Port of Brisbane Mangrove Monitoring-2024

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Author	Julian Manning
Approved By	Darren Richardson
Project Manager	Mackenzie Stacey

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Executive Summary

This study aimed to characterise spatial and temporal patterns in mangrove health, using the Normalised Difference Vegetation Index (NDVI), across various time scales: long-term (1988-2024) with medium-resolution Landsat, medium-term (2017-2024) with high resolution Sentinel-2, and short-term (2023-2024) with both Sentinel-2 and very high-resolution WorldView-3 imageries. The study was conducted at test sites and control sites. Previous monitoring episodes had focussed on linkages between mangrove health and climatic factors (i.e. rainfall, Southern Oscillation Index). The indicator suite was expanded in the 2024 assessment to provide a more robust assessment of mangrove condition (i.e. canopy density cover, mangrove 10% photosynthetic fractional cover) and potential linkages to long term tidal cycles.

At decadal time scales (Landsat imagery), declines in NDVI were detected during periods of low rainfall, as previously reported. However, a stronger positive correlation was detected between NDVI and mean sea level (MSL). This finding is consistent with recent studies which found that mangrove condition was strongly influenced by long term tidal cycles, and rainfall. The assessment of high-resolution Sentinel imagery at medium timescales (2017-24) detected a stronger positive correlation between mangrove NDVI and rainfall compared to the long-term analysis derived from Landsat data. The period 2023-24 was characterised by average rainfall, and mangrove NDVI at all test sites remained stable.

Both the long-term and medium-term analysis found that test sites had higher mangrove NDVI values, and lower temporal variability in NDVI, compared to control sites. This indicates that mangrove canopy condition was better, and more stable, at test sites. Analyses of other mangrove condition indicators (Soil Adjusted Vegetation Index, Leaf Area Index) and mangrove community structure (extent of Closed Forest, Open Forest, and Woodland) detected similar long and medium-term trends as the NDVI analysis.

Recent studies in Moreton Bay and elsewhere identify the importance of canopy gaps in the natural regeneration of mangrove forests. These gaps are typically caused by environmental factors such as water stress and lightning strikes. In healthy forests, there is natural mangrove regeneration, and the canopy re-establishes. In stressed systems, mangroves do not recover, and the canopy gaps may persist or expand. Canopy gaps are therefore a potential indicator for tracking long-term mangrove health. In the present study, very high-resolution satellite imagery (1.2-meter WV-3) was used to classify and map mangrove forests at test sites. The analysis identified mature, closed-canopy forests with many large elliptical canopy gaps (>10m²). Our findings show that these gaps can recover relatively quickly, as evidenced by a 10% photosynthetic fractional cover in mangroves, a key indicator of canopy condition.

Overall, these results underscore the effect of net ocean/climatic events on mangrove health and the importance of monitoring environmental stressors to maintain ecosystem resilience. It suggests cyclic changes in mangrove loss and recovery across different time scales at both test and control sites. There is no evidence that contemporary port operations are resulting in mangrove forest degradation or loss.

The present existing mangrove program design and methodology provides a robust, cost-effective and objective means for detecting changes in mangrove forests and for identifying potential divers of change. Recommendations are provided to improve the capacity to detect mangrove change and better understand drivers.

Contents

1 Introduction

1.1 Background

Moreton Bay hosts extensive, species rich mangrove forests, that span over approximately 140 square kilometres (Davie *et al*., 2011; Lovelock *et al*., 2019), and provide multiple ecosystem services (Gaylard *et al.,* 2020). The Port of Brisbane Pty Ltd (PBPL) operates adjacent to several mangrove forests in western Moreton Bay, most notably at Fisherman Islands, Whyte Island and Bulwer Island. These mangrove forests are among the largest in western Moreton Bay (Accad *et al*. 2016; Queensland Herbarium and Biodiversity Science 2022).

PBPL has developed the Port of Brisbane Mangrove Monitoring Program (MMP) to monitor the health of mangrove communities at and adjacent to the Port, to identify potential drivers of change and manage any port related impacts (WBM 1992; CSIRO 1992; BMT WBM 2016; BMT 2017, 2018, 2019, 2020, 2021, 2022, 2023). The MMP has identified complex changes in mangrove extent and condition in time and space. Short and long-term changes in several vegetation health markers such as the Normalised Difference Vegetation Index (NDVI), Leaf Area Index (LAI), Enhanced Vegetation Index (EVI), and Soil Adjusted Vegetation Index (SAVI) were found to be closely associated with rainfall patterns. The study of cumulative rainfall over a long-term period has shown there is a linkage between the amount of rainfall and the El Niño–Southern Oscillation (ENSO) cycles (BMT WBM 2016). Long-term patterns in mangrove canopy cover across Australia are also strongly correlated with lunar cycles and variability in sea level (Saintilan et al. 2022).

The most recent assessment of long-term patterns in mangrove condition was conducted in 2016 (BMT WBM 2016). Since 2016, the MMP has focussed on short-changes to mangrove condition (seasonal and inter-annual changes). Climatic conditions since the 2016 study have included a flood event (2022) and extended periods of above average temperatures. Further, linkages between mangrove condition and long-term tidal cycles have not been explored in a local context. There is a need to understand changes in mangrove condition in the context of long-term natural variability in environmental drivers, to better understand potential human-induced impacts.

1.1 Aims and Objectives

The primary aim of this study is to characterise temporal patterns in mangrove vegetation condition over various temporal scales, and potential linkages to climatic drivers and local human-induced impacts. To achieve this aim, the study has the following main objectives:

1. Quantify the spatial extent of mangrove areas in 2024.

2. Describe the spatial-temporal variations in mangrove vegetation health using remotely sensed data sets, focusing on:

- Long-term patterns from 1988 to 2024

- Medium-term patterns from 2017 to 2024

- Short-term patterns between July 2023 and July 2024

2 Methodology

2.1 Study Area

The study area is comprised of mangrove forests in the following treatments:

- Test Sites—Comprised of mangrove forests directly adjacent to port operations on the southern side of the Brisbane River, namely Fisherman Islands, Coal Loader, and Whyte Island/Wynnum foreshore. It also encompassed areas in the vicinity of operational works undertaken by the Port of Brisbane Pty Ltd (PBPL), including habitat restoration works at Bulwer Island and cruise ship construction works at Luggage Point. These sites were selected to assess the impact of port-related activities on the mangrove ecosystems.

- Control Sites—Comprised of mangrove forests outside the direct influence of PBPL activities, which provide contextual information on background variability. These control sites included minimally disturbed environments at St Helena Island, as well as areas subject to historical disturbances and ongoing human disturbances.

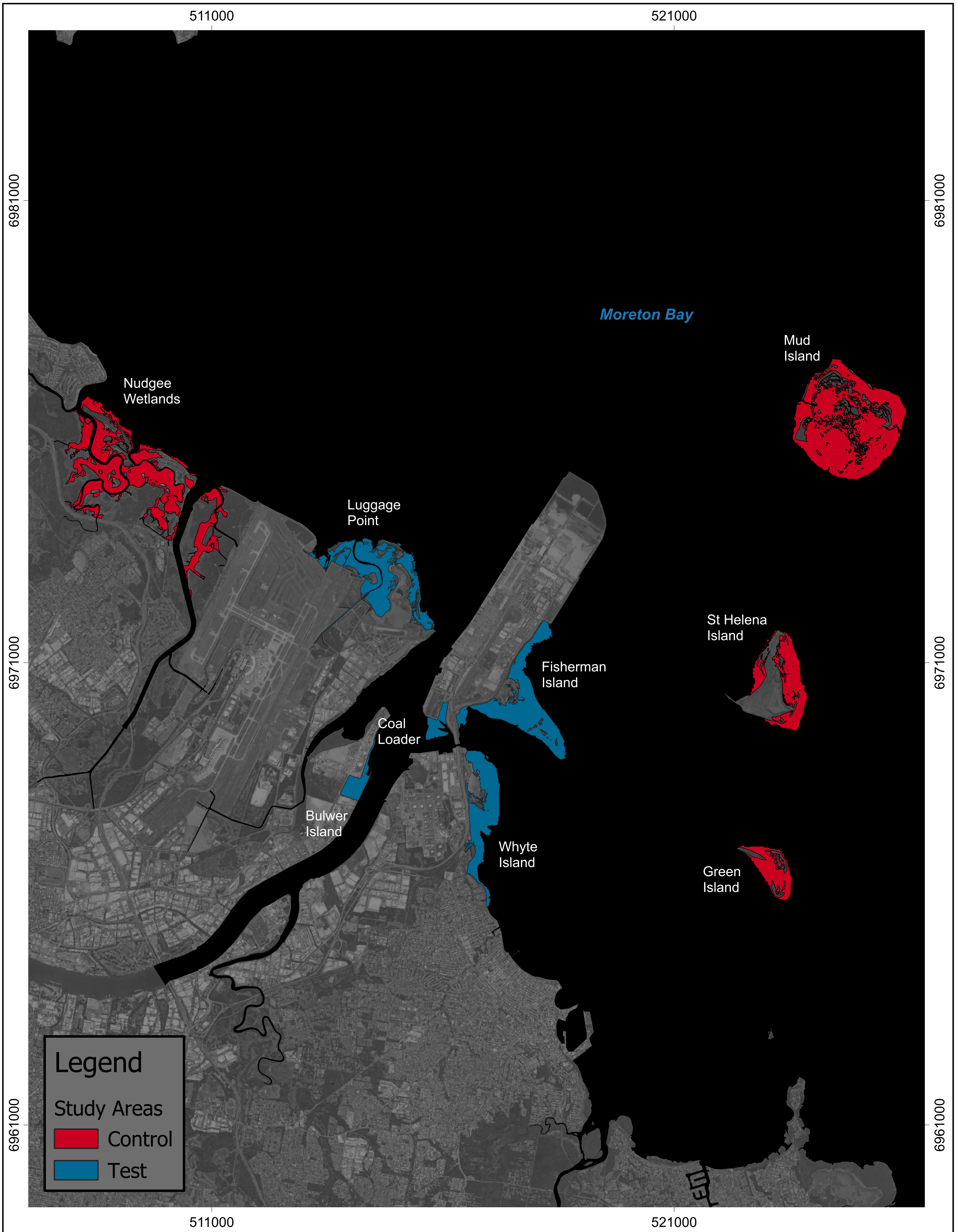
The boundaries defining the mangrove areas in this study were established using the most recent government data from the Queensland Herbarium and Biodiversity Science (2022)[1], which is based on 2021 data. This approach contrasts with previous studies that relied on data from 1997, ensuring a more accurate and up-to-date delineation of mangrove extents. Figure 2.1 illustrates the revised boundaries of the study areas, reflecting data from 2021.

2.2 Analysis of Mangrove Health Indicators

In this study, we utilised imagery from both the Sentinel-2 satellites (Sentinel-2A and Sentinel-2B) and the Landsat constellations (Landsat-5, Landsat-7, Landsat-8, and Landsat-9) to gather comprehensive data with exceptional spatial and temporal resolutions. It should be noted that Landsat-9 imagery was added to this year image dataset. Sentinel-2 images provided multispectral imagery with a 10-meter spatial resolution in the blue, green, red, and near-infrared bands, while Landsat images offered a 30-meter spatial resolution. Although the spatial resolution of Landsat imagery was lower than that of Sentinel-2, it offered a much longer temporal coverage, spanning from 1988 to the present day. In contrast, the Sentinel-2 dataset only extended from 2017 to the current period. This extensive spatio-temporal range of Landsat and Sentinel-2 imagery allowed for a detailed and long-term observation and analysis of vegetation cover on the Earth's surface. By combining the high-resolution data from Sentinel-2 with the long-term historical data from Landsat, we achieved a more comprehensive understanding of vegetation dynamics and changes over time. This integration enhanced our ability to monitor and analyse environmental changes, providing valuable insights into the health and evolution of ecosystems.

These image datasets underwent extensive post-processing on the Digital Earth Australia (DEA) Data Cube platform to enhance its accuracy and usability. This included surface reflectance correction to remove atmospheric distortions, nadir correction for consistent reflectance values, BRDF adjustment to account for light reflection at different angles, and terrain correction to address elevation variations. These adjustments collectively result in the Nadir BRDF-Adjusted Reflectance Terrain-corrected (NBART) product, providing reliable and accurate surface reflectance data for vegetation cover studies.

[1] An interactive map viewer that visualises changes in the extent of mangroves and associated communities in Moreton Bay can be seen here.



Title:
Mangrove Health Assessment Test and Control Sites

Figure: **2.1**

Rev: **A**

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

Coordinate System: GDA2020 / MGA zone 56

N 2 0 2 4
Scale in kilometres

www.bmt.org

Filepath: I:\B23621.PoB Monitoring 2019-25\QGIS\Mangrove_2024\Mangrove_2024.qgz

Several vegetation indices, such as the Leaf Area Index (LAI), Normalised Difference Vegetation Index (NDVI), and Soil-Adjusted Vegetation Index (SAVI), were derived from the NBART Sentinel-2 dataset using the Digital Earth Australia (DEA) Data Cube platform. These indices were used to evaluate the health and condition of the vegetation cover in the study area. By analysing these indices, we gained valuable insights into the vitality, density, and overall health of the vegetation, which enabled more informed decisions for environmental management and conservation efforts. These vegetation indices were selected for their ability to provide diverse insights.

