reduced LAI observed that year. Spatially, this partial regeneration was most prevalent along waterways and in the transitional zones between woodland, schlerophyll forests and rainforest.

- Of the three SVIs used in this study, the EVI was considered to provide the most accurate representation of vegetation cover change in the high biomass and high LAI environment of the Wet Tropics. Classification of vegetation change from the EVI enabled identification of the areas of most change in the Wet Tropics bioregion and within the WTWHA. Results obtained in this analysis support similar conclusions from past research on the use of EVI for tropical forest monitoring (Huete *et al.* 2002, Lucas *et al.* 2004).

- Due to its reliance on a red band, the NDVI was subject to saturation effects therefore low levels of increased or decreased vegetation cover at high biomass levels were unable to be detected using this method.

- The estimates of vegetation change classes used in this study should be treated with caution as the images used to perform the mapping represent two snapshots, at single points in time, of a highly dynamic system. It is possible that clearance and regrowth of different vegetation may have occurred during the ten years between each of the image mosaics and this change is not represented in these mapping results.

The EVI was considered to provide the most accurate representation of vegetation cover change in the high biomass and high LAI environment of the Wet Tropics, except for the cloud shaded areas. The reliance on the red band by the NDVI lead to saturation effects that caused a small increase or decrease in vegetation cover at high biomass levels to be undetectable though the NDVI was of benefit for identifying the full range of vegetation cover classes.

4.2 FUTURE MAPPING AND MONITORING OF VEGETATION COVER CHANGE

Results presented in this paper highlight the capacity of SVIs to map and monitor vegetation cover changes in the Wet Tropics. There are two operational possibilities for continuing this monitoring on an annual or more frequent basis.

1. The Statewide Landcover and Trees Study (SLATS) (Queensland Department of Natural Resources and Mines) is now mapping woody vegetation cover from a modified Landsat-based SVI for the entire state of Queensland on an annual basis. The SVI used by SLATS could be requested and examined for the Wet Tropics and then compared to previous years SVI to identify areas of change in vegetation cover.

2. Researchers of Rainforest CRC Project 1.2 have designed a mapping and monitoring program using freely available MODIS EVI image data that are provided on a daily or weekly basis. By developing this proposed system further, weekly image data could be used for mapping and monitoring vegetation cover and its change over time.

ACRONYMS

CASI .... Compact Airborne Spectrographic Imager
CSIRO .... Commonwealth Scientific and Industrial Research Organisation
EVI................. Enhanced Vegetation Index
IRI.................. Infrared Index
LAI .... Leaf Area Index
MIR................ Mid infrared
NDVI.............. Normalised Difference Vegetation Index
NIR .... Near-infrared
PIF................. Pseudo-Invariant-Features
SAR .... Synthetic Aperture Radar
SLATS .... Statewide Landcover and Trees Study
SVI................. Spectral Vegetation Indices
WTWHA .... Wet Tropics World Heritage Area

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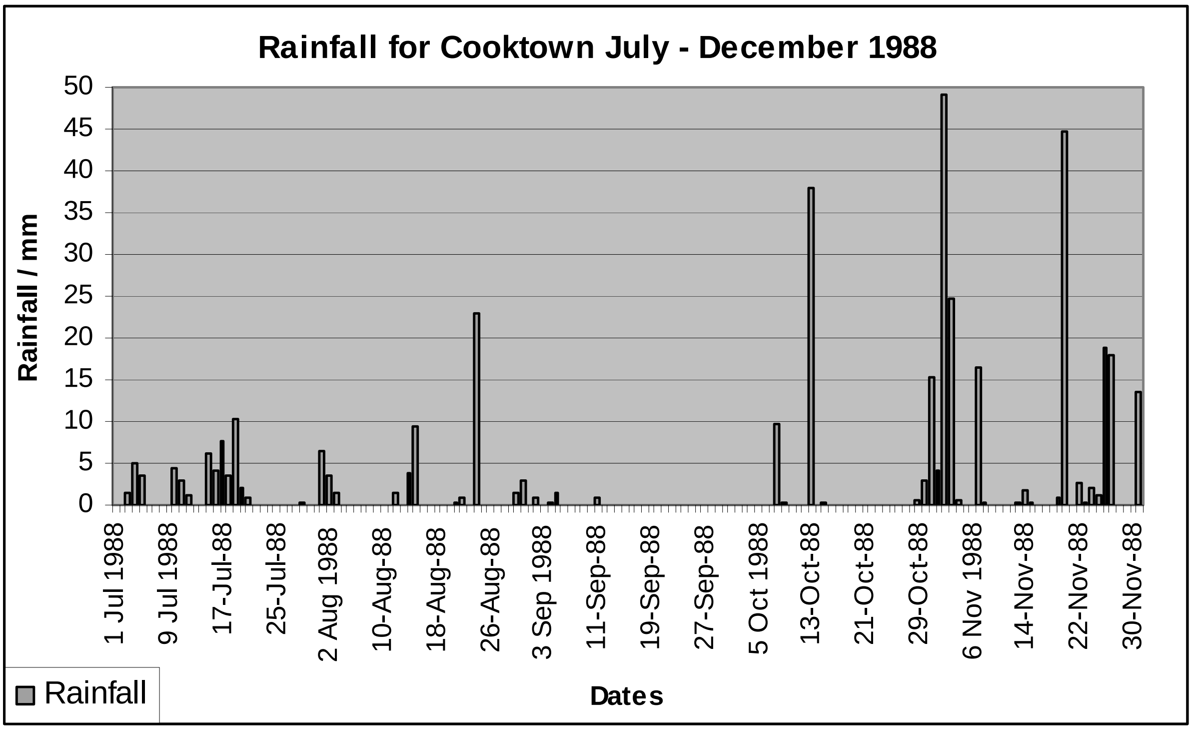
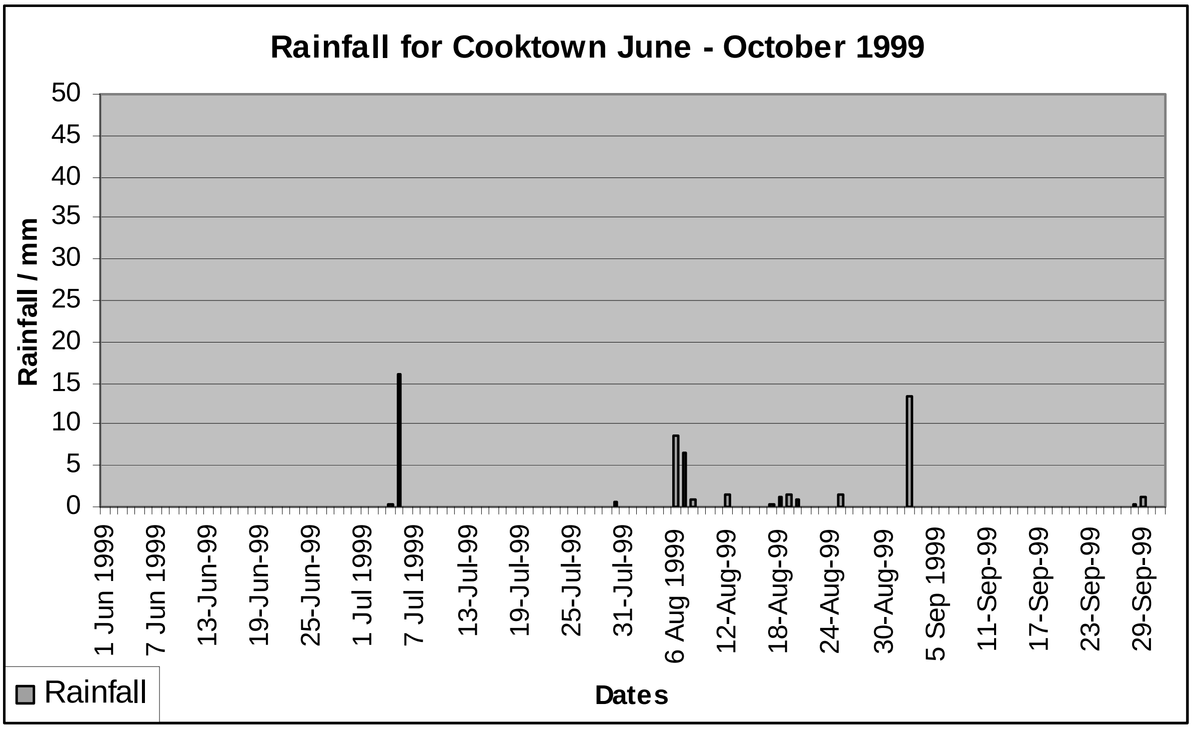
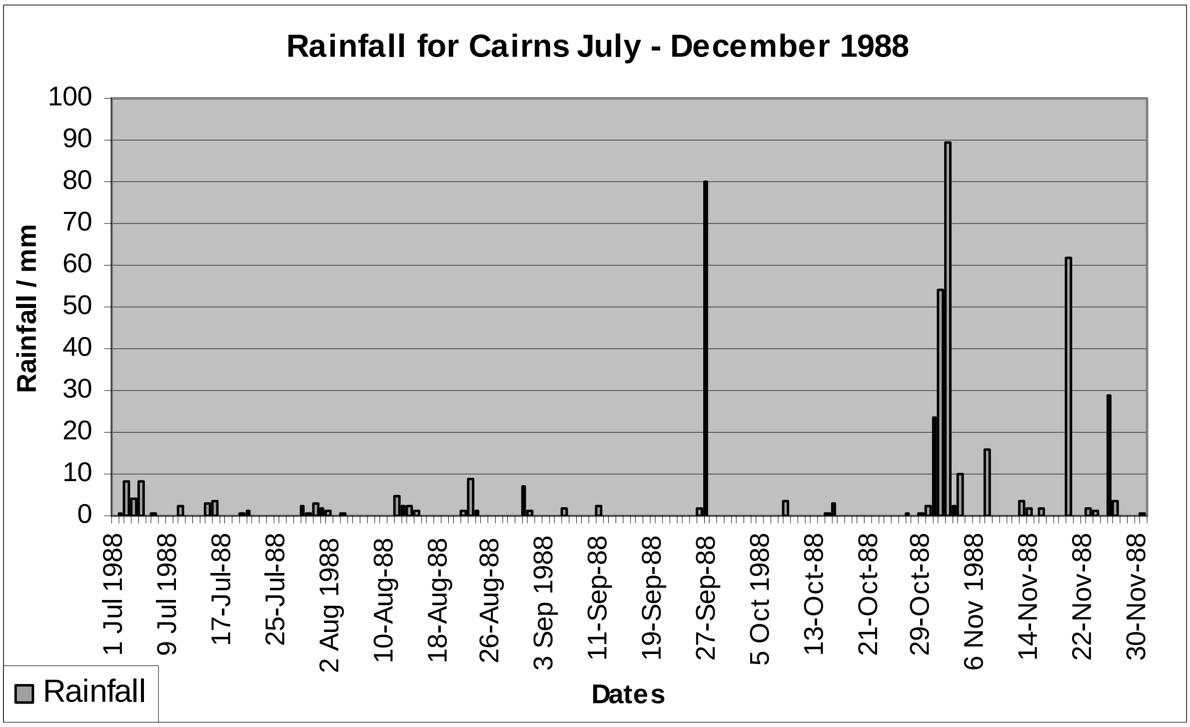
APPENDIX 1 – RAINFALL DATA



