BMT WBM

Port of Brisbane Mangrove Health Assessment - Historical Analysis and 2016 Survey (Final Report)

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Synopsis:	**This report describes historic trends in mangrove health based on archived remote sensing and meteorological data from 1987 to 2016. It also provides updated mangrove mapping, health, and canopy elevations based on UAV surveys and high-resolution satellite imagery in June and August 2016.**	

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Executive Summary

Background

The lower Brisbane River and adjacent nearshore waters of western Moreton Bay support extensive areas of mangrove forests and saltmarsh/claypan communities, both of which have high environmental value. Mangroves and saltmarsh/claypan communities at, and adjacent to, the Port of Brisbane, particularly at Fisherman Islands and Whyte Island/Wynnum, have been regularly monitored by Port of Brisbane since the 1990's using a wide variety of monitoring techniques. The mangrove health monitoring program was revised in 2016 to provide an improved understanding of mangrove condition and potential drivers of condition.

The specific objectives of the revised monitoring program were to:

- Develop a methodology for long-term monitoring of mangrove vegetation health
- Obtain medium-resolution (30 m grid) Landsat satellite imagery for assessment of historical changes in mangrove health
- Analyse the Normalised Difference Vegetation Index (NDVI) calculated from historical Landsat imagery to assess temporal and spatial variability in green biomass (a surrogate measure of vegetation condition)
- Assess potential factors controlling spatial and temporal patterns in NDVI, including the effects of climate and sources of error during image capture and analysis
- Obtain recent high-resolution (2 m grid) multispectral satellite imagery (Pléiades 1B - August 2016) to provide a quantitative, objective baseline assessment of spatial patterns in vegetation community structure and NDVI as a baseline to assess future changes
- Obtain fine-scale remote imagery, and canopy and ground elevation data using an un-manned aerial vehicle (UAV) to provide a quantitative, objective baseline assessment of spatial patterns in NDVI and ground levels as a baseline to assess future changes.

Existing Communities and their Condition

The high-resolution mapping undertaken in the present study identified complex spatial patterns in intertidal wetland community structure and condition, which were broadly consistent with previous mapping studies in the study area. Based on supervised community classification techniques, the seaward margin of mangrove forests was generally comprised of a tall *Avicennia marina* (grey mangroves) dominated closed and open forest, whereas mangals further landward were comprised of low closed to open *Avicennia marina* forest, eventually grading to claypan with or without saltmarsh. *Ceriops australis* dominated or co-dominated with *Avicennia marina* in places, consistent with previous field surveys. This spatial pattern in community structure is thought to be controlled largely by salinity stress, which is a function of decreasing water availability from either tidal inundation or fresh-water seepage with elevation.

The NDVI values derived from high-resolution satellite imagery and UAV identified areas where mangrove canopy chlorophyll levels were low, either as a result of poor mangrove health or where there were changes in community composition. In summary:

- The highest NDVI values at Fisherman Islands were recorded along the seaward fringe within the well-flushed tall *Avicennia* dominated closed and partially-closed forest. High-resolution UAV-based data showed that there was variation in NDVI at the individual tree level. NDVI tended to be highest in trees (and forest areas) where the canopy was more open and/or tree height was more variable, and the edges of trees were partially shaded (which tend to produce more chlorophyll than the top of canopies).

- Low NDVI values in mangrove forests at Fisherman Islands were generally recorded adjacent to the western claypan area containing low closed *Avicennia* forest and open *Avicennia* forest where water/salinity stress would be greatest. Mangroves on the eastern tip immediately north of ponded waters were in moderately good condition, whereas those on the far eastern tip near die-back areas had lower NDVI.
- The *Ceriops australis* and mixed mangrove forest at Fisherman Islands had low NDVI values. The leaves of *Ceriops australis* have more yellow pigments (carotenoids) (hence the common name of yellow mangrove), and therefore had a different NDVI signal than *Avicennia marina.*
- Mangrove forests at Whyte Island displayed complex spatial patterns. Similar to Fisherman Islands, the mangrove forest on the seaward fringe of Whyte Island had high NDVI values, whereas lower NDVI values typically occurred in landward areas on and adjacent to claypan and saltmarsh. Highest NDVI values were recorded in areas directly adjacent to freshwater inputs: the mouth of a small unnamed creek and a point directly adjacent to the Wynnum Wastewater Treatment Plant discharge point on Crab Creek. It is likely that the freshwater, nutrient enriched wastewater discharges enhanced chlorophyll and mangrove vegetation in this area.

In mangrove areas where water stress is already high, even small hydrological alterations can lead to compounding effects to salinity and plant health, particularly if the primary hydrological stressor is persistent. Previous mangrove monitoring studies at Fisherman Islands have identified a range of potential hydrological stressors that could interfere with critical tidal flushing, including sand ridges, algal mats and seagrass wrack along the foreshore (including drainage channels) on the southern margin of Fisherman Islands. It is unknown to what extent disruptions to groundwater and surface water runoff affect mangals at Fisherman Islands and Whyte Island.

Historical Trends in Mangrove Forest Condition

Rainfall and soil moisture together control water/salinity stress, a key driver of growth, reproduction, and community structure of mangroves and saltmarsh. Case-studies world-wide indicate that mangrove shoot/leaf production is generally positively correlated with rainfall, temperature and soil moisture, all of which vary across a range of time-scales.

Consistent with the above, analysis of historical Landsat imagery detected significant positive correlations between 12 month cumulative rainfall and NDVI values. NDVI was typically not significantly correlated with cumulative rainfall occurring at shorter (i.e. monthly and six monthly) timeframes, suggesting that NDVI was not responsive to short-term rainfall patterns.

Inter-annual rainfall patterns are strongly associated with SOI and the El Niño–Southern Oscillation (ENSO) cycle. The ENSO cycle has an average period of about four years, but can vary between two and seven years. The medium-term trends in average NDVI at most investigation areas included higher NDVI values in the period 1987-89 (coincident with strong La Niña conditions); consistent, moderate NDVI values in the period 1990-2005; a decline in NDVI in 2006-08 (during the final years of the Millennium Drought); and a slight rise in NDVI post 2009, following the end of the Millennium Drought. The overall long-term trend from

1987 to present was of declining NDVI values, without evidence of recovery (to pre Millennium drought conditions).

Long-term rainfall patterns only partly explained temporal patterns in NDVI, indicating that other processes also influence patterns in mangrove health. Slight, albeit statistically significant (p<0.05) long-term declines in mean NDVI were recorded in areas that have been subject to historical disturbance and reduced mangrove extent (i.e. Fisherman Islands, Whyte Island, Bulwer Island, Luggage Point and Mud Island investigation areas). By contrast, less disturbed mangrove forests at King Island, St Helena Island and Nudgee did not display a statistically significant long-term trend in mean NDVI.

The long-term decline in green biomass reflects chronic long-term changes in mangrove health (i.e. loss of canopy cover), which ultimately lead to the conversion of mangroves to claypan or ponded areas. Multiple ‘natural’ and anthropogenic local-scale stressors operating at the test sites would reduce the resilience of mangrove vegetation (and their associated community), and the capacity of communities to tolerate water/salinity stress arising from cyclic periods of drought. This could include, for example, impediments to tidal flushing (sediment accretion, litter, seagrass wrack etc.), and surface water runoff and groundwater recharge regimes (e.g. roads, drains, and reclamation).

NDVI values were also generally higher during winter than summer/autumn periods. This seasonal pattern was broadly consistent across most investigation areas, but the magnitude of change varied from year to year and spatially. This indicates that the process/es responsible for seasonal changes in vegetation were operating at broad, whole of study area spatial scales, but were not always consistent between years. Temporal patterns in leaf litter fall and reproductive ecology of mangroves in western Moreton Bay also suggest that mangrove growth and productivity show complex inter-annual and seasonal patterns.

Recommendations

The results of the present study indicate that rainfall/drought cycles strongly influence long-term patterns in mangrove green biomass, but that local scale stressors may reduce vegetation resilience, ultimately leading to mangrove stress and mortality.

While a range of hydrological stressors have been identified, there is uncertainty regarding the extent to which these affect tidal hydraulics and mangrove condition, and whether it is practical to manage these. It is recommended that a small field study (using electrical conductivity, temperature, depth loggers and cameras) be undertaken as part of the 2017 mangrove monitoring campaign to assess tidal amplitude in healthy, degraded and dieback areas. This will provide important information regarding the roles of tidal amplitude, surface water, and ground water salinity in healthy and dieback areas at Fisherman Islands. Substantial variations in tidal amplitude and salinity may warrant investigation into management activities to reinstate tidal connectivity.

For ongoing monitoring, it is recommended that future assessments continue to use high-resolution (2 m pixel size) satellite imagery on an annual basis as a basis for assessing broad-scale trends in mangrove health, and rapid ground inspections to assess sub-canopy environmental conditions.

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1 Introduction

1.1 Background

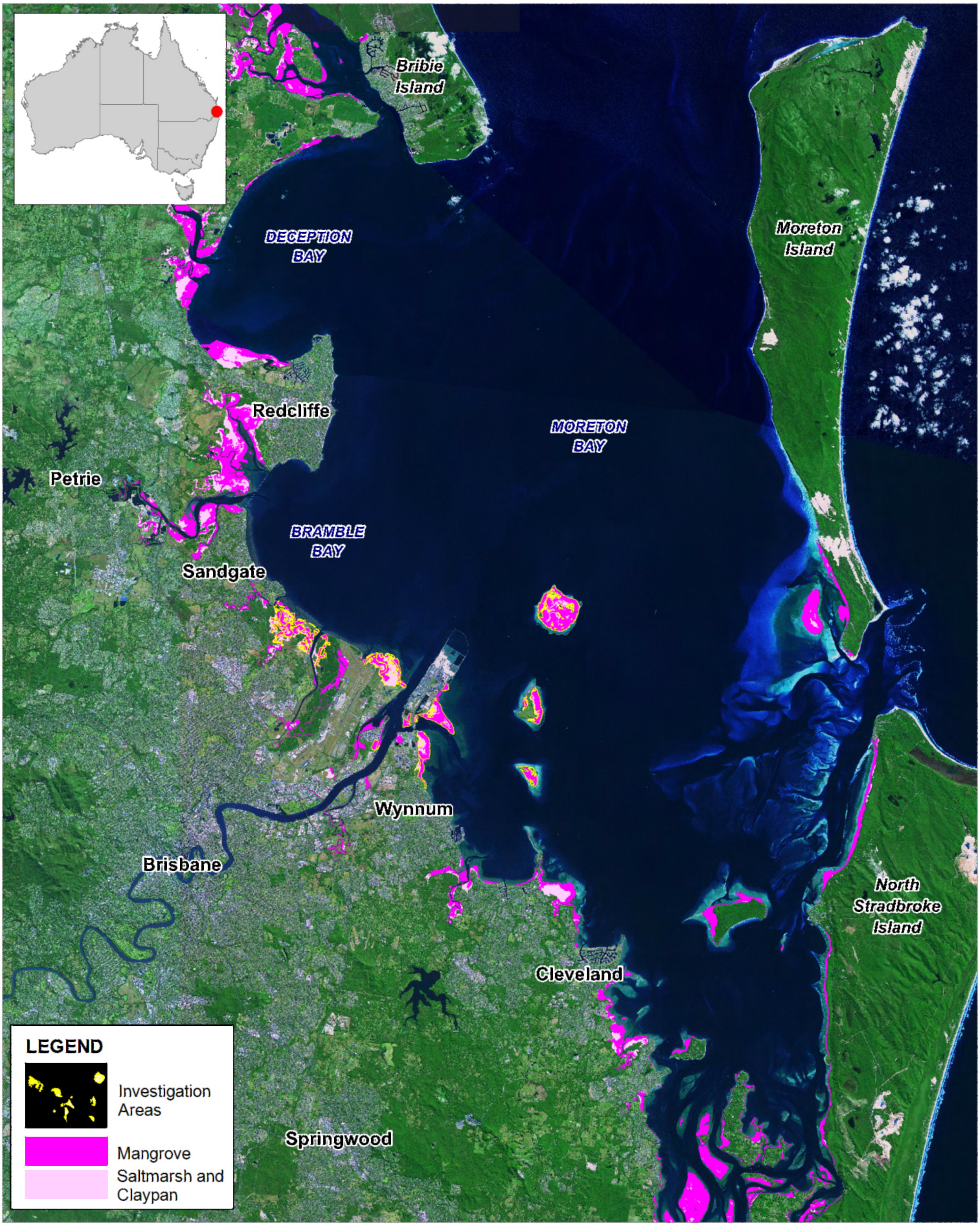
The lower Brisbane River and Waterloo Bay area supports extensive areas of mangrove forests, as well as saltmarsh communities, both of which have high environmental values. The mangrove forests of Fisherman Islands and Whyte Island (see Figure 1-1) are among the largest in western Moreton Bay (Accad *et al.* 2016), and the structure and form of these communities is unique to this area (Davie 2011). In recognition of their biodiversity values, mangrove and saltmarsh areas at Fisherman Islands and Whyte Island form part of the Moreton Bay Ramsar wetland site; a wetland of international significance that is protected under the Commonwealth *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC). Saltmarsh communities are also listed as a *Vulnerable* ecological community under the EPBC Act, and both mangroves and saltmarsh are protected marine plants under the Queensland *Fisheries Act 1994*.

Mangroves and saltmarsh at and adjacent to the Port of Brisbane, particularly at Fisherman Islands and Whyte Island/Wynnum, have been regularly monitored by Port of Brisbane since the 1990s (e.g. WBM 1992; CSIRO 1992; BMT WBM 2014). A wide variety of monitoring techniques have been adopted, reflecting changes in monitoring technologies and the focus of the monitoring program over time. These studies have been undertaken at different time intervals, using a combination of quantitative and semi-quantitative approaches, some of which are subject to observer bias.

The mangrove health monitoring program was re-evaluated in 2016, and BMT WBM recommended a number of changes to the program to provide a better understanding of mangrove/saltmarsh condition and potential drivers of condition. Specifically, the revised monitoring program is based on the following components:

- Analysis of medium-resolution Landsat satellite data to explore long-term trends in mangrove and wetland health using a consistent, objective, remotely sensed signal that could be compared to a range of environmental parameters
- Analysis of recent high-resolution (2 m grid) satellite imagery (June 2016) to provide a quantitative, objective baseline assessment of spatial patterns in vegetation community structure and NDVI
- Collection of high-resolution remote imagery, and canopy and saltpan ground elevation data using an un-manned aerial vehicle (UAV).

This report presents the methodology, and results to date for the revised mangrove health monitoring program.



Title:

Locality plan showing 2012 mangrove and saltmarsh extent based on data in Accad et al. (2016)

Figure: **1-1**

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Approx. Scale

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1.2 Aims and Objectives

The aim of the present study is to describe spatial and temporal patterns in mangrove and saltmarsh vegetation structure and condition, and potential drivers controlling patterns in condition. The specific objectives of this study are to:

- Develop a robust methodology for long-term monitoring of mangrove vegetation health
- Obtain medium-resolution Landsat satellite imagery for assessment of historical changes in mangrove health
- Analyse the Normalised Difference Vegetation Index (NDVI) calculated from historical Landsat imagery to assess temporal and spatial variability in green biomass (a surrogate measure of vegetation condition)
- Assess potential factors controlling spatial and temporal patterns in NDVI
- Obtain recent high-resolution (2 m grid) satellite imagery (June 2016) to provide a quantitative, objective baseline assessment of spatial patterns in vegetation community structure and NDVI as a baseline to assess future changes
- Obtain fine-scale remote imagery, and canopy and ground elevation data using an un-manned aerial vehicle (UAV) to provide a quantitative, objective baseline assessment of spatial patterns in vegetation community structure, NDVI and elevation in key mangrove, claypan and saltmarsh areas, as a baseline to assess future changes.

2 Review of Previous Studies

2.1 Mangrove Mapping Studies

Numerous studies have mapped the extent of mangroves and saltmarsh within the study area (Table 2-1). This table shows that there was great variability among studies in mapping methodologies, vegetation classes, and the spatial accuracy/mapping error. It is therefore, inappropriate to directly compare the mapped mangrove/saltmarsh extents between the different mapping studies. The following provides a brief summary of the findings of previous mangrove mapping and health assessments carried out in the study area.

Table 2-1 Previous mangrove and saltmarsh mapping studies

Source	Years	Spatial coverage	Mapping Method	Assessment
Hyland and Butler (1988)	1987	All of Moreton Bay	Aerial photograph - manual	Total mangrove and saltmarsh/claypan extent
Dowling (1986)	1974	All of Moreton Bay	Aerial photograph – manual tracing	Total mangrove and saltmarsh/claypan extent
Dowling and Stephens (2001) in Accad *et al.* (2016)	1997	All of Moreton Bay	Aerial photography - GIS	Total mangrove and saltmarsh/claypan extent
WBM (1992)	1958, 1991	Fisherman Islands (FI), Wynnum/ Whyte	Aerial photograph – manual tracing	Total mangrove and saltmarsh/claypan extent
WBM (1998)	1986, 1992, 1998	FI	Aerial photography - GIS	Total mangrove and saltmarsh/claypan extent
WBM (2000)	1972, 1978, 1983, 1987, 1991, 1993, 1995, 1999	FI	Aerial photograph – manual tracing	Total mangrove and saltmarsh/claypan extent Qualitative mangrove health assessment
WBM (2002)	1972, 1978, 1983, 1991, 2002	Wynnum/ Whyte	Aerial photography - GIS	Total mangrove and saltmarsh/claypan extent
FRC (2004)	2004	FI, Wynnum/ Whyte	Aerial photograph – manual tracing	Mangrove community and saltmarsh/claypan extent Qualitative mangrove health assessment
BMT WBM (2014)	2014	FI, Wynnum/ Whyte	Aerial photography - GIS	Mangrove community and saltmarsh/claypan extent Qualitative mangrove health assessment
Accad *et al.* (2016)	1958, 1997, 2012	All of Moreton Bay	Aerial photography - GIS	Mangrove community and saltmarsh/claypan extent

FI – Fisherman Islands

Accad *et al.* (2016) provides the most comprehensive historical mapping of vegetation community types in the study area (1955, 1997, 2012), and at a high-resolution (1: 5,000). The vegetation community types mapped by FRC Environmental (2004) and BMT WBM (2014) are of a higher resolution than mapped by Accad *et al.* (2016) at Fisherman Islands and Whyte Island/Wynnum, reflecting differences in intensity of ground-truthing. Note that no field surveys have been carried out by BMT WBM or FRC in the other investigation areas listed in Table 2-1, and therefore, community mapping prepared by Accad *et al.* (2016) forms the highest quality vegetation community data across the entire study area.

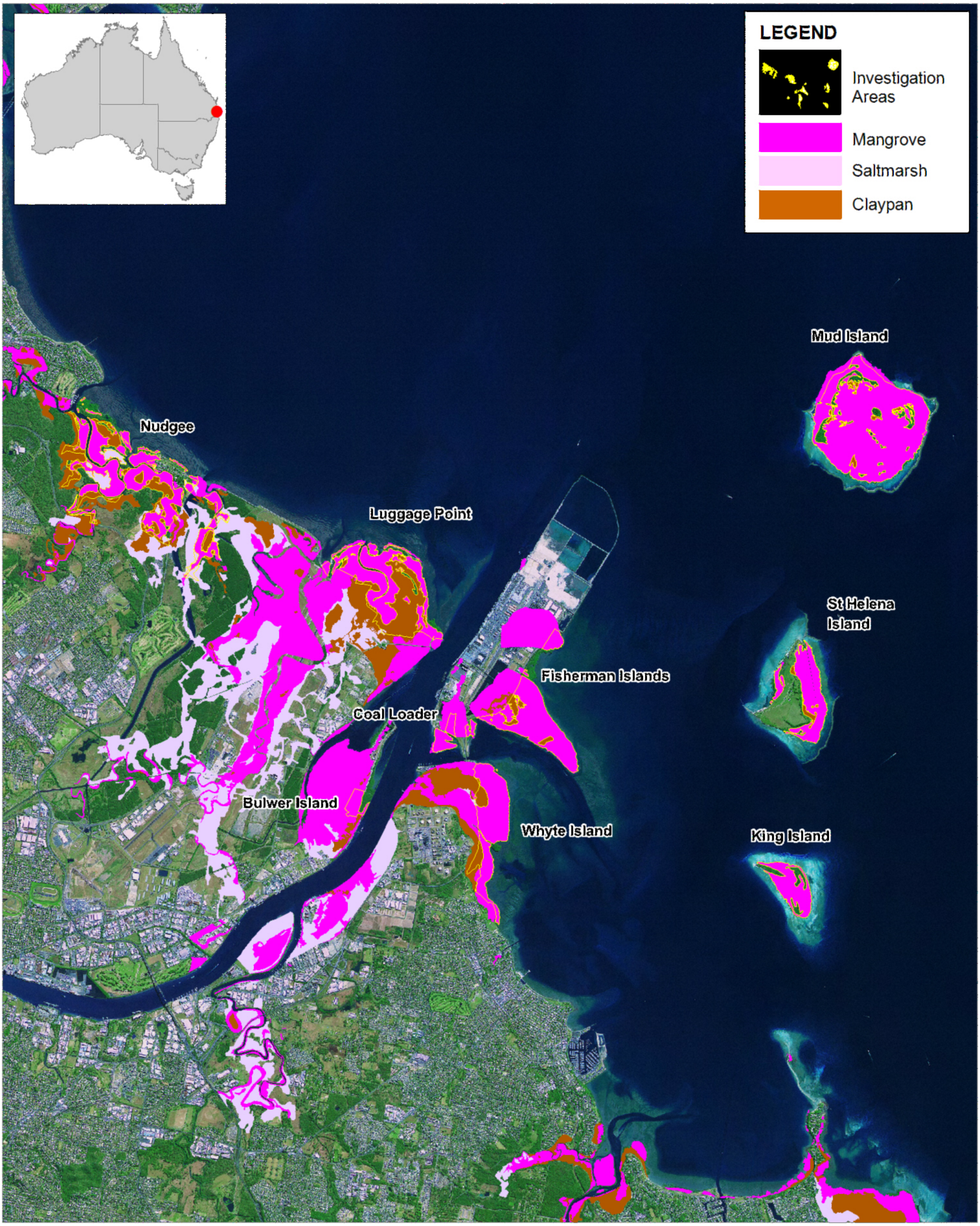
Vegetation communities in the investigation areas mapped by Accad *et al.* (2016) are shown in Figure 2-1 (1955), Figure 2-2 (1997), and Figure 2-3 (2012). Figure 2-4 shows the loss and expansion of mangrove areas between 1955 and 2012.

In summary:

- the dominant vegetation community type within the investigation areas was Regional Ecosystem (RE) type 1B(i)/1B(ii)a; *Avicennia marina subsp. australasica* closed-forest, open-forest, woodland, low closed-forest, low open-forest, low woodland, low open-woodland. This community type was dominant at all the investigation areas.
- the next most extensive vegetation community was RE community type 2 claypan, which was co-dominant at Fisherman Islands, Whyte Island/Wynnum and Luggage Point, but less so at the other investigation areas. Present-day claypan areas at Fisherman Islands and Whyte Island/Wynnum include both remnant claypan communities, and areas that previously supported mangroves or saltmarsh (see BMT WBM 2014; Accad *et al.* 2016).
- RE community type 3 *Sarcocornia spp. - Suaeda australis - Suaeda arbusculoides* succulent shrubland, open succulent shrubland was found in association with claypan on the southern tip of Fisherman Islands, as well as other investigation sites.

There were significant changes in mangrove, claypan, and saltmarsh extent over time, varying among investigation areas (Figure 2-5). In summary:

- Mainland investigation areas (Fisherman Islands, Wynnum/Whyte Island, Bramble Bay investigation areas) all experienced decreases in mangrove and saltmarsh extent over time, particularly in the period 1958 to 1987. Most of the decreases in mangrove/saltmarsh extent were due to clearing and reclamation works (see further discussion below). Claypan increased over time at Fisherman Islands and Nudgee, whereas at Whyte Island claypan decreased between 1955 and 1997, but increased between 1997 and 2012.
- Island investigation areas had comparatively less changes in mangrove, saltmarsh and claypan extent over time. The direction and magnitude of change was inconsistent among investigation areas, with Mud Island displaying the largest change (decreased mangrove extent, and increased claypan and saltmarsh extent) over time. The extent of intertidal habitats at Mud Island has decreased over time (possibly in response to coral dredging), leading to complex changes in wetland communities.