2.2.2 LAI

This index is an important biophysical parameter for vegetation. It is a dimensionless variable that represents the ratio of total leaf area to ground surface area. LAI offers valuable insights into the density and health of vegetation, with higher values indicating more extensive leaf area, typically associated with robust plant growth and increased photosynthetic activity. Hence, it is particularly useful for understanding canopy structure, assessing ecosystem productivity, and guiding environmental management practices. LAI for each pixel was calculated using the formula provided by Boegh, 2002:

$$LAI = (3.618 * ((2.5 * ((NIR - Red))/(NIR + 6 * \mathrm{Red} - 7.5 * \mathrm{Blue}\ + 1)) - 0.118$$

Where $Blue$ is the blue band.

2.2.3 NDVI

This index quantifies vegetation photosynthetic capacity by measuring the difference between Near-Infrared (NIR) light, which vegetation strongly reflects, and red light, which vegetation absorbs. Although NDVI is not a physical property of vegetation cover, it is widely used as an indicator for monitoring live green vegetation. Physical values range from -1 to 1, with values above 0.2 indicating vegetation cover. Higher values suggest better photosynthetic activity. NDVI for each pixel was calculated using the formula provided by Rouse, 1974.

$$NDVI = (NIR - Red)/(NIR + Red)$$

where NIR is the near-infrared and Red is the red band.

2.2.4 SAVI

This index minimises soil brightness influences by using a soil-brightness correction factor. It is often employed in arid regions where vegetative cover is low and outputs values ranging from -1.0 to 1.0. The interpretation of these values is similar to that of NDVI. SAVI for each pixel was calculated using the formula developed by Huete, 1988:

$$SAVI = (NIR - Red)/(NIR + Red + L) * (1 + L)$$

where L is the vegetation correction factor.

2.2.5 Analysis using LAI, NDVI and SAVI

The following analyses were undertaken based on the above indices:

1. **Time-Series Analysis—** vegetation condition indices were plotted over time based on analyses of Landsat (1988 to July 2024) and Sentinel-2 (July 2017 to July 2024) imagery. Southern Oscillation

Index (SOI) and rainfall data[2] were superimposed on the time-series plots. For this analysis the data was grouped into wet and dry seasons as defined below:

- Wet Season: November, December, January, February, March, and April
- Dry Season: May, June, July, August, September, October

Vegetation indices during dry seasons were analysed using Ordinary Least Squares (OLS) and Multiple Linear Regression (MLR) regression to assess relationships with climatic conditions from the preceding wet season.

2. **Change Detection**— We performed change detection to identify and quantify significant alterations in the landscape over the past year. By comparing indices from Sentinel-2 imagery from July 2023 with those from July 2024, we were able to detect changes in land cover, vegetation, and other critical environmental factors. This approach allowed us to pinpoint and analyse dynamic shifts in the study area effectively.

2.3 Analysis of Mangrove Canopy Cover Density

We employed the methodology and dataset developed by Lymburner et al. (2020) to classify the extent of mangroves into three distinct canopy density classes:

- Closed forest—Pixels with more than 80% mangrove canopy cover.
- Open forest—Pixels with 50% to 80% mangrove canopy cover.
- Woodland—Pixels with 20% to 50% mangrove canopy cover.

This approach is based on the relationship between the 10th percentile green vegetation component of the Fractional Cover data product and Light Detection and Ranging (LiDAR) derived Planimetric Canopy Cover% (PCC). This classification helps us understand canopy thinning, which can occur due to both anthropogenic (human-induced) and non-anthropogenic events. By analysing these categories, we can better monitor and manage the health and sustainability of mangrove ecosystems.

2.4 Analysis of Mangrove Spatial Extent

Mangrove spatial extent mapping was based on the analysis of very-high spatial resolution imagery from WorldView-3, captured in April 2024. This imagery features 8 bands in the visible and near-infrared spectrum and a spatial resolution of approximately 1.2 meters. By leveraging the detailed imagery from WorldView-3, we were able to precisely assess the actual areas occupied by mangroves, providing a clear and comprehensive understanding of their spatial distribution. This approach ensured that our analysis was based on the most accurate and up-to-date information available, thereby enhancing the reliability of our findings. Unlike previous studies that relied on visible range RGB (Red, Green, Blue bands) NearMap images, our method allowed us to exclude irrelevant classes such as shadows, mangrove dieback, water, and non-mangrove vegetation. This resulted in a highly accurate representation of the current state of mangroves.

[2] Rainfall data were obtained from the Bureau of Meteorology for the period from January 1988 to July 2022. The primary weather station used was Brisbane Airport (040842), which is the closest to the study area. However, this station's data did not cover the entire duration of the study. To address this gap, missing rainfall records were supplemented with data from the nearby Fort Lytton (040320) station. Specifically, rainfall data from 1988 to 2000 were sourced from Fort Lytton (040320), while data from 2000 onwards were obtained from Brisbane Airport (040842).

2.5 Analysis of Mangrove Photosynthetic Fractional Cover

Analysing the annual 10% photosynthetic fractional cover (PFC) is useful for explaining mangrove dieback. The 10% fractional cover highlights vegetated areas that remain persistently green throughout the year, free from the seasonal or other variations that directly affect vegetation indices such as NDVI:

- Persistence and stability—The 10% fractional cover focuses on the lower percentile of green vegetation, identifying areas that remain consistently green throughout the year.

- Reduced sensitivity to seasonal changes— Unlike NDVI, which can be influenced by seasonal changes, the 10% fractional cover is less affected by these fluctuations, making it more reliable for identifying persistently green areas.

- Specificity to photosynthetic activity—The 10% fractional cover directly measures the photosynthetic fraction, providing a more accurate representation of areas with continuous photosynthetic activity. This is crucial for distinguishing dieback incidents.

The annual 10% fractional cover was calculated using Landsat imagery between 2016 and 2023. By focusing on these persistently green areas, we could detect changes in the vitality of mangroves, identifying areas where dieback was most likely occurring.

3 Result

3.1 Time-Series Analysis

The Sentinel-2 images from July 2017 to July 2024 and the Landsat images from July 1988 to July 2024 were processed under conditions that were mostly 98% cloud-free. The number of images processed for each site is detailed in Table 3.1.

Table 3.1 Availability of Images Across Different Sensors and Time Periods

Site	Sentinel-2 A & B (July 2017 – July 2024)		Landsat 5, 7, 8, 9 (July 1988 – July 2024)	
	Quality Pixel	Time Steps	Quality Pixel	Time Steps
Pelican Banks / Coal Loader	75%	530	98%	429
Nudgee Wetlands	98%	370	98%	329
Luggage Point	98%	385	98%	408
Bulwer Island	98%	500	98%	406
Whyte Island	98%	394	98%	491
St Helena Island	98%	488	98%	614
Green Island	98%	485	98%	621
Mud Island	98%	439	98%	561
Fisherman Islands	75%	514	98%	431

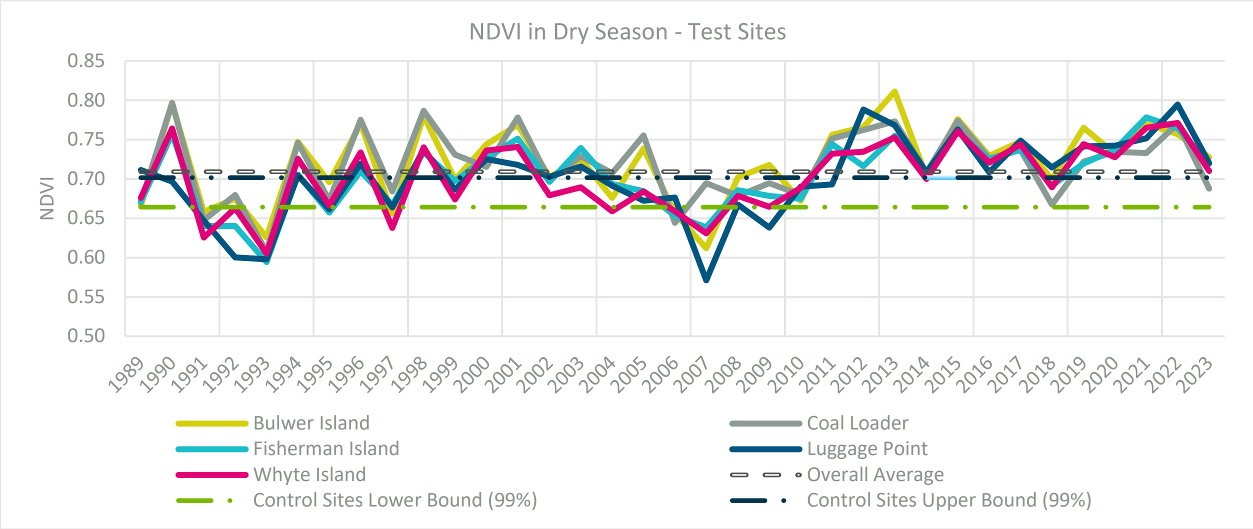
3.1.1 Long-Term Analysis from Landsat (1989 to 2023)

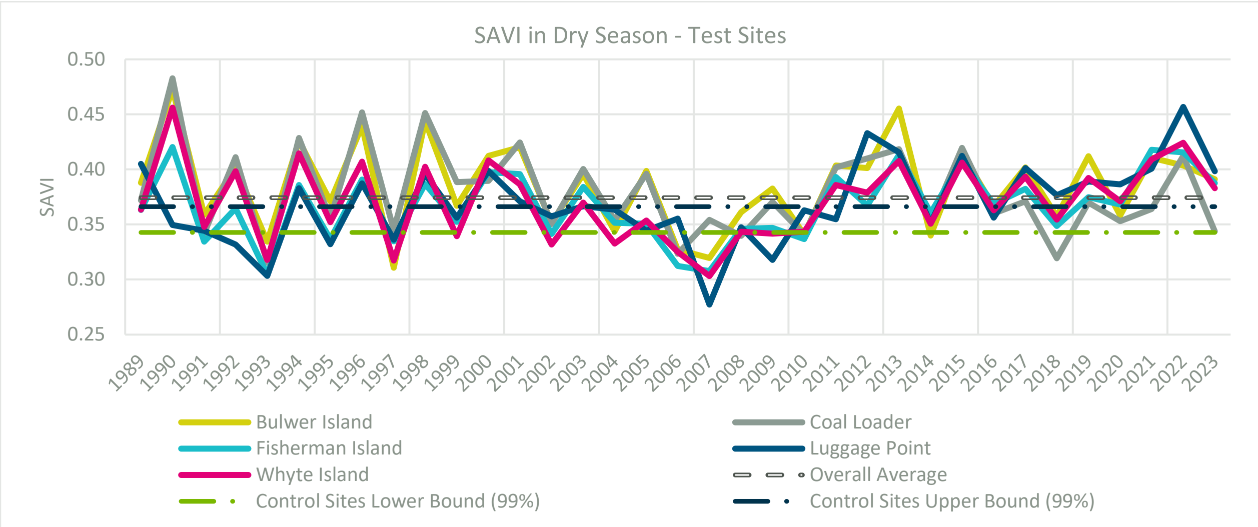
Vegetation indices such as NDVI, SAVI, and LAI were derived from the Landsat long-term dataset (1989 to 2023) for the dry season. Table 3.2 displays the average values of these indices for each site, along with the overall averages for the test and control sites throughout this period. Figure 3.1 and Figure 3.2 illustrate the long-term trends of these indices for the test and control sites during the dry seasons.