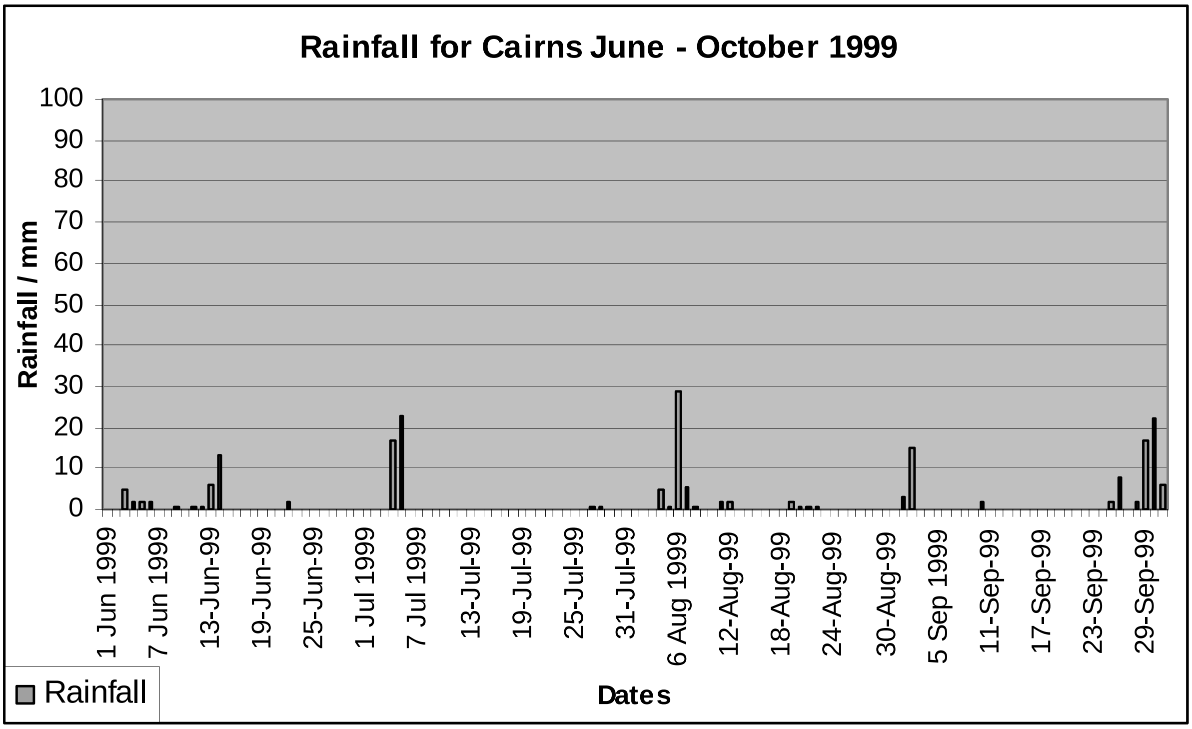
July 1986 to July 1988 – 2,539mm
July 1987 to July 1988 – 899mm



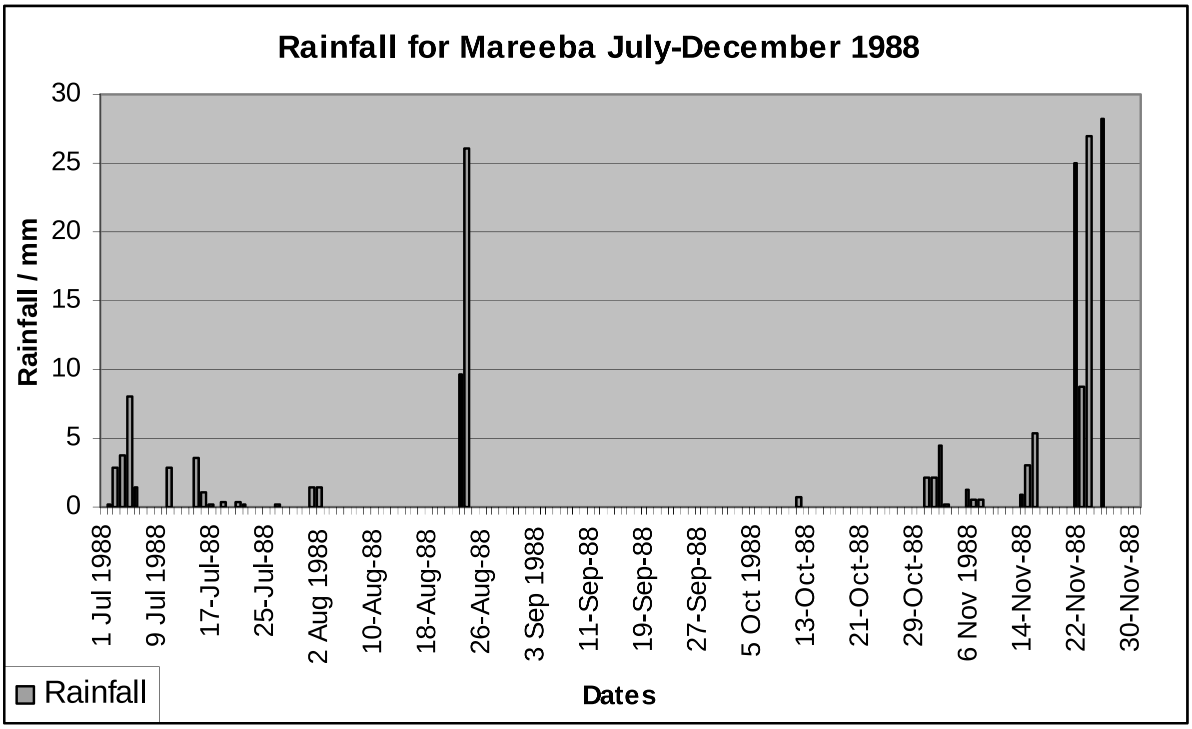
June 1997 to June 1999 – 4,478mm
June 1998 to June 1999 – 2,104mm



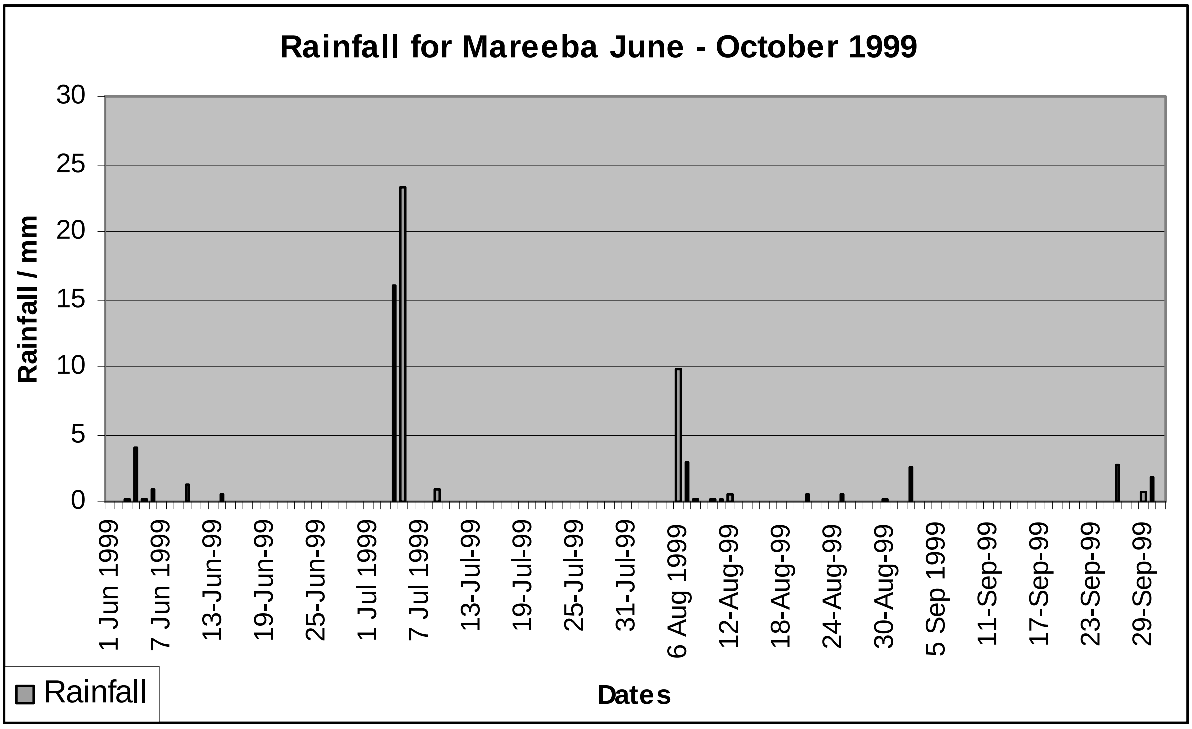
June 1986 to July 1988 – 3,105mm
July 1987 to July 1988 – 1,359mm