Title:

Mangrove, saltpan, and saltmarsh community types in the investigation areas - 1955 (Source: Accad et. 2016)

Figure: 2-1

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BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

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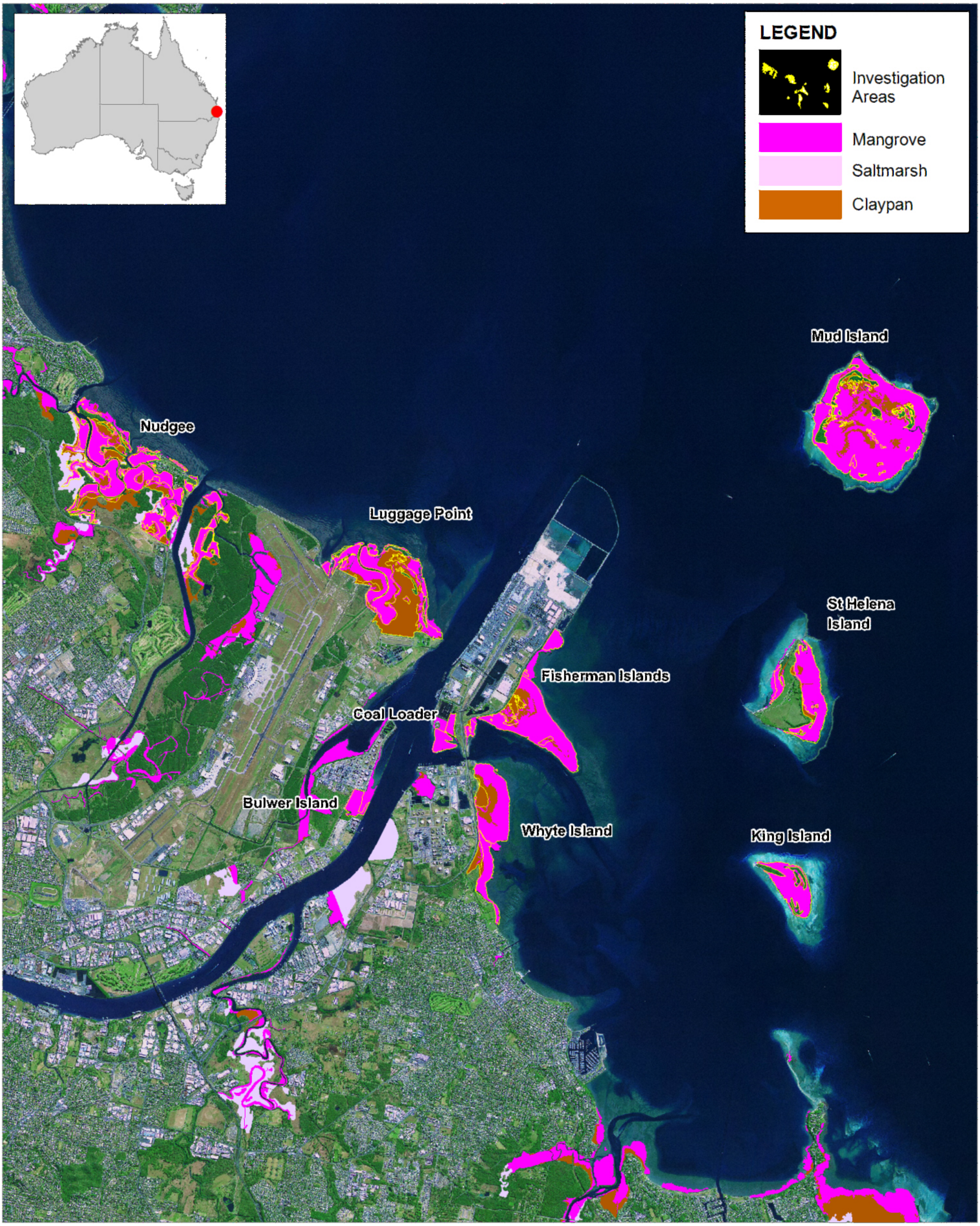

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Mangrove, saltpan and saltmarsh community types in the investigation areas - 1997 (Source: Accad et. 2016)

Figure: **2-2**

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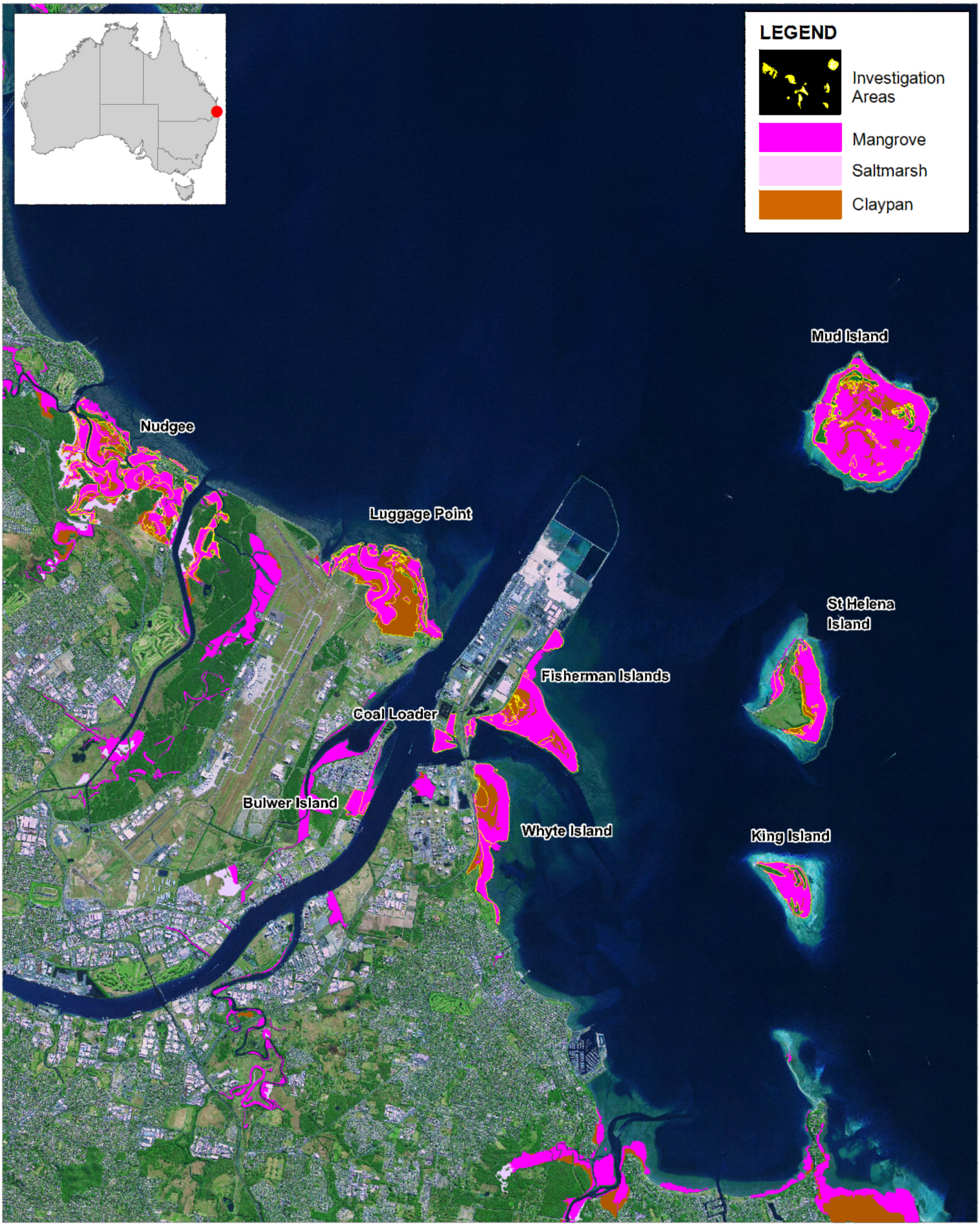

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Mangrove, saltpan and saltmarsh community types in the investigation areas - 2012 (Source: Accad et. 2016)

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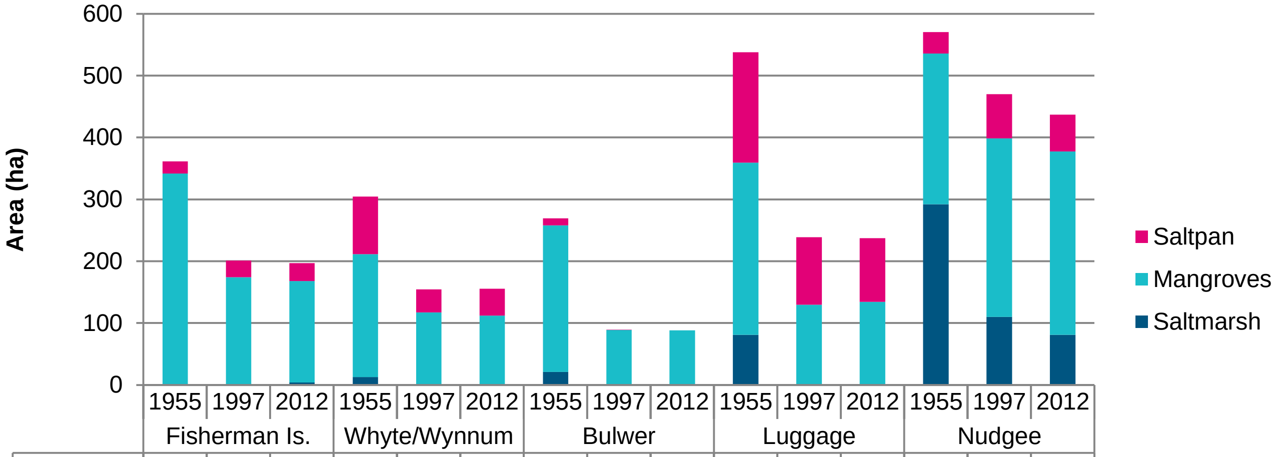
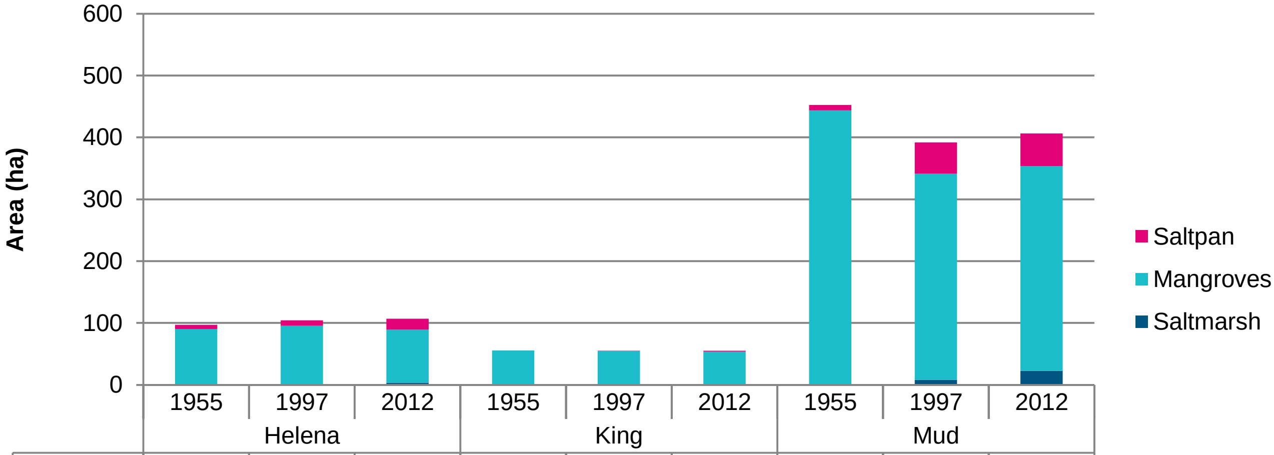


	Fisherman Is. 1955	Fisherman Is. 1997	Fisherman Is. 2012	Whyte/Wynnum 1955	Whyte/Wynnum 1997	Whyte/Wynnum 2012	Bulwer 1955	Bulwer 1997	Bulwer 2012	Luggage 1955	Luggage 1997	Luggage 2012	Nudgee 1955	Nudgee 1997	Nudgee 2012
Saltpan	20.0	26.7	28.8	92.7	37.4	43.5	11.5	0.43	0.00	178.	109.	103.	34.9	71.7	59.3
Mangroves	340.	174.	164.	198.	117.	112.	236.	88.8	88.1	278.	129.	134.	243.	288.	296.
Saltmarsh	0.80	0.00	3.79	12.7	0.00	0.00	20.8	0.00	0.00	81.0	0.00	0.00	291.	109.	81.2

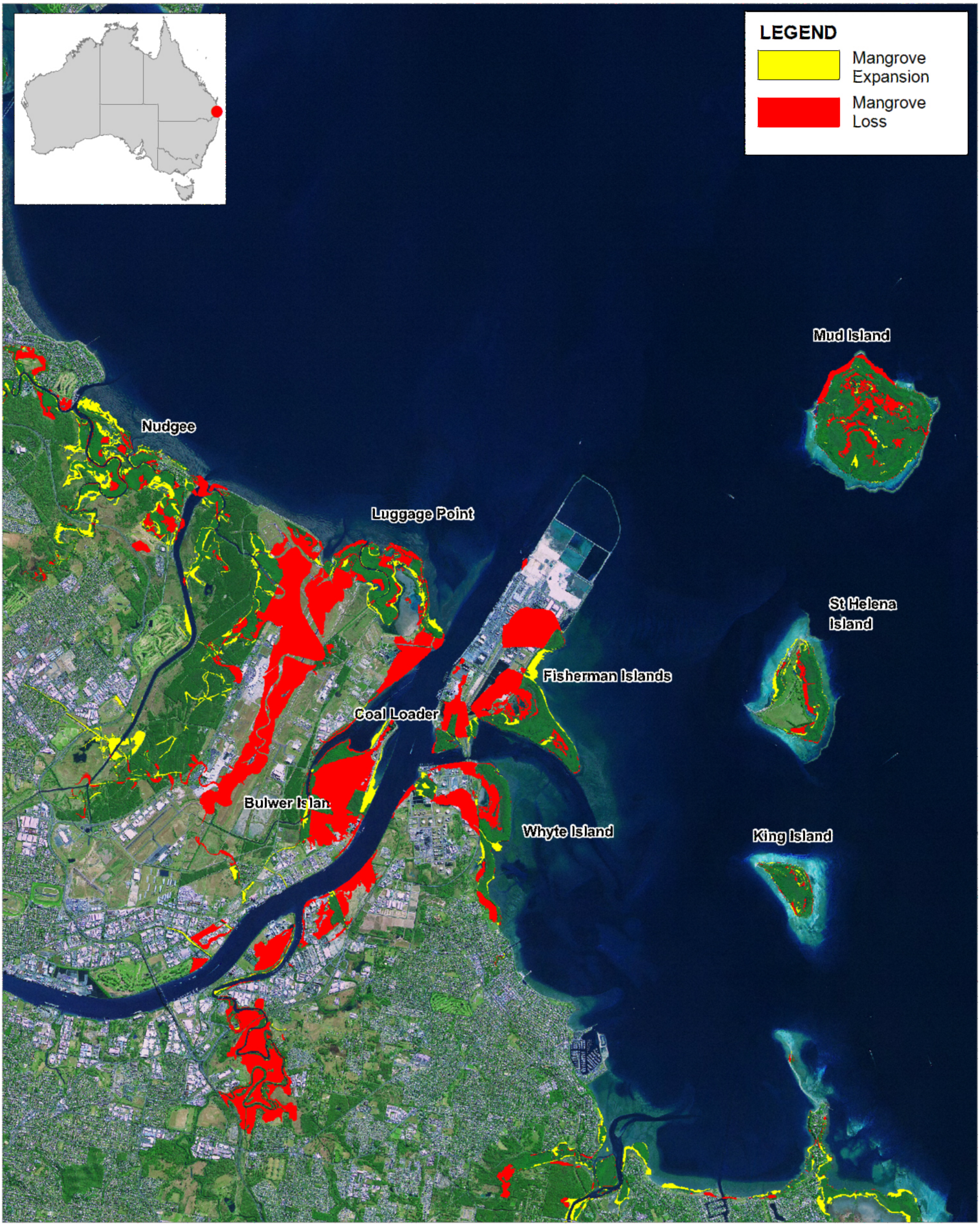


	Helena 1955	Helena 1997	Helena 2012	King 1955	King 1997	King 2012	Mud 1955	Mud 1997	Mud 2012
Saltpan	6.46	9.00	17.43	0.00	0.71	1.76	8.50	50.95	52.66
Mangroves	90.50	95.28	85.99	55.71	54.56	53.51	442.14	333.06	330.80
Saltmarsh	0.00	0.00	3.28	0.00	0.00	0.00	1.56	8.02	22.67

Figure 2-4 Vegetation community extents (ha) in the investigation areas – 1955, 1997 and 2012 (Data Source: Accad *et al.* 2016)

WBM (1992) and WBM (2000) describe historical changes in mangroves at Fisherman Islands. Port reclamation works amalgamated several mangrove islands (Fisherman Islands, Bishop Island) into a single island now referred to as Fisherman Islands. The port reclamation works resulted in mangrove extent at Fisherman/Bishop Islands declining from 341 ha in 1955, to 174 ha in 1997.

WBM (1998) investigated the potential impacts of port reclamation works commencing in 1992 (referred to as the 'Superbund' project) on mangroves and other environmental features at Fisherman Islands. It was estimated that a further 39 ha of mangrove forest was lost between 1992 and 1998 at Fisherman Islands. The Future Port Expansion Project (early 2000s) did not involve mangrove clearing.



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Changes in mangrove extent between 1955 and 2012 (Data source: Accad et al. 2016)

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Table 2-2 Timeline of development activities at Fisherman Islands and Wynnum

Period	Activity	Location
1972-78	Reclamation of western FI	Fisherman Islands
1978	Port Drive construction Oil Refinery expansion Reclamation at FI	Wynnum/Whyte Island Whyte Island west Fisherman Islands (west)
1983-1991	Stage 1 Port expansion at FI Tug berths, Port Operations Base, Water Police Base	Fisherman Islands/Bishop Island Whyte Island west
1991-1992	Stage 2 Port expansion at FI (‘Superbund’ project)	Fisherman Islands
1991-2002	Qld Rail Depot, develop of land west of Port Drive	Whyte Island west
2002-05	FPE Construction	Fisherman Islands

Mangrove extent at Whyte Island/Wynnum also declined over time, from 199 ha (1955), to 117 ha (1997) and 112 ha (2012). Reclamation and road construction works at Whyte Island/Wynnum resulted in changes to mangrove extent between 1970s and 2002 (WBM 2002b). The development of Port Drive resulted in the clearing of approximately 45 ha of mangroves, and further losses not directly resulting from clearing, such as changes to hydrology (WBM 2002b). Other factors causing mangrove die-back are examined in Section 2.2.

2.2 Mangrove Condition and Die-back

2.2.1 Patterns in Die-back

BMT WBM (2014) provides the most recent assessment of mangrove health at Fisherman Islands and Whyte Island/Wynnum foreshore. The distribution and patterns of mangrove health were generally consistent to those recorded in 2012. There was however, a decline in mangrove health across the study area since the 2012 survey. Key areas exhibiting declines in mangrove health included (by category):

- Dead – Patches of dead mangroves mapped towards the outer seaward boundaries around Whyte island and the eastern section of Fisherman Islands;
- Recently dead – New patches of recent dieback observed across Fisherman Island, including the outer boundaries of the northern, western and eastern sections, as well as the Coal Loading Area; and
- Poor – There was an increase in the area of mangroves in poor condition across Fisherman Islands, including significant bands towards the eastern boundary of both the western and eastern sections, and areas on the outer boundary of the Coal Loading Area.

Mangrove recovery was also observed but typically in small and/or isolated areas, including:

- Continued establishment of regrowth mangrove vegetation, at two photographic monitoring sites (western and eastern sections of Fisherman Islands), and where regrowth had previously been mapped at the eastern section of Fisherman Islands; and
- Improved saltmarsh condition and extent at one photographic monitoring site at Fisherman Islands.

While mangrove forests across the Fisherman Islands and Whyte Island were mostly in good to fair condition, there were extensive areas of dead or dying mangroves, consistent with the steady decline in mangrove condition observed over the last two decades. There is presently insufficient information to assess long-term trends in coastal saltmarsh extent and condition.

Historical clearing and reclamation projects have resulted in major changes to mangrove forest extent within the study area, as described in Section 2.1 (WBM 2000). However, there are a range of other factors controlling mangrove health as described below.

2.2.2 Potential Controls on Mangrove Condition and Dieback

Lugo (1998) developed a simple model of stressor types in mangrove forests, as follows (see Figure 2-6):

(1) those that change the main energy source (i.e., tides, runoff, etc.)

(2) those that divert a fraction of the inflow of resources to the mangroves before these resources can be used within the mangroves

(3) those that remove photosynthate before [it is] stored or used by plants

(4) those that remove soil nutrients or mass from the system

(5) those that affect metabolism… In general, the severity of the stress decreases from type 1 to type 5 stressors." (p. 427).

A change in any of these stressors can lead to mangrove stress and mortality. Similarly, the reversal of these stressors can provide a basis for future rehabilitation actions (Lewis *et al.* 2016).

WBM (2000; 2002) provides the most comprehensive local scale assessment of potential drivers of mangrove health to date, whereas subsequent studies by FRC Environmental and BMT WBM (2014) focussed more on describing patterns in condition and potential stressors.

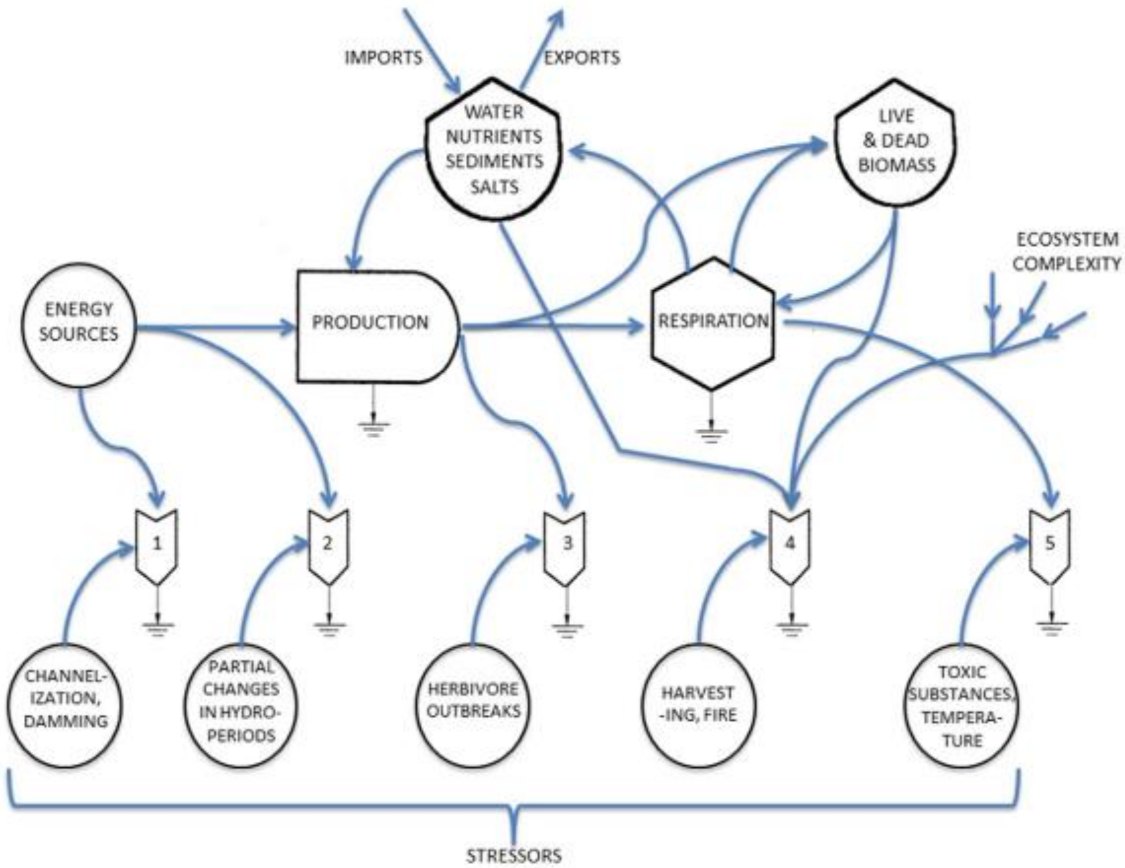


Figure 2-6 Chronic stressors to mangroves (labelled 1-5) (Source: Lewis *et al.* 2016, redrawn from Lugo *et al.* (1981)

There are multiple drivers and processes known or likely to be affecting mangrove health and die-back (Table 2-3). WBM (2000) suggested that disruptions to hydrodynamic processes and flushing within mangroves forests were key drivers of mangrove condition at Fisherman Islands. In particular, the deposition of sand, litter and seagrass wrack, together with the formation of algal mats, may have inhibited drainage patterns, resulting in ponding and multiple cascading effects. Erosion was also found to result in the loss of fringing mangroves along the southern shoreline of Fisherman Islands. The WBM (2000) study predicted there would be further large-scale die-back of mangrove forests in the centre of eastern Fisherman Islands. Since 2000, adult trees in these communities have remained in poor health (BMT WBM 2014), but recruitment of young trees and seedlings has also occurred.

While it has been speculated that toxicants and nutrient loading also adversely affect mangrove forests in the study area, concentrations of toxicants and nutrients have not been linked to dieback. Leachate from Wynnum tip, and discharges of treated effluent from Wynnum sewage treatment plant, were suggested by WBM (1992) to be pressures on mangrove forests and ecosystems at Whyte Island/Wynnum foreshore. WBM (2002) found that nutrient levels were similar to Fisherman Islands and Bulwer Island, and not remarkably elevated. BMT WBM (2014) recorded elevated concentrations of the pesticide DDE and TPHs across Fisherman Islands and Whyte Island, and in contrast to WBM (2002), trace metal concentrations generally met guideline levels. While toxicants exceeded guideline levels in places, no correlations between toxicant concentrations and mangrove condition were found.

Climatic conditions are a key driver of mangrove condition and extent over time. Mangroves in Moreton Bay have made significant landward expansions after relatively wet decades (Eslami-Andargoli *et al.* 2009) and the health of mangroves in Florida has been linked to temperature and seasonal rainfall (Zhang *et al.,* 2016). Widespread mangrove dieback in the Gulf of Carpentaria observed in September 2016 is thought to be the result of strong El Niño conditions including reduced rainfall and high temperatures. Elsewhere in Moreton Bay, hail storms have caused damage to mangrove canopies, and recovery has been slow (Pedersen 2002). Long-term drought conditions have been speculated to reduce groundwater levels in mangrove forests, leading to unstable soil profiles and subsequent loss of mangroves. No studies to date have examined linkages between rainfall and drought cycles and mangrove health in the study area.

WBM (2000) recommended that future monitoring should investigate whether secondary infection by the fungal disease *Phytophora* was affecting study area mangroves. Mangrove die-back due to *Phytophora* was observed in grey mangroves (*Avicennia marina*) at the mouth of Calliope River (Gladstone), which resulted in significant die-back in this area (Pegg and Foresberg 1981). *Phytophora* disease has not been considered further in subsequent studies in the study area.

Table 2-3 Stressors and drivers affecting mangrove condition

Primary stressor	Driver	Physical or chemical effect	Ecological consequence	Locations in study area	Source	Potential severity
Sand deposition creating sand ridges	Historical dredging leading to long-term changes in wave energy and sediment transport	Burial of pneumatophores Reduced flushing and potential ponding → anaerobic conditions	Asphyxiation of mangroves →loss of root mass → soil profile collapse →reduced ground levels preventing recolonisation	SE tip of Fisherman Islands	WBM (2000)	Possible key driver of mangrove loss on eastern tip of Fisherman Islands
Bank erosion	Historical dredging leading to ongoing changes in wave energy and sediment transport	Substrate instability	Seaward loss of available habitat and mangroves	SW shoreline of Fisherman Islands and northern shore of Whyte Island	WBM (2000)	Likely highly localised effect, but source of sediment for sand ridges
Deposition of litter and dead seagrass	Hydrodynamic processes (waves, currents) Increase in seagrass and litter loads over time	Burial of pneumatophores Reduced flushing and potential ponding → anaerobic conditions	Drowning of mangroves Smothering of saltmarsh	SE tip of Fisherman Islands Western foreshore of Fisherman Islands	WBM (2000)	Possible synergistic effect with sand ridges – unknown to what degree Clean-up days likely to reduce this pressure in recent times
Algal mats	Changes in flushing leading to ponding Nutrient loading	Burial of pneumatophores leading to decay Burial of bare substrates Reduced flushing and potential ponding → anaerobic conditions	Asphyxiation of mangroves →loss of root mass → soil profile collapse →reduced ground levels preventing recolonisation Inhibition of seedling recruitment	Fisherman Islands	WBM (2000)	Possible synergistic effect with sand ridges – unknown to what degree Improvements of effluent quality and nutrient lading may mitigate effects in recent times
Toxicants	Diffuse sources Landfill	Toxic effects to plants and the biota (fauna, bacteria) that sustain them	Plant stress and mortality	Fisherman Islands Whyte Island/Wynnum	WBM (2002), FRC (2004), BMT WBM (2014)	Toxicants do not appear to be a major driver of mangrove health in the study area
Physical damage caused during	Storms, floods, lighting strikes	Damage to leaves by wind, rain and hail	Mangrove canopy loss resulting in reduced	Recorded elsewhere in Moreton Bay	Pedersen (2002); DEHP (2016)	Not known to be a key driver in study

Primary stressor	Driver	Physical or chemical effect	Ecological consequence	Locations in study area	Source	Potential severity
severe weather events			photosynthesis			area
Drought/rainfall cycles leading to changes in physio-chemical properties of soils	El Niño	Reduced groundwater levels during droughts leading to oxidation of acid sulfate soils and collapse of soil profile an ponding	Asphyxiation of mangroves Reduced ground levels prevent recolonisation	Unknown	Pedersen (2002)	Elsewhere in Moreton Bay
Insects and disease	Phytophora fungus infection Insect infestation	Physical damage to leaves and stems by insects Physical damage by fungus infection	Mangrove canopy loss resulting in reduced photosynthesis Reduce health and mortality due to disease	Unknown	Pegg and Foresberg (1981)	Cause of severe die-back in Gladstone

3 Methodology

3.1 Historical Assessment of Marine Vegetation

The following tasks were undertaken:

(1) Determine the boundaries of marine vegetation communities based on the present day representation of the 1955 baseline mapping from Accad *et al.* (2016) – see Section 3.1.1.2

(2) Determine the NDVI at different spatial scales over time using Landsat satellite imagery – see Section 3.1.2.