Table 3.2 Average Vegetation Indices for Dry Seasons (1989-2023) – Long-Term Analysis

Type	Site	NDVI	SAVI	LAI
Test Sites	Bulwer Island	0.721	0.385	1.344
	Coal Loader	0.718	0.380	1.319
	Fisherman Island	0.704	0.367	1.263
	Luggage Point	0.701	0.369	1.270
	Whyte Island	0.702	0.371	1.282
	Overall Average	0.709	0.374	1.296
Control Sites	Green Island	0.674	0.345	1.170
	Helena Island	0.664	0.341	1.147

Type	Site	NDVI	SAVI	LAI
	Mud Island	0.685	0.355	1.196
	Nudgee Wetlands	0.709	0.378	1.294
	Overall Average	0.683	0.355	1.202





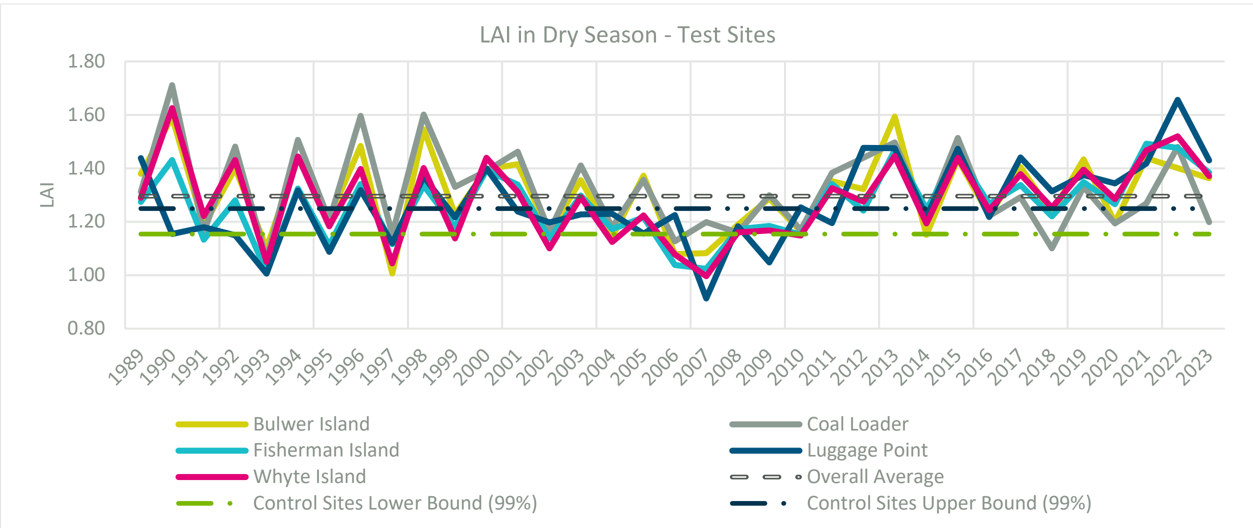


Figure 3.1 Landsat-Derived Vegetation Indices for Test Sites During Dry Seasons

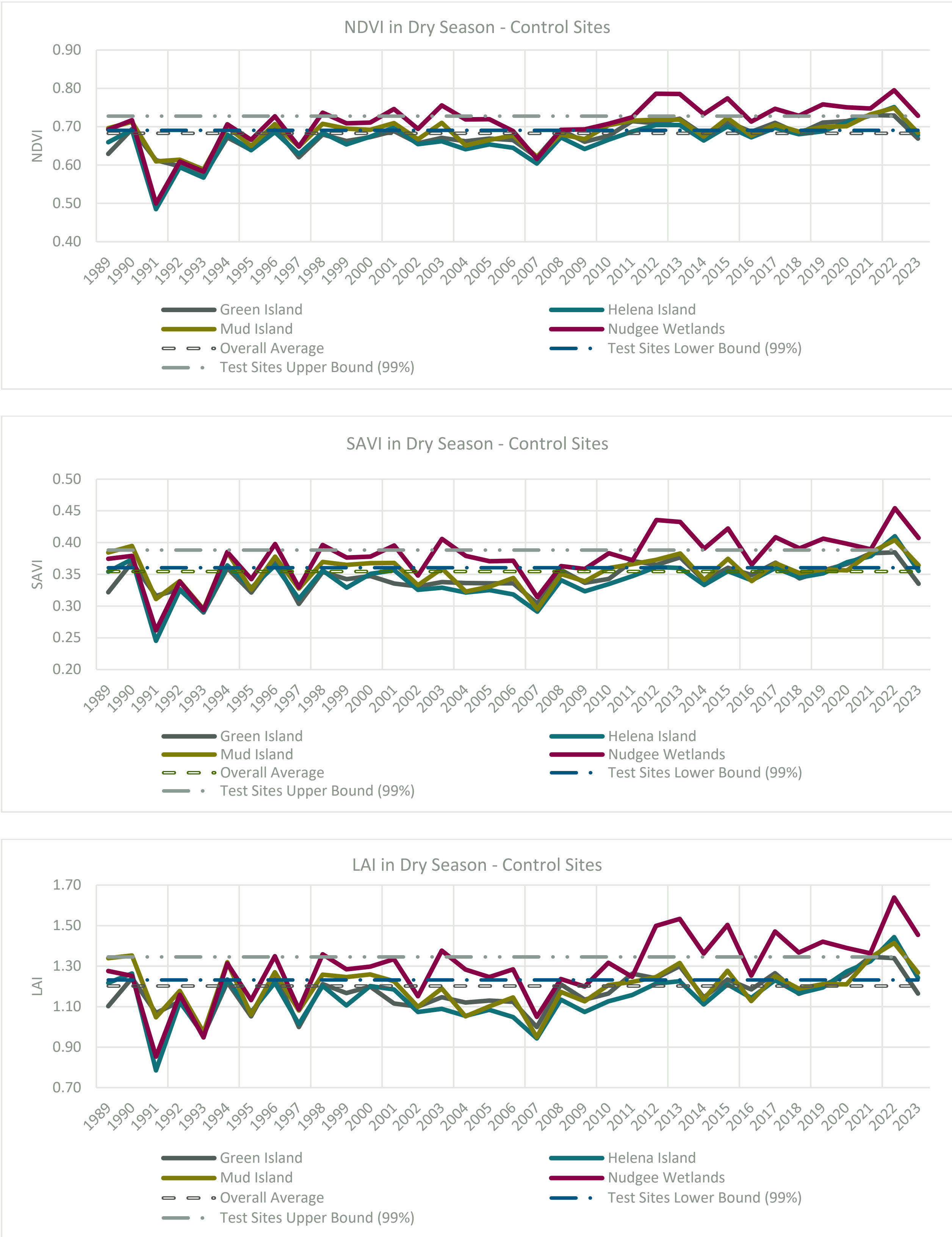


Figure 3.2 Landsat-Derived Vegetation Indices for Control Sites During Dry Seasons

The NDVI results presented in Table 3.2 indicate that both the test and control sites exhibited similar values, reflecting a consistent level of vegetation health across these locations:

- Test Sites - Bulwer Island (0.721) and Coal Loader (0.718) had slightly higher NDVI values than Fisherman Islands (0.704), Whyte Island (0.702), and Luggage Point (0.701).

- Control Sites – Only Nudgee Wetlands (0.709) had an NDVI value within the range of test sites. Green Island (0.674), Helena Island (0.664) and Mud Island (0.685) had lower NDVI values, and therefore canopy cover, than other control sites.

The overall average NDVI of the test sites (0.709) was higher than the control sites (0.683), indicating that the test sites had higher canopy chlorophyll. The other vegetation indices followed a similar trend, indicating that on average test and control sites had consistent vegetation conditions.
Figure 3.1 shows there were two periods where NDVI values fell below the long-term average of 0.7 for ≥2 years: 1991 to 1994 and 2006-2010. Extended (≥2 consecutive years) of above average NDVI were recorded from 2010-2017 and 2019-2022. For the remainder of the period, NDVI values fluctuated around the average line, with changes of about 0.05 in value on either side. This pattern was similar for SAVI and LAI. Among the test sites, Luggage Point generally had greater variability in NDVI over time (CV[3] = 7.11) than Bulwer Island (CV = 6.71), Coal Loader (CV = 6.27), Whyte Island (CV = 6.21), and Fisherman Islands (CV = 5.96). As shown in Figure 3.1, there were major declines in NDVI at Luggage Point in 1990, 1992 and 2007, whereas smaller or no changes in NDVI were observed at other test sites. Fisherman Islands maintained more stable NDVI values over time than other test sites.
Nudgee Wetlands (CV = 8.34) had greater variability than Helena Island (CV = 7.10), Green Island (CV = 5.54) and Mud Island (CV = 5.22). The average CV value for control sites was 6.55, indicating control sites had greater variability in NDVI than the average for test sites (CV = 6.4). Figure 3.2 shows that NDVI at control sites fell below the long-term average from 1991 to 1994, coincident with patterns at test sites. Like test sites, below average NDVI was observed in 2007 to 2010. In the period 2007-2010, Bulwer Island and Luggage Point (>0.1 change) showed larger declines in NDVI values than control sites (<0.05) and the other test sites. For the remainder of the period, NDVI and other vegetation indices for the control sites were near the long-term average.

These results indicated that compared with control sites, test sites had: (i) higher NDVI values (i.e., denser canopy vegetation) and (ii) similar average levels of temporal variability. The average NDVI for test sites was 0.709, while for control sites it was 0.683, confirming that test sites had higher NDVI values, indicating denser canopy vegetation. The average coefficient of variation (CV) for test sites was 6.4, and 6.55 for control sites. This similar CV suggests that the test sites generally maintained healthier vegetation over time. Additionally, the variability in NDVI values at the test sites was comparable to that of the control sites, indicating consistent vegetation conditions across both types of sites.

Relationship Between NDVI and Environmental Drivers

The periods 1991-1994 and 2006-2010 were extended periods of below average NDVI. 1991 to 1994 were El Niño years (SOI -7 to -14.03), and below average rainfall was recorded at Brisbane in 1991, 1993-1994. The average monthly mean sea level for these years (1.225 – 1.262 m) were also lower than the long-term average (1.284 m). In contrast, the years before and after these periods had higher NDVI values, which corresponded to neutral to La Niña conditions. The period 2006-2010 occurred during the Millenium Drought (2001-2009). Below average rainfall was recorded in Brisbane from 2000 to 2007, with average rainfall recorded in 2008-2009. The average monthly mean sea level for 2000-2007 (1.272 – 1.284 m) were also at or lower than the long-term average (1.284 m).

[3] Coefficient of variation (CV)

The trend of Landsat-derived NDVI for test and control sites during dry seasons, along with climatic variables (rainfall and SOI) from the preceding wet season, is shown in Figure 3.3. There was a long-term linear trend of increasing NDVI over time at test and control sites.

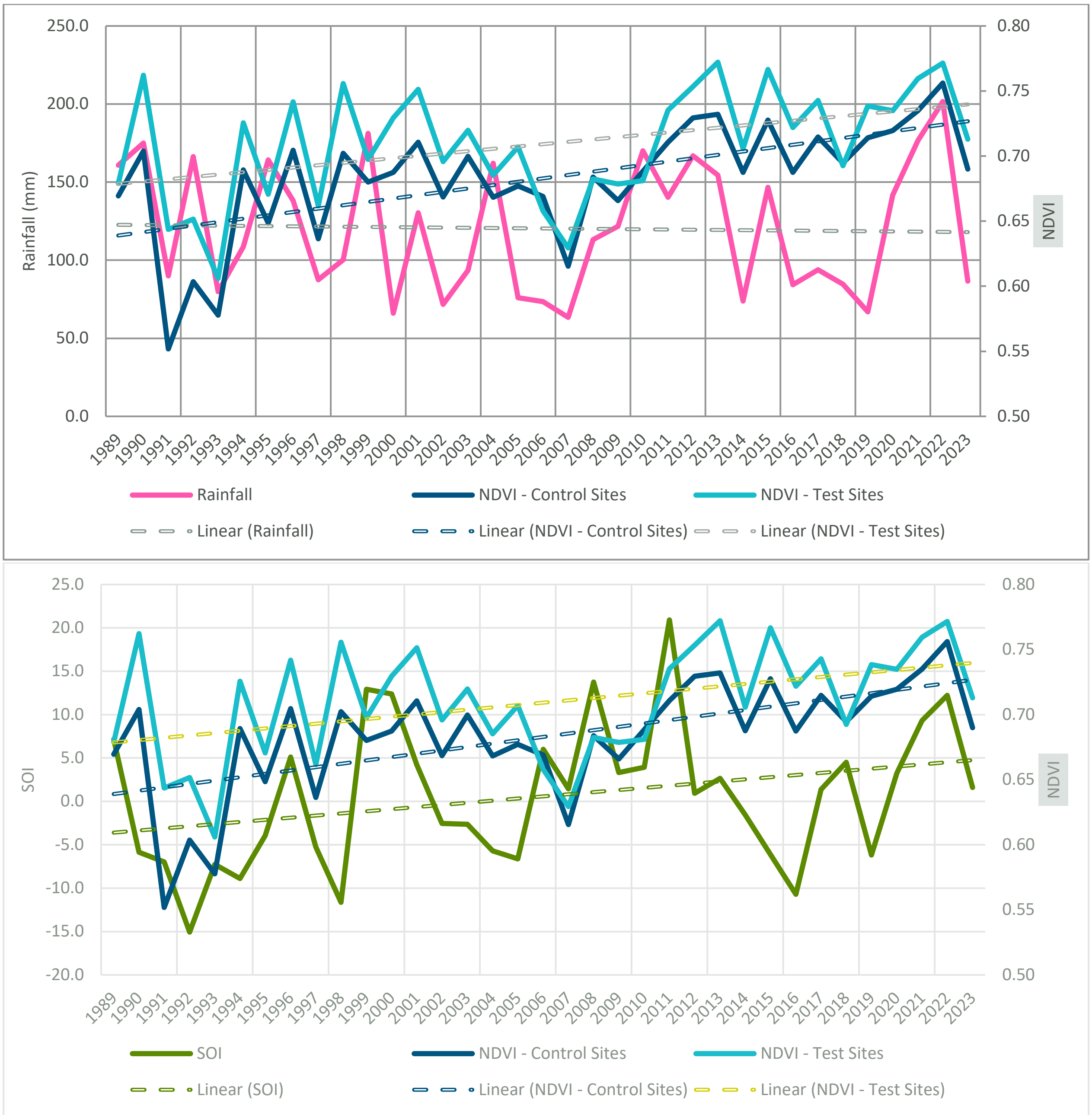


Figure 3.3 Landsat-Derived NDVI for Test and Control Sites During Dry Seasons, and Climatic Variables (Rainfall (top) and SOI (bottom)) from the Preceding Wet Season

Although the model demonstrated some evidence of a relationship between SOI and NDVI, the overall explanatory power was relatively low. Multiple regression analysis was undertaken to assess the relationship between NDVI with cumulative annual rainfall departure and annual mean monthly sea level. The regression model explained 41% of variation in NDVI at control sites ($r^2 = 0.41$, $p = 0.002$) and 31% of variation in NDVI variation at test sites ($r^2 = 0.31$, $p = 0.0029$). Annual mean monthly sea level explained most of the variation in NDVI at control (Figure 3.4) and test (Figure 3.5) sites. Annual mean monthly sea level has progressively increased over time ($r^2 = 0.709$, p <0.001).