June 1997 to June 1999 – 4,230mm
June 1988 to June 1999 – 2,484mm



July 1986 to July 1988 – 1,366mm
July 1987 to July 1988 – 694mm



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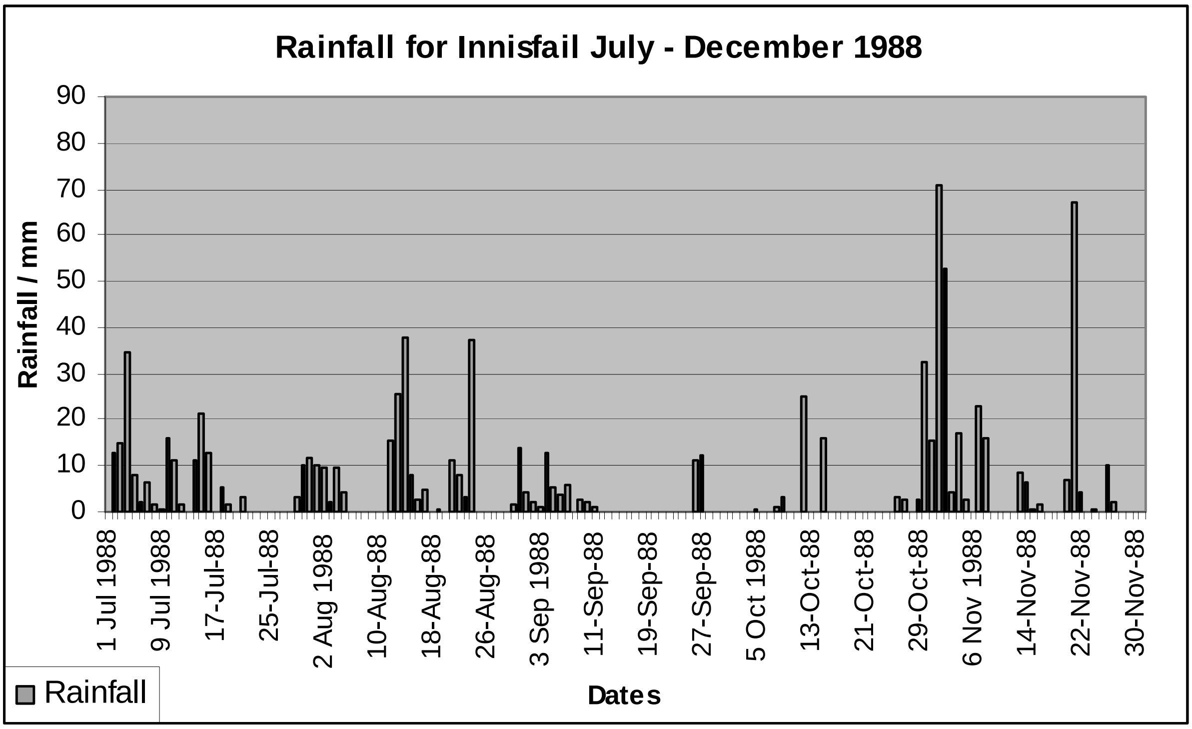

July 1986 to July 1988 – 5,851mm
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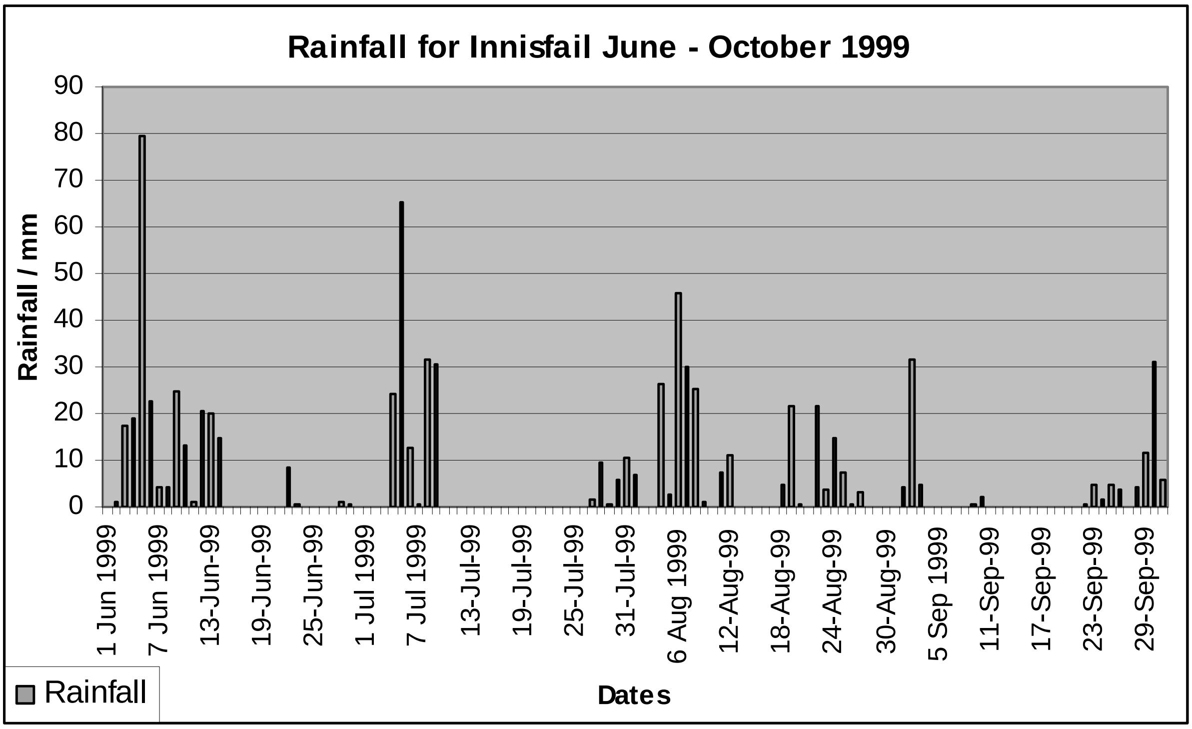

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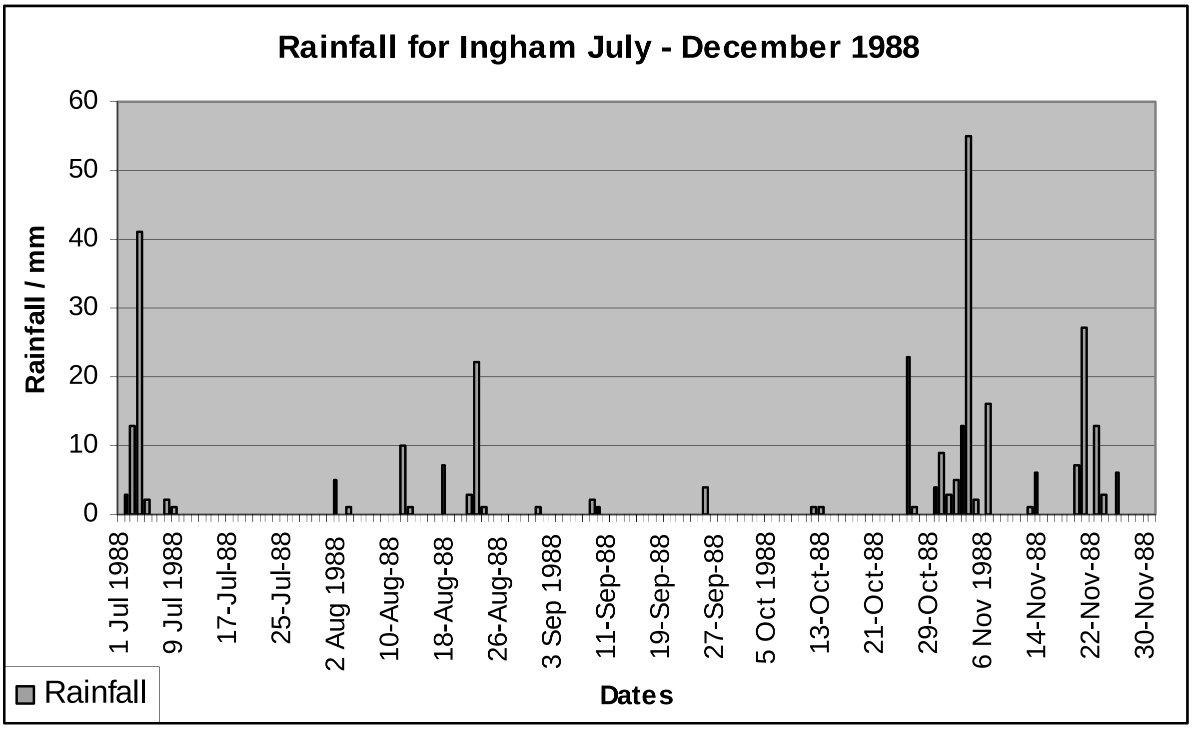