3.1.1 Spatial Scales

The historical analysis of mangroves and saltmarsh (based on NDVI) was undertaken at a range of spatial scales (Table 3-1):

- Whole of study area
- Investigation area
- Community type within investigation area
- Plots within community type (30 x 30 m pixels).

Table 3-1 Spatial scales considered in historical analysis of mangrove health

Factor	Spatial scale	No. of pixels
Whole of study area	Full extent of image capture at the 9 investigation areas = 1647 ha	18,304
Investigation area	Discrete polygon within areas of interest, varying in size from 22.9 to 444.5 ha	Varies depending on size: 255-4309
Community type	Varies depending on investigation area and also vary in size	Varies depending on investigation area: 1-4
Plots	30 x 30 m = 0.09 ha	1

3.1.1.1 Investigation Areas

The Mangrove Health Monitoring Program previously focused on investigation areas at Fisherman Islands (including the coal loader) and Whyte Island/Wynnum foreshore. There are several additional mangrove areas on the northern bank of Brisbane River that have undergone some form of direct modification over the investigation period, and provide contextual information for assessing temporal trends. These investigation areas which have undergone direct human disturbance are considered to represent ‘Test’ areas for the purposes of this assessment (see Table 3-2.

Additional mangrove investigation areas were evaluated to provide contextual information on background variability in mangrove condition. These investigation areas were classified as control sites, in that, wetland communities here had not experienced extensive clearing over the investigation period. Importantly, the vegetation within all of the investigation areas (test and control) remained some form of wetland between 1955 and 2012; test areas experienced clearing nearby. The purpose of this was to analyse temporal changes in health without the confounding influence of vegetation clearing.

The locations of test and control investigation areas are shown in Figure 3-1. The extent and number of pixels in each investigation area is summarised in Table 3-2. Landsat 5 provided between 255 and 4,939 pixels per investigation area (depending on size of the investigation areas), which was considered to be of sufficient resolution to assess broad temporal trends in mangrove health index (NDVI).

Table 3-2 Investigation area details

Treatment/Location	Investigation Area	Area ha	No. Pixels
Test – Waterloo Bay	Fisherman Islands (main)	181.5	2017
Test – Waterloo Bay	Fisherman Islands (coal loader)	23.0	255
Test – Waterloo Bay	Whyte Island/Wynnum	144.5	1605
Test – Northern Bris. River	Luggage Point	265.7	2952
Test – Northern Bris. River	Bulwer Island	29.0	322
Control – Northern Bris. River	Nudgee Wetlands	365.2	4058
Control – island	King Island	67.5	750
Control - island	St Helena Island	126.5	1406
Test – island	Mud Island	444.5	4939
TOTAL		**1647.4**	**18,304**

3.1.1.2 Vegetation Community Mapping and Masking of Non-Wetland Areas

Different vegetation community types will display different NDVI values. Therefore, investigation areas were stratified *a priori* into vegetation community types. This allowed changes within community types to be assessed over time, with reference to a baseline.

Accad *et al*. (2016) provides estuarine vegetation community mapping for all of Moreton Bay including the study area. Mapping was derived from interpretation aerial photographs from three years: 1955, 1997 and 2012. Vegetation community extent varied greatly over time (Accad *et al.* 2016; see Section 2.1), and the boundaries of strata derived from vegetation community mapping vary accordingly. The modern day extent of mangroves over the 1955 extent was used as the baseline for this assessment; therefore, all temporal changes in NDVI due to changes in vegetation communities are made with reference to this baseline condition. As mentioned previously, the objective of this assessment was to examine long-term changes in health without the confounding influence of major changes to landform, so this was done by using mangrove extents that were common to both the present day and 1955. The advantages of this approach were that it was relatively straightforward for repeated spectral analyses (48 scenes), and that community changes resulting from mangrove colonisation would present an increase in NDVI, while changes from mangrove to claypan or saltmarsh would result in a reduction in NDVI. Because mangroves provide higher NDVI values than saltmarshes and are the key response variable in this study, this approach was well suited to mangrove monitoring.

Due to extensive development between 1955 and 2012 (Figure 2-1 to Figure 2-3), most of the original saltmarsh extent in the study area has been lost. For the purposes of this assessment, the baseline condition considered areas of mangrove, saltmarsh and claypan as per the 1955 extent (Accad *et al.,* 2016). Claypan and saltmarsh extents were combined together as "saltmarsh" because the distinction between the two habitat types was less clear, particularly over decades.

The vegetation community types adopted in this study were:

- Mangrove forest – mapped as 1B(i)/1B(ii)a *Avicennia marina subsp. australasica* closed-forest, open-forest, woodland, low closed-forest, low open-forest, low woodland, low open-woodland. 1B(i) and 1B(ii)a vegetation community types were combined by Accad *et al.* (2016) at some investigation areas, and therefore, were considered as a single community unit across the study area in this study.
- Claypan – mapped as community type 2 by Accad *et al.* (2016). These are largely unvegetated areas located at or above HAT, and were considered as a single community type with saltmarsh.
- Saltmarsh – mapped as community type 3 *Sarcocornia spp. - Suaeda australis - Suaeda arbusculoides* succulent shrubland, open succulent shrubland.

3.1.1.3 Plots

The smallest spatial unit in this study was the pixel, which was 30 x 30 m. Pixels are referred to as 'plots' for the purpose of this study.

Title:

Test and Control Investigation Areas

Figure:	Rev:
3-1	A

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

N

0 2.5 5km

Approx. Scale

www.bmtwbm.com.au

Filepath: I:\B20259_I_BRH Port of Brisbane DLR\DRG\Mangrove_2016\ECO_006_160914_Test_Areas.wor

3.1.2 NDVI Analysis

3.1.2.1 Data Sources and Availability

A combination of Landsat 5 and 8 satellite images were used for this analysis:

- Landsat 5, which is a long running, freely available, remotely sensed dataset produced by NASA[1]. Landsat 5 has a pixel size of 30 m and therefore has medium scale spatial resolution. Therefore, Landsat 5 data were analysed (for the period of 1987 to 2011, at 30 m pixel scale, providing 100% spatial coverage over the study area.
- Landsat 8 was launched in 2013 and provides higher resolution imagery than Landsat 5 (15 m pixel size Panchromatic band). Landsat 8 data were used from 2013 to 2016 and provided 100% coverage of the study area. Landsat 8 images were not pan-sharpened to reduce potential artefacts of pan-sharpening and to maximise compatibility with earlier Landsat 5 imagery.

Two scenes (images) were obtained in each year where available, corresponding to nominal wet (February – April) and dry (July – September) seasons. Alternate scenes were selected where cloud cover obscured the scene within the defined seasonal windows, avoiding the need for undertaking cloud masking post-processing. Overall, 48 scenes were analysed in the period 1987 to 2016, inclusive (Table 3-3). There were four scenes where most of the image was useable, but one or more investigation areas were obscured by clouds. These obscured areas were removed from the dataset.

Table 3-3 Landsat imagery sources

Period	Data source	Number of images
1987-2000	Landsat 5	2 per year (wet and dry) = 26 images
2000-mid 2003	No imagery analysed	N/A
Mid-2003-2011	Landsat 5	2 per year (wet and dry) = 16 images
2012	No imagery analysed	N/A
2013	Landsat 8	2 per year (wet and dry) = 2 images
2014	No imagery analysed	N/A
2015-2016	Landsat 8	2 per year (wet and dry) = 4 images

Overall, there was one data gap in Landsat 5 from 2000 to mid-2003, and Landsat 8 data were also used from 2013 to 2016, providing a time-series of data from 1987 to present with two gaps in data; 2000-2003, 2012 and 2014.

While the US NOAA satellite program aims for continuous quality coverage of the afternoon orbit, contingencies in the operation of the spacecraft and in the processing requirements have introduced periods of no coverage or reduced data quality. Specifically:

[1] Landsat 7 includes a 15 m pixel Panchromatic band for higher resolution analyses than Landsat 5. However, Landsat 7 imagery was not used as a scan line corrector failure resulted in large parts of the study area having unusable data

- Data commenced in April 1992, and is contiguous, except for a gap from October 1994 to January 1995 due to the lack of a sensor following the unexpected end of NOAA-11 operation.
- Coverage and quality are reduced during the winters of 1993, 1994 and 2000 due to very low sun elevations (and consequent shadowing on the surface) during the last year or so of operation of some satellites.
- Maps for September 2003, and possibly October, November and December 2003, display some artefacts due to a NOAA-16 sensor scan-motor problem.

3.1.2.2 Landsat Data Pre-Processing

Landsat 5 and 8 scenes were downloaded from the United States Geological Service (USGS) Earth Explorer website (http://earthexplorer.usgs.gov/) using the bulk-downloader application. The majority of the scenes were cloud free, with only four images requiring some sites to be ignored. For each year, a scene from the post wet period (February to April) and from the dry season (July to September) was included. Due to the presence of cloud cover, scenes occasionally needed to be used outside of these periods.

Landsat 5 data as raw 8-bit digital numbers (DN) were converted to equivalent Landsat 7 DNs using bias and gain values using the inverse linear equations in Vogelmann *et al.* (2001). Adjusted Landsat 7 DNs were then back-calculated to radiance using the formula, including gain and bias values in Chander *et al.* (2009):

$$L_\lambda = \left(\mathrm{gain}_\lambda * \mathrm{DN7}\right) + \mathrm{bias}_\lambda$$

Back-calculated radiance (L_λ) was then converted to “top of atmosphere” (TOA) reflectance values using the following equation:

$$R_\lambda = \frac{\pi * L_\lambda * d^2}{E_{sun,\lambda} * \sin(\theta_{SE})}$$

where R_λ is the reflectance (a ratio without units), L_λ is the back-calculated radiance, d is the earth-sun distance (in astronomical units), $Esun,_\lambda$ is the band-specific radiance emitted by the sun, and θ_{SE} is the solar elevation angle. $Esun,_\lambda$ values from Chander *et al.* (2009) were used, with earth-sun distance and solar elevation gathered from the associated metadata.

For Landsat 8 scenes, 16-bit integer data were converted to TOA planetary reflectance using the following equation, derived from the USGS website:

$$\rho\lambda = \frac{M\rho * Qcal + A\rho}{\sin\left(\theta SE\right)}$$

where $\rho\lambda'$ is the TOA planetary reflectance, $M\rho$ is the band-specific multiplicative rescaling factor from the metadata, $A\rho$ is the band-specific additive rescaling factor from the metadata, *Qcal* is the quantized and calibrated standard product pixel values (DN), and θ_{SE} is the solar elevation angle from the metadata.

These calculations were performed using ArcMAP 10.3.1, which was also used to calculate vegetation indices and query the attributes of each investigation area.

3.1.2.3 NDVI Data Extraction and Processing

NDVI data were extracted from each 30 x 30 m pixel and community type. Vegetation indices calculated included Normalised difference of vegetation (NDVI). This index is shown below:

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$$

where *NIR* is the near infra-red TOA reflectance, *Red* is the TOA reflectance of the red band/

3.1.3 Assessment of Other Factors Affecting NDVI

There are a range of environmental factors affecting NDVI values. The following sources of variation were considered:

- Rainfall – Two Bureau of Meteorology weather stations are located near the study area: 040320 Fort Lytton and 040842 Brisbane Airport. There is an incomplete rainfall record for the two stations over the monitoring period. There is a significant correlation in rainfall between the two stations ($r^2 = 0.93$, $p<0.01$), and on this basis it was considered appropriate to combine data from the two stations to provide a complete monthly rainfall record for the period January 1984 to May 2016. Data used for this assessment are provided in Appendix A. Cumulative rainfall data were derived for 1, 2, 6 and 12 month periods over the monitoring period.
- Seasons – for the purposes of this study two seasons were examined in each year: wet (February-April) and dry (July-September).
- Tides. Tide levels were calculated from tidal predictions for the Brisbane Bar at 10 minute intervals, based on the Landsat acquisition date and capture mid-point time. Tides were plotted against NDVI for saltmarsh and mangrove communities to examine potential relationships.
- Monthly averages of daily solar exposure (MJ/m^2), were collected between January 1990 and June 2016 from the Bureau of Meteorology weather station 040320 at Fort Lytton. Correlations among NDVI values for site and solar exposure were also examined.

The effects of rainfall, tide and solar exposure on NDVI values were examined using linear regression analyses.

3.2 Contemporary Patterns in Wetland Communities

3.2.1 Rationale

Fine scale surveys of the habitat characteristics and health of intertidal wetland areas were carried out using remotely piloted aircraft at the Fisherman Islands, coal loader, and Wynnum/Whyte Island foreshore investigation areas (Test areas – see Section 3.1.1.1). These two investigation areas occur at and adjacent to port lands and therefore, are of interest to port management.

Two methodologies were used to assess contemporary patterns in wetland communities and their condition:

- Drone or unmanned aerial vehicle (UAV) - UAV based monitoring offers the ability to gather spectral information and elevation data within the same survey, allowing for the determination of changes in elevation, community, and health to be assessed over the investigation areas at high to ultra-high resolution (cm scale).
- High-resolution satellite imagery - The Pleiades-1A satellite provides ortho-rectified multispectral colour data at 2 meter resolution and revisits any point on Earth daily. Pleiades-1A is capable of acquiring high-resolution stereo imagery in one pass, and can accommodate large areas (up to 1,000 km x 1,000 km). High-resolution satellite imagery was used to map vegetation community structure and health to be assessed over the investigation areas at high-resolution (meter scale).

Table 3-4 Approaches used to map contemporary patterns in vegetation communities and health

Attribute	UAV	High-resolution satellite
Resolution (pixel size)	Multi-spectral 0.5 m	Panchromatic 0.5m (resampled) Multispectral 2m (resampled)
Ortho-mosaics of the investigation areas	Yes	Yes
Normalised Difference Vegetation Index (NDVI)	Yes	Yes
Digital Elevation Model (DEM) of canopy height and salt-pan elevation (using photogrammetry).	Yes	No

The following tasks were undertaken:

(1) Determine the NDVI at different spatial scales using high-resolution satellite imagery and UAV

(2) Map vegetation community structure based on supervised classification of high-resolution satellite imagery.

3.2.2 High-resolution Satellite Imagery

3.2.2.1 Data Source

The Pleiades-1A satellite features four spectral bands (blue, green, red, and IR), as well as image location accuracy of 3 meters (CE90) without ground control points. These spectral bands allow high-resolution vegetation mapping and the calculation of NDVI.

A multispectral Pleiades satellite image bundle (2 m spatial resolution) was acquired for the study area (10 August 2016). The image was delivered geometrically corrected and ortho-rectified to

UTM 56J WGS84. Radiometric calibration was also applied for the Pleiades 1A image using the ATCOR model, which implements the MODTRAN4+ radiative transfer code (Geosystems, 2013).

3.2.2.2 Data Processing

ArcMap 10.3.1 was used to perform raster processing which included the vegetation community classification and NDVI analysis.

Vegetation communities were classified using pixel statistics from known community types based on past ground-truthing events. Classifications were made in the investigation areas using supervised classification and maximum likelihood methods. Maximum likelihood classification was used in ArcMap 10.3.1 under default parameters, based on training polygons of known vegetation classes (based on BMT WBM 2014). The vegetation community map was smoothed firstly using the boundary clean algorithm in ArcGIS, then using the nibble function to keep polygons with a minimum size of 100 pixels. Because areas of poor mangrove health could not be discerned from yellow mangrove (*C. tagal*) using pixel-based classification, yellow mangrove polygons were accepted or rejected based on prior vegetation community mapping.

A map of the following vegetation community classes was produced:

- *Avicennia marina* closed to open forest, >10 m canopy height +/- *Aegiceras corniculatum, Ceriops australis*, and *Rhizophora stylosa*
- *A. marina* low closed to low open forest, 2-10 m canopy height +/- *A. corniculatum, C. tagal*, and *R. stylosa*
- *A. marina* shrubland, 1-2 m canopy height +/- *A. corniculatum* and *C. tagal*
- *C. australis* open to closed to open forest, 2-5 m canopy height +/- *A. corniculatum* and *A. marina*
- Claypan
- Saltmarsh assemblage.

Normalized Difference Vegetation Index (NDVI) was calculated for each 2 x 2 m pixel across the entire study area.

3.2.3 Unmanned Aerial Vehicle Data Collection

3.2.3.1 Data Capture

A small UAV (Figure 3-2) was used to collect data over two three day periods in July and November 2016. A Sensefly Ebee fixed-wing UAV was positioned by a Trimble R10 real time kinematic (RTK) GPS base station. The base station’s location was corrected by the Trimble virtual reference station network, which was streamed to the RPA via a ground modem. Images collected by a downward facing camera during the flight were tagged with positional and heading information gathered from the UAV and the ground link. This information was used in the construction of ortho-mosaics and DEMs (see Section 3.2.3.2).

Figure 3-2 EBee fixed wing UAV

The first aerial survey was conducted over a two day period on 20 and 21 July 2016 using an eBee RTK[2] fixed wing aircraft. A total of 14 flights were completed to cover the area of interest, with each flight lasting up to 30 minutes. In accordance with the Area Approval granted by the CASA[3] a maximum flying height of 90 m was observed. Images were collected with a 75% forward and lateral overlaps.

A second aerial survey was conducted over a three day period from 7 to 9 November 2016, in an attempt to fill some gaps in elevation from the first survey. This was the earliest survey window afforded by CASA.

Flying conditions during 20 and 21 July were optimal; bright clear skies, excellent visibility, slight breeze and calm water. Where practical, flying over salt pan areas was undertaken at low tide. An example flight track is shown in Figure 3-3. Conditions for the second survey were less favourable, with strong to moderate northerly breezes and short windows of operation allowed by CASA. Flights were conducted in the morning until wind speeds prevented effective survey.

[2] The real time kinematic (RTK) GPS on the aircraft receives GPS positional corrections from the flight computer by radio communication. The flight computer receives a real-time GPS correction feed from the Virtual Reference Network (VRS). The VRS is a network of GPS receivers, each located at a known position. The difference in position between the base GPS and the known position is the error in the GPS signal, which is streamed to the flight computer via the cellular network. The aircraft applies the correction to the signal it receives from the on-board GPS to obtain centimetre level accuracy.

[3] Civil Aviation Safety Authority (CASA) granted authority to fly in consultation with Air Services Australia, who manage the air traffic control at the Brisbane Airport.

Figure 3-3 Flight track for area on Whyte Island (red dots indicate locations where photos were taken)

A total of 2,261 images were captured during the July survey. Image resolution is approximately 32 mm per pixel. Refer to Figure 3-4 for sample image.

The UAV was flown by a Civil Aviation Safety Authority (CASA) certified operator, with a second stand-by pilot also utilised for long distance flights where the UAV was out of visual range from the take-off and land points. The flights were within the 5 km Brisbane Airport exclusion zone, therefore, flight plans were pre-approved by CASA and limited to 90 m altitude.

Combined results from the first and second surveys were used to create elevation models, but near infra-red imagery was not used from the second survey due to strong differences in climate between the two survey periods and poor mosaic alignment due to excessive wind and image capture at low altitude.

3.2.3.2 Data Processing

Image post-processing has been undertaken according to the following workflow.

- eMotion2:
  - combines flight log positional data with image data
  - converts native CR2 format near infrared images to JPG

- Pix4D:
  - generates point clouds from images. A point cloud is a series of 3D points, with colour attribute, used to generate a 3D model of the terrain and vegetation
  - prepares an orthomosaic aerial image
- Adam3DM:
  - similar to Pix4D assists with processing complex areas that cannot be processed by Pix4D due to the altitude restrictions imposed by CASA for the project
- Global Mapper:
  - applies the datum shift due to the Geoid-Ellipsoid Separation (difference in coordinate system datums used by the aircraft GPS and Australian Height Datum
  - exports digital terrain model (DTM) and digital surface model (DSM) for use in other GIS software.

Due to the low altitude of the flights, homogeneity and vertically complex nature of the canopy, data were unable to be processed with the standard post-flight software suite. A proprietary pixel matching algorithm was used instead to create photo-mosaics and triangulate pixels, providing a digital elevation model. This technique was successful in a small number of locations, and where possible, photo-mosaics were produced from these data.

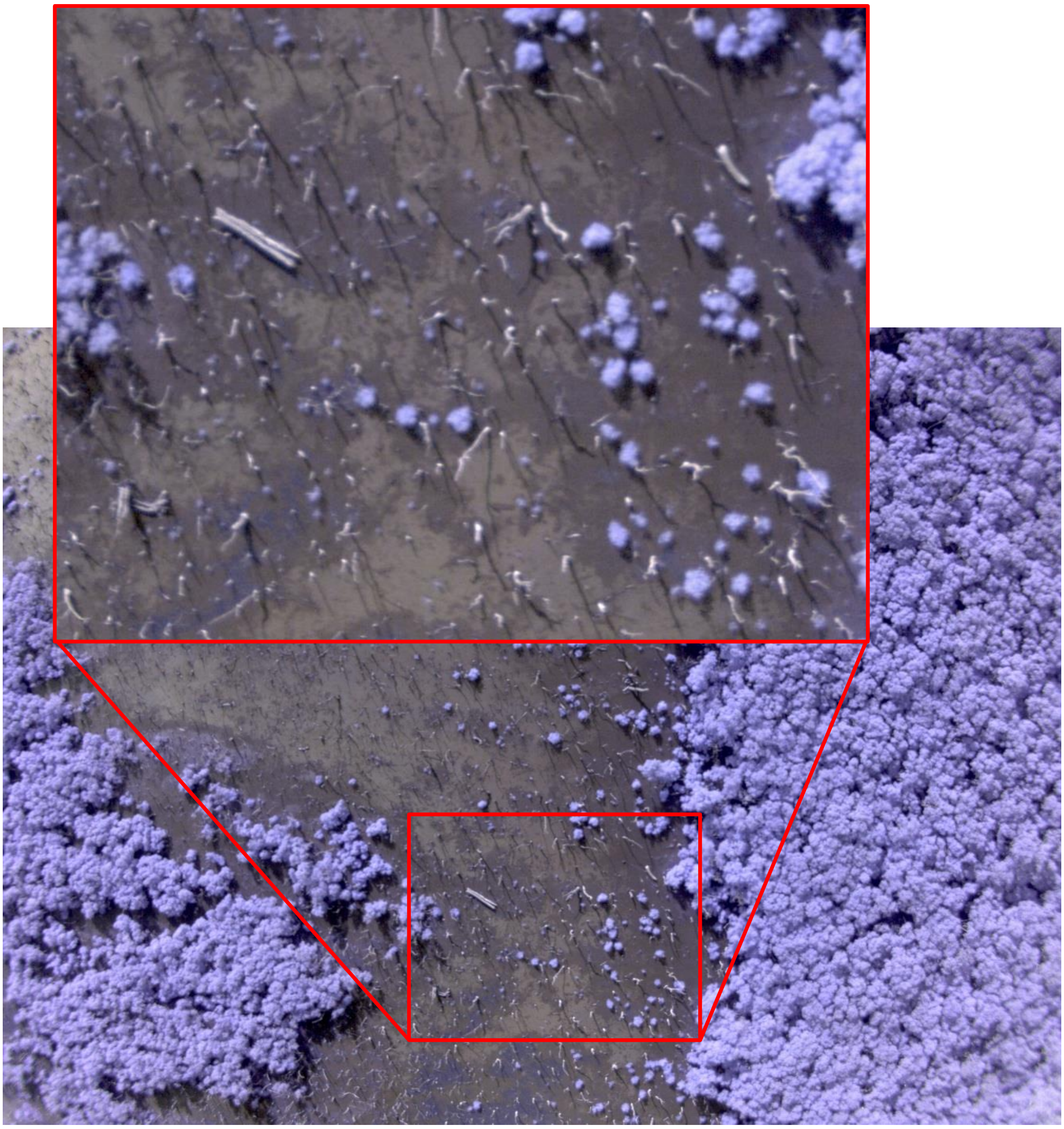


Figure 3-4 Sample image

3.2.3.3 Weather Conditions Prior to and During Survey

Figure 3-5 shows monthly rainfall measured at the Bureau of Meteorology station at Brisbane Airport from 1 January to 21 July 2016, and long-term average and median monthly rainfall. A total of 445 mm was recorded in this period. Rainfall was well below average in February, April and May 2016, and well above average in June 2016. The Southern Oscillation Index (SOI) was -7 (El Niño events) over most months from July 2014 to May 2016 (i.e. drought), increasing to near average SOI in June and July 2016 (Figure 3-6).