Regression Summary
NDVI_Control_Dry vs. 2 Independents

Count	35
Num. Missing	0
R	.642
R Squared	.413
Adjusted R Squared	.376
RMS Residual	.035

ANOVA Table
NDVI_Control_Dry vs. 2 Independents

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	2	.027	.013	11.235	.0002
Residual	32	.038	.001		
Total	34	.065			

Regression Coefficients
NDVI_Control_Dry vs. 2 Independents

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
Intercept	.040	.168	.040	.236	.8151
12 month departure	2.979E-5	1.590E-5	.260	1.873	.0702
Annual mean SL	.498	.130	.533	3.843	.0005

Figure 3.4 Multiple regression analysis results -control sites

Regression Summary
NDVI_Test_Dry vs. 2 Independents

Count	35
Num. Missing	0
R	.553
R Squared	.306
Adjusted R Squared	.262
RMS Residual	.037

ANOVA Table
NDVI_Test_Dry vs. 2 Independents

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Regression	2	.019	.010	7.046	.0029
Residual	32	.044	.001		
Total	34	.063			

Regression Coefficients
NDVI_Test_Dry vs. 2 Independents

	Coefficient	Std. Error	Std. Coeff.	t-Value	P-Value
Intercept	.220	.180	.220	1.226	.2293
Annual mean SL	.378	.139	.411	2.722	.0104
12 month departure	3.294E-5	1.706E-5	.291	1.931	.0624

Figure 3.5 Multiple regression analysis results -test sites

Figure 3.6 illustrates the overall trend of NDVI (test and control sites) using a 6-month rolling average alongside 6-month cumulative rainfall. There were two negatives' departures: one in the early 1990s and another around 2007. The largest decline was recorded in the 1990s, which coincided with a period of low rainfall following above average rainfall and NDVI in the previous years (Figure 3.7). The decline in NDVI during 2007 occurred during the Millenium Drought, but a period of increasing rainfall. Annual mean sea level (MSL) was also below the overall average during both the early 1990s and 2007 (Figure 3.8).

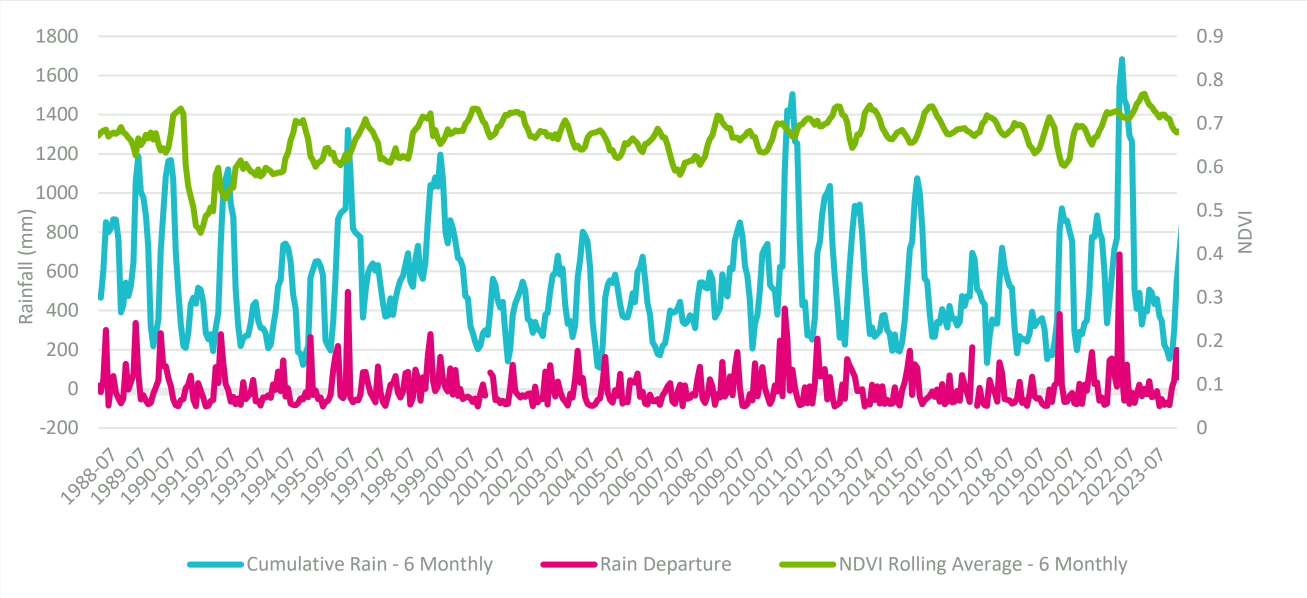


Figure 3.6 Six-Monthly Cumulative Rainfall, Rain Departure and Six-Monthly Rolling Average of NDVI at Test and Control Sites Combined

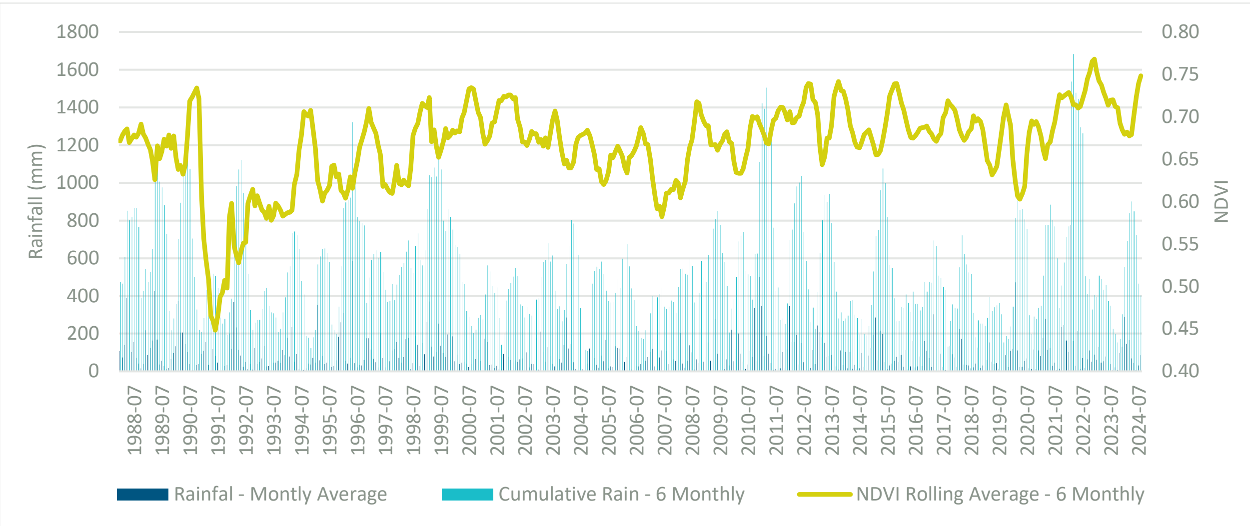


Figure 3.7 Monthly Average Rainfall (Dark Blue) and 6-Month Cumulative Rainfall (Light Blue). The Yellow Line Represents the 6-Month Rolling Average of NDVI.

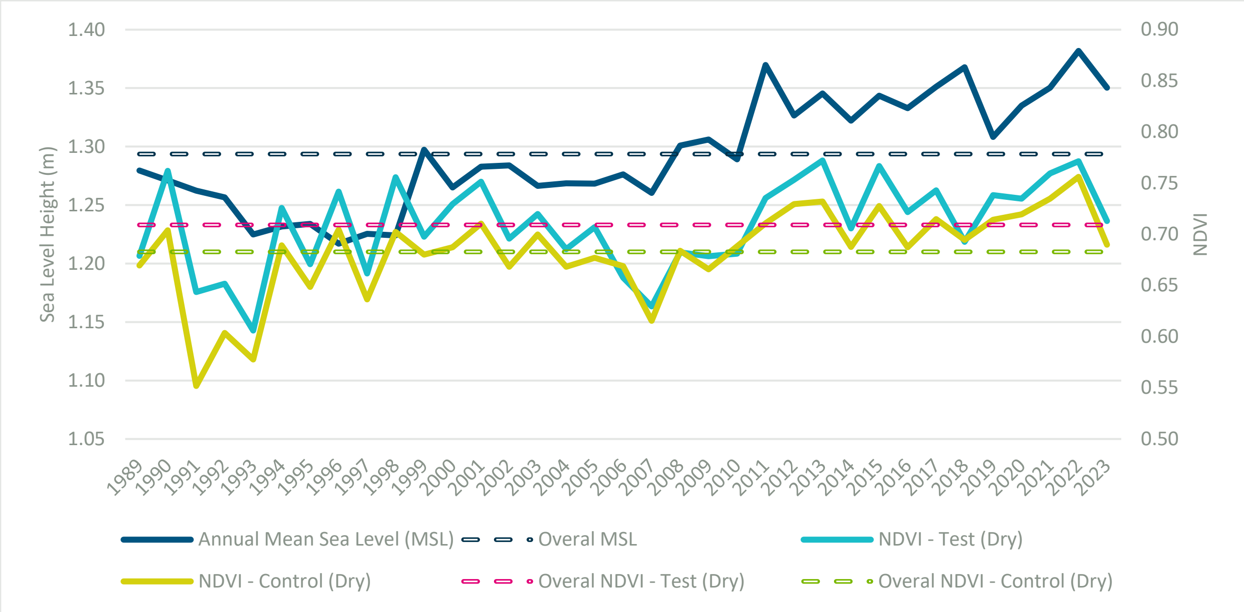


Figure 3.8 Annual Mean Sea Level (MLS) and NDVI for Test and Control Sites During Dry Seasons

3.1.2 Medium-Term Analysis from Sentinel-2 (2017 to 2023)

Over the 7-year period from the dry season of 2017 to 2023, vegetation indices such as NDVI, SAVI, and LAI were derived from the Sentinel-2 medium-term dataset. Table 3.3 displays the average values of these indices for each site, along with the overall averages for the test and control sites throughout this period. The results show that for all test sites Bulwer Island, Coal Loader, Fisherman Island, Luggage Point, and Whyte Island the NDVI values were within 0.03 of the overall average of 0.73. Similarly, the SAVI values ranged within 0.03 of the overall average of 0.37. For LAI, the values were within 0.11 of the overall average of 1.29. For the control sites Green Island, Helena Island, Mud Island, and Nudgee Wetlands the NDVI values were within 0.04 of the overall average of 0.72. Similarly, the SAVI values ranged within 0.04 of the overall average of 0.37. For LAI, the values were within 0.15 of the overall average of 1.28.

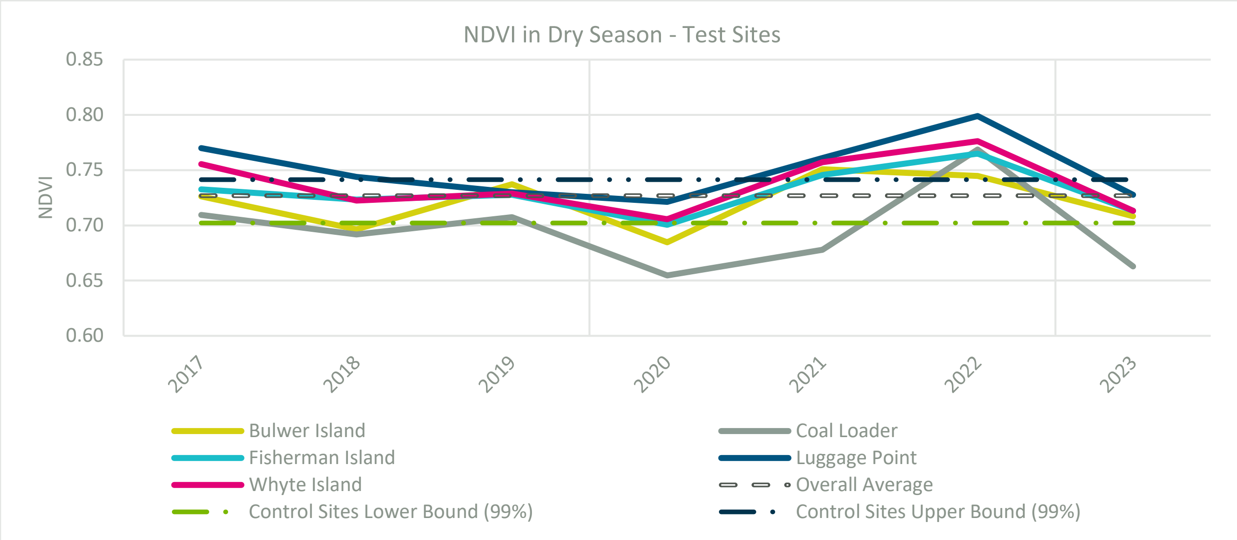
Table 3.3 Average Vegetation Indices for Dry Seasons (2017-2023) – Medium-Term Analysis