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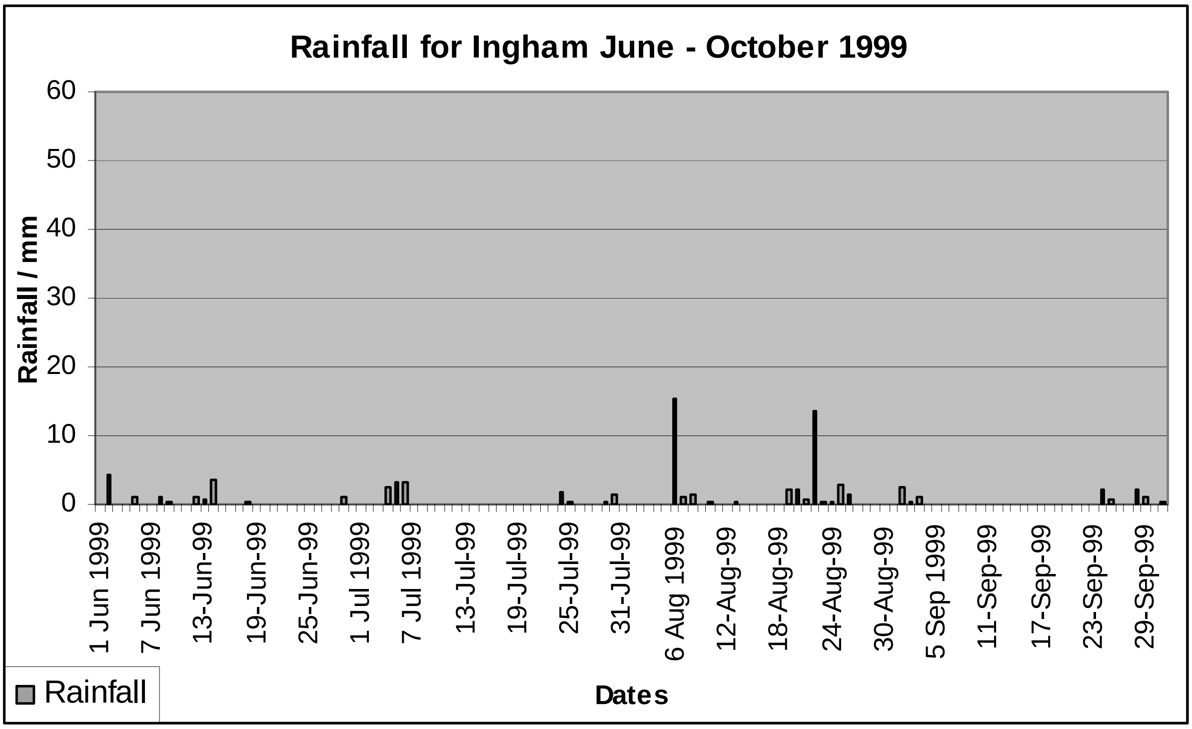
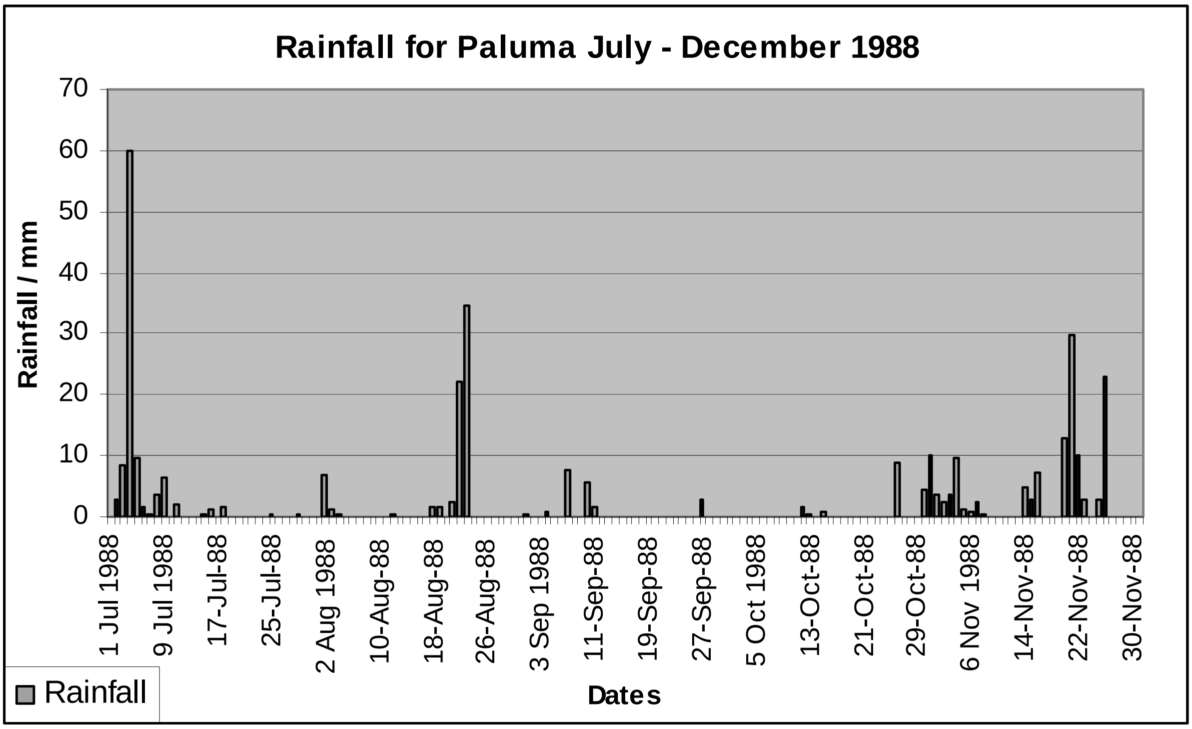


June 1997 to June 1999 – 5,542mm
June 1998 to June 1999 – 2,702mm



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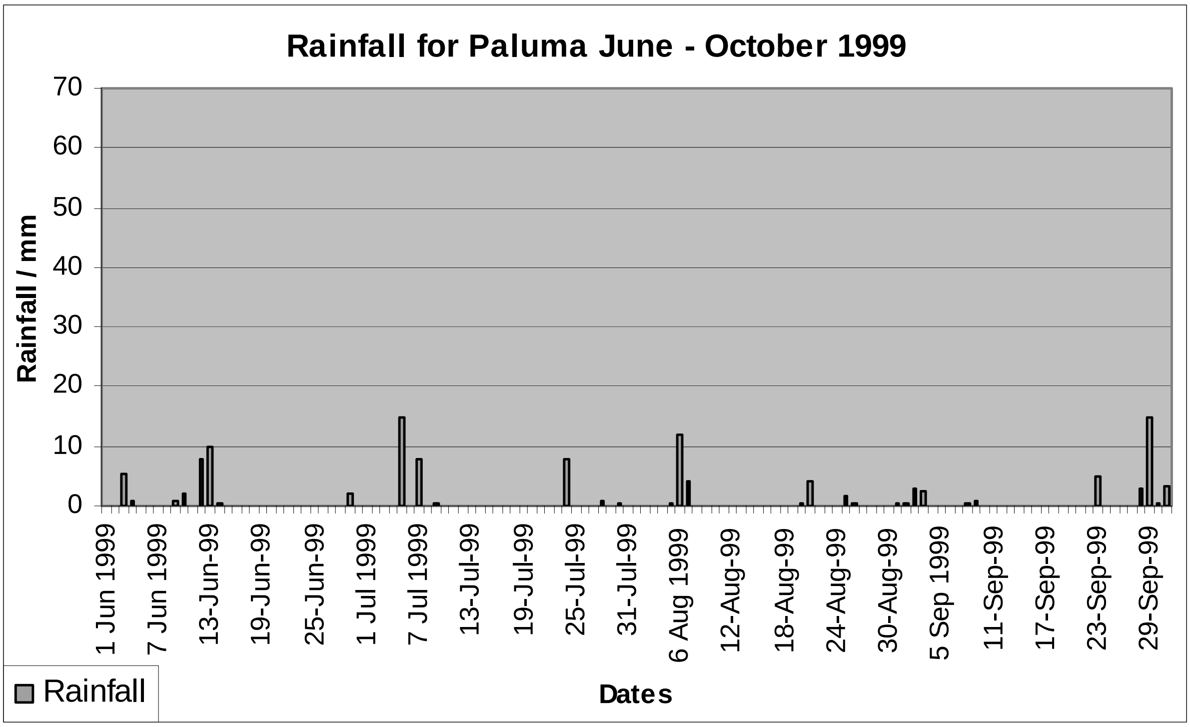
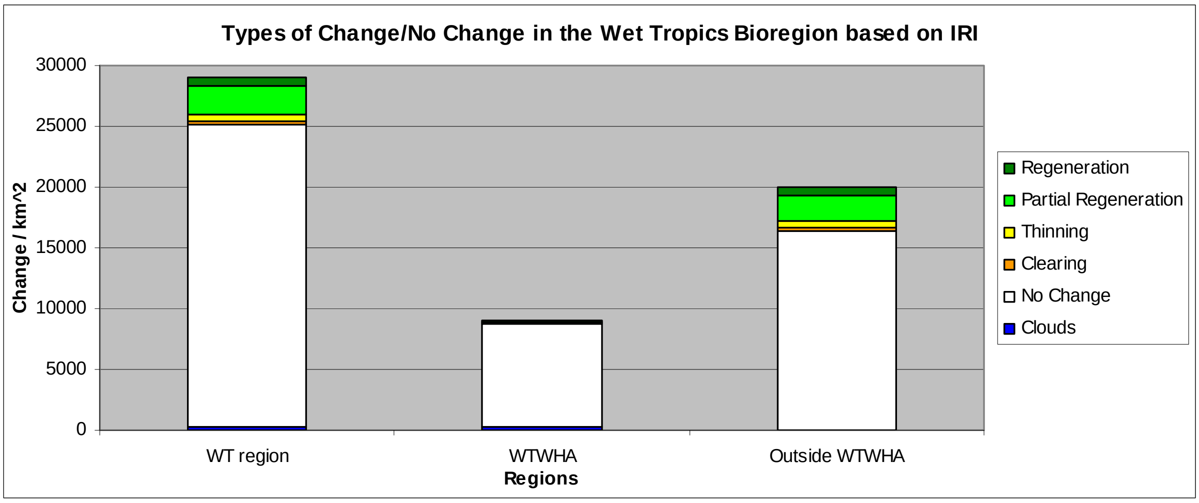
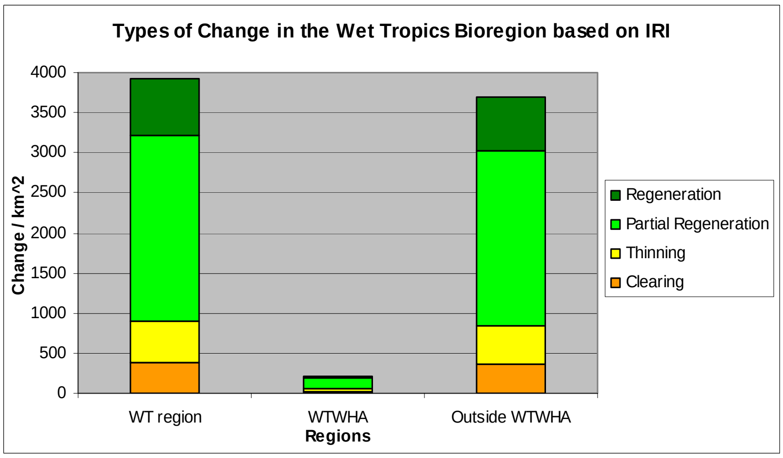
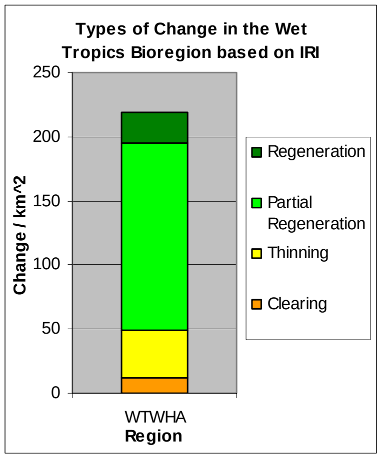