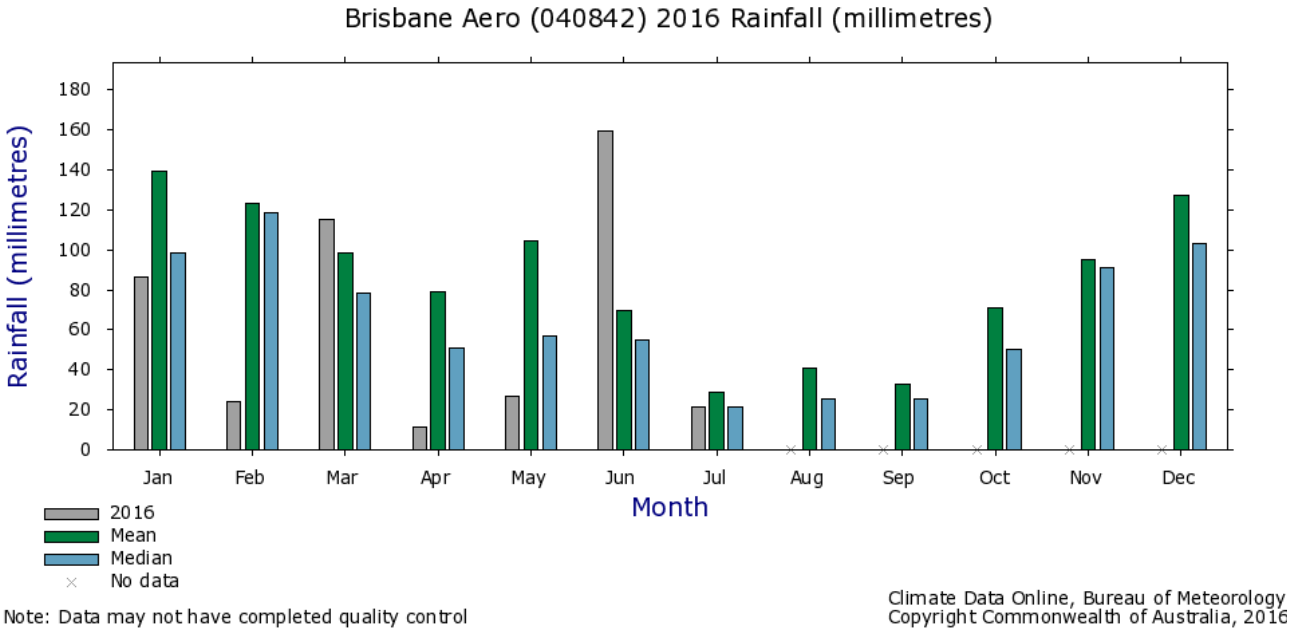


Figure 3-5 Monthly rainfall at Brisbane Airport (BOM Station 040842) – 1 January to 21 July 2016

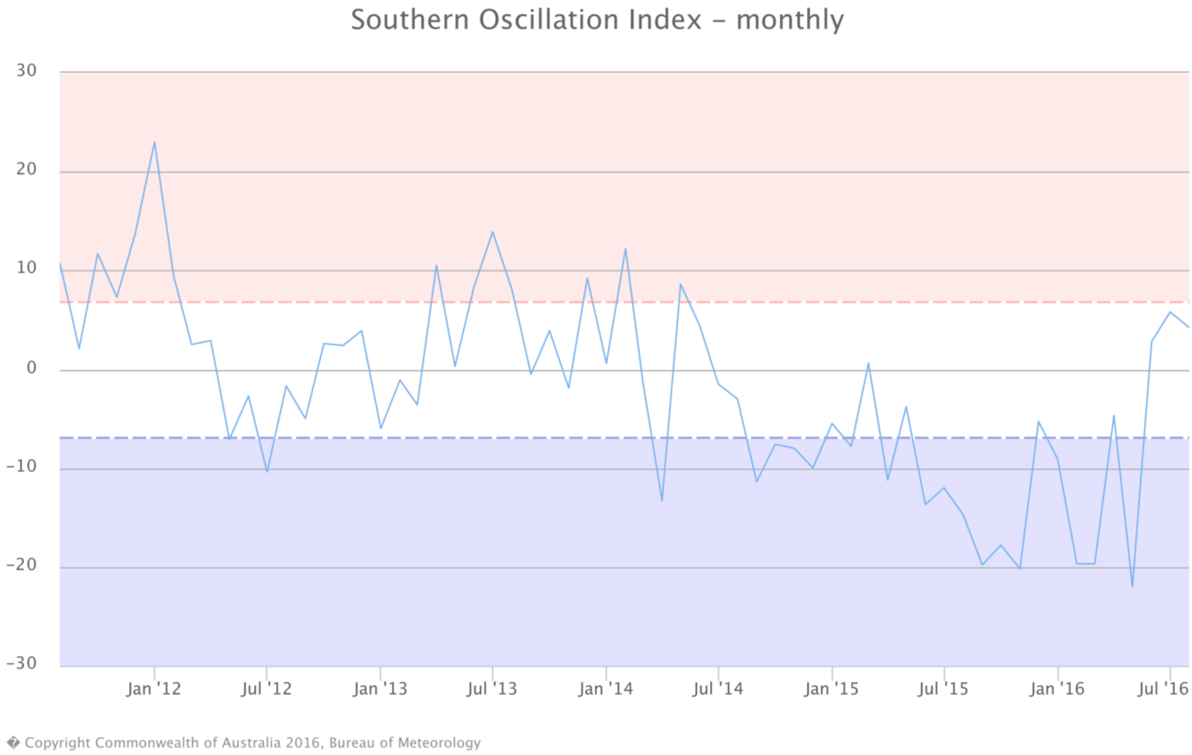


Figure 3-6 Monthly Southern Oscillation Index (SOI)

3.3 Assumptions and Limitations

It is important to note that the survey equipment used in the present study use different sensor types, and therefore, derived metrics are not directly comparable between methods. Therefore, NDVI results should only be directly compared within survey methods, although broad-scale patterns produced by different sensors can be qualitatively compared.

As noted in Section 3.2.3.2, there are limitations with the UAV data resulting from the low altitude of the flights (90 m compared with the standard 120 m), homogeneity and vertically complex nature of the canopy. The second UAV survey was not permitted by CASA to be reflown at an altitude above 90 m and compressed flight windows were not sufficient for a higher than normal level of image overlap.

4 Results

4.1 Existing Conditions

4.1.1 Vegetation Community Mapping from Satellite Imagery

The following mangrove species have been recorded in the investigation areas during rapid site inspections in 2016 (coincident with UAV flights) and in previous studies (WBM 2002; BMT WBM 2014):

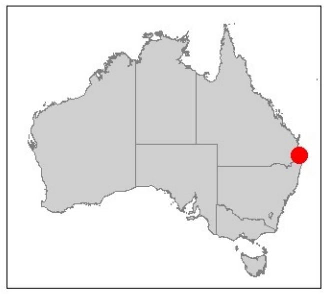
- Grey mangroves *Avicennia marina* var *australasica*
- Yellow mangroves *Ceriops australis*
- Red mangroves *Rhizophora stylosa*
- Orange mangrove *Bruguiera gymnorhiza*
- River mangrove *Aegiceras corniculatum*.

Milky mangrove *Excoecaria agallocha* and Black mangrove *Lumnitzera racemosa* are known to occur in Moreton Bay (Dowling 1979), and may occur in the investigation areas in small numbers.

Figure 4-1 and Figure 4-2 show the raw, preliminary vegetation classifications based on four band (RGB+NIR) data from Pleiades satellite imagery. Vegetation community data, past ground truthing, and canopy elevation data were used to interpret these preliminary vegetation maps, and the resulting community map is shown in Figure 4-3.

Avicennia marina (grey mangrove) dominated assemblages were the main vegetation class in all investigation areas. The *Ceriops* +/- degraded mangrove mixed assemblage were mapped in patches throughout the study area, consistent with BMT WBM (2014) and FRC Environmental (2012). Based on canopy height (Figure 4-10), high-resolution imagery of the canopy, and previous ground truthing, *Ceriops* forest polygons were mapped as directly south of the saltpan near the Port Office, at Fisherman Islands, at the southern extremity of the Coal Loader area, and in the northern part of Whyte Island.

The central interior portions of Fisherman Islands and Whyte Island contain a mosaic of saltmarsh and claypan vegetation classes. The claypan class also includes ponded waters containing benthic microalgae mats. The supervised classification also mapped portions of intertidal mud flats immediately seaward of mangrove forests, which should not be used in subsequent temporal comparisons in future monitoring reports, and have been removed from Figure 4-3.



LEGEND

- Class 1
- Class 2
- Class 3
- Class 4

Title:

RGB colour extent at Fisherman Islands (Pleiades August 10, 2016)

Figure
4-1

Rev:
A

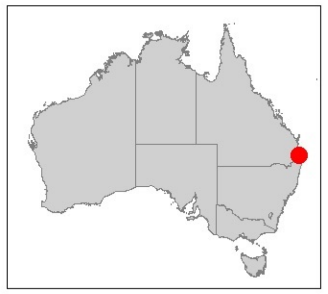
N

0 0.4 0.8km

Approx. Scale

BMT WBM
www.bmtwbm.com.au

Filepath : C:\Users\Conor.Jones\Desktop\PoB_landsat\Mapinfo\Fig_4-1.wor



LEGEND

- Class 1
- Class 2
- Class 3
- Class 4

Title:

RGB colour extent at Whyte Islands (Pleiades August 10, 2016)

Figure

4-2

Rev:

A

N

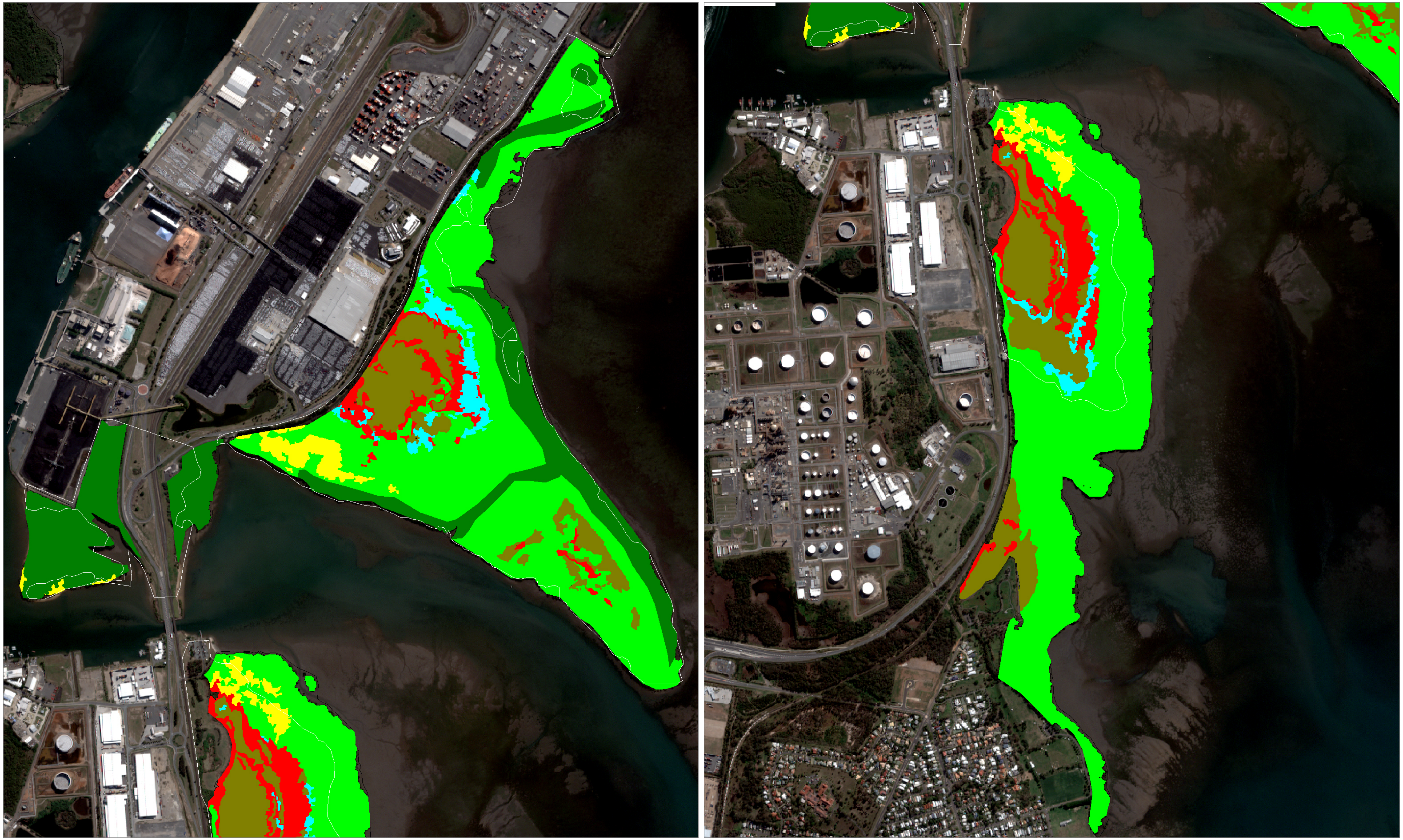
0 0.4 0.8km

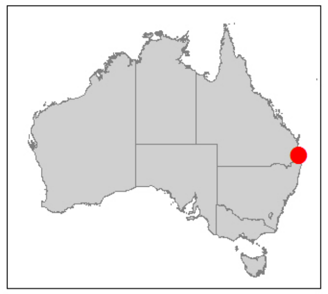
Approx. Scale

BMT WBM

www.bmtwbm.com.au

Filepath : C:\Users\Conor.Jones\Desktop\PoB_landsat\Mapinfo\Fig_4-2.wor





LEGEND

- Claypan
- Saltmarsh/ saltbush
- Ceriops australis open to closed scrub +/- Am, Ac, (2-5 m)
- A. marina low closed to open forest +/- Ct, Rs, Ac, (2-10 m)
- A. marina closed to open forest +/- Ct, Rs, Ac, (>10 m)
- A. marina shrubland +/- Ct, Ac, (1-2 m)
- UAV-based elevation available

Title:

Smoothed habitat classes and adopted boundaries at Fisherman Islands, Coal Loader and Whyte Island

Figure: 4-3

Rev: A

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N

0m 400 800

Approx. Scale

BMT WBM

www.bmtwbm.com.au

Filepath: I:\B20259_I_BRH Port of Brisbane DLR\DRG\Mangrove_2016\ECO_011b_170221_Smoothed_habitats_4-3.wor

4.1.2 NDVI from Satellite Imagery

Table 4-1 presents NDVI metrics for each vegetation class and investigation area (and in the case for Fisherman Islands, sub-areas east and west), based on high-resolution satellite imagery shown in Figure 4-5. Figure 4-4 presents mean (± S.E.) NDVI values for each vegetation class and investigation area.

NDVI was calculated in a total of 845,459 pixels (2 x 2 m size). There were distinct differences in NDVI among vegetation classes, and to a lesser extent among investigation areas. *Avicennia* dominated forest had the highest NDVI values, with the maximum NDVI ranging from 0.704 at Fisherman Islands east to 0.802 at Whyte Island.

While Whyte Island had the highest recorded NDVI value, the overall mean NDVI at this investigation area was within the range recorded at other investigation areas for this vegetation class. The highest NDVI values at Whyte Island were recorded in mangrove forest at the licensed discharge point of Wynnum WWTP at Crab Creek, and the mangrove-terrestrial interface adjacent to the mangrove boardwalk (Figure 4-4).

Table 4-1 NDVI summary metrics from the high-resolution satellite imagery based on Pleiades satellite imagery (August 2016)

Vegetation type	Investigation area (and location)	No. pixels	Area (ha)	Max NDVI	Mean NDVI	Standard Deviation NDVI	Coefficient of variation NDVI
Avicennia	Coal Loader	48,626	194,504	0.707	0.507	0.079	0.156
Avicennia	Fisherman Is. - east	109,985	439,940	0.704	0.522	0.094	0.180
Avicennia	Fisherman Is. - west	212,872	851,488	0.717	0.522	0.083	0.159
Avicennia	Whyte Is.	216,074	864,296	0.802	0.513	0.081	0.158
Ceriops + mixed	Coal Loader	3,794	15,176	0.600	0.387	0.132	0.341
Ceriops + mixed	Fisherman Is. - east	3,662	14,648	0.637	0.391	0.111	0.284
Ceriops + mixed	Fisherman Is. - west	45,008	180,032	0.624	0.400	0.101	0.252
Ceriops + mixed	Whyte Is.	30,059	120,236	0.655	0.416	0.100	0.240
Saltmarsh/ claypan	Coal Loader	1,011	4,044	0.618	0.259	0.163	0.629
Saltmarsh/ claypan	Fisherman Is. - east	15,406	61,624	0.639	0.130	0.157	1.207
Saltmarsh/ claypan	Fisherman Is. - west	56,957	227,828	0.647	0.161	0.166	1.031
Saltmarsh/ claypan	Whyte Is.	102,005	408,020	0.711	0.148	0.160	1.081

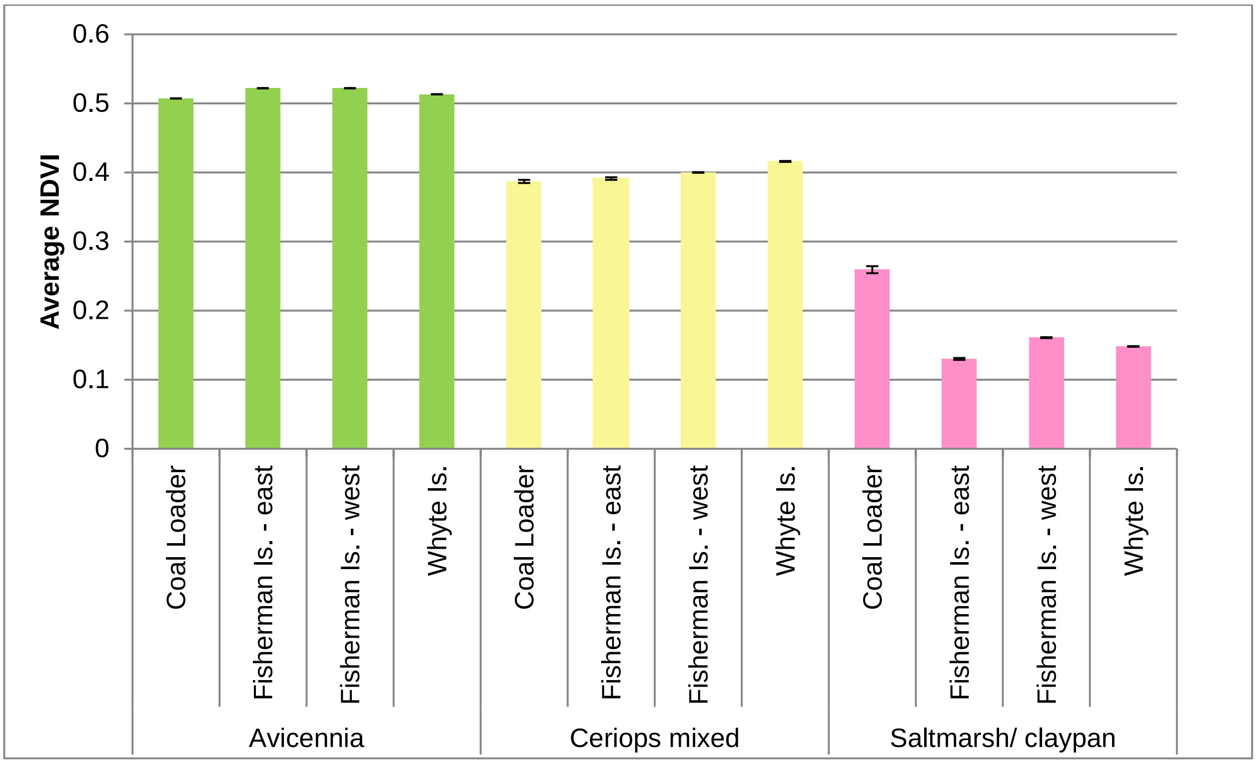
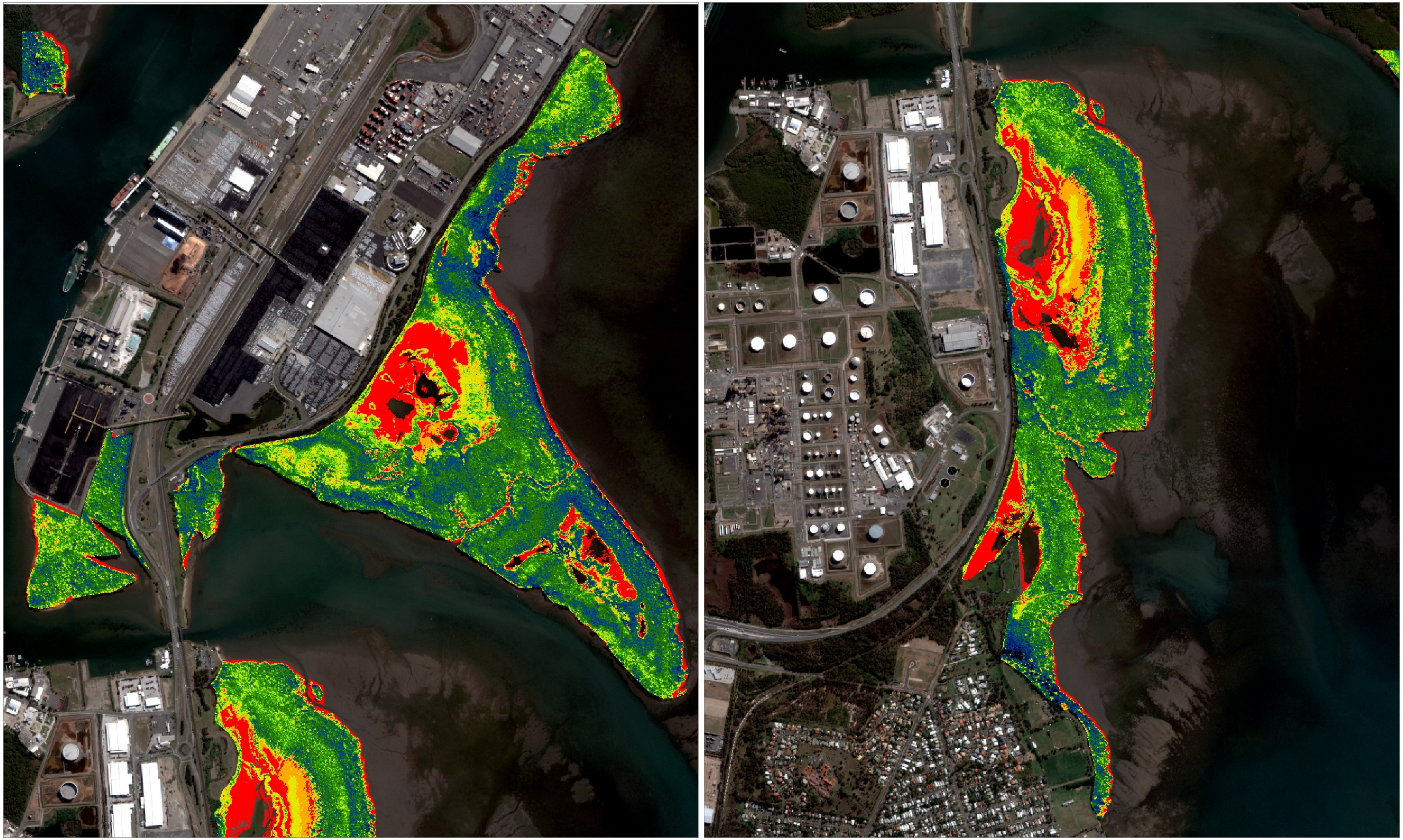
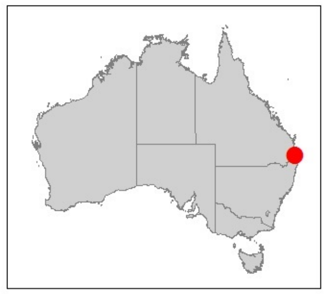


Figure 4-4 Average NDVI values for each vegetation class based on high-resolution satellite imagery. Error bars represent standard error

Elsewhere at Whyte Island and the Fisherman Island investigation areas, NDVI tended to be highest on the seaward fringe of *Avicennia* dominated forest, whereas the central areas containing low *Avicennia* forest had lower NDVI values. *Ceriops*/mixed mangrove assemblages had consistently lower NDVI values that *Avicennia* dominated forest, and also displayed a higher degree of variability in NDVI (coefficient of variation at *Ceriops*/mixed = 0.24-0.34; 0.15-0.18 in *Avicennia*). The higher variability is a function of the mixed species composition of this vegetation class, whereas the lower NDVI reflects differences in bandwidth reflectance among species (see Section 5.1).

The saltmarsh/claypan had the lowest NDVI values and the highest degree of variability in NDVI (Table 4-1), reflecting differences in the amount of saltmarsh, 'bare' claypan and benthic microalgae cover in ponded areas.





NDVI

0 - 0.2	
0.2 - 0.3	
0.3 - 0.4	
0.4 - 0.45	
0.45 - 0.5	
0.5 - 0.55	
0.55 - 0.6	
0.6 - 0.65	
0.65 - 0.8	

Title:

NDVI of high-resolution satellite imagery at Fisherman Islands and Whyte Island

Figure 4-5

Rev: A

N

0 0.4 0.8km

Approx. Scale

BMT WBM

www.bmtwbm.com.au

Filepath : C:\Users\Conor.Jones\Desktop\PoB_landsat\Mapinfo\Fig_4-4.wor

4.1.3 NDVI and Elevation Data from UAV

NDVI maps based on data collected using UAV are presented in Figure 4-6 (northern Fisherman Islands), Figure 4-7 (eastern Fisherman Islands), Figure 4-8 (western Fisherman Islands) and Figure 4-9 (Whyte Island). Low flight altitudes and homogeneous canopies prevented effective photogrammetry in some parts of the canopy, resulting in data gaps. The July and November UAV data collections were then combined to create an overall elevation model.

The July NDVI maps show that there was great variability in NDVI values both among vegetation classes (e.g. mangroves compared to claypan), and within classes. At broad (measured in 100s of metres) spatial scales, NDVI tended to be highest on the seaward fringe of *Avicennia* forests, and lowest in interior portions containing saltmarsh[4]. Saltpan tended to have low or no NDVI signal, although there were several areas of very shallow water (containing dense microalgae mats) on the western saltpan of Fisherman Island that had very high NDVI values.