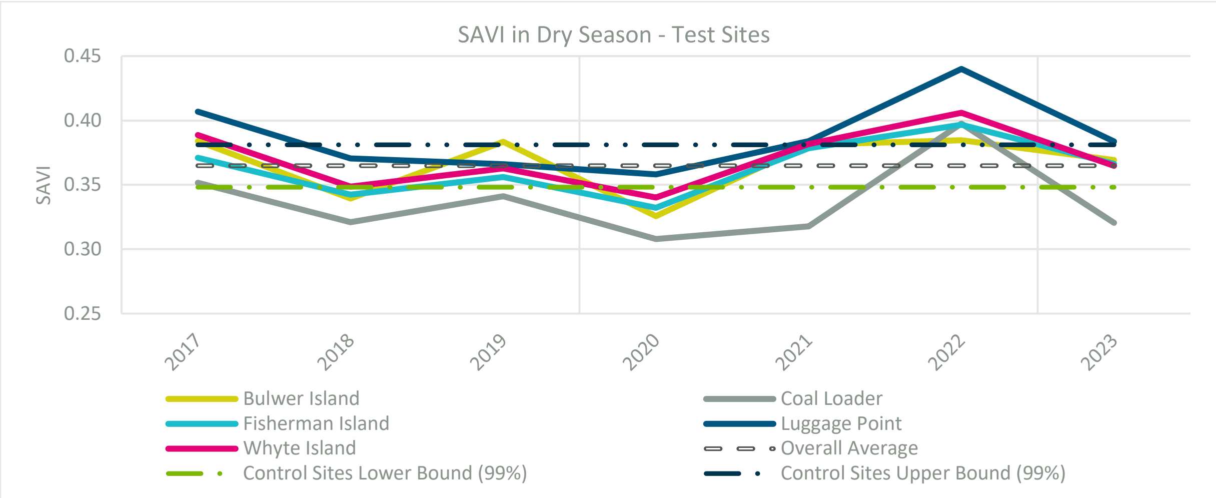
Type	Site	NDVI	SAVI	LAI
Test Sites	Bulwer Island	0.721	0.367	1.311
	Coal Loader	0.696	0.337	1.185
	Fisherman Island	0.730	0.363	1.286
	Luggage Point	0.750	0.387	1.377
	Whyte Island	0.737	0.370	1.311
	Overall Average	0.727	0.365	1.294
Control Sites	Green Island	0.699	0.346	1.214
	Helena Island	0.708	0.352	1.232
	Mud Island	0.717	0.359	1.256
	Nudgee Wetlands	0.763	0.401	1.429

Type	Site	NDVI	SAVI	LAI
	Overall Average	0.722	0.365	1.283

Figure 3.9 and Figure 3.10 illustrate the medium-term trends of these indices for the test and control sites during the dry seasons, respectively. Among the test sites Coal Loader generally had greater variability in NDVI over time (CV = 5.07) than Luggage Point (CV = 3.44), Whyte Island (CV = 3.29), Bulwer Island (CV = 3.24), and Fisherman Islands (CV = 2.67). Figure 3.10 shows that control sites displayed similar temporal patterns to test sites, and trends over time were consistent among all control sites. Test sites had greater temporal variability in NDVI than control sites (CV: St Helena Island = 3.23; Green Island = 3.04; Mud Island = 2.89; Nudgee = 2.60).

The NDVI results presented in Table 3.3 indicate that both the test and control sites exhibited similar values, reflecting a consistent level of vegetation health across these locations. For the test sites, Bulwer Island had an NDVI of 0.721, Coal Loader recorded 0.696, Fisherman Island showed 0.730, Whyte Island had 0.737, and Luggage Point registered 0.750. The overall average NDVI for all these test sites was 0.727, demonstrating minimal variation among them. However, Luggage Point and Whyte Island performed slightly better than the other three test sites, with their NDVI values being marginally higher. This suggests that these two sites may have slightly healthier or denser vegetation compared to Bulwer Island, Coal Loader, and Fisherman Islands. For the control sites, Green Island had an NDVI of 0.699, St. Helena Island was 0.708, Mud Island was 0.717, and Nudgee Wetlands was 0.763. These values suggest that the vegetation health at these control sites was relatively uniform, with Nudgee Wetlands having higher NDVI (denser canopy cover) than the other sites.
The overall average NDVI was similar between control (0.722) and test sites (0.727). Consistent with analyses based on Landsat, this indicates that both test and control sites maintained similar vegetation health. Additionally, other vegetation indices followed a similar trend, showing only small changes across these sites. This further supports the observation of consistent vegetation health and minimal variation among the different locations.





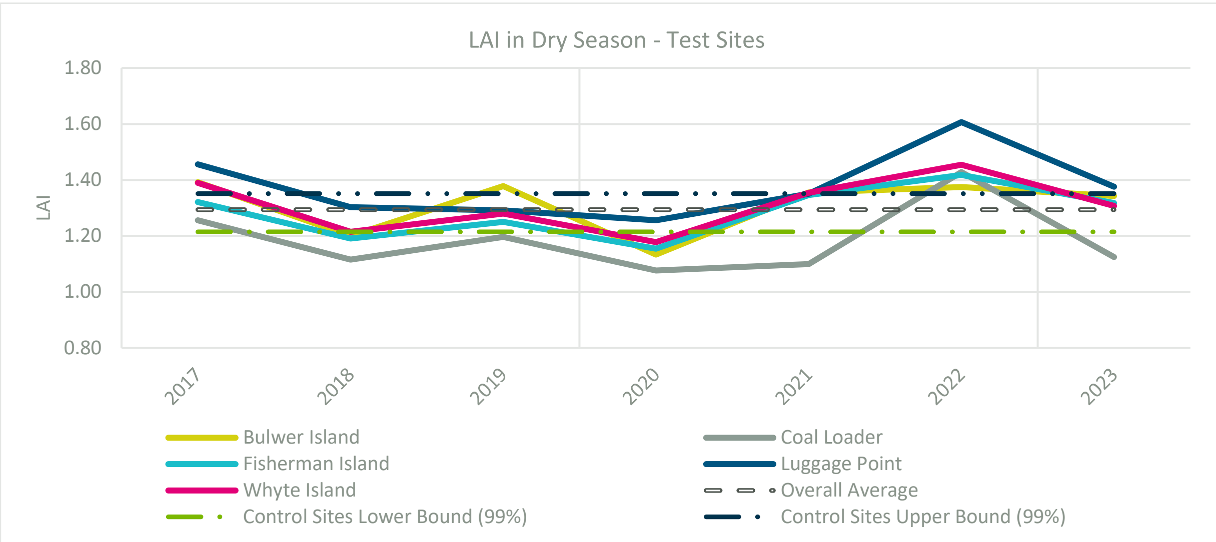
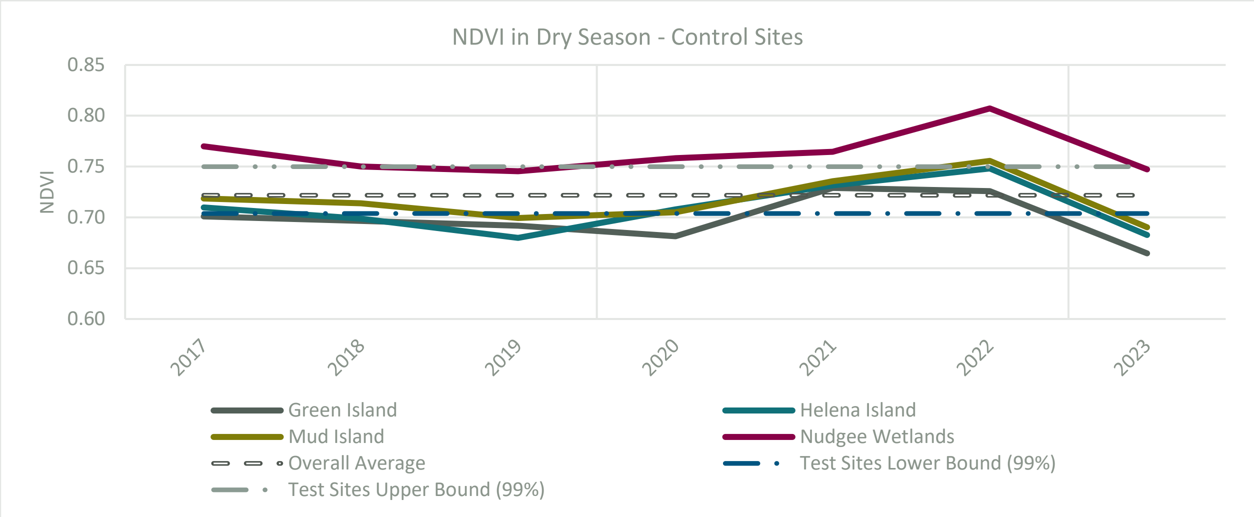
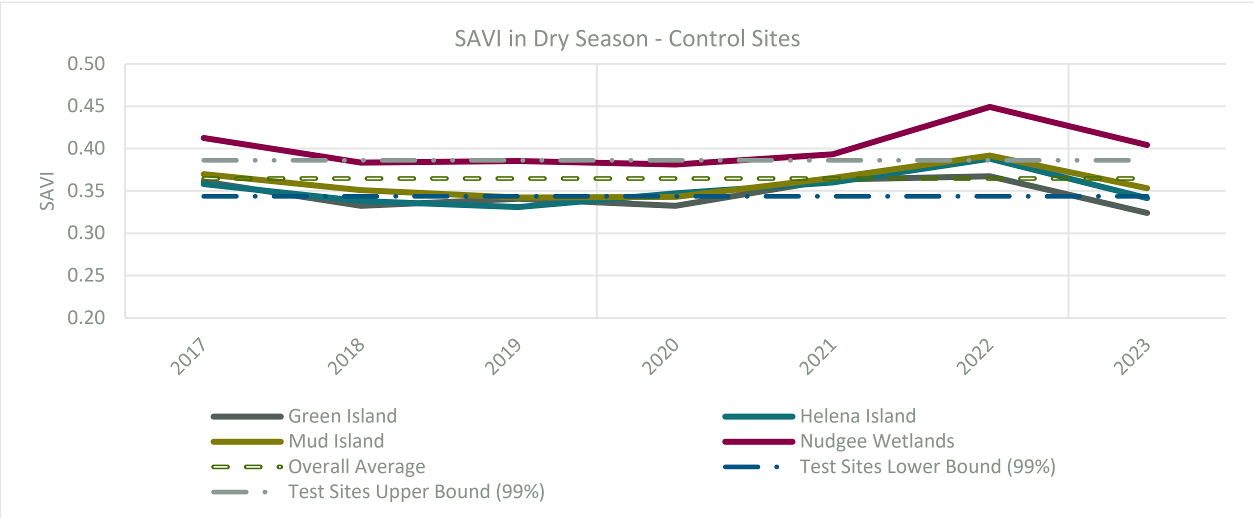


Figure 3.9 Sentinel-2 Derived Vegetation Indices for Test Sites During Dry Seasons





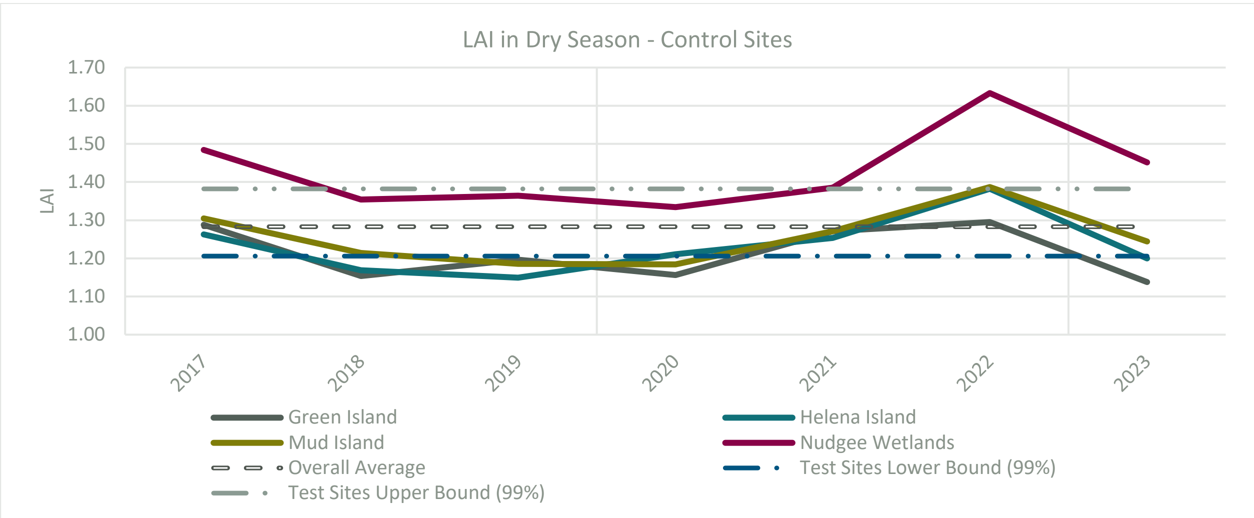


Figure 3.10 Sentinel-2 Derived Vegetation Indices for Control Sites During Dry Seasons

The trend of Sentinel-2 derived NDVI for test and control sites during dry seasons, along with climatic variables (rainfall and SOI) from the preceding wet season, is shown in Figure 3.11. The highest average NDVI values were recorded in 2022 at all test and control sites. This period was coincident with major flooding in the Brisbane River.