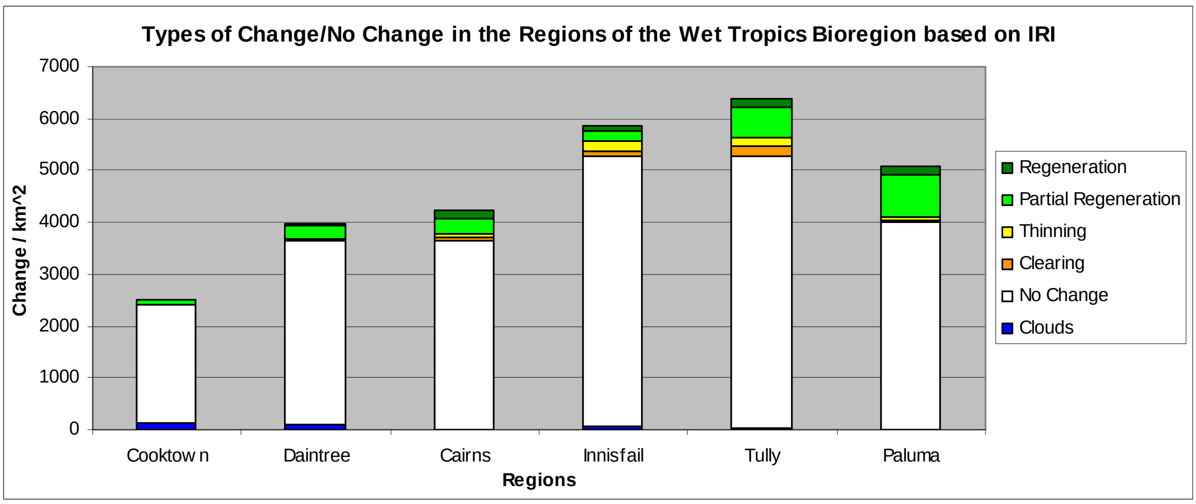
June 1997 to June 1999 – N/A
August 1998 to June 1999 – 2,853mm

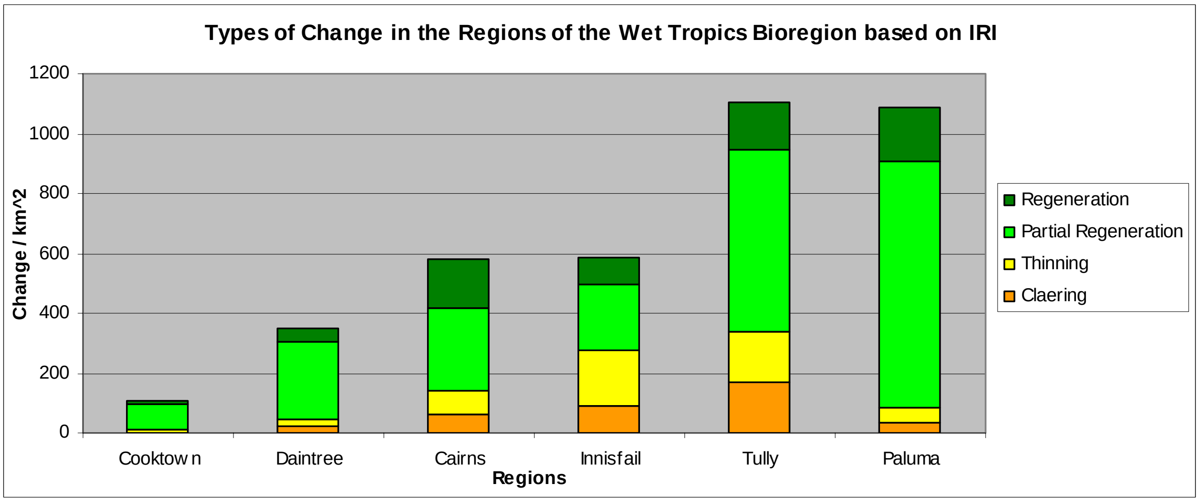
APPENDIX 2 – CHANGES MAPPED BY IRI AND EVI