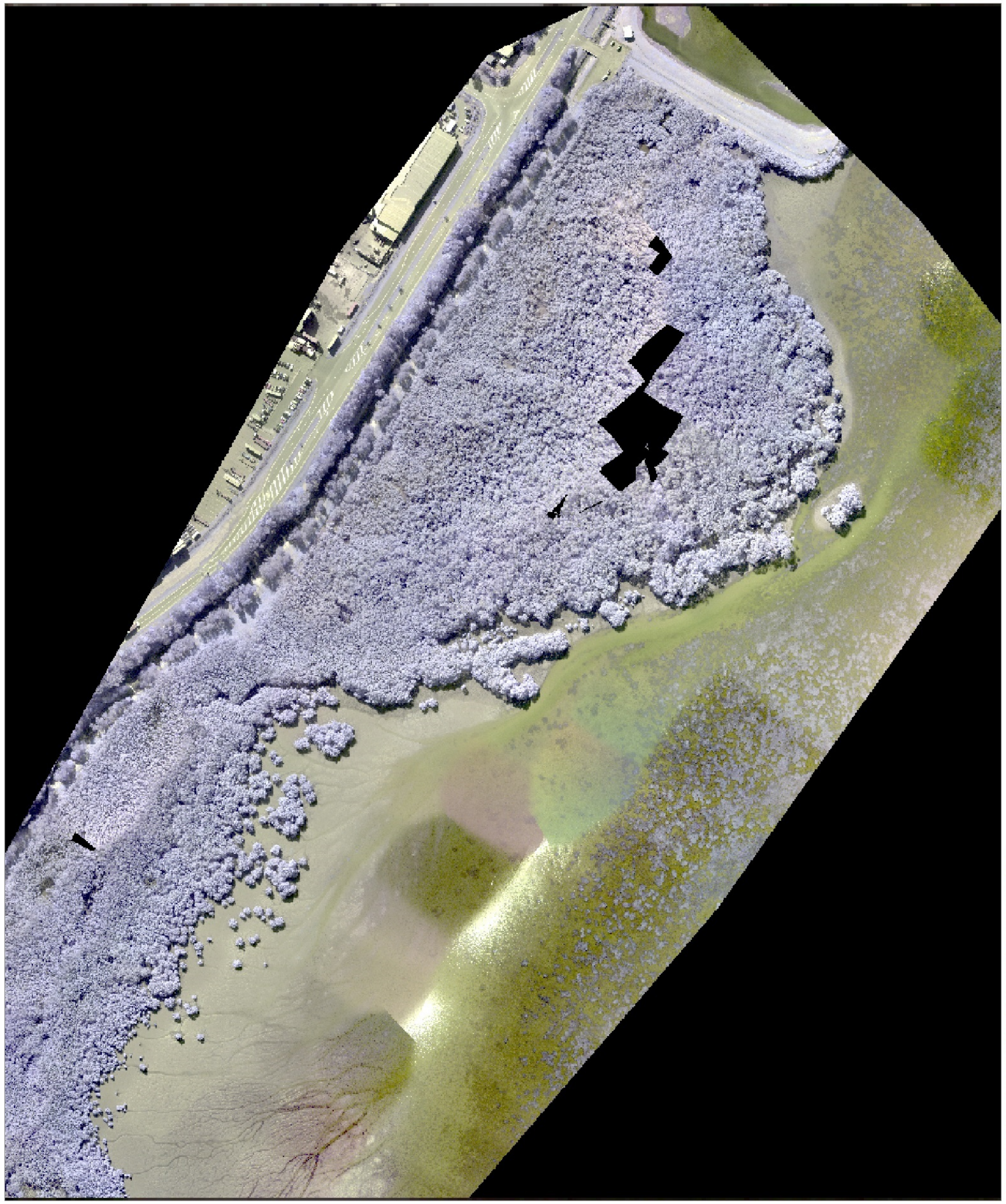
The high degree of 'within-class' variability in NDVI reflects fine-scale heterogeneity, measured in 10's of metres (i.e. differences among trees, to meters (i.e. differences in NDVI in different parts of the tree canopy, e.g. side compared to top of the canopy). This ultra-fine scale spatial variability results in a high degree of small-scale patchiness in NDVI.

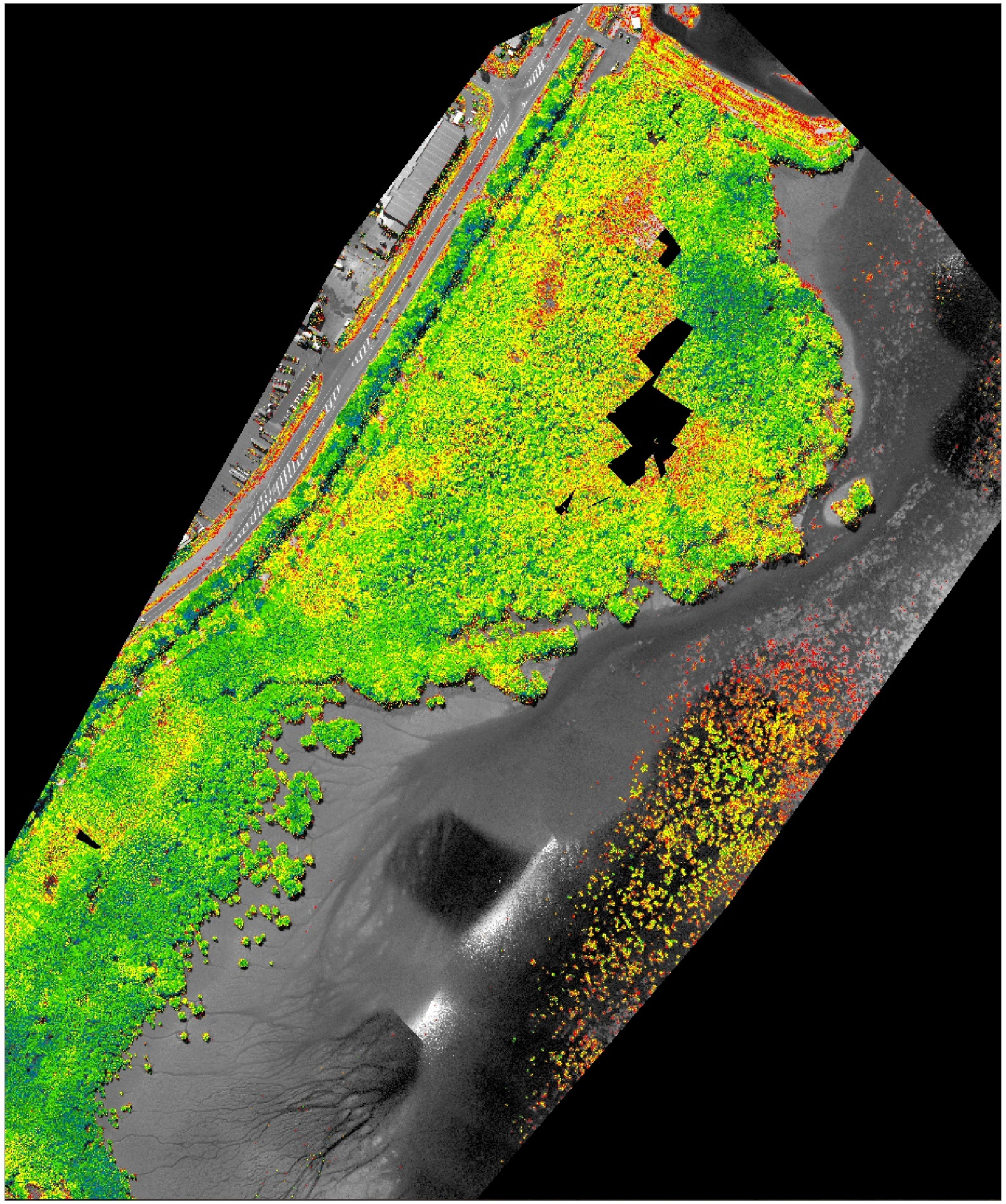
Elevation data collected using UAV for the entire study area and claypans only are shown in Figure 4-10 and Figure 4-11, respectively. Elevation data are missing from the coal loader and parts of Fisherman Island and Whyte Island where photogrammetry was unable to match pixels between sets of overlapping photos (due again to low flight altitudes).

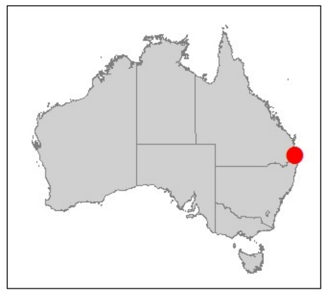
The highest parts of the canopy were located along the northern fringe of Fisherman Island and adjacent to the coal loader. It is likely that elevations of trees on the outer fringe of Whyte Island were also high, but this part of the elevation model was not reliably interpolated. Interestingly, there was a strong agreement between the highest parts of the canopy and the strength of the NDVI signal in both satellite imagery and UAV data. This could be related to shading and higher NDVI, and/or greater depth of canopy for a stronger signal.

In terms of claypan elevation (Figure 4-11), the claypans at Fisherman Island had a much flatter gradient than the claypan at Whyte Island, which lost elevation in a southerly direction. No distinct east-west or north-south elevation gradients were observed at either of the Fisherman Islands claypans.

[4] Note that the high NDVI values on the landward fringe of Whyte Island are terrestrial vegetation







LEGEND

- 0.1 - 0.12
- 0.12 - 0.145
- 0.145 - 0.175
- 0.175 - 0.2
- 0.2 - 0.22
- 0.22 - 0.245
- 0.245 - 0.275
- 0.275 - 0.3
- 0.3 - 0.5

Title:
NDVI of UAV imagery at northern Fisherman Islands

Figure 4-6

Rev: A

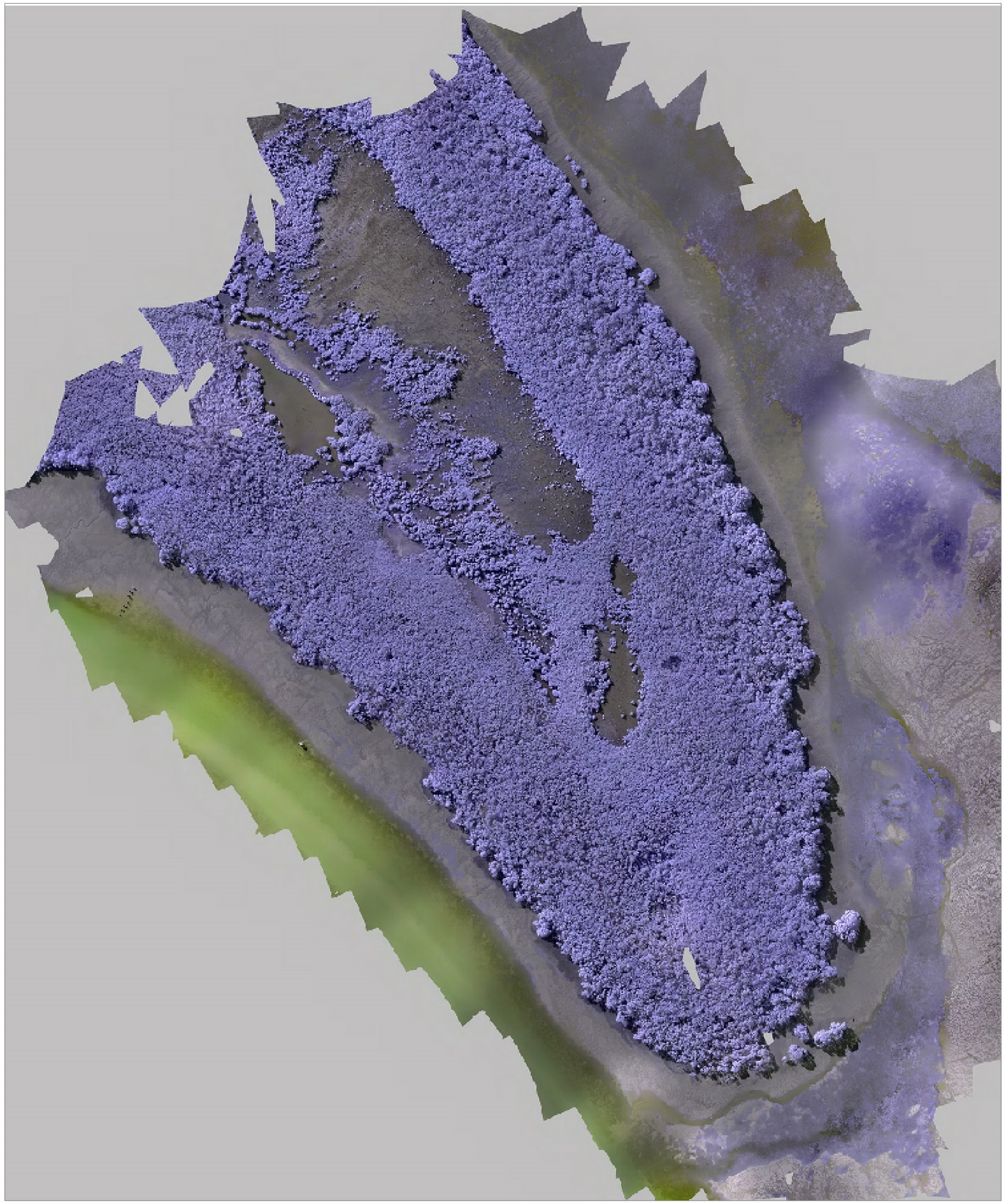
N

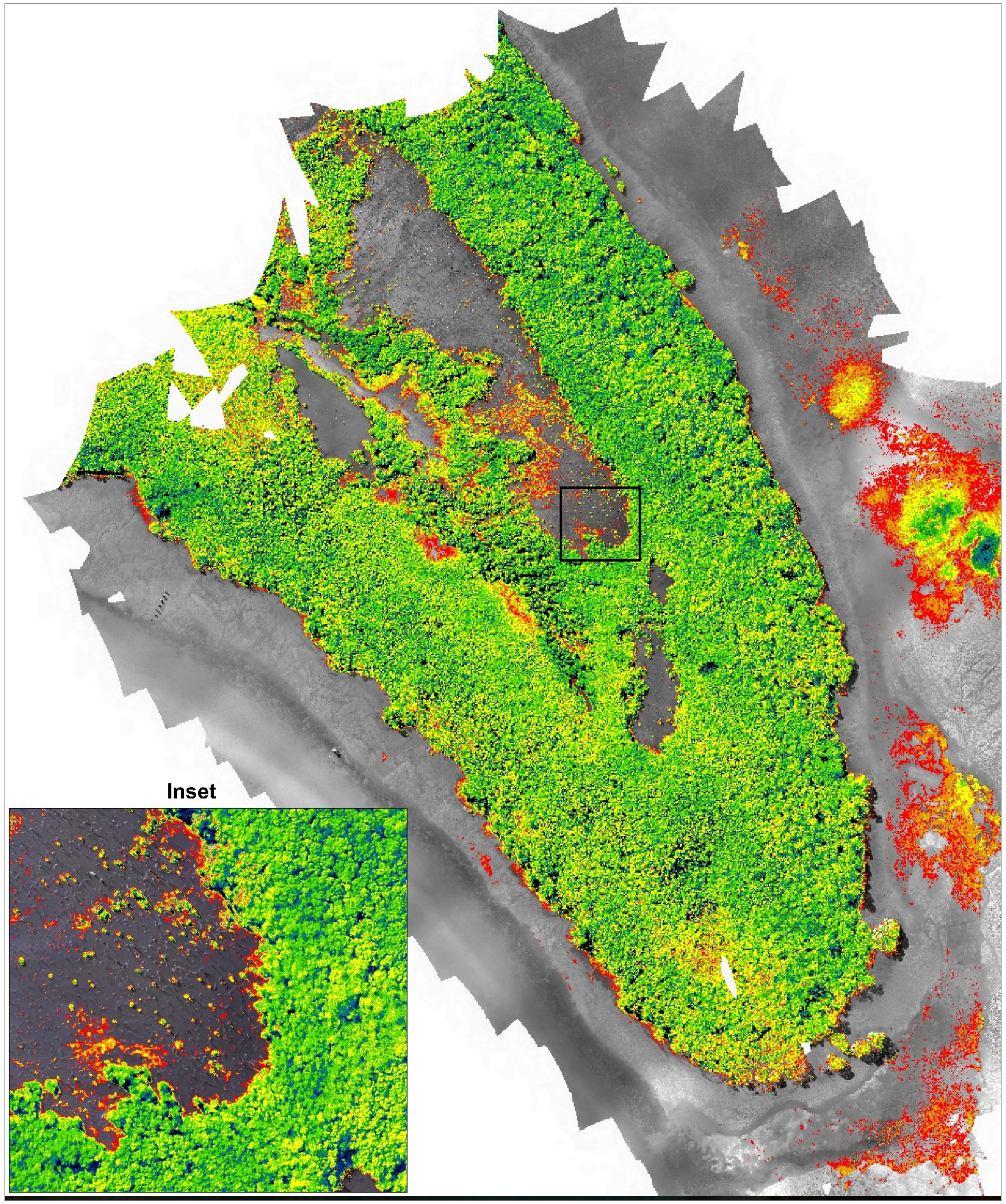
0 50 100m

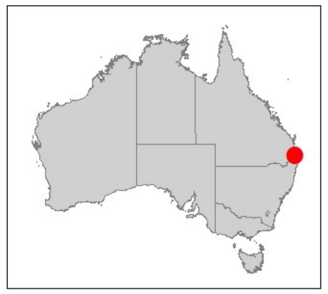
Approx Scale

BMT WBM
www.bmtwbm.com.au

Filepath : C:\Users\Conor.Jones\Desktop\PoB_landsat\Mapinfo\Fig_4-5.wor







LEGEND

- 0.1 - 0.12
- 0.12 - 0.145
- 0.145 - 0.175
- 0.175 - 0.2
- 0.2 - 0.22
- 0.22 - 0.245
- 0.245 - 0.275
- 0.275 - 0.3
- 0.3 - 0.5

Title:

NDVI of UAV imagery at eastern Fisherman Islands

Figure **4-7**

Rev: **A**

N

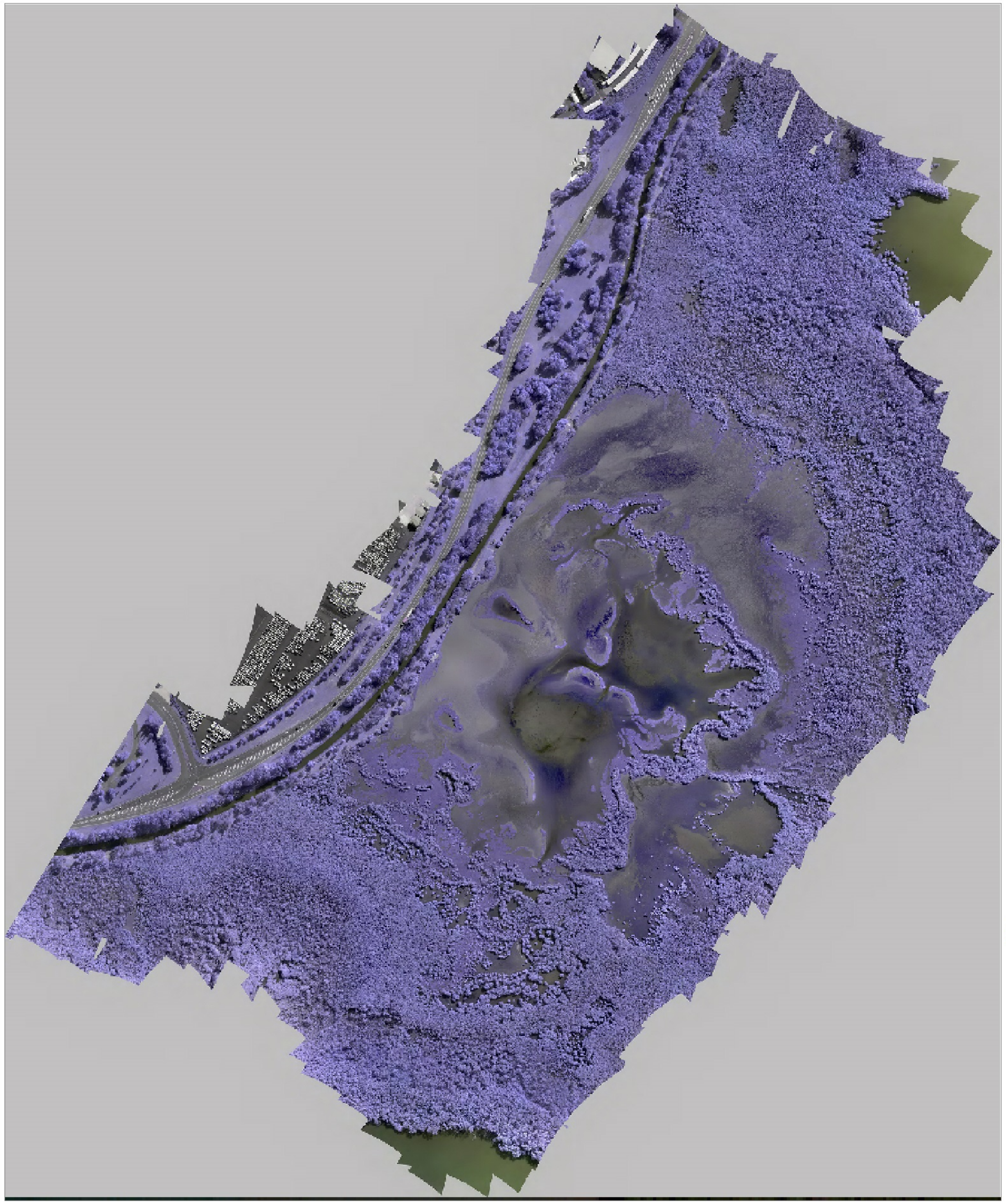
0 50 100m

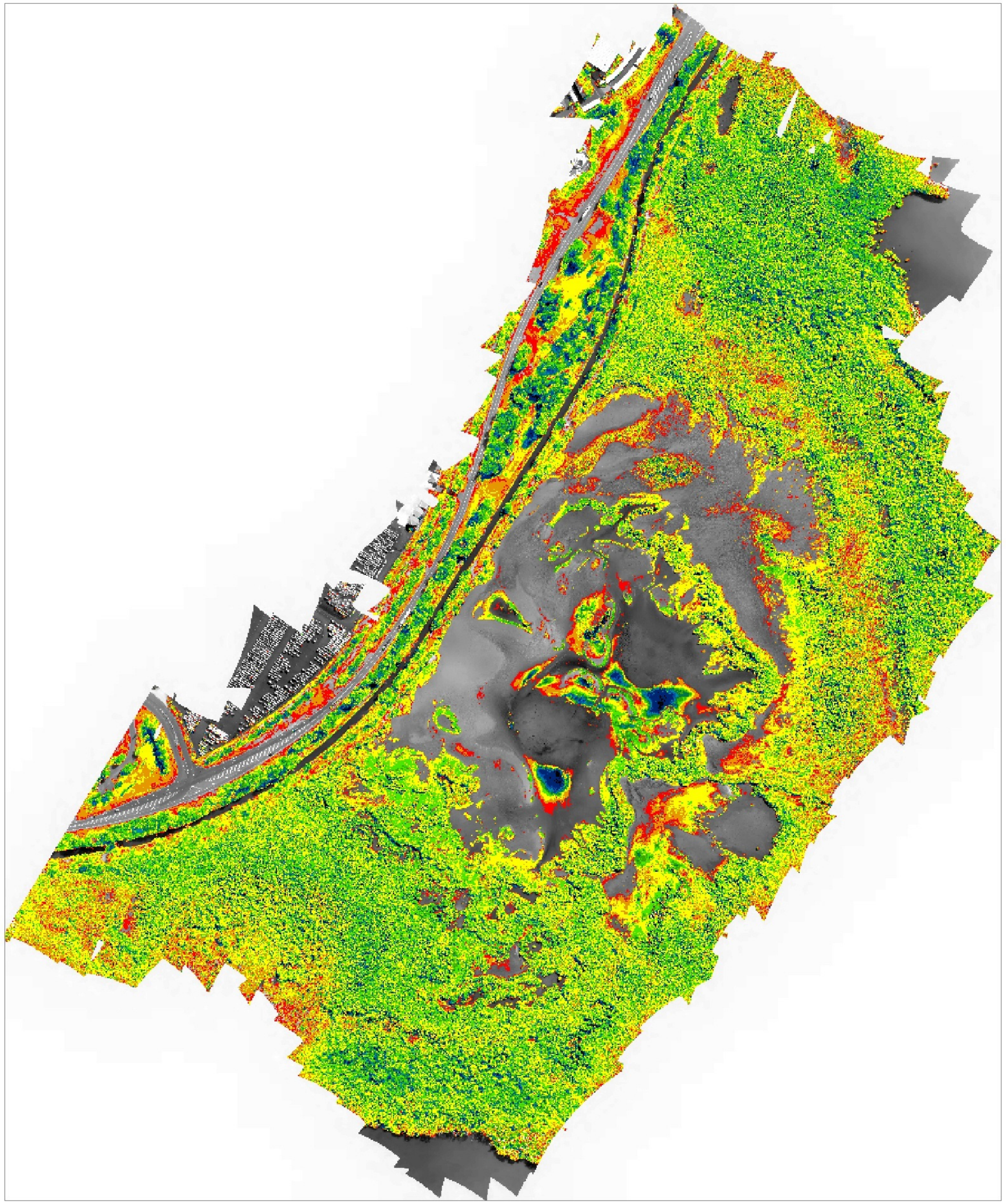
Approx Scale

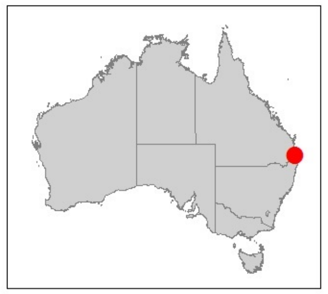
BMT WBM

www.bmtwbm.com.au

Filepath : C:\Users\Conor.Jones\Desktop\PoB_landsat\Mapinfo\Fig_4-6.wor







LEGEND

0.1 - 0.12	
0.12 - 0.145	
0.145 - 0.175	
0.175 - 0.2	
0.2 - 0.22	
0.22 - 0.245	
0.245 - 0.275	
0.275 - 0.3	
0.3 - 0.5	

Title:

NDVI of UAV imagery at western Fisherman Islands

Figure

4-8

Rev:

A

N

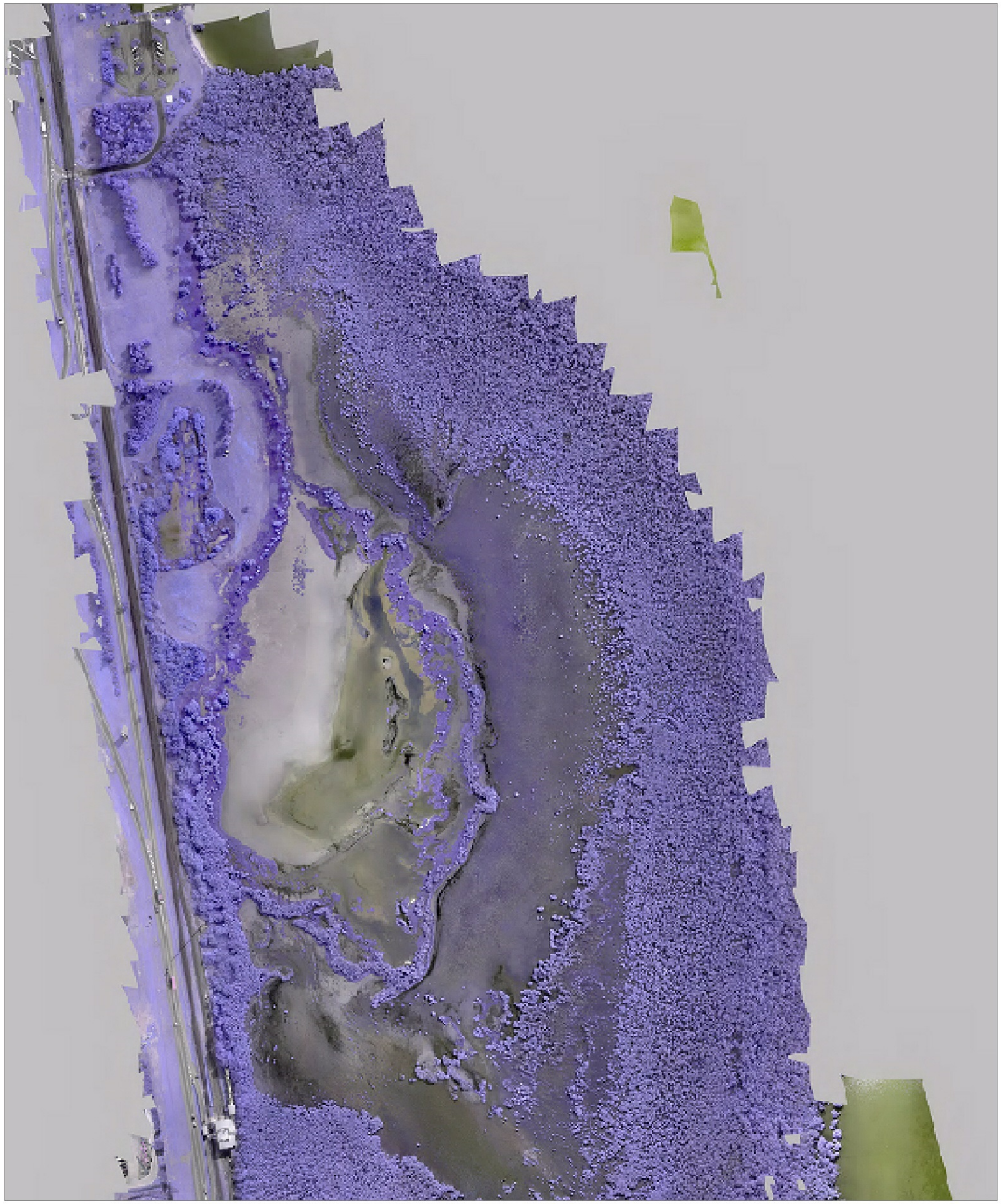
0 50 100m

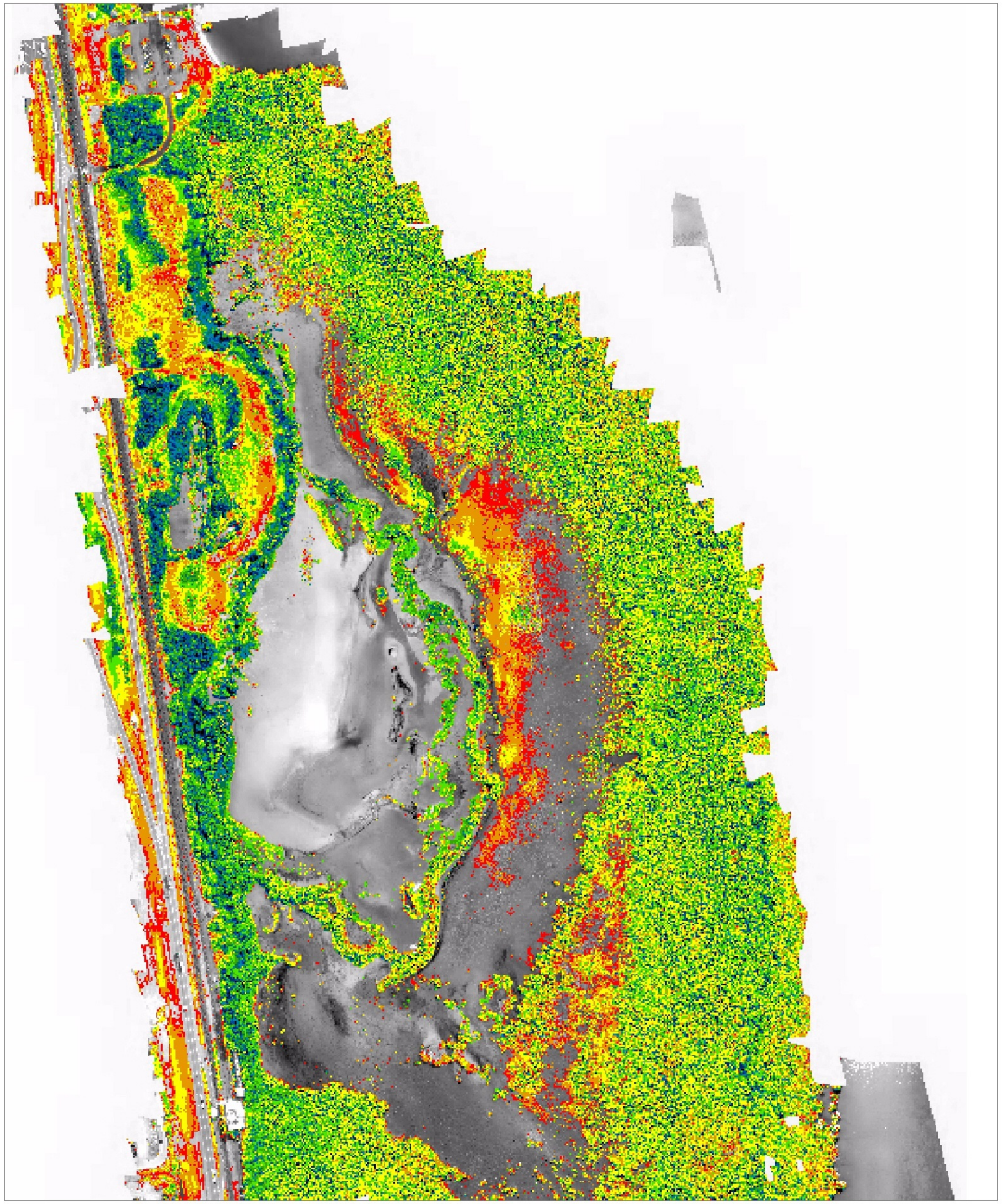
Approx Scale

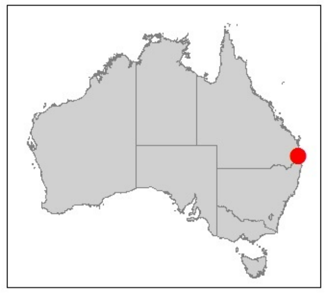
BMT WBM

www.bmtwbm.com.au

Filepath : C:\Users\Conor.Jones\Desktop\PoB_landsat\Mapinfo\Fig_4-7.wor







LEGEND

- 0.1 - 0.12
- 0.12 - 0.145
- 0.145 - 0.175
- 0.175 - 0.2
- 0.2 - 0.22
- 0.22 - 0.245
- 0.245 - 0.275
- 0.275 - 0.3
- 0.3 - 0.5

Title:

NDVI of UAV Imagery at Whyte Island

Figure

4-9

Rev:

A

N

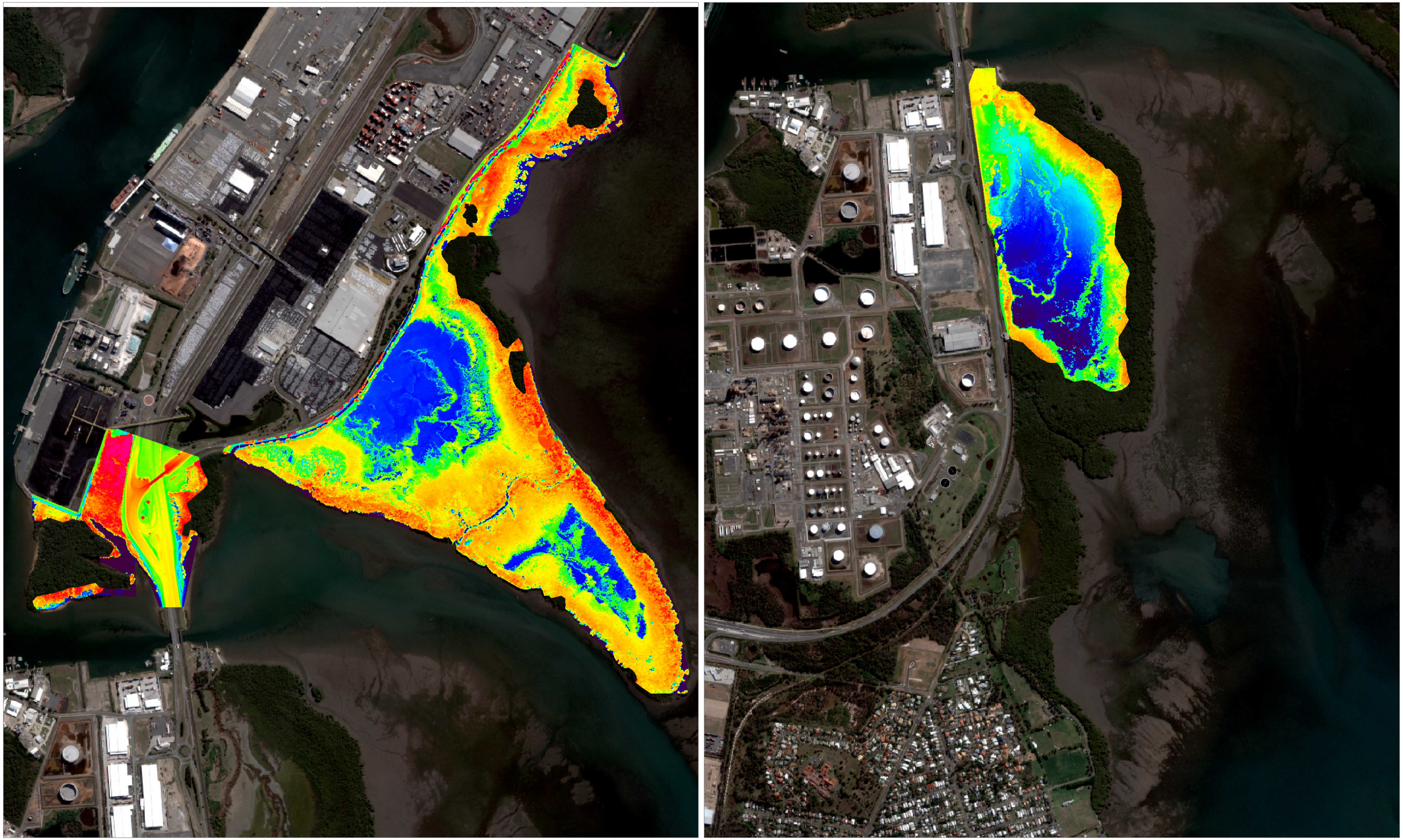
0 50 100m

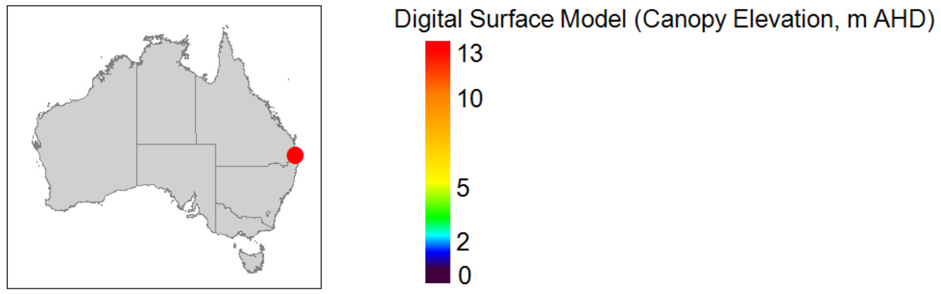
Approx.Scale

BMT WBM

www.bmtwbm.com.au

Filepath : I:\B20259_I_BRH Port of Brisbane DLR\DRG\Mangrove_2016\ECO_008_160919_NDVI of UAV Imagery_Whyte Island.wor





Title:

UAV-based Elevation at Fisherman Islands and Whyte Island

Figure: 4-10

Rev: A

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N

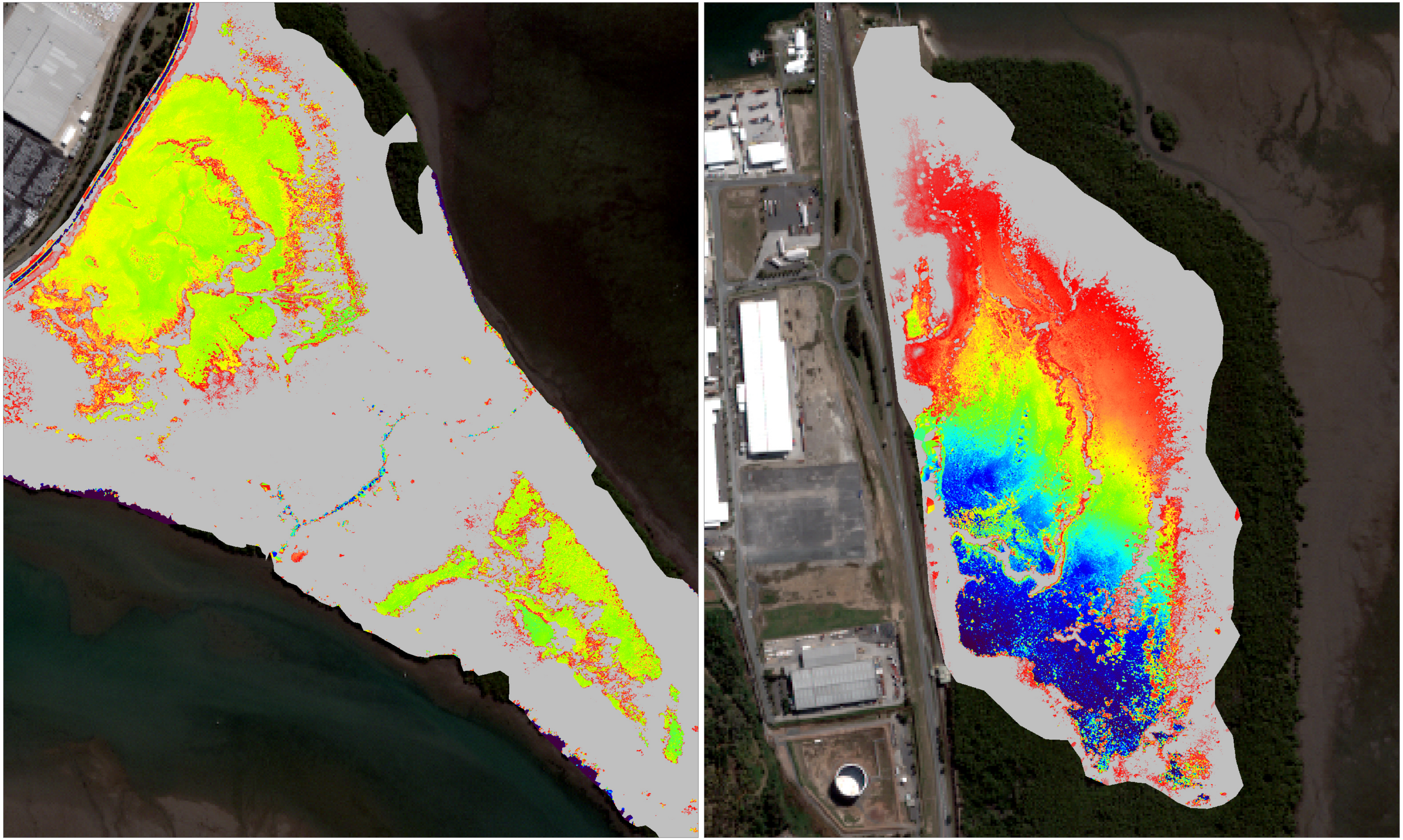
0m 400 800

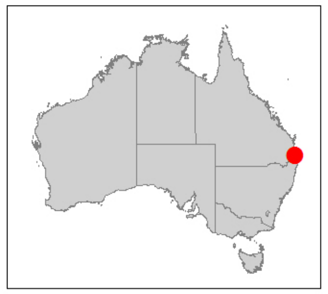
Approx. Scale

BMT WBM

www.bmtwbm.com.au

Filepath: I:\B20259_I_BRH Port of Brisbane DLR\DRG\Mangrove_2016\ECO_017_170118_Elevation.wor





Elevation (m AHD)

3
2.0
1.5
1.25
1.0
0.75
0.5
0.0

Title:
UAV-based Elevation of Claypans at Fisherman Islands and Whyte Island

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N

0 150 300m

Approx.Scale

Figure
4-11

Rev:
A

BMT WBM
www.bmtwbm.com.au

Filepath : I:\B20259_I_BRH Port of Brisbane DLR\DRG\Mangrove_2016\ECO_018_170118_Elevation_Saltpans.wor

4.2 Historical Trends in Mangrove Health

4.2.1 Long-term Trends in SOI and Rainfall

Figure 4-12 shows annual rainfall (including 2 year moving average), long-term annual average rainfall for the period 1964-2013 (Fort Lytton) and 2014-16 (Brisbane Airport), and the annual average Southern Oscillation Index (SOI). Wet years (above average rainfall) typically occurred during La Niña periods (strong positive SOI), droughts typically occurred during El Niño periods (strong negative SOI). The study period (1987-2016) was characterised by:

- Successive wet years 1987-1990
- Drought in 1991-95, followed by above average rainfall in 1996, low/average rainfall in 1997-1998, and well above average rainfall in 1999
- Successive drought years in 2000-2009, broken by above average rainfall in 2010
- Drought in 2014 and 2016.

With few exceptions, the study period was characterised by below average rainfall with occasional high rainfall years. The 2 year moving average shows that the period post-1999 had lower rainfall than the period decades.

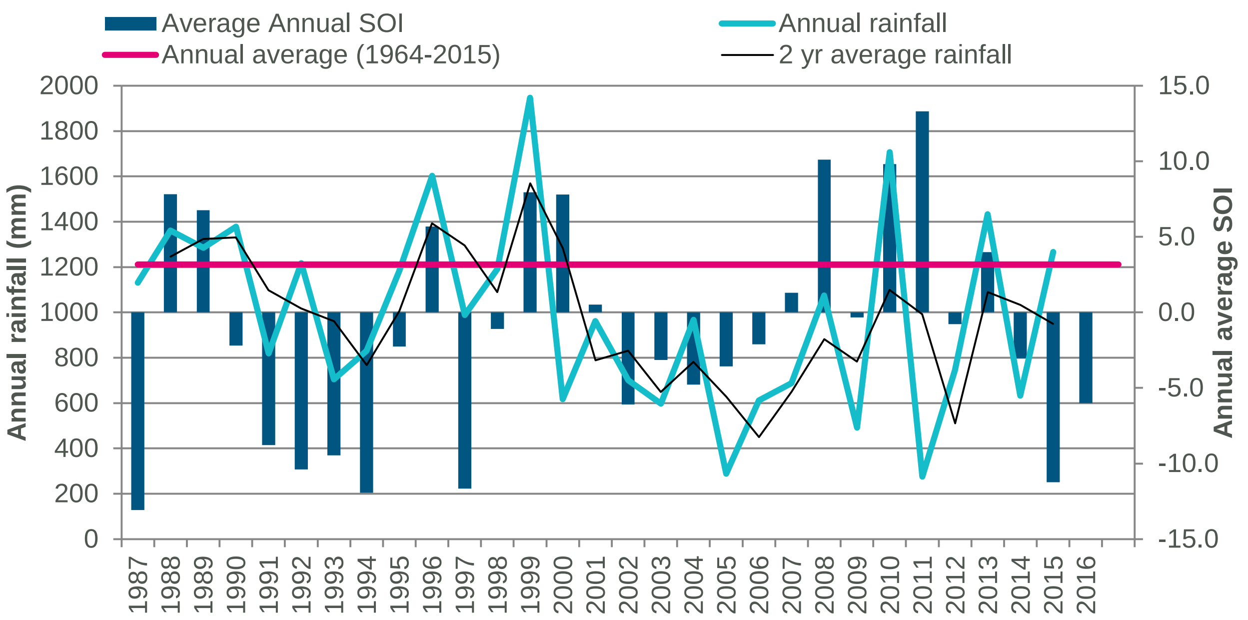


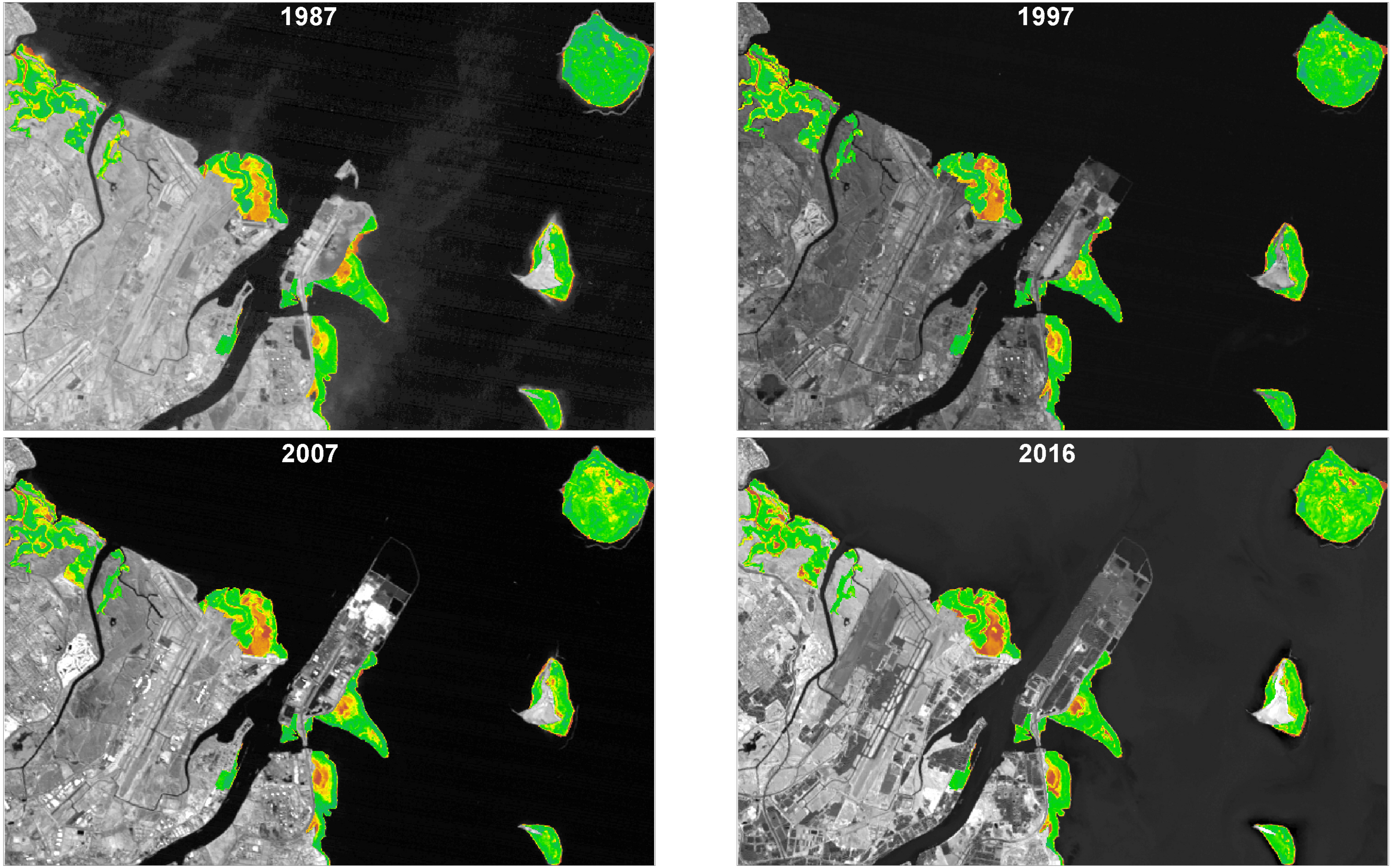
Figure 4-12 Rainfall (annual average, 2 year moving average, long-term annual average 1964-2016) and annual average SOI

4.2.2 Spatial and Temporal Patterns in NDVI

4.2.2.1 Differences among Investigation Areas

Figure 4-13 shows NDVI values in each pixel during 1987, 1997, 2007 and 2016. NDVI varied spatially in response to differences in vegetation types. Mangrove forests had consistently high NDVI values (NDVI >0.7), whereas saltmarsh and claypan had low NDVI values.

Figure 4-14 shows mean average and standard deviation of NDVI values in mangrove forests at each investigation area. The mean average NDVI value varied significantly among investigation areas (one-way ANOVA: *d.f.* = 8, 423; *F* = 23.72; $p<0.001$). *Post hoc* comparisons indicate that mangrove forests at Bulwer, Nudgee and Coal Loader had significantly higher average NDVI values than other investigation areas.



LEGEND

NDVI Score
0 1

Title:
Broad-scale patterns in NDVI values

Figure
4-13

Rev:
A

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N
0 2 4km
Approx. Scale

BMT WBM
www.bmtwbm.com.au

Filepath : I:\B20259_I_BRH Port of Brisbane DLR\DRG\Mangrove_2016\ECO_007_160914_NDVI_1987-1997-2007-2016.wor

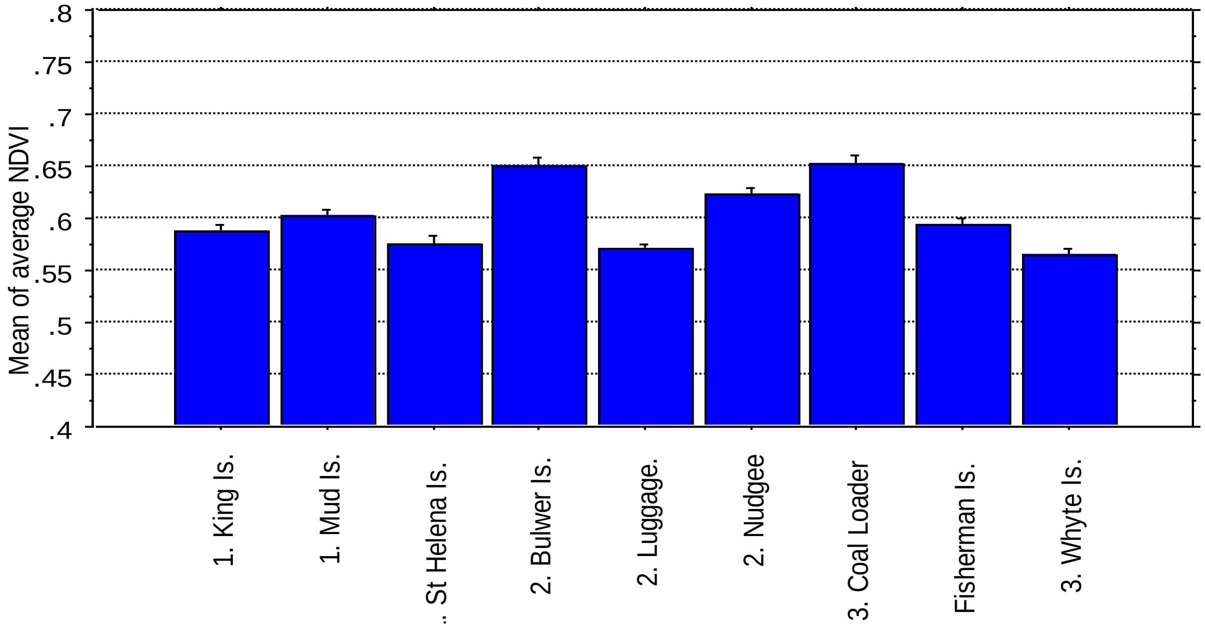


Figure 4-14 Mean (error bars ± S.E.) of average of NDVI values in mangrove forests at each investigation area (times pooled)

4.2.2.2 Long-term Patterns

Box plots showing mean NDVI (hereafter referred to as NDVI) values in mangrove forests for nominal three year time intervals are shown in Figure 4-15. NDVI tended to be highest in the period 1987-89 at most investigation areas.