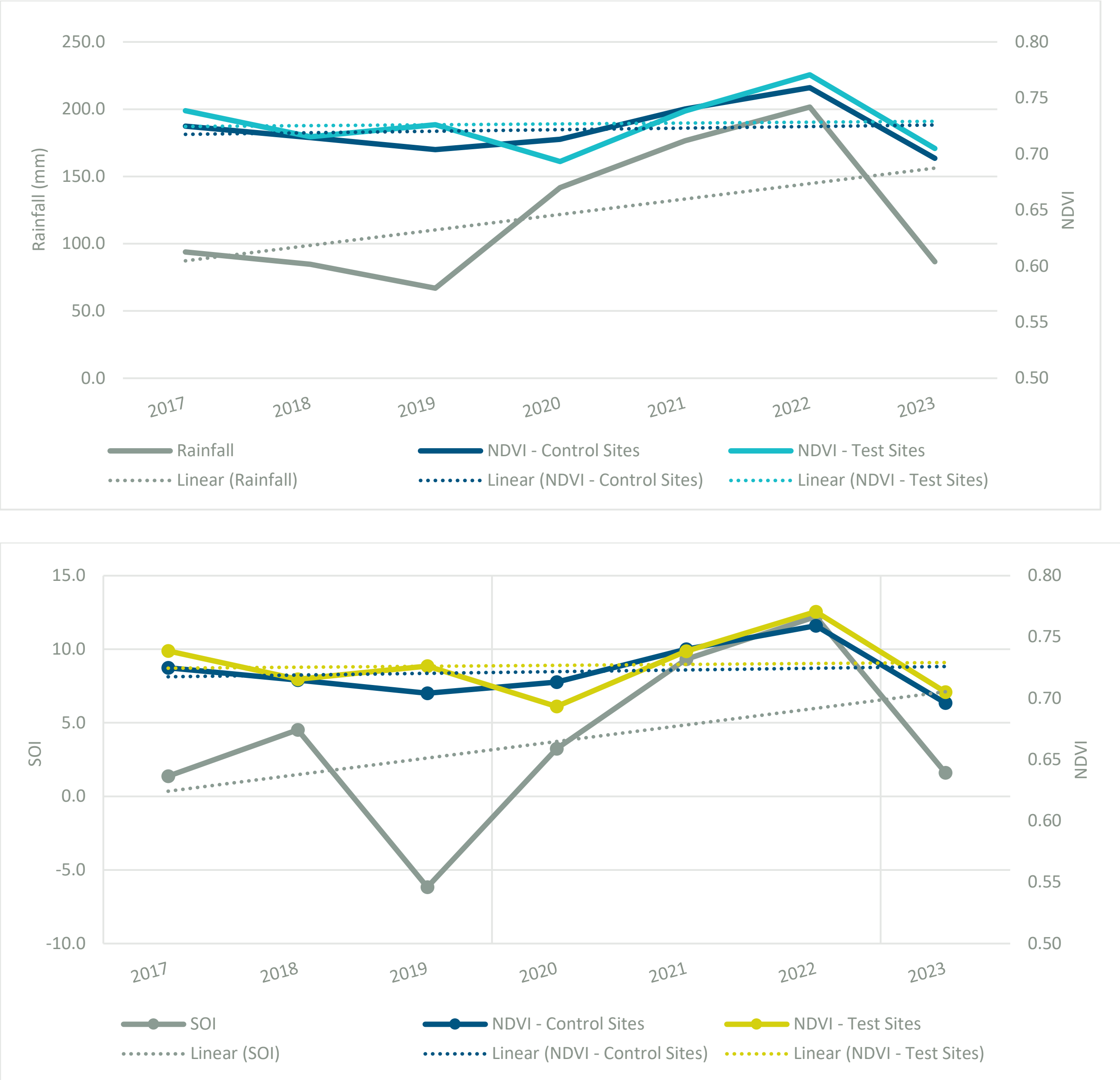


Figure 3.11 Sentinel-2 Derived NDVI for Test and Control Sites During Dry Seasons, Alongside Climatic Variables (Rainfall and SOI) from the Preceding Wet Season

Statistical Analysis

The average NDVI value (pooled sites) for the period 2017 - 2023 was analysed in relation to rainfall and SOI. The OLS regression analysis, Figure 3.12, revealed a positive linear relationship between rainfall and NDVI ($r^2 = 0.52$), indicating that rainfall explained 52% of the variability in NDVI. The coefficient for rainfall was 0.0003, which due to the small sample size (d.f. = 5), was statistically significant at a p-value of 0.067. Furthermore, the OLS regression analysis identified a positive linear relationship between the

Southern Oscillation Index (SOI) and NDVI ($r^2 = 0.468$), which was statistically significant at a p-value of 0.09.

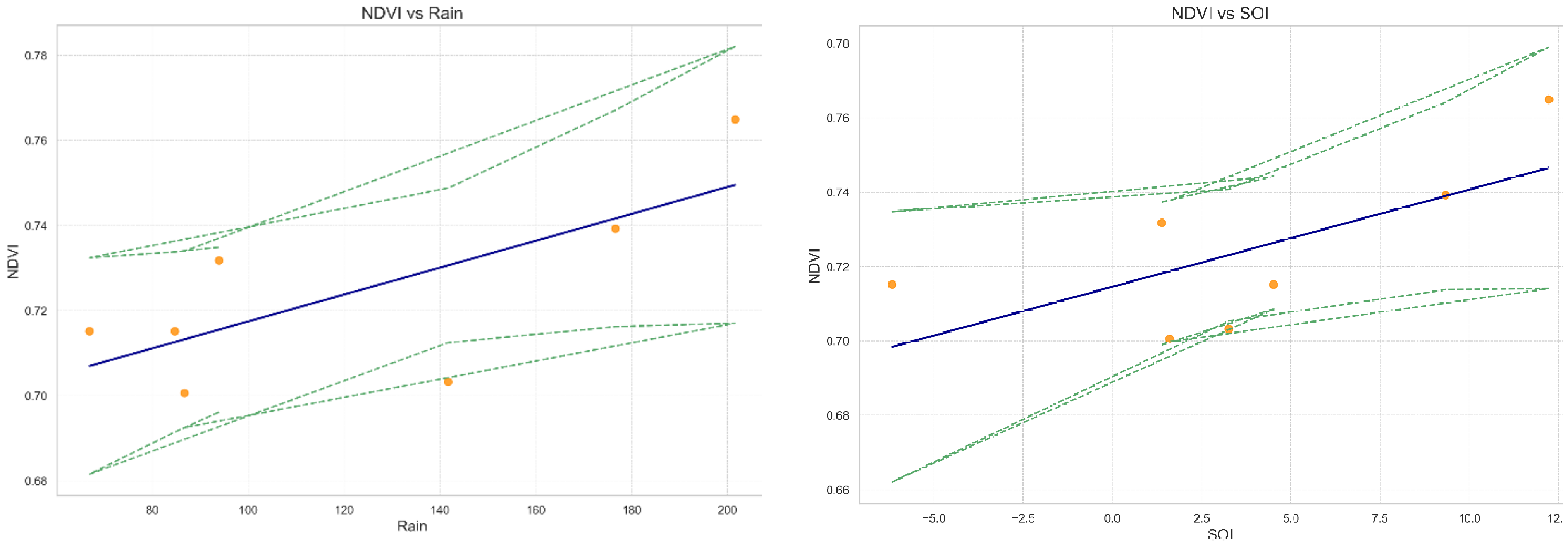


Figure 3.12 Regression Analysis of Overall NDVI vs. Rainfall (mm) and SOI

3.1.3 Comparative Analysis of NDVI Values from Overlapping Periods of Landsat and Sentinel-2

The graph presented below () illustrated a comparative analysis of NDVI values derived from Sentinel-2 and Landsat satellite data for both test and control sites. This comparison spanned the period during which both satellites' data overlapped, providing a comprehensive view of the NDVI variations captured by each satellite. As observed, the overall NDVI values derived from these two sensors for the control sites are more closely aligned compared to the test sites, although the differences are minimal.

Figure 3.13 NDVI Values from Sentinel-2 and Landsat for Test and Control Sites During Overlapping Period

3.1.4 Short-Term Analysis from Sentinel-2 (July 2023 – July 2024)

The change vector (change detection) for the median NDVI from July 2023 to July 2024, captured by Sentinel-2, is illustrated in Figure 3.15 and Figure 3.14. This vector represents the direction and magnitude of changes in NDVI values over the specified period which is a basis for identifying areas of mangrove canopy improvement or decline during the period. Across all sites, the inland sections of mangrove forests adjoining saltpans showed the greatest improvement over the period. Small patches of mangrove declines were observed on the seaward margins at Luggage Point and the northern section of Bulwer Island. An inspection of aerial photography indicates there were small areas of mangrove tree fall at Luggage Point in the area with NDVI reductions. The other patches of NDVI decline did not display visual evidence of tree fall or apparent canopy thinning, which could be an early sign of stress. Table 3.4 and Figure 3.14 present the area (ha) of mangrove forest categorised by the magnitude of NDVI change between July 2023 and July 2024. Mangrove condition remained relatively stable (i.e., minimal change) between July 2023 and July 2024.

Table 3.4 Area (ha) of Mangrove Forest Showing NDVI Changes Between July 2023 and 2024

Site	Area (ha)		
	Declined NDVI Change < -0.1	Minimal Change NDVI Change -0.1 to 0.1	Improved NDVI Change > 0.1
Bulwer Island	0.23	23.9	1.1
Coal Loader	0.11	17.7	2.63
Fisherman Island	0.6	145.74	11.25
Luggage Point	0.78	135.77	21.92
Whyte Island	0.33	97.25	12.72

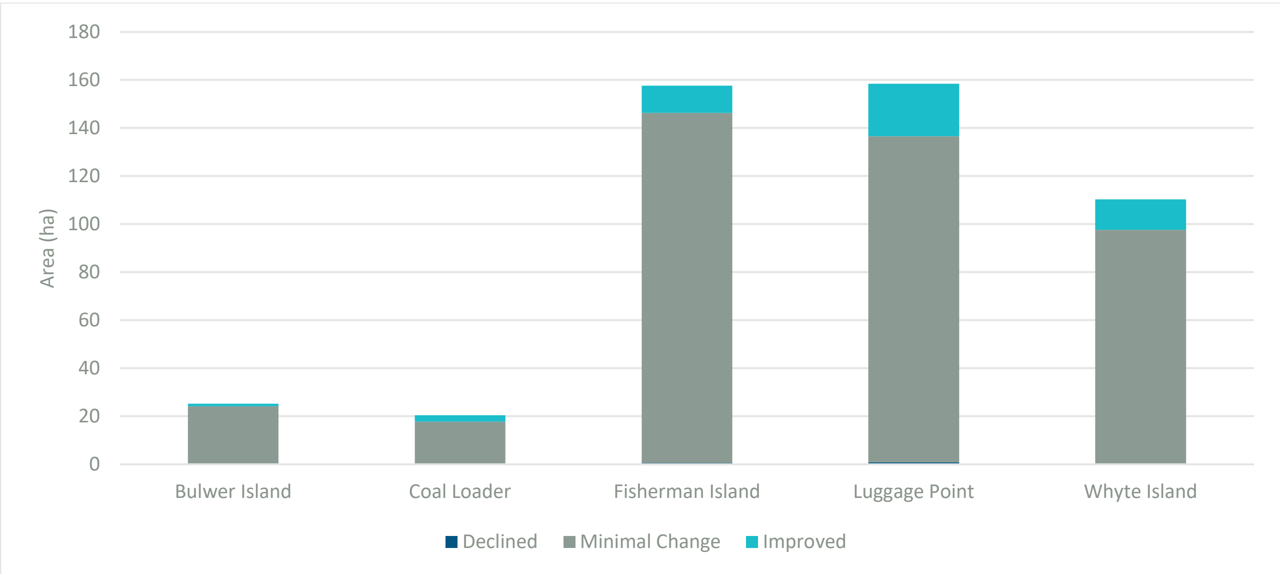
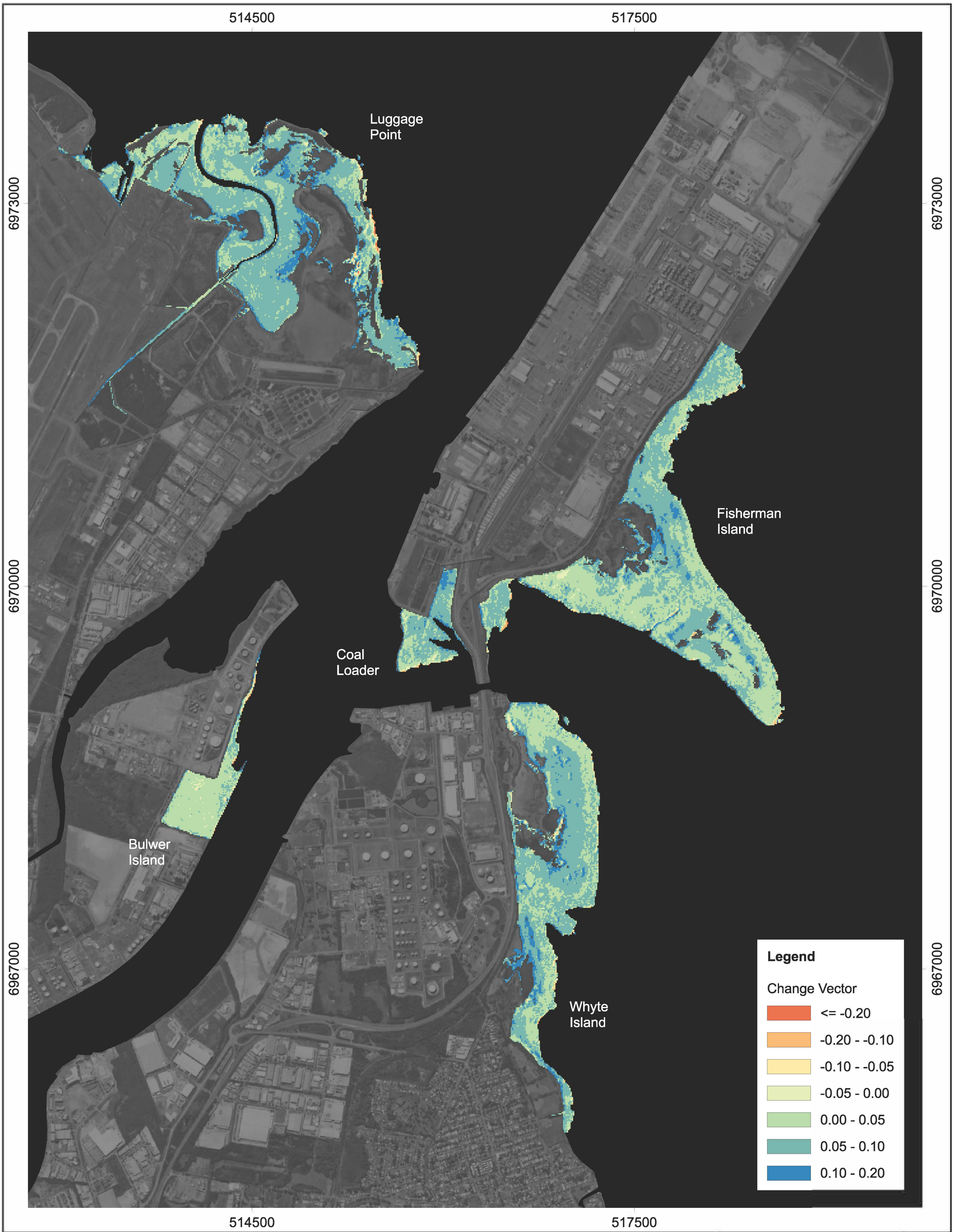