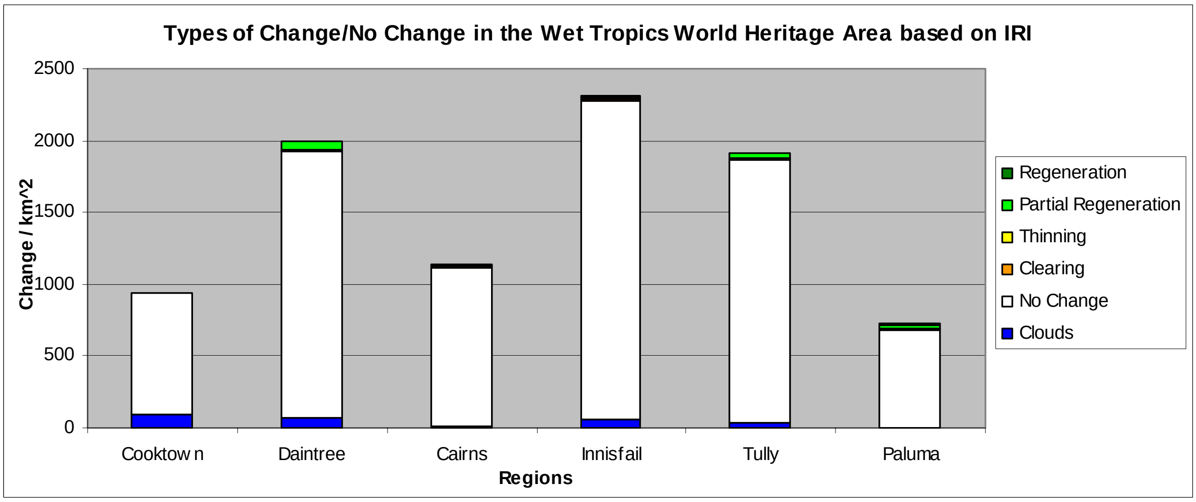


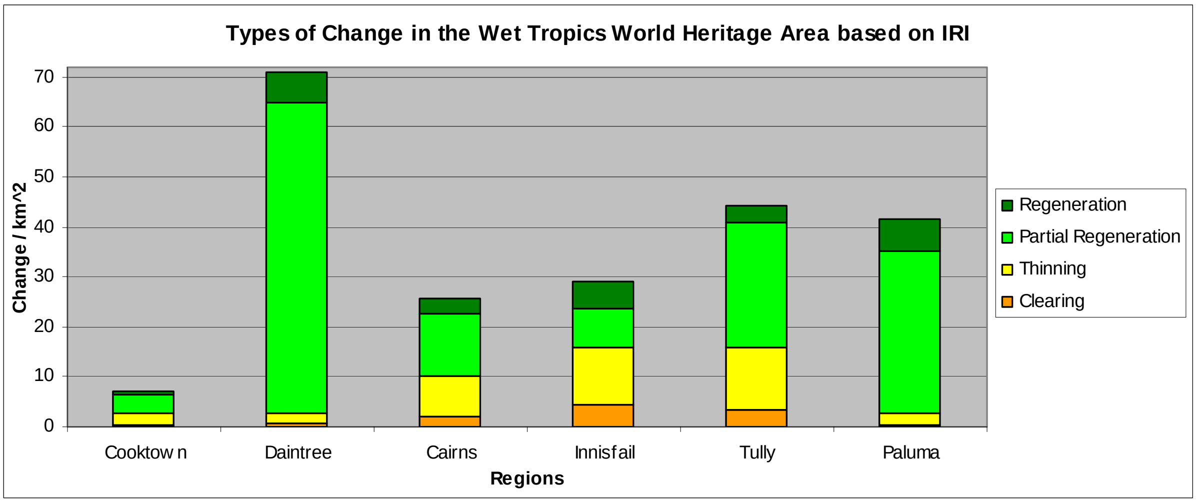


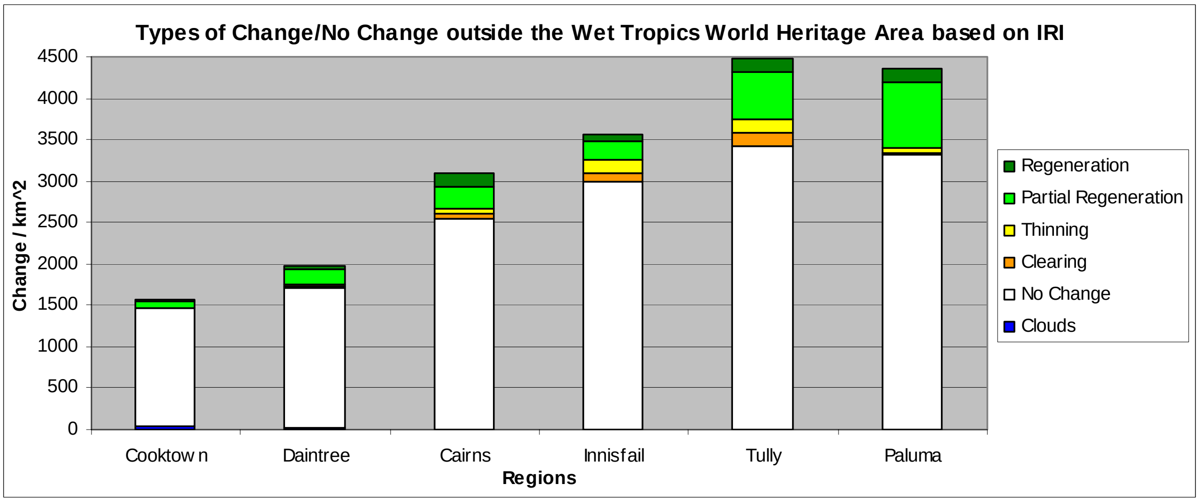


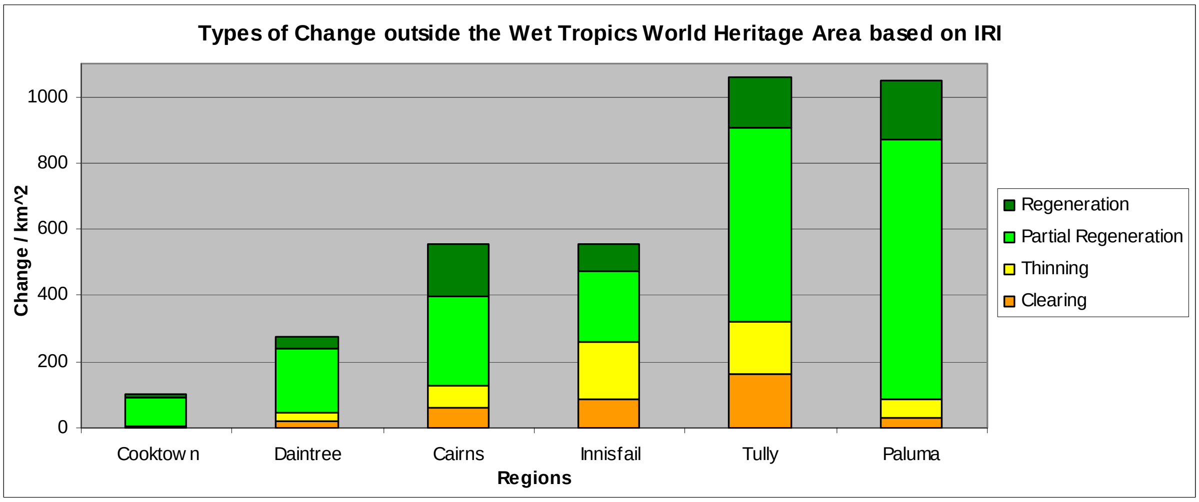


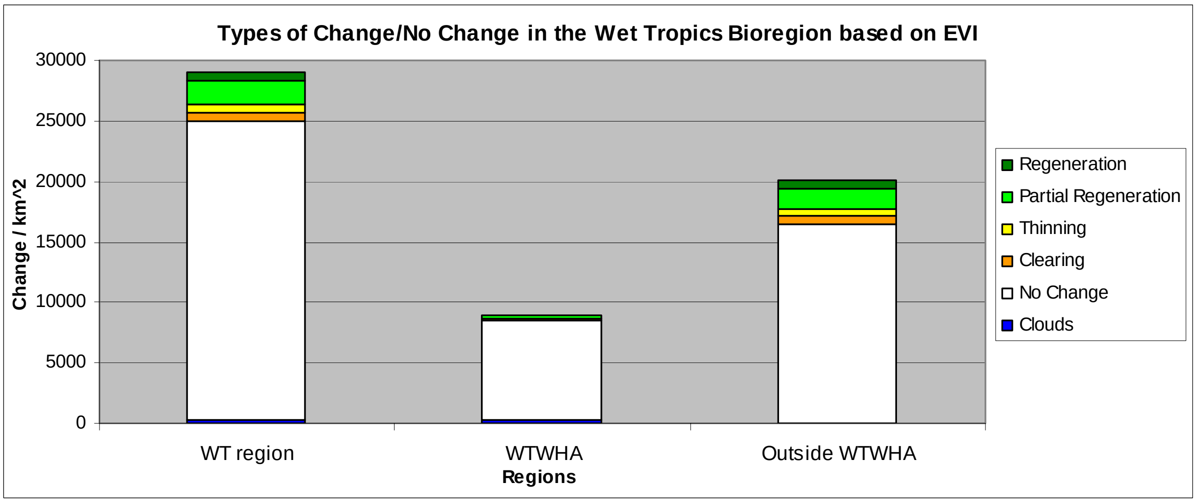

Types of Change in the Regions of the Wet Tropics Bioregion based on IRI
Change / km^2
1200
1000
800
600
400
200
0
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Claering

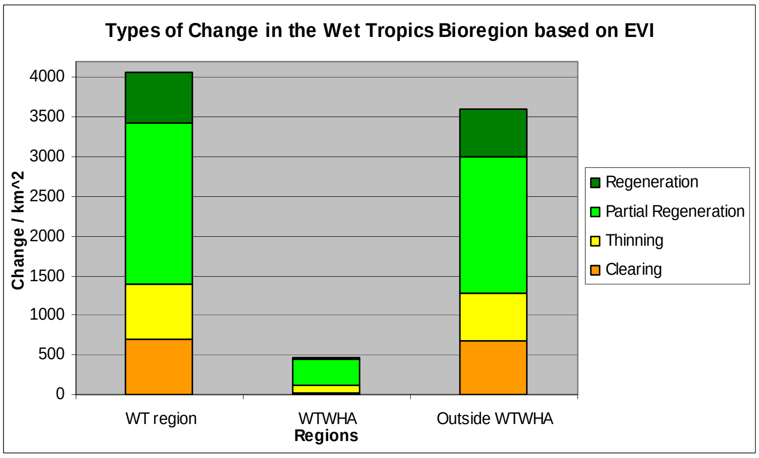

Types of Change/No Change in the Wet Tropics World Heritage Area based on IRI
Change / km^2
2500
2000
1500
1000
500
0
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing
No Change
Clouds

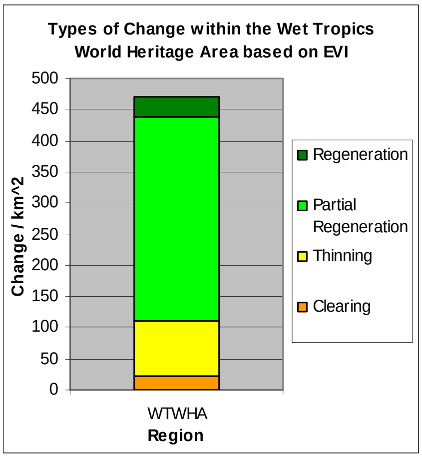

Types of Change in the Wet Tropics World Heritage Area based on IRI
Change / km^2
70
60
50
40
30
20
10
0
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing

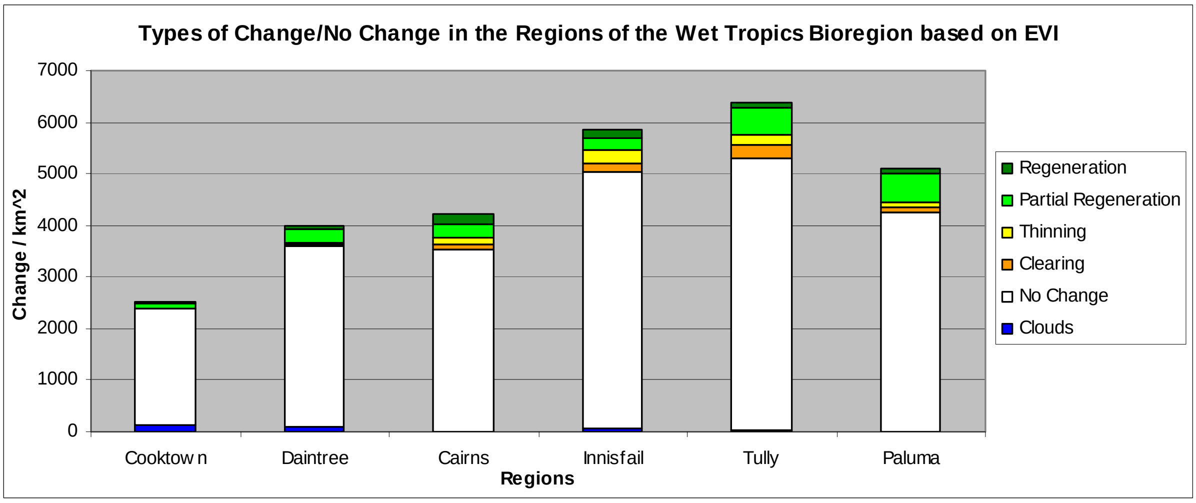

Types of Change/No Change outside the Wet Tropics World Heritage Area based on IRI
Change / km^2
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing
No Change
Clouds