Figure 4-16 is a time-series of NDVI values in mangrove forests within each investigation area, with the trend line (Sen slope) fitted through NDVI values. Table 4-2 presents the results of equivalence tests of the de-seasonalised long-term trend in NDVI.

NDVI values showed a statistically significant ($p<0.05$) long-term decline at all three investigation areas in Waterloo Bay (Fisherman Islands, Coal Loader and Whyte Island/Wynnum), as well as Luggage Point, Bulwer Island and Mud Island. Whyte Island/Wynnum displayed the largest decline in NDVI values (Sk = -0.003, $p<0.001$). There was no significant long-term trend in in NDVI at King Island, St Helena Island and Nudgee ($p>0.05$). The largest changes in NDVI occurred between 1987-89 and 1990-92, and 2009-11 and 2013-16, varying among investigation areas.

Table 4-2 De-seasonalised equivalence test for long-term changes in NDVI values in mangrove forests

Investigation Area	No. years	Slope per year	SE	df	*p*
Control Island Sites					
King Is.	28.8	-0.001	0.000	44	0.226
Mud Is.	28.8	-0.002	0.000	45	0.002
St Helena Is.	28.8	-0.001	0.000	45	0.075
Bramble Bay					
Bulwer Is.	28.8	-0.001	0.001	44	0.028
Luggage Pt	28.8	-0.001	0.000	45	0.006
Nudgee	28.8	-0.001	0.000	43	0.055
Waterloo Bay					
Fisherman Is.	28.8	-0.001	0.001	45	0.025
Coal Loader	28.8	-0.001	0.001	45	0.032
Whyte Is.	28.8	-0.003	0.001	45	0.0001

Pink shading statistically significant long-term trend

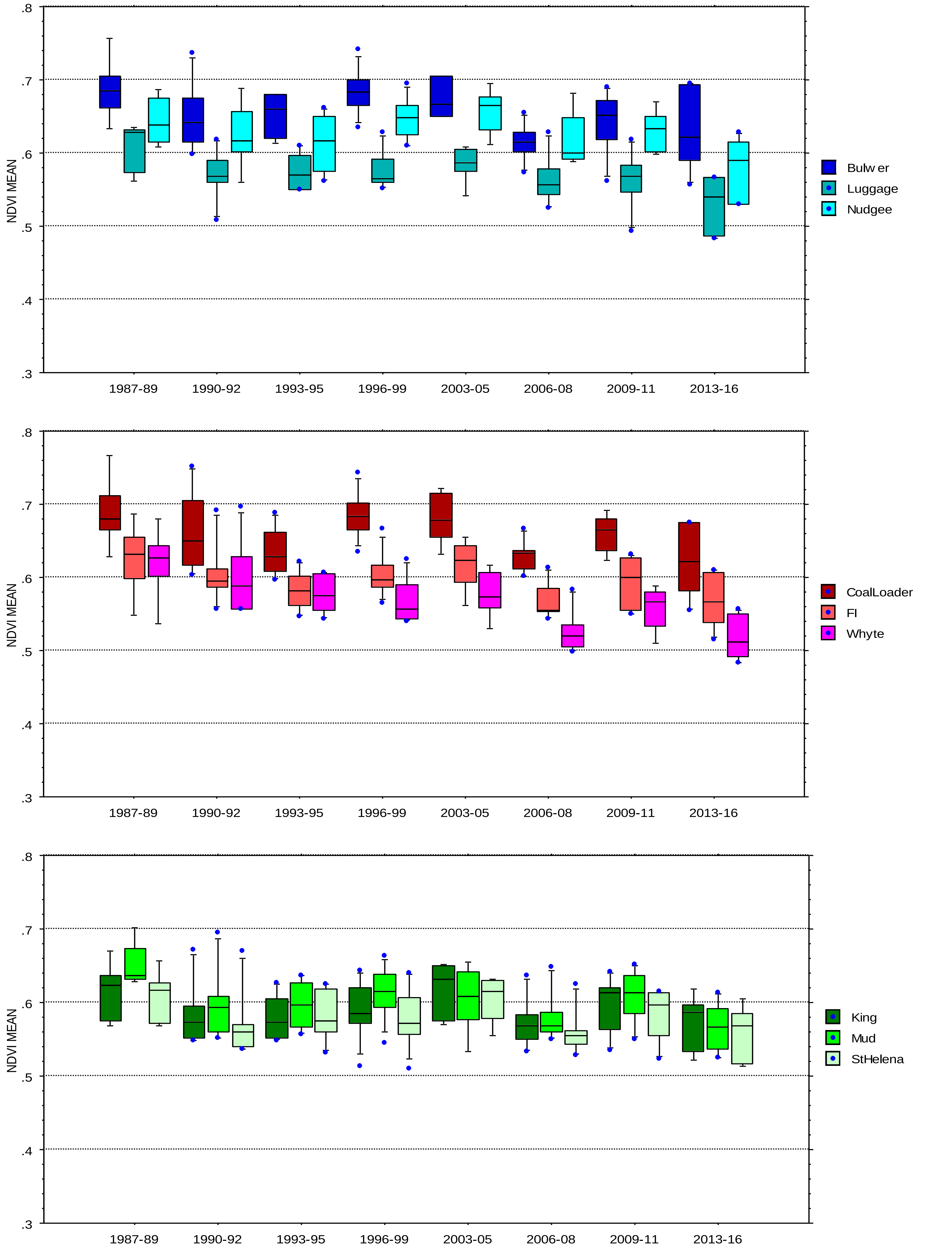


Figure 4-15 Box plots showing the statistical distribution (outliers, inter-quartile range and median) of average NDVI values in mangrove forests at three year time intervals

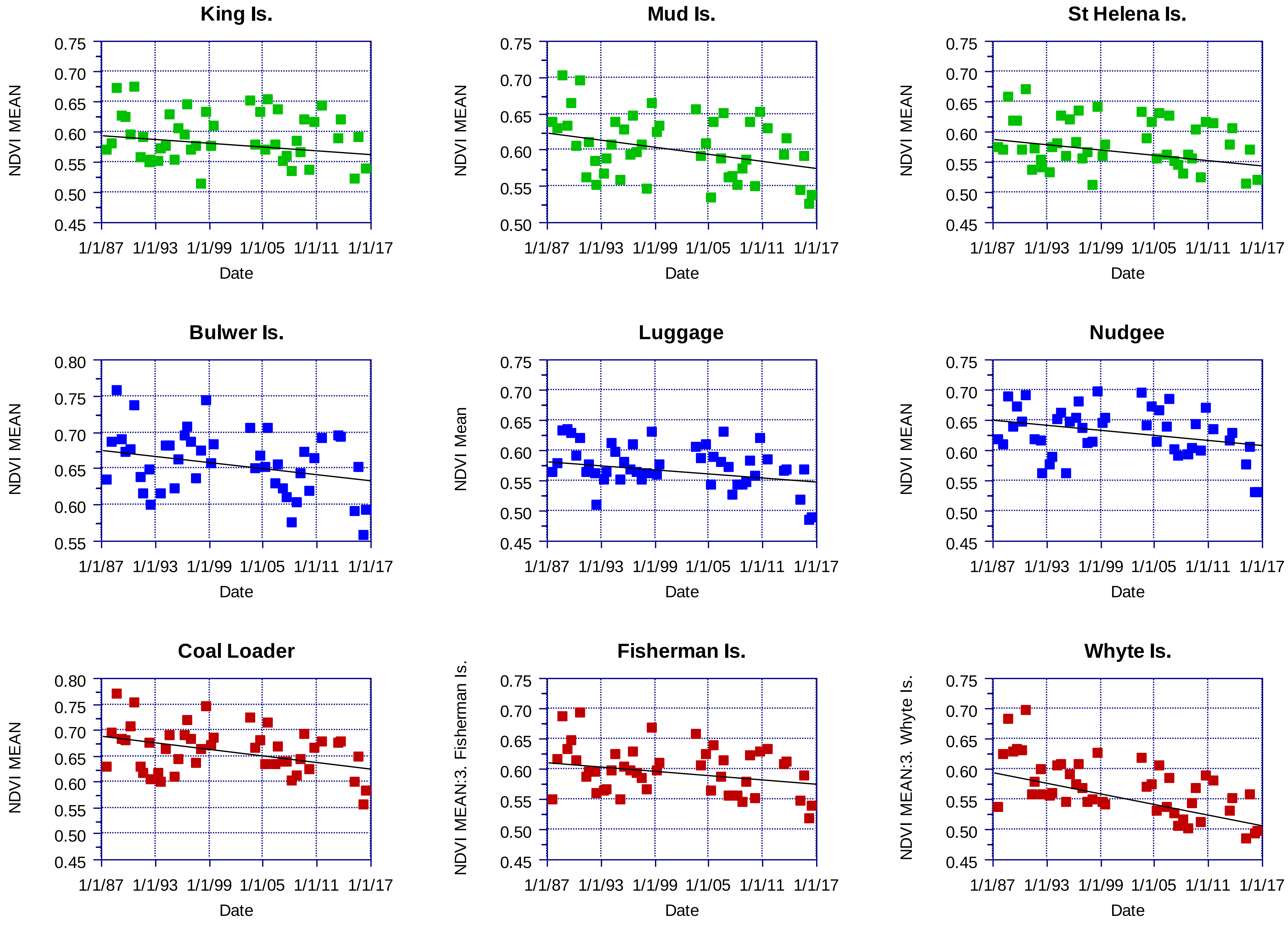


Figure 4-16 Mean NDVI values for mangrove forests for each episode and line of best fit (sen slope)

4.2.3 NDVI and Environmental Factors

4.2.3.1 Seasonal, Climatic and Tidal Conditions

Figure 4-17 shows mean NDVI values for mangrove forests in three time categories: January-March, April-June and June-September. At all investigation areas, mean NDVI values tended to be greatest in July-September and lowest in January-March, but there was also variability within these seasonal categories indicating year to year variability. The potential effects of rainfall and irradiance on these seasonal and inter-annual patterns were further explored.

Figure 4-18 is a time series of NDVI values classified by sampling episode, and also includes monthly rainfall data. Temporal patterns in average NDVI was highly consistent among the three 'control' island investigation areas, and were positively correlated (r = 0.87-0.96, p<0.01). Temporal patterns in average NDVI values in mainland investigation areas were broadly consistent to each other and control island investigation areas.

Table 4-3 Pearson Product Moment correlation coefficients (r) for average NDVI values in each time period among investigation areas. All relationships were significant (p<0.05)

	Fisherman	Coal Loader	Whyte	Bulwer	Luggage	Nudgee	King	Mud
`								
Coal Loader	0.92							
Whyte	0.89	0.82						
Bulwer	0.89	0.95	0.80					
Luggage	0.85	0.78	0.81	0.77				
Nudgee	0.88	0.87	0.75	0.83	0.90			
King	0.89	0.81	0.75	0.80	0.81	0.84		
Mud	0.90	0.82	0.81	0.79	0.84	0.85	0.88	
St Helena	0.87	0.80	0.76	0.79	0.84	0.84	0.96	0.87

Average NDVI and cumulative 12 month rainfall were significantly positively correlated at all investigation areas (Table 4-4). Figure 4-18 shows that there was sometimes a lag between cumulative rainfall and NDVI, with the lag duration varying over time. In the period 1987-1990, there was a lag of ~6 months between NDVI and 12 month cumulative rainfall, whereas in the period 1990-99 and 2004-17, patterns in average NDVI generally tracked with 12 month rainfall. Years with above average (typically major flood) rainfall (i.e. 1996, 1999 and 2011) had similar NDVI values to other 'wet' years.

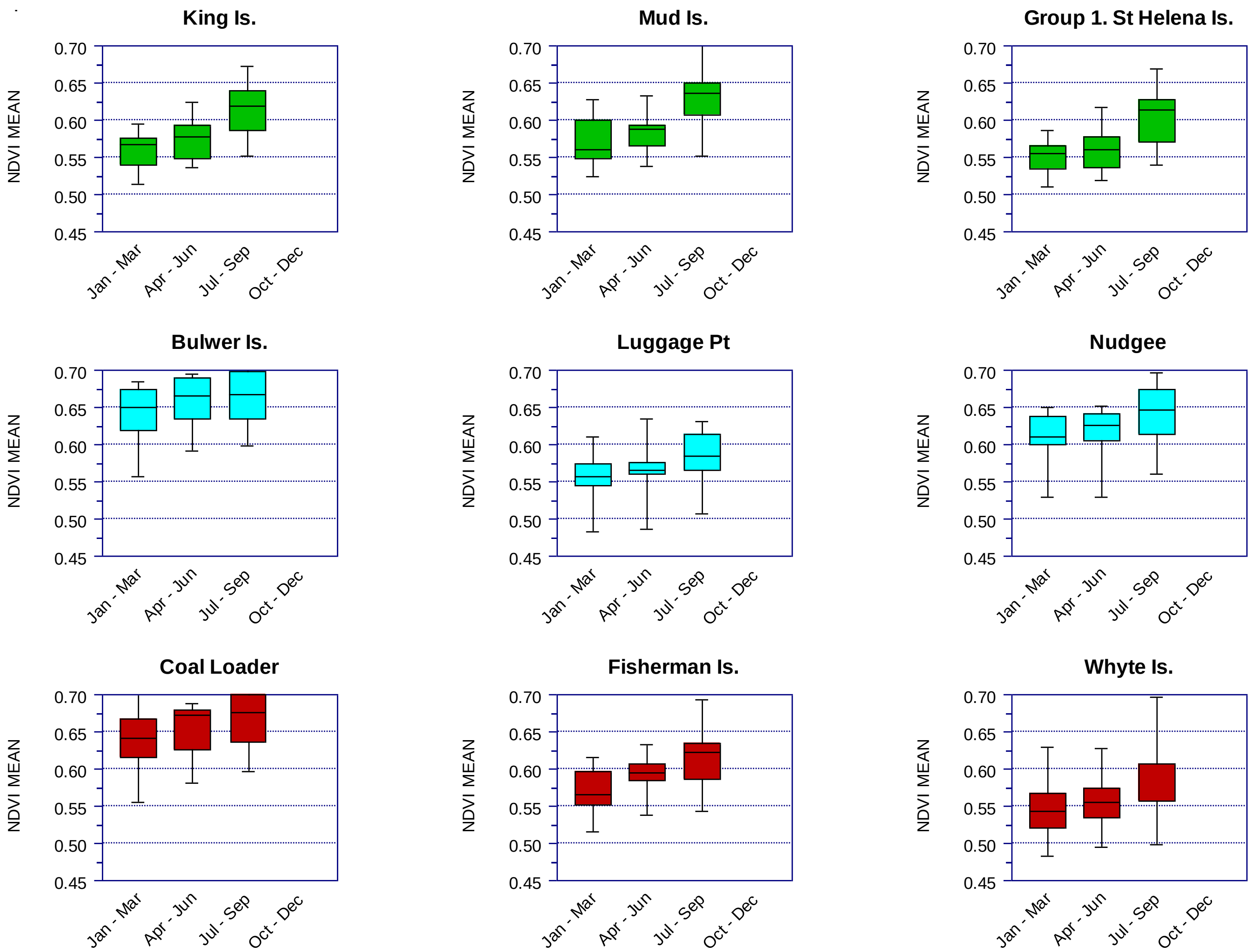


Figure 4-17 Seasonal differences in average NDVI at mangrove forests in each investigation area (blue = Bramble Bay, red = Waterloo Bay, green = control islands)

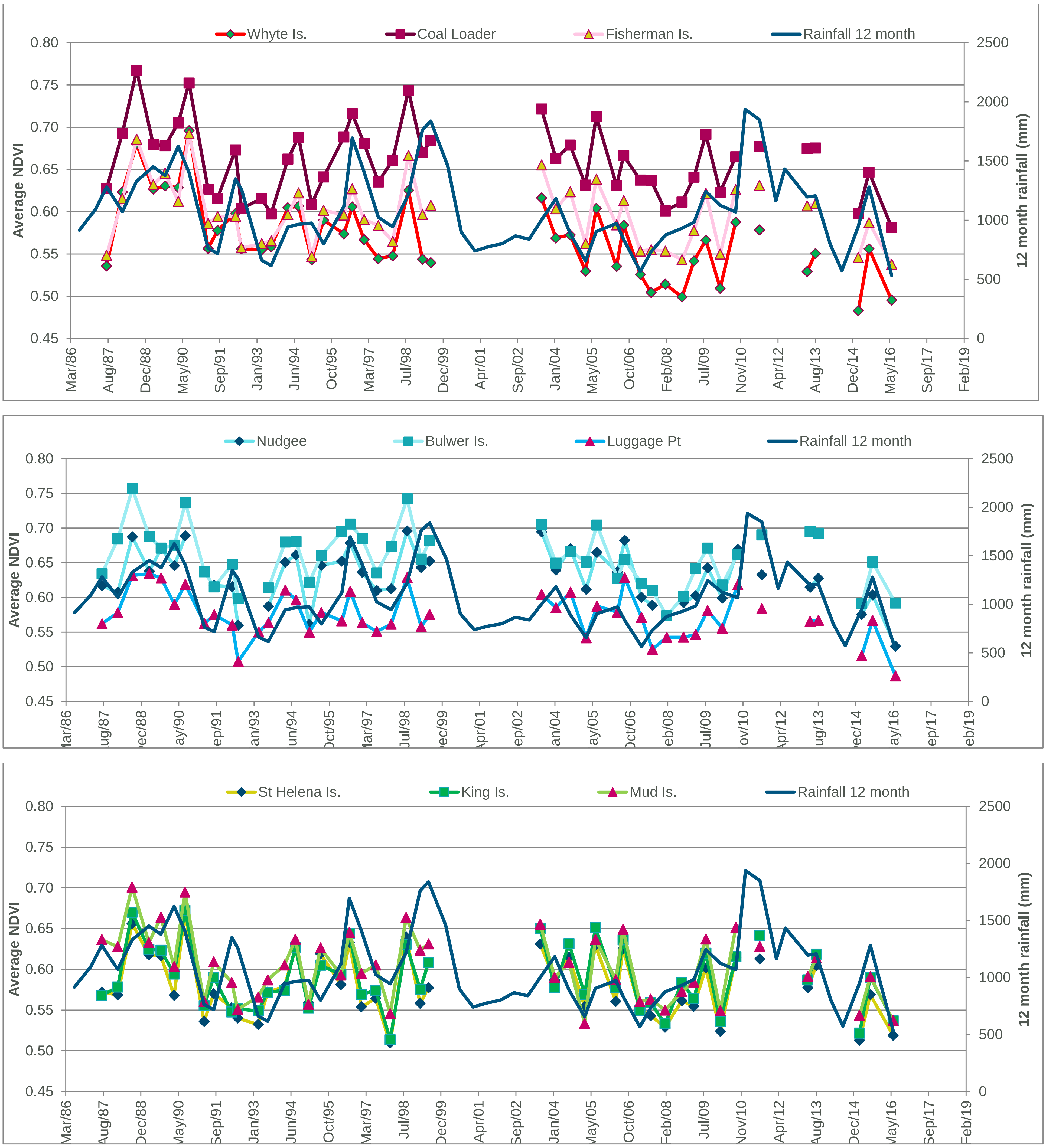


Figure 4-18 Mean NDVI at each investigation area and 12 month cumulative rainfall data over time

Relationships between cumulative rainfall and average NDVI was analysed using Spearman rank correlation analysis (Table 4-4). There was a significant positive relationship between average NDVI values and 12 month cumulative rainfall at all investigation areas, consistent with trends shown in Figure 4-18. With the exception of Bulwer Island (6 month and 18 month cumulative), Coal Loader (18 month) and Fisherman Islands (18 month), there was no other significant correlation between 6 month and 18 month cumulative rainfall and average NDVI. There was also no significant relationship between NDVI and cumulative monthly rainfall in any investigation area.

Table 4-4 Spearman rank correlation analysis (Rho ρ) examining relationships between NDVI and cumulative rainfall in each investigation area

Investigation Area	Monthly	6 month	12 month	18 month
Mud	-0.094 ns	0.164 ns	0.469***	0.285 ns
King	-0.230 ns	0.035 ns	0.356*	0.206 ns
St Helena	-0.149 ns	0.078 ns	0.315*	0.117 ns
Bulwer	0.055 ns	0.371*	0.516***	0.408*
Nudgee	-0.033 ns	0.230 ns	0.358*	0.191 ns
Luggage	-0.022 ns	0.120 ns	0.333*	0.190 ns
Fisherman Is.	-0.069 ns	0.236 ns	0.469***	0.340*
Coal Loader	0.079 ns	0.366*	0.564***	0.359*
Wynnum/Whyte Is.	-0.026 ns	0.218 ns	0.371*	0.281 ns

Pink shading – statistically significant: *p<0.05, **p<0.01; ***p<0.005. ns = not significant

Figure 4-19 shows average NDVI values within seven rainfall categories based on long-term annual rainfall percentile data at Lytton station (≤10th, <20th, <30th, <40th, <50th, <70th, >70th percentile). Years with low rainfall (i.e. <10th percentile of long-term data) had lower NDVI values than wet years (>50th percentile of long-term data). This temporal trend was consistent across investigation areas.

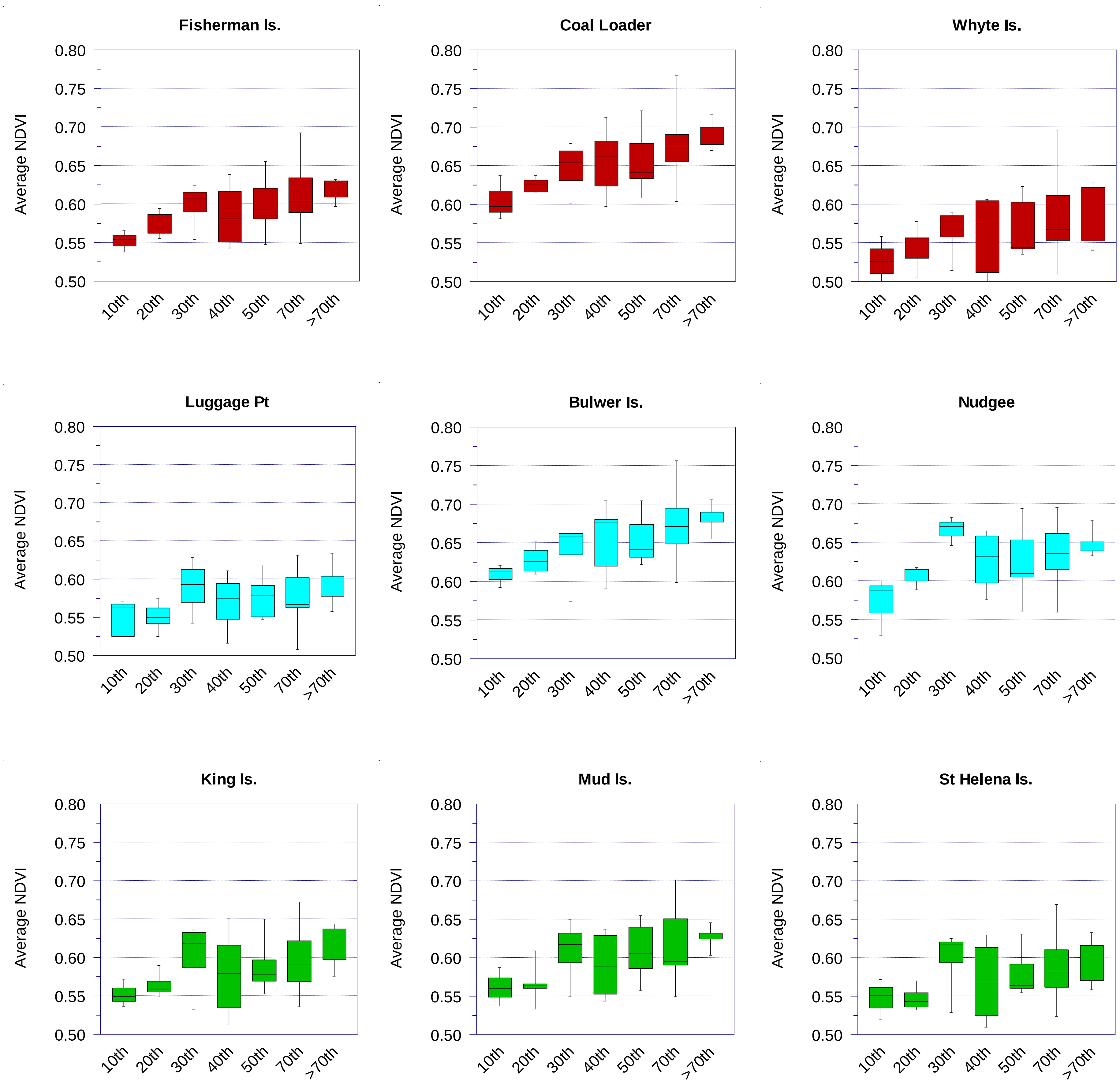


Figure 4-19 Box plots for average NDVI values within seven rainfall categories based on long-term annual rainfall deciles at Lytton station (≤10th, <20th, <30th, <40th, <50th, <70th, >70th percentile)

The effect of tidal height on NDVI was analysed in each community type over the entire study period. Tidal height did not have a significant effect on the mean NDVI for either of the community types (pooled across investigation areas, $p<0.05$ Figure 4-20).

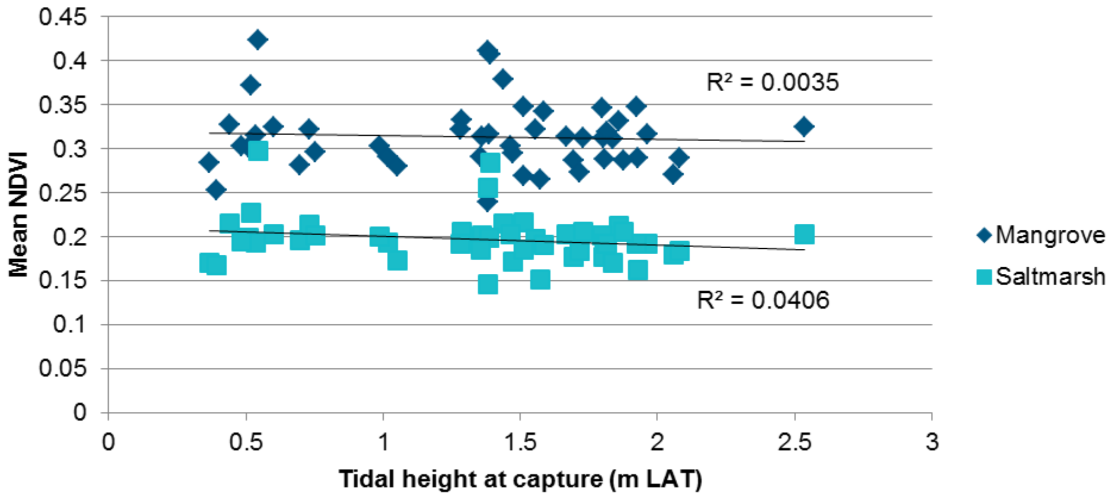


Figure 4-20 Relationship between NDVI and tidal height in each community type across the entire study period

There were significant negative correlations between NDVI scores at some of the investigation sites and averaged solar exposure values from the time of image capture (Table 4-5). These relationships were highly significant at offshore island sites and less significant at Fisherman Islands and Whyte Island. This suggests that peak solar irradiance was correlated with reduced NDVI at some sites, which may relate directly to solar intensity, or be correlated with other variables associated with high summer irradiance such as wind-speed, direction or temperature.