Figure 3.14 Area (ha) of Mangrove Forest Showing NDVI Changes Between July 2023 and 2024



Title:

Median NDVI Change Vector from July 2023 to July 2024 (Sentinel-2)

Figure: **3.15**

Rev: **A**

Coordinate System: GDA2020 / MGA zone 56

N

0.5 0 0.5 1

Scale in kilometres

BMT

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3.2 Analysis of Mangrove Canopy Cover Density

As shown in Figure 3.16, the closed mangrove forest (with >80% canopy cover) experienced two major declines: one in the early 1990s and another around 2007, as also observed in NDVI. Nevertheless, in both instances, mangrove canopy density recovered quickly, as also noted in NDVI.

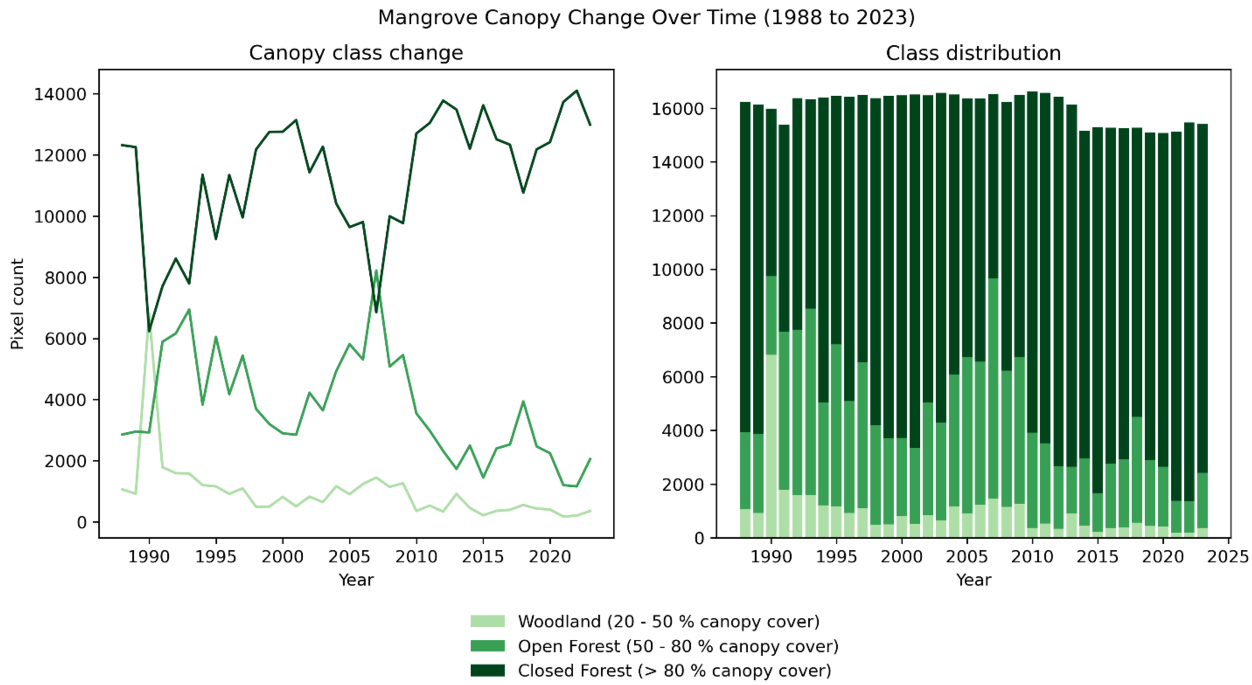

Figure 3.16 Mangrove Canopy Cover Density For both Test and Control Sites (1988 – 2023)

3.3 Mangrove Spatial Extent in 2024

The spatial extent of the mangrove areas for Bulwer Island, Coal Loader, Fisherman Island, and Whyte Island was objectively classified using high resolution multispectral satellite imagery (Worldview 3). This involved distinguishing between vegetation and non-vegetation classes within the boundaries of each test location. During this process, mangrove diebacks, gaps, shadows, water bodies, and other types of vegetation were carefully excluded from the mangrove class to ensure accuracy.

The mangrove extents for each test location are illustrated in Figure 3.17-Figure 3.20 with the corresponding area calculations detailed in Table 3.5.

Table 3.5 Area of Key Mangrove Sites

Site	Area (ha)
Bulwer Island	20.45
Coal Loader	16.61
Fisherman Island	132.39
Whyte Island	92.89

Title:

The Extent of Mangrove Class in Bulwer Island Derived from WorldView-3 - April 2024

Figure: 3.17

Rev: A

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Coordinate System: GDA2020 / MGA zone 56

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Scale in metres

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Title:

The Extent of Mangrove Class in Coal Loader Derived from WorldView-3 - April 2024

Figure: 3.18

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Title:

The Extent of Mangrove Class in Fisherman Islands Derived from WorldView-3 - April 2024

Figure: 3.19

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Coordinate System: GDA2020 / MGA zone 56

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Scale in metres

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Title:

The Extent of Mangrove Class in Whyte Island Derived from WorldView-3 - April 2024

Figure: 3.20

Rev: A

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Scale in metres

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3.4 Mangrove 10% Photosynthetic Fractional Cover

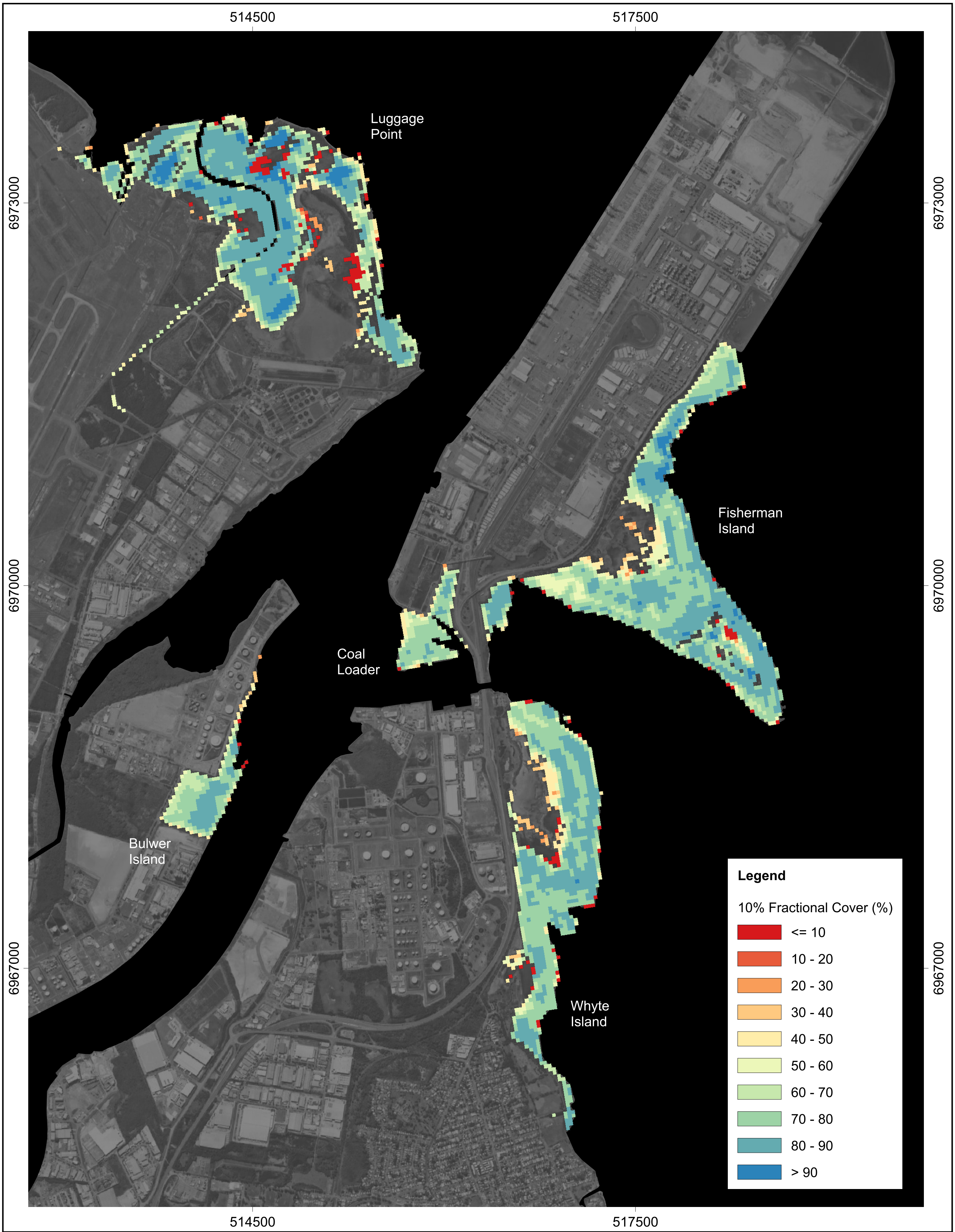
The geo-median 10% fractional cover of green vegetation, derived from Landsat imagery, spans the period from 2016 to 2023. This metric represents the median value of green vegetation cover across multiple years, providing a robust and stable measure of vegetation health and extent for the test sites. By analysing this data, we could identify locations where mangrove diebacks occurred, as illustrated in Figure 3.21. The fractional cover values are expressed as percentages, with higher values indicating areas less likely to experience dieback during this period, and lower values suggesting a greater likelihood of dieback. This analysis helps in understanding the spatial distribution of vegetation health and identifying vulnerable areas that may require conservation efforts.

Table 3.6 Mangrove 10% Photosynthetic Fractional Cover

Sites	Area (ha)				
	Very Low (%) < 20	Low (%) 20 ≤ x < 40	Moderate (%) 40 ≤ x < 60	High (%) 60 ≤ x < 80	Very High (%) ≥ 80
Bulwer Island	0.36	0.72	2.97	15.39	7.65
Coal Loader	0.09	0.27	2.88	14.85	3.24
Fisherman Island	1.98	2.52	15.30	75.69	69.75
Luggage Point	8.64	3.51	18.09	50.94	88.11
Whyte Island	3.42	3.33	10.35	54.09	45.27

Table 3.6 presented the mangrove 10% PFC, classified into five categories: very low, low, moderate, high, and very high. It showed the area in hectares (ha) for each of these classes across the test sites. As seen, Bulwer Island had a total of 27.09 hectares of green vegetation, with the majority (15.39 ha) having 60-80% cover, indicating dense vegetation in this range. Coal Loader covered 21.33 hectares, with the highest area (14.85 ha) in the 60-80% cover range, showing significant vegetation density. Fisherman Island spanned 165.24 hectares, with substantial areas in both the 60-80% (75.69 ha) and ≥80% (69.75 ha) cover ranges, indicating very dense vegetation. Luggage Point covered 169.29 hectares, with the highest areas in the ≥80% (88.11 ha) and 60-80% (50.94 ha) cover ranges, showing very dense vegetation. Whyte Island totalled 116.46 hectares, with significant areas in the 60-80% (54.09 ha) and ≥80% (45.27 ha) cover ranges, indicating dense vegetation.