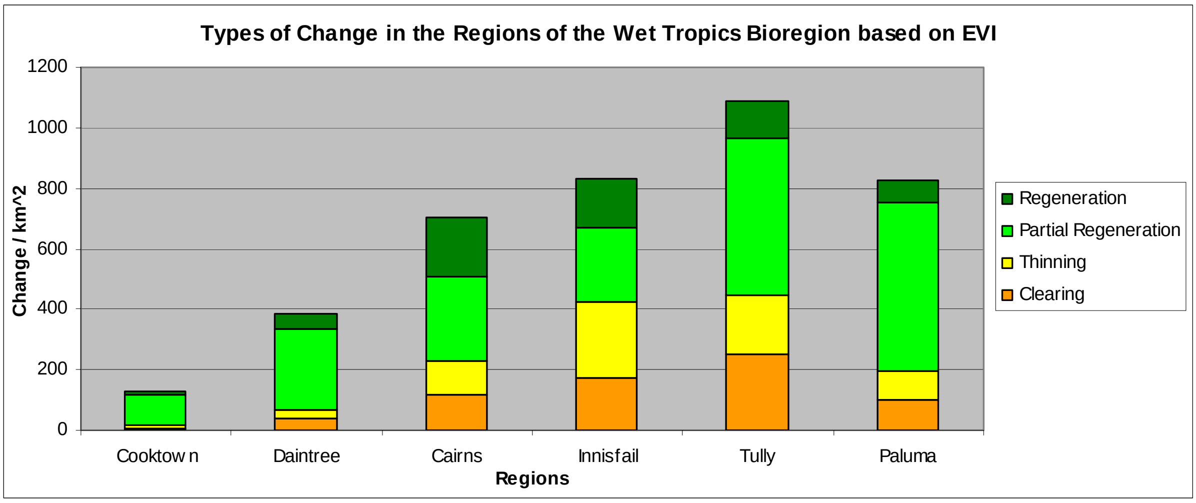

Types of Change outside the Wet Tropics World Heritage Area based on IRI
Change / km^2
1000
800
600
400
200
0
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing

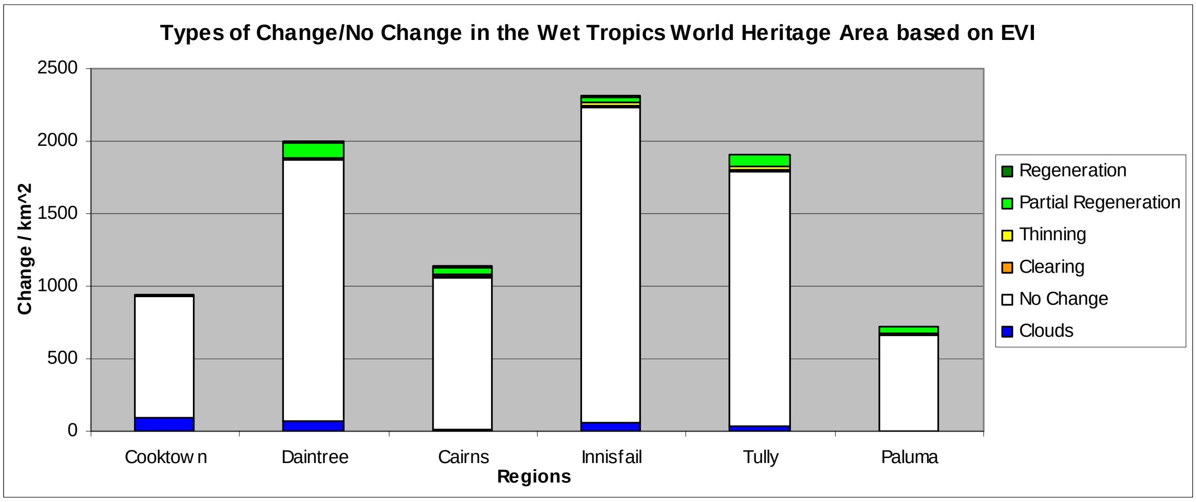

Types of Change/No Change in the Wet Tropics Bioregion based on EVI
Change / km^2
30000
25000
20000
15000
10000
5000
0
WT region
WTWHA
Outside WTWHA
Regions
Regeneration
Partial Regeneration
Thinning
Clearing
No Change
Clouds


Types of Change in the Wet Tropics Bioregion based on EVI
Change / km^2
4000
3500
3000
2500
2000
1500
1000
500
0
WT region
WTWHA
Outside WTWHA
Regions
Regeneration
Partial Regeneration
Thinning
Clearing

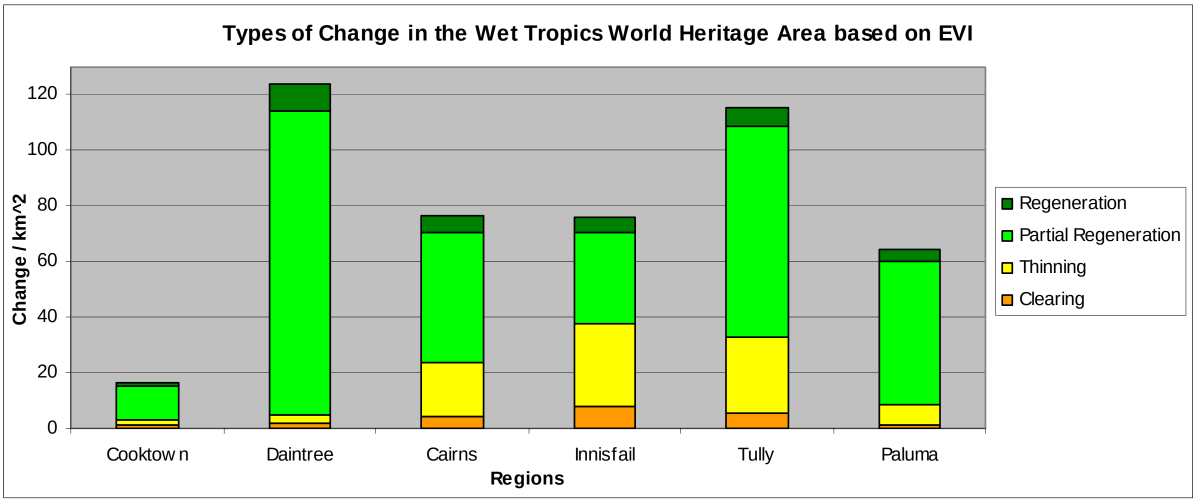

Types of Change within the Wet Tropics World Heritage Area based on EVI
Change / km^2
500
450
400
350
300
250
200
150
100
50
0
WTWHA
Region
Regeneration
Partial Regeneration
Thinning
Clearing


Types of Change/No Change in the Regions of the Wet Tropics Bioregion based on EVI
Change / km^2
7000
6000
5000
4000
3000
2000
1000
0
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing
No Change
Clouds

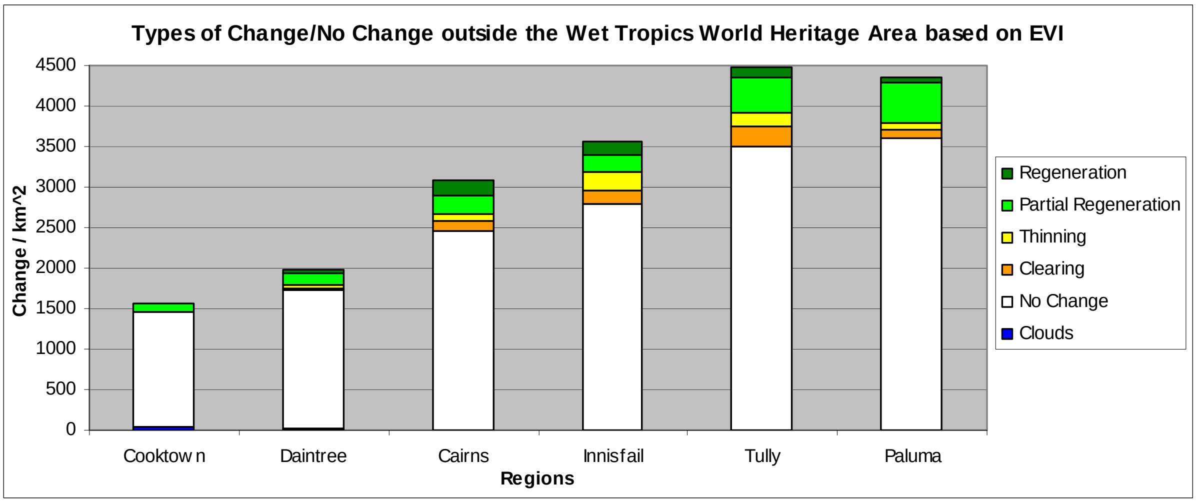

Types of Change in the Regions of the Wet Tropics Bioregion based on EVI
Change / km^2
1200
1000
800
600
400
200
0
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing



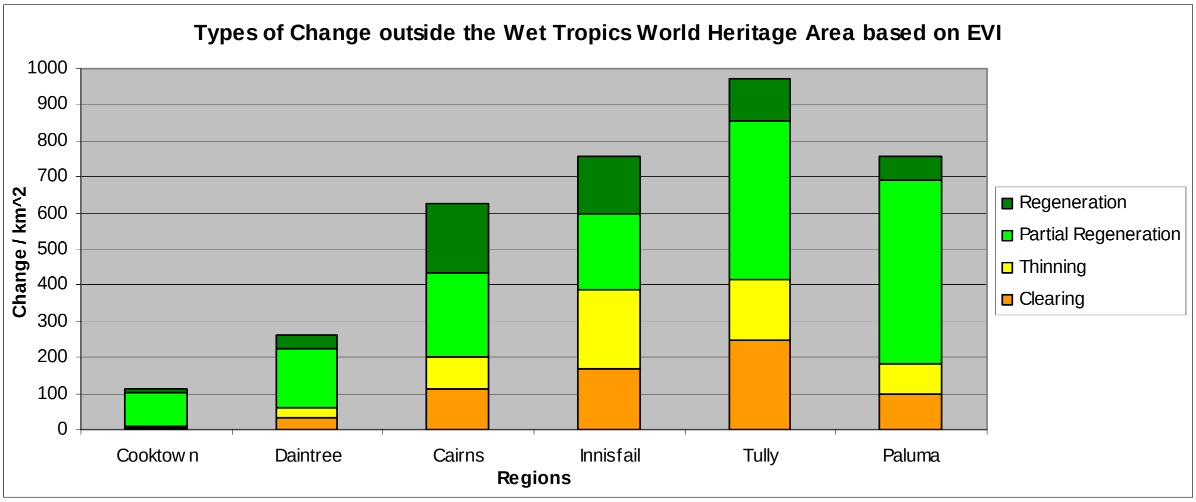
Types of Change/No Change in the Wet Tropics World Heritage Area based on EVI
2500
2000
1500
1000
500
0
Change / km^2
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing
No Change
Clouds