Table 4-5 Spearman rank correlation analysis (Rho ρ) examining relationships between NDVI and solar exposure in each investigation area

Investigation Area	Spearman's Rho (ρ)	Significance
Mud Is.	-0.51	0.002***
King Is.	-0.44	0.011**
St Helena Is.	-0.44	0.010**
Bulwer	-0.13	0.460 ns
Nudgee	-0.32	0.068 ns
Luggage	-0.29	0.104 ns
Fisherman Is.	-0.37	0.032*
Coal Loader	-0.19	0.293 ns
Wynnum/Whyte Is.	-0.35	0.043*

Pink shading – statistically significant: *$p<0.05$, **$p<0.01$; ***$p<0.005$. ns = not significant

4.2.3.2 Mangrove Expansion

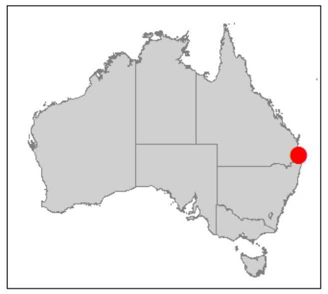
Some of the temporal changes in NDVI were a result of mangrove expansion within small areas of claypan mapped as mangrove. The area between remnants of Fisherman Islands and Bishop Island saw a seaward expansion in mangrove extent between 2005 to present, resulting in 14.75 ha of new mangroves. However, this expansion (seaward) was not captured in the changes in NDVI because the areas of interest included wetland areas common to both 1955 and 2012. This area of accretion between the former Bishop Island and Fisherman Island was predicted in the FPE IAS (pg. 8-89) to be an area of fine sediment accretion during northerly wind conditions, due to sheltering by the FPE.

WBM (2000) also found that area between remnants of Fisherman Islands and Bishop Island experienced an increase in mangrove extent prior to the FPE, with mangroves largely absent prior to 1983, and then progressively expanding between 1983 and 2000. This expansion in mangroves post 1983 was coincident with port reclamation works, which joined Fisherman Islands to Bishop Island. No other areas were observed to experience major expansions in mangrove vegetation and associated long-term increases in NDVI values.

Looking at changes in mangrove distribution between 1958 and 2016 (Figure 4-21) it is clear that there has been a substantial change in landform over this period. Accurate georectification is difficult due to changing shorelines, roads, and land use; however, changes in the width of the channel between eastern and western Fisherman Islands suggest that there has been significant mangrove expansion into this channel since 1958. The southern opening of this channel was 40-45 m in 1958, and this had reduced to approximately 30 m in 2016. Expansion of the tree canopy is likely the result of increased sediment deposition.

4.2.3.3 Claypan Expansion and Mangrove/Saltmarsh Loss

Mangrove die-back occurred at Fisherman Islands over the measurement period, and was replaced with ‘unvegetated’ bare areas. The replacement of mangroves with bare substrate resulted in a commensurate reduction in NDVI values over time within these areas.



Title:

Mangrove Extent at Fisherman Islands (August 10, 2016 and April 17, 1958)

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

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Approx. Scale

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5 Discussion

5.1 Spatial Patterns in Vegetation Communities and Health

5.1.1 Community Structure

The high-resolution mapping undertaken in the present study identified complex spatial patterns in intertidal wetland community structure and condition, which were broadly consistent with previous mapping studies in the study area. Mangals at both Fisherman Islands and Whyte Island were dominated by grey mangrove *Avicennia marina,* with other species sub-dominant except in small patches. *Ceriops australis and Rhizophora stylosa* dominated or co-dominated with *Avicennia marina* in places, consistent with previous field surveys by BMT WBM (2014).

Canopy height in mangals progressively declines from approximately mean high water tide level in Moreton Bay (Davie 1984), consistent with the patterns observed in the present study (Figure 4-10 and Figure 4-11). The seaward margins of mangals were generally comprised of a tall *Avicennia marina* dominated open forest, whereas mangals further landward were comprised of low closed to open *Avicennia marina* forest, eventually grading to saltmarsh and claypan at higher elevations. Areas of mangrove die-back at the eastern tip of Fisherman Islands can also contain ponded water, which is still retained at low tide, depending on the amplitude of successive tides. These ponds contain dense mats of micro-phytobenthos (microalgae), which are detected in NDVI analyses (see Section 5.1.2).

Davie (1984) found that elevation-based spatial gradients in vegetation community structure (height, canopy cover, species composition) at Mud Island were largely controlled by salinity stress, which was a function of decreasing water availability from either tidal inundation or fresh-water seepage. Tidal flats at the upper tidal limit are frequently hypersaline due to infrequent tidal inundation and subsequent evaporation. Davie (1984) also found that increasing water/salinity stress along the elevation gradient resulted in a reduction in canopy height, less foliage in the canopy, and increased understorey cover of the saltmarsh species *Suaeda australis* and *Sarcocornia quinqueflora*.

5.1.2 Mangrove Health

The NDVI values derived from high-resolution satellite imagery and UAV identified areas where mangrove canopy chlorophyll levels were low, as a result of either poor mangrove health or where there were changes in community composition.

In summary:

- The highest NDVI values at Fisherman Islands were recorded along the seaward fringe within the well flushed tall *Avicennia* dominated closed and partially-closed forest. High-resolution UAV-based data showed that there was variation in NDVI at the individual tree level. NDVI tended to be highest in trees (and forest areas) where the canopy was more open and/or tree height was more variable, and the edges of trees were partially shaded (which tend to produce more chlorophyll than the top of canopies).

- Low NDVI values in mangals at Fisherman Islands were generally recorded adjacent to the western claypan area containing low closed *Avicennia* forest and open *Avicennia* forest where water/salinity stress would be greatest. Interestingly, mangroves on the eastern tip immediately north of ponded waters were in moderately good condition, whereas those on the far eastern tip near die-back areas had lower NDVI.
- The *Ceriops australis* (yellow mangrove) dominated and co-dominated forest at Fisherman Islands had low NDVI values. The leaves of *Ceriops australis,* as well the sub-dominant *Aegiceras corniculatum* which can co-occur with this species, have high densities of yellow pigments (see Basak *et al.* 1996), and therefore, had a different NDVI signal than *Avicennia marina.*
- Mangals at Whyte Island displayed complex spatial patterns. Similar to Fisherman Islands, the tall mangrove forest on the seaward fringe of Whyte Island had high NDVI values, whereas lower NDVI values typically occurred in landward areas on and adjacent to claypan and saltmarsh. Highest NDVI values were recorded in areas directly adjacent to freshwater inputs: the mouth of a small unnamed creek and a point directly adjacent to the Wynnum Wastewater Treatment Plant discharge point on Crab Creek. It is likely that the freshwater, nutrient enriched wastewater discharges enhanced chlorophyll and mangrove vegetation in this area.

The main areas of mangrove die-back and poor health were recorded in the central mangrove /saltmarsh where ground levels, and therefore, water/salinity stress, is highest (see also WBM 2000; BMT 2014). Davie (1984) suggested that while the boundary between closed and open forest would vary over time in response to rainfall patterns, the position appears to coincide with a tidal level of >2.4 m LAT (Davie 1983), which is shown in light blue/green in Figure 4-10.

The elevation difference between suitable (but marginal) and sub-optimal habitat conditions for mangroves is measured in 10s of centimetres (Davie 1984; Duke 2006), depending also on local environmental conditions. In mangrove areas where water stress is already high, even small hydrological alterations could lead to compounding effects to salinity and plant health, particularly if the primary hydrological stressor is persistent.

Previous mangrove monitoring studies within the study area (WBM 2000, 2002a, 2002b, BMT WBM 2014) have suggested a range of hydrological stressors that could interfere with critical tidal flushing. The tidal flushing regimes of mangals within the study area have not been studied in detail to date. The following observations are made:

- Despite the apparent presence of flow barriers in the seaward margins of mangrove forests (i.e. sand bunds, wrack, algae mats), these areas are regularly flushed by tides (as observed during site inspections), and no ponding has been observed in these seaward margins.
- Extensive areas of ponding can occur in mangrove die-back areas in the central/interior sections of mangrove forests. Ponding of water can lead to multiple stresses, including asphyxia, impediments to nutrient availability and up-take, pH changes, and changes to the microbial and fauna communities that ultimately control mangrove plant health. Mangrove death can occur within six weeks in the absence of drying (Hutchings and Saenger 1987). It is not clear at this stage whether ponding is the direct result of tidal flow impediments (i.e. damming effect) and/or a consequence of the reduced ground levels due to mangrove die-back.

- Not all areas which contain dead/dying mangrove have ponded waters.

Measurements of water levels, and time-lapse imagery showing routes of inundation would greatly assist the understanding of flushing regimes in mangals and possible future management strategies designed to increase flushing (see Section 5.3). However, given that changes in health appear to be related to broad-scale climatic processes as well as local scale processes (Section 5.2), such investigations would need to consider coincident longer-term climatic variability. It is also possible that long-term and broad-scale sediment accretion around fringing mangroves has supported seaward mangrove expansion, but reduced tidal flushing to the interior of the mangal. Understanding these processes is required prior to considering any remediation works.

5.2 Long-term Patterns in NDVI

NDVI is a spectral index that estimates the amount of green biomass, with high NDVI values indicating higher green biomass. The analysis of Landsat imagery showed that the vegetation biomass index NDVI displayed complex patterns across multiple temporal scales and in response to multiple drivers, as described below.

5.2.1 Linkages to Rainfall

Climatic processes are a key control on temporal patterns in mangrove growth and productivity (Hutchings and Saenger 1987), and are likely to be the key drivers of inter-annual patterns in NDVI across the overall study area. In particular, mangrove shoot/leaf production is generally positively correlated with rainfall, temperature and soil moisture (Hutchings and Saenger 1987), all of which vary seasonally and among years, and in the case of soil moisture, on a diel cycle.

The present study found that inter-annual trends in NDVI were consistent among investigation areas, suggesting that the processes controlling these patterns were operating at a broad, whole of study area spatial scale. The present study detected significant positive correlations between 12 month cumulative rainfall and NDVI, with peak NDVI values coincident within or occurring within six months after peaks in 12 month rainfall. NDVI was typically not significantly correlated with cumulative rainfall occurring at shorter (i.e. monthly and six monthly) timeframes, suggesting that NDVI was not responsive to short-term rainfall patterns.

Rainfall controls both surface water runoff and ground water processes, which together have interactive effects on mangrove communities. Surface water runoff controls sediment and nutrient delivery, sediment biogeochemical processes and recharge of water table within mangrove forests (Alongi 2009). Case studies in Moreton Bay and elsewhere demonstrate that during droughts, the water table within mangrove forests declines, leading to:

- Reduced flushing of salt extruded by tree roots (Alongi 2009), leading to salt stress and poor plant health (Davie 1984)
- Reduced flushing of microbial by-products that can adversely affect biota , such as sulphides and methane (Alongi 2009)
- Reduced nutrient delivery to mangroves and saltmarsh vegetation, potentially reducing mangrove productivity (Alongi 2009)

- Reduced subsurface swelling of soils and ultimately ground levels, leading to ponding and further mangrove stress (Lewis *et al.* 2016).

Water table recharge times in mangrove forest vary in space and time, but tend to occur at timescales measured in months, depending on soil type, vegetation community structure, rainfall and groundwater levels (Alongi 2009). In the present study, the lack of correspondence between short-term changes in rainfall and NDVI, and periodic lags in the response of NDVI and 12 month cumulative rainfall, are in agreement with the hypothesis that groundwater is a key control on cyclic inter-annual patterns in mangrove green biomass within the study area. Little is known about the groundwater hydrology of mangrove forests in the study area[5], and additional data would be required to test this hypothesis.

Inter-annual rainfall patterns are strongly associated with SOI (see Section 4.2.1) and the El Niño–Southern Oscillation (ENSO) cycle. The ENSO cycle has an average period of about four years, but can vary between two and seven years. There is great variability in the ENSO cycle from one decade to the next, with some decades where the cycle was relatively inactive, and other decades where it was pronounced. In terms of the study period for this assessment:

- the 1980's and 1990's featured a very active ENSO cycle, with five El Niño episodes (1982/83, 1986/87, 1991-1993, 1994/95, and 1997/98) and three La Niña episodes (1984/85, 1988/89, 1995/96) occurring during the period. This period also featured two of the strongest El Niño episodes of the century (1982/83 and 1997/98), as well as two consecutive periods of El Niño conditions during 1991 - 1995 without an intervening cold episode.
- The ‘‘Millennium Drought’’ (2001–2009) was the worst drought on record for southeast Australia, and prevailing El Niño conditions explained about two thirds of rainfall deficit in east Australia (van Dijik *et al.* 2013).
- The period 2010-2012 was a strong La Niña period, and was followed by El Niño episodes in 2014-16.

The long-term trend in average NDVI at most investigation areas was high NDVI values in the period 1987-89 (coincident with strong *La Niña*) conditions, consistent, moderate NDVI values in the period 1990-2005, a decline in NDVI in 2006-08 (during the final years of the Millennium Drought), and a slight rise in NDVI post 2009, following the end of the Millennium Drought. Satellite data indicate that mangrove condition has not recovered to pre Millennium drought conditions. However, field observations in 2016 indicate that there was significant mangrove recruitment in dieback areas at Fisherman Islands, which may lead to a return to higher NDVI levels if these recruits establish and continue to grow.

5.2.2 Local Scale Processes

Long-term rainfall patterns partly explained temporal patterns in NDVI, indicating that other processes also influence patterns in mangrove health. Long-term declines in mean NDVI were recorded at the three Waterloo Bay investigation areas, Bulwer Island, Luggage Point and Mud Island investigation areas. All these investigation areas (including Mud Island) have been subject

[5] Groundwater monitoring at bores located on terrestrial lands (above HAT) at Fisherman Islands and Bulwer Island in 2014 and 2015 indicate that the water table was typically <2.5 m below ground level and stable between years (BMT WBM 2015).

to historical disturbance, with a 25-52% reduction in mangrove forest extent since 1955 (Accad *et al.* 2016; Figure 2-4). By contrast, mangrove forest extent remained relatively stable over time at King Island and St Helena Island, and increased in extent at Nudgee (Figure 2-4), and mean NDVI was also more stable over time in these areas.

The long-term decline in green biomass (as measured by NDVI) reflects long-term changes in mangrove health (i.e. loss of canopy cover), which ultimately lead to the conversion of mangroves to claypan. Multiple 'natural' and anthropogenic local-scale stressors operating at the test sites (Section 2.2.2 and 5.1.2) would reduce the resilience of mangrove vegetation (and their associated community), and the capacity of communities to tolerate water/salinity stress arising from cyclic periods of drought.

5.2.3 Seasonality

NDVI values were generally higher during winter than summer/autumn periods. This seasonal pattern was broadly consistent across most investigation areas, but the magnitude of change varied from year to year and spatially. This indicates that the process/es responsible for seasonal changes in vegetation were operating at broad, whole of study area spatial scales, but were not always consistent between years. Negative correlations between irradiance and NDVI, particularly at island sites suggest that seasonal declines in NDVI may be the result of climatic stress (ultra-violet light, temperature, and wind-speed) and/or photo-adaptation to high-light environments.

There have been several studies on temporal patterns in leaf litter fall and reproductive ecology of mangroves in western Moreton Bay, but few studies have examined seasonal changes in leaf biomass or the ecology of saltmarsh vegetation. These studies suggest that mangrove growth and productivity show complex inter-annual and seasonal patterns. WBM (1992) found that leaf fall (i.e. biomass falling to the substrate) at Fisherman Islands was cyclic, and while tending to be lowest in cooler months, did not show consistent seasonal patterns between years. Davie (1984) reported minimum shoot growth (and canopy cover) and litter fall in *Avicennia* dominated mangrove forests at Mud Island during winter months (June to August), and peak leaf production and litter fall during spring and summer, with minor peaks in autumn. However, seasonal patterns varied inter-annually in response to timing of rainfall and storm events.

Reproductive cycles also display complex temporal patterns. WBM (1992) found that *Avicennia* fruit litter fall occurred only once during the 21 months of monitoring (March 1993), rather than seasonally. Similar biennial fruiting was recorded by Mackey and Smail (1995) in mangrove forests at Bulwer Island, but they found that fruit fall occurred in the dry winter season. The drivers for short-term (seasonal) cycles in mangrove reproduction and green biomass (NDVI) are not well presently well understood.

5.3 Recommendations

5.3.1 Informing Potential Management Actions

Drought-rainfall cycles have a major influence on mangrove forest health in the study area. The results of the present study also suggest that mangroves subject to historical physical disturbance tended to be less resilient to environmental stress resulting from drought. The relative influence of local-scale (i.e. other than climate) stressors on mangrove health is not well understood. It is clear that any future developments adjacent to intertidal wetlands will require careful consideration of indirect hydrological modifications (surface water and groundwater), and associated flow-on effects.

Prior to undertaking any rehabilitation works, it is critical to understand:

(1) the primary and secondary processes affecting health, such as the role of tidal impediments on water quality

(2) the financial and environmental costs/benefits of rehabilitation.

Tidal Flushing Study

It is recommended that additional studies be conducted to understand tidal processes and water quality at Fisherman Islands. Time-lapse imagery could be acquired from cameras stationed on the ground, capturing the return of water after a period of complete dryness. During neap tide periods without rainfall, the ponded areas dry out. Imagery collected during the return to spring tide periods will help establish if the tide infiltrates through the soil, or flows over land, which direction(s) the water arrives from, and primary flow paths. Conductivity, temperature, depth (CTD) loggers deployed out at the same time would provide water levels and a picture of conductivity through time. If the tide flows overland, the next step would be to look at impedance. Logger deployment periods long enough to capture significant rainfall (or multiple shorter deployments) would also be useful to understand the respective roles of tide and rainfall in maintaining appropriate salinity conditions.

Investigating tidal impedance would involve measuring the height of tidal restrictions. This could be determined with GPS laser range-finding while walking the perimeter of Fisherman Islands at low tides, to ground-truth vegetation filtered LiDAR. Vegetation-filtered LiDAR is unlikely to be appropriate if pneumatophores are interpreted as ground strikes. This study would also benefit from an assessment of long-term changes in landform based on historical aerial imagery and multiple past LiDAR datasets, if available.

Costs/Benefit Analysis of Rehabilitation

The flushing study will provide a basis for determining the need and practicalities for undertaking rehabilitation works. A cost/benefit analysis is a critical part of rehabilitation planning, and should consider:

- Environmental costs - remediation may not be appropriate if the dieback is a result of natural broad scale processes that cannot be easily managed, or creates suitable high value habitat for species of high biodiversity significance, or leads to unintended environmental changes need to be considered (e.g. disturbance of acid sulfate soils).

- Financial costs - including costs for approvals and supporting studies, capital works, and maintenance costs. For example, creating channels to maintain tidal connectivity can be highly successful in promoting recovery, if the channel openings can be maintained (WBM 2003).
- Expected benefits – taking into account biodiversity values, ecosystem service values (shoreline stabilisation, fisheries habitat), and re-establishing of wetlands communities that have been severely affected by historical clearing in western Moreton Bay.

5.3.2 Ongoing Monitoring

Sampling of mangrove, saltmarsh and claypan habitats using UAV provides ultra-high resolution and quantitative information regarding the health, elevation, and structure of these communities. However, key issues/constraints that need to be considered are:

- Approvals – CASA approval is required for flights in the study area, and an allowance of several months is required to gain such approvals.
- Height restrictions – CASA sets a maximum elevation at which the UAV can be operated (90 m). This increases the time required to undertake surveys. This also presents significant challenges in terms of mosaicking (joining) imagery, particularly in areas with a homogenous canopy cover with no distinctive landmarks, and where there are significant elevation changes.
- The UAV does not sample areas under the mangrove canopy, and therefore, does not provide information on pressures affecting vegetation.
- High small-scale spatial heterogeneity in NDVI due to tree to tree and ‘within-tree’ variability.

High-resolution satellite imagery has slightly lower resolution than UAV, and is considered sufficient for the purposes of the present vegetation community and condition assessment. It is recommended that future monitoring assessments continue to use high-resolution satellite imagery. Rapid ground inspections should be undertaken to assess sub-canopy environmental conditions. The ground-truthing should involve:

- Inspections of ground features that may impede tidal flushing at higher risk sites (e.g. sand banks along the southern edge of Fisherman Islands)
- Rapid ground-truthing and photographic monitoring at representative areas.

It is recommended that this is undertaken annually.

UAV can also be used (where required) in combination with satellite imagery to ground-truth fine-scale features, and collect elevation data in selected areas of interest at five-year intervals.

6 Conclusions

- The high-resolution mapping undertaken in the present study identified complex spatial patterns in intertidal wetland community structure and condition, which were broadly consistent with previous mapping studies in the study area.
- The seaward margin of mangrove forests was generally comprised of a tall *Avicennia marina* (grey mangroves) dominated closed and open forest, whereas mangals further landward were comprised of low closed to open *Avicennia marina* forest, eventually grading to claypan with or without saltmarsh. *Ceriops* dominated or co-dominated with *Avicennia marina* in places, consistent with previous field surveys.
- The NDVI values derived from high-resolution satellite imagery and UAV identified areas where mangrove canopy chlorophyll levels were low, either as a result of poor mangrove health or where there were changes in species composition.
- The highest NDVI values at Fisherman Islands were recorded along the seaward fringe within the well flushed tall *Avicennia* dominated closed and partially open forest.
- Low NDVI values in mangrove forests at both Fisherman Islands were generally recorded adjacent to the western claypan area containing low closed *Avicennia* forest and open *Avicennia* forest where water/salinity stress would be greatest. Interestingly, mangroves on the eastern tip immediately north of ponded waters were in moderately good condition, whereas those on the far eastern tip near die-back areas were showing lower NDVI.
- The *Ceriops australis* dominated and co-dominated forest at Fisherman Islands had low NDVI values. The leaves of *Ceriops australis* have more yellow pigments (carotenoids) (hence the common name of yellow mangrove), and therefore, had a different NDVI signal than *Avicennia marina.*
- Patches of mangroves on the landward margin of Whyte Island directly adjacent to terrestrial discharges (the Wynnum Wastewater Treatment Plant discharge point on Crab Creek and the drainage from local sports fields) had the highest NDVI values overall. It is likely that the freshwater, nutrient enriched wastewater discharges enhanced chlorophyll and mangrove vegetation in these areas.
- Significant positive correlations were detected between 12 month cumulative rainfall and NDVI. NDVI was typically not significantly correlated with cumulative rainfall occurring at shorter (i.e. monthly and six monthly) timeframes suggesting that NDVI was not responsive to short-term rainfall patterns.
- The results of the present study indicate that rainfall/drought cycles strongly influence long-term patterns in mangrove green biomass, but that local scale stressors (particularly hydrological barriers) may reduce the resilience of assemblages, ultimately leading to mangrove stress and mortality.
- WBM (2000) outlined a number of options relating to the management mangrove forests and their biodiversity values, which remain largely applicable and were further considered here. Continued degradation and loss of mangroves at Fisherman Islands (particularly the eastern tip)

may continue in the absence of management intervention. If tidal flow is impeded by landform, then drainage works that reinstate tidal flushing is likely to be the only direct means for rehabilitating mangroves. This would require further assessment to assess likely benefits relative to costs.

- It is recommended that a small field study (using conductivity, temperature, depth loggers and time-lapse cameras) be undertaken to assess tidal healthy, degraded and dieback areas. This will provide important information regarding the modes of inundation and help understand whether there are tidal restrictions to overland flow.
- For ongoing monitoring, it is recommended that future monitoring assessments continue to use high-resolution (2 m pixel size) satellite imagery as a basis for assessing broad-scale trends in mangrove health and rapid ground inspections to assess sub-canopy environmental conditions. on an annual basis, in combination with UAV every five years in critical areas (claypan and die-back areas).

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Appendix A Landsat scenes selected for analysis

Landsat source	Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Landsat 5	22/05/1987					■							
	18/02/1988		■										
	28/08/1988								■				
	9/04/1989				■								
	16/09/1989									■			
	11/03/1990			■									
	2/08/1990								■				
	15/04/1991				■								
	21/08/1991								■				
	17/04/1992				■								
	6/07/1992							■					
	4/04/1993				■								
	10/08/1993								■				
	22/03/1994			■									
	13/08/1994								■				
	5/02/1995		■										
	15/07/1995							■					
	12/04/1996			■									
	2/08/1996								■				
	9/01/1997	■											
	20/07/1997							■					
	28/01/1998	■											
	8/08/1998								■				
	4/03/1999			■									
	25/06/1999						■						
	21/07/2003							■					
	29/01/2004	■											
	8/08/2004								■				
	4/03/2005			■									
	26/07/2005							■					
	24/04/2006				■								
	29/07/2006						■						
	10/03/2007			■									
	1/08/2007								■				
	9/02/2008		■										
	20/09/2008									■			

Landsat scenes selected for analysis

Landsat source	Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	27/02/2009												
	6/08/2009												
	10/09/2010												
	16/01/2011												
	27/07/2011												
Landsat 8	27/04/2013												
	17/08/2013												
	16/03/2015												
	7/08/2015												
	15/02/2016												
	6/06/2016												
Number of scenes		4	5	7	6	1	3	6	12	3	0	0	0

Appendix B Weather conditions during survey

Table B-1 Weather observations leading up to and including the mangrove survey

Date (July 2016)	Rainfall (mm)	Sunshine (hours)	9am cloud amount (oktas)	9am wind direction	9am wind speed (km/h)	3pm cloud amount (oktas)	3pm wind direction	3pm wind speed (km/h)
1	0	9.6	0	WSW	11	1	WSW	28
2	0	9.8	0	SSW	15	0	NE	13
3	0	9.9	1	SSW	17	1	NE	13
4	0	8.9	4	SSW	15	1	NE	13
5	1.8	1	7	W	7	7	N	13
6	6.6	9.7	1	W	24	1	WSW	50
7	0	9.7	1	SW	35	0	W	26
8	0	9.8	1	SW	9	1	NNE	11
9	0	9.6	0	SSW	11	1	ENE	11
10	0	9.4	1	SSW	17	1	ESE	19
11	0	2.1	7	SSW	17	6	NNE	13
12	0.4	2.7	7	NW	11	7	NNE	17
13	0	3.1	7	WSW	22	8	WSW	31
14	0	0.1	8	SSW	22	8	SSW	17
15	0	0	7	SSW	17	7	SE	13
16	0	0	8	SE	15	8	S	11
17	10.6	3	7	SSW	11	7	SE	15
18	2.2	6.8	5	SSW	15	3	E	13
19	0	8.2	1	SSW	15	1	NNE	19
20	0	8.9	2	SW	11	3	NNE	26
21	0	8.7	7	W	9	2	NNE	22

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