Types of Change in the Wet Tropics World Heritage Area based on EVI
120
100
80
60
40
20
0
Change / km^2
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing



Types of Change/No Change outside the Wet Tropics World Heritage Area based on EVI
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Change / km^2
Cooktow n
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing
No Change
Clouds


Types of Change outside the Wet Tropics World Heritage Area based on EVI
Change / km^2
1000
900
800
700
600
500
400
300
200
100
0
Cooktown
Daintree
Cairns
Innisfail
Tully
Paluma
Regions
Regeneration
Partial Regeneration
Thinning
Clearing

APPENDIX 3 – CHANGE AREAS (KM²) MAPPED BY NDVI, IRI AND EVI

Regional Subsets – NDVI	Cooktown	Daintree	Cairns	Innisfail	Tully	Paluma
Clouds	130.37	83.46	12.23	68.99	41.03	2.27
No Change	2,330.04	3,704.09	3,729.22	5,246.61	5,464.42	4,195.74
Cleared Areas	3.86	28.01	106.09	154.85	256.13	85.08
Thinned Areas / Seasonal Change	6.50	19.42	60.99	128.37	113.28	70.26
Partial Regeneration / Seasonal Change	29.23	108.54	167.63	130.07	385.11	654.06
Regeneration	8.42	38.37	152.54	138.33	131.83	80.78
Total Area	**2,508.42**	**3,981.89**	**4,228.70**	**5,867.21**	**6,391.79**	**5,088.19**

WTWHA Subsets – NDVI	Cooktown	Daintree	Cairns	Innisfail	Tully	Paluma
Clouds	92.10	65.87	11.56	63.17	39.54	0.02
No Change	847.49	1917.48	1,112.77	2,221.23	1,847.40	709.87
Cleared Areas	0.95	1.20	4.55	9.78	4.75	1.50
Thinned Areas / Seasonal Change	0.97	1.85	2.93	6.62	6.26	3.43
Partial Regeneration / Seasonal Change	0.96	11.57	3.90	5.66	11.09	9.59
Regeneration	0.56	2.40	1.77	3.74	2.63	1.32
Total Area	**943.04**	**2,000.37**	**1,137.48**	**2,310.21**	**1,911.68**	**725.73**

Outside WTWHA – NDVI	Cooktown	Daintree	Cairns	Innisfail	Tully	Paluma
Clouds	38.27	17.59	0.67	5.82	1.48	2.24
No Change	1,482.55	1,786.62	2,616.45	3,025.38	3,617.02	3,485.87
Cleared Areas	2.91	26.81	101.54	145.07	251.38	83.58
Thinned Areas / Seasonal Change	5.52	17.57	58.06	121.74	107.02	66.83
Partial Regeneration / Seasonal Change	28.27	96.97	163.73	124.42	374.02	644.47
Regeneration	7.86	35.97	150.77	134.58	129.20	79.46
Total Area	**1,565.38**	**1,981.52**	**3,091.22**	**3,557.01**	**4,480.11**	**4,362.46**

NDVI	Wet Tropics Bioregion	WTWHA	Outside WTWHA
Clouds	333.44	269.34	64.11
No Change	2,5510.63	8,603.42	16,907.20
Cleared Areas	639.19	23.16	616.03
Thinned Areas / Seasonal Change	407.15	21.83	385.32
Partial Regeneration / Seasonal Change	1,532.87	40.95	1,491.91
Regeneration	582.40	12.90	569.50
Total Area	**29,005.67**	**8,971.60**	**20,034.07**

Regional Subsets – IRI	Cooktown	Daintree	Cairns	Innisfail	Tully	Paluma
Clouds	130.37	83.46	12.23	68.99	41.03	2.27
No Change	2,269.13	3,551.39	3,636.90	5,213.67	5,245.10	3,997.82
Cleared Areas	1.88	21.40	64.48	91.58	167.58	32.14
Thinned Areas / Seasonal Change	7.12	26.07	75.32	182.10	167.93	55.09
Partial Regeneration / Seasonal Change	88.94	254.68	278.63	221.26	610.15	818.06
Regeneration	10.98	44.90	161.14	89.60	160.01	182.81
Total Area	**2,508.42**	**3,981.89**	**4,228.70**	**5,867.21**	**6,391.79**	**5,088.19**

WTWHA Subsets – IRI	Cooktown	Daintree	Cairns	Innisfail	Tully	Paluma
Clouds	92.10	65.87	11.56	63.17	39.54	0.02
No Change	843.90	1,863.36	1,100.12	2,218.08	1,827.98	684.18
Cleared Areas	0.47	0.59	2.11	4.36	3.31	0.38
Thinned Areas / Seasonal Change	2.08	2.09	8.05	11.51	12.56	2.31
Partial Regeneration / Seasonal Change	3.90	62.27	12.43	7.91	24.98	32.55
Regeneration	0.59	6.20	3.21	5.18	3.30	6.29
Total Area	**943.04**	**2,000.37**	**1,137.48**	**2,310.21**	**1,911.68**	**725.73**

Outside WTWHA – IRI	Cooktown	Daintree	Cairns	Innisfail	Tully	Paluma
Clouds	38.27	17.59	0.67	5.82	1.48	2.24
No Change	1,425.23	1,688.03	2,536.78	2,995.59	3,417.11	3,313.64
Cleared Areas	1.41	20.81	62.37	87.22	164.27	31.76
Thinned Areas / Seasonal Change	5.04	23.99	67.27	170.60	155.37	52.78
Partial Regeneration / Seasonal Change	85.04	192.41	266.20	213.35	585.17	785.51
Regeneration	10.39	38.70	157.93	84.43	156.70	176.52
Total Area	**1,565.38**	**1,981.52**	**3,091.22**	**3,557.01**	**4,480.11**	**4,362.46**

IRI	Wet Tropics Bioregion	WTWHA	Outside WTWHA
Clouds	333.44	269.34	64.11
No Change	24,754.87	8,482.81	16,272.06
Cleared Areas	383.16	12.10	371.07
Thinned Areas / Seasonal Change	516.72	36.58	480.14
Partial Regeneration / Seasonal Change	2,318.73	145.79	2,172.94
Regeneration	699.04	25.00	674.04
Total Area	**29,005.96**	**8,971.60**	**20,034.36**

Regional Subsets – EVI	Cooktown	Daintree	Cairns	Innisfail	Tully	Paluma
Clouds	130.37	83.46	12.23	68.99	41.03	2.27
No Change	2,251.80	3,512.88	3,512.71	4,965.38	5,262.68	4,262.62
Cleared Areas	5.66	36.36	117.96	175.79	251.76	97.76
Thinned Areas / Seasonal Change	8.85	30.81	108.53	248.42	194.63	95.06
Partial Regeneration / Seasonal Change	101.63	269.71	278.98	246.88	517.36	559.03
Regeneration	10.09	48.67	198.30	161.76	124.33	71.45
Total Area	**2,508.42**	**3,981.89**	**4,228.70**	**5,867.21**	**6,391.79**	**5,088.19**

WTWHA Subsets – EVI	Cooktown	Daintree	Cairns	Innisfail	Tully	Paluma
Clouds	92.10	65.87	11.56	63.17	39.54	0.02
No Change	834.57	1,810.83	1,049.32	2,170.89	1,756.60	661.12
Cleared Areas	1.16	1.65	4.37	8.20	5.69	1.15
Thinned Areas / Seasonal Change	1.74	3.00	19.29	29.46	26.92	7.52
Partial Regeneration / Seasonal Change	12.42	109.67	47.09	32.98	75.91	51.22
Regeneration	1.05	9.35	5.85	5.50	7.01	4.69
Total Area	**943.04**	**2,000.37**	**1,137.48**	**2,310.21**	**1,911.68**	**725.73**

Outside WTWHA – EVI	Cooktown	Daintree	Cairns	Innisfail	Tully	Paluma
Clouds	38.27	17.59	0.67	5.82	1.48	2.24
No Change	1,417.23	1,702.05	2,463.38	2,794.49	3,506.08	3,601.49
Cleared Areas	4.50	34.71	113.59	167.59	246.07	96.61
Thinned Areas / Seasonal Change	7.12	27.80	89.24	218.96	167.71	87.54
Partial Regeneration / Seasonal Change	89.21	160.04	231.89	213.90	441.46	507.81
Regeneration	9.05	39.32	192.45	156.25	117.31	66.76
Total Area	**1,565.38**	**1,981.52**	**3,091.22**	**3,557.01**	**4,480.11**	**4,362.46**

EVI	Wet Tropics Bioregion	WTWHA	Outside WTWHA
Clouds	333.44	269.34	64.11
No Change	24,605.28	8,230.92	16,374.36
Cleared Areas	705.82	22.58	683.24
Thinned Areas / Seasonal Change	683.51	88.88	594.63
Partial Regeneration / Seasonal Change	2,044.33	327.80	1,716.53
Regeneration	633.28	32.08	601.20
Total Area	**29,005.67**	**8,971.60**	**20,034.07**