Overall, the table revealed that most sites had the largest areas in the high and very high PFC categories, indicating dense green vegetation. Sites like Fisherman Island and Luggage Point had particularly extensive areas with very high PFC, suggesting very healthy and dense vegetation cover. Conversely, areas with very low and low PFC were minimal across all sites, indicating that sparse vegetation was less common. However, the presence of these low PFC areas suggests that diebacks can occur at this magnitude and locations. This distribution highlighted the overall health and density of vegetation across these sites, which was crucial for ecological monitoring and management. The data underscored the importance of these areas for conservation efforts.



Title:

Median 10% Fractional Cover from 2016 to 2023 (Landsat)

Figure: **3.21**

Rev: **A**

Coordinate System: GDA2020 / MGA zone 56

N

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Scale in kilometres

BMT

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4 Discussion

This study analysed vegetation health using Landsat (1988-2024) and Sentinel-2 (2017-2024) satellite imagery for test sites (Coal Loader, Luggage Point, Bulwer Island, Whyte Island, Fisherman Islands) and control sites (Nudgee Wetlands, St Helena Island, Green Island, Mud Island. From this, patterns in mangrove condition were defined at three-time scales: (i) Long-Term Analysis from Landsat (1989 to 2023), (ii) Medium-Term Analysis from Sentinel-2 (1989 to 2023); and (iii) Short-Term Analysis from Sentinel-2 (July 2023 to July 2024).

4.1 Spatial Patterns in 2023—2024

High resolution (1.2-meter WV-3 satellite images) was used to classify and map current mangrove forest extent at test sites. These mangrove forests were predominantly comprised of closed mature forests, as previously reported by BMT. The mapping identified large elliptical canopy gaps (>10m^2) in the mangrove forests at all sites, which were indicative of canopy loss in several neighbouring trees.

The presence of canopy gaps is a common feature in mature closed mangrove forests both in Moreton Bay (Amir and Duke 2019) and elsewhere (Lassalle and Souza Filho 2022). There are several drivers leading to the formation of canopy gaps. As described in Section 4.2, water stress, which is a function of water levels, is a key driver of mangrove forest structure. Periods of low rainfall and drops in tidal levels etc. can result in mangrove canopy loss, with recovery in subsequent years. Lighting strikes are also a key driver of canopy gap formation (Zhang et al. 2008; Amir and Duke 2019; Lassalle and Souza Filho 2022).

The short-term NDVI analysis provides a basis for identifying areas of canopy loss during the 2023-24 period. During the last 12 months mangrove condition remained relatively stable, with small areas of mangrove loss (tree fall) on the seaward margins at Luggage Point. There was no evidence of new canopy gaps forming during the period based on analysis of NDVI. Average rainfall conditions were also recorded during the period 2023-24.

Canopy gaps are a component of the mangrove forest's turnover and rejuvenation process (Lassalle and Souza Filho 2022). In healthy systems, canopy loss allows light to penetrate the understorey, enabling mangrove seedling colonisation and recruitment. However, chronic environmental stress can prevent mangrove recruitment, leading to longer-term mangrove forest loss and the formation of ponded waters or saltpan/saltmarsh communities.

While satellite imagery-based approaches are useful for identifying areas of canopy loss, other approaches are to validate conditions on the ground. For example, a degraded mangrove forest could be replaced by other types of vegetation that might still exhibit high NDVI values, reducing the capacity to detect change. The analysis of mangroves using high-resolution images, coupled with other data (see recommendations), provides a robust basis to monitor these changes. Refer to Section 4.3 for recommendations.

4.2 Long and Medium-Term Analysis

4.2.1 Spatial Patterns

The test sites had higher NDVI values and lower coefficient of variation values compared to the control sites. This indicates that mangrove canopy condition at test sites were on average higher than controls. The smaller NDVI coefficient of variation at test sites points to more consistent and less variable NDVI values over time or space, suggesting a more uniform and stable vegetation cover than control sites.

Overall, these results do not suggest that tests sites were in poor condition compared with control sites.

4.2.2 Temporal Patterns

Various factors influence the spatial and temporal patterns observed in mangrove community structure and condition. These factors can include environmental conditions such as soil salinity, water availability, and nutrient levels, as well as biological interactions like competition and predation. Additionally, human activities, climate change, and natural disturbances also play significant roles in shaping these patterns over time and across different locations. The long-term study indicated that significant declines in NDVI were primarily influenced by environmental conditions. The notable drop in the early 1990s was linked to two major environmental events: El Niño, which brought higher temperatures, reduced rainfall, and a significant drop in mean sea level (MSL). The less pronounced decline around 2007 was associated with the Millennium Drought, characterised by prolonged low rainfall. The results from the medium-term study also highlighted the influence of the SOI and rainfall on NDVI values. The decline in NDVI observed in 2019 was associated with an El Niño event, which brought lower rainfall and higher temperatures, adversely affecting vegetation health. Conversely, the increase in NDVI in 2022 was linked to a La Niña event, which resulted in higher rainfall and more favourable growing conditions for mangroves. The short-term evaluation also did not reveal any significant decline at test sites. These findings underscore the critical impact of climatic events on mangrove health and stability, highlighting the importance of monitoring environmental stressors to maintain ecosystem resilience.

The composition of the mangrove forest, including factors such as type, height, and canopy size, can significantly influence observed variability. The results of the mangrove canopy cover density analysis corroborated findings from both long-term and medium-term studies. The closed mangrove forest (with >80% canopy cover) experienced two notable declines: one in the early 1990s and another around 2007. The first decline was more detrimental to mangrove health, as the affected areas transitioned to mangrove woodland cover (20-50% canopy cover). In contrast, the second decline resulted in the affected areas being replaced by mangrove open forest (50-80% canopy cover). The mangrove forests recovered relatively quickly, with canopy cover returning to healthier levels by 2022.

Overall, these results suggest that cyclic changes in mangrove loss and recovery are operating across a range of temporal scales at both test and control sites. There is no evidence that port activities are leading to unplanned impacts to mangrove forest extent and condition.

4.3 Recommendations

The present mangrove program design and methodology provides a robust, cost-effective and objective means for detecting changes in mangrove forests and for identifying potential drivers of change. It is recommended that the following indicators are integrated into the program to better understand potential drivers of change:

- Tidal fluctuations and hydrology— The present study highlights the potential influence of long-term tidal cycles on mangrove condition. It is recommended that sea level height and tidal patterns are integrated as standard indicators in future monitoring program.

- Integration of lightning data— Incorporating a lightning archive can provide valuable insights into the formation and dynamics of canopy gaps within mangrove forests. By analysing the frequency and location of lightning strikes, potential drivers of change can be identified.

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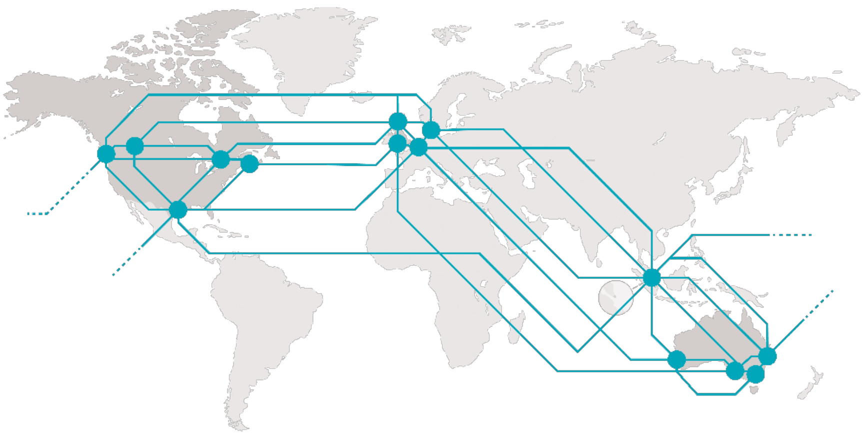

BMT is a leading design, engineering, science and management consultancy with a reputation for engineering excellence. We are driven by a belief that things can always be better, safer, faster and more efficient. BMT is an independent organisation held in trust for its employees.

Level 5
348 Edward Street
Brisbane
QLD 4000
Australia
+61 7 3831 6744

Registered in Australia
Registered no. 010 830 421
Registered office
Level 5, 348 Edward Street,
Brisbane QLD 4000 Australia

For your local BMT office visit www.bmt.org

Contact us

enquiries@bmtglobal.com

www.bmt.org

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Short Form Terms and Conditions of Service

1. Definitions

In this Agreement (unless the context otherwise requires):

Agreement means the agreement between BMT and the Client for the provision of Services to the Client, which incorporates these Terms, the Proposal, and where applicable, the Purchase Order.

Background IP means any IP of a party (or licenced to a party) which is: (a) in existence at the date of this Agreement; or (b) comes into existence after the date of this Agreement otherwise than in connection with this Agreement.

BMT means BMT Commercial Australia Pty Ltd (ABN 54 010 830 421).

Business Methods means all business processes and business methods developed by BMT and used during the provision of the Services under the Agreement.

Client means the party purchasing the Services from BMT in this Agreement as may be specified in BMT's quotation or proposal, the Purchase Order or BMT's invoices.

Client Information means all information, documents, data, materials or other content supplied, or required to be supplied, to BMT by or on behalf of the Client (regardless of its material form) for the purposes of this Agreement.

Customised Software means all third-party proprietary software, which BMT has amended, modified or otherwise altered for use in the Services.

Deliverables means the documents, materials or information which BMT is required to develop, prepare and/or provide to the Client in performance of the BMT's obligations under this Agreement, as further described in the Services.

Fee means BMT's fee to perform the Services as specified in the Proposal or the Purchase Order, or as otherwise calculated in accordance with these Terms and as varied in accordance with the Agreement.

GST means goods and services tax levied under the GST Act.

GST Act means *A New System (Goods and Services Tax) Act 1999* (Cth).

IP means all intellectual and industrial property rights, including patents, copyright, trademarks, designs, design rights, specifications, processes, methods of working, know-how, technical data, databases, formulae, inventions, improvements, logos, rights of confidential information, and other similar intellectual and industrial property rights.

Project IP means all IP created, discovered or coming into existence for the purpose of this Agreement including IP developed by BMT in performing this Agreement and any IP rights in the Deliverables.

Proposal means BMT's quotation or proposal submitted to the Client containing its offer to provide the Services.

Purchase Order means the purchase order(s) that may be issued by the Client to BMT for the performance of the Services.

Services means the services, as set out in BMT's Proposal and/or the Purchase Order, or as agreed, that BMT must perform for the Client in accordance with this Agreement (and includes the Deliverables).

Terms means these terms and conditions.

2. Commencement and Term

2.1. The Agreement is formed (and these Terms will apply) on the earlier of: (a) the date in which the Client issues a Purchase Order to BMT; (b) the date in which the Client instructs BMT to perform the Services or otherwise accepts the Proposal; or (c) the date in which BMT starts to deliver the Services, and shall continue until all the Services have been provided or the Agreement is terminated pursuant to its provisions. The parties agree that any reference to the Client's terms on the Purchase Order or any other document will not apply unless the parties have expressly agreed so in writing.

2.2. In the event of any inconsistency between the terms and documents of this Agreement, the inconsistency shall be resolved in accordance with the following descending order of precedence: (a) these Terms; (b) the Proposal; (c) the Purchase Order; and (d) all other attachments to the Purchase Order and Agreement. If the inconsistency remains incapable of resolution by reading down, the inconsistent provisions will be severed from the Agreement without otherwise diminishing the enforceability of the remaining provisions of the Agreement.

2.3. Unless agreed otherwise in writing, BMT will not be bound by any flow down conditions of any head contract between the Client and its client or otherwise.

3. Standard of Services

3.1. BMT must: (a) perform the Services in accordance with this Agreement and to the standard of professional care, skill, judgment, and diligence expected of a professional consultant experienced in providing the same or similar services as the Services; and (b) ensure the Services are appropriately performed by personnel that are experienced, skilled and trained to undertake the Services.

4. Payment

4.1. The Client must pay BMT the Fee for the Services and reimburse BMT for any out-of-pocket expenses it incurs in the performance of the Services on a cost-plus basis.

4.2. BMT's invoices are issued monthly or as otherwise set out in the Proposal. BMT shall be entitled to issue invoices based on progress, irrespective of whether BMT has issued any of the Deliverables to the Client yet or not.

4.3. Where the Fee is a lump sum, the amount payable in relation to each invoice will be calculated by applying the proportion of Services performed during the payment period to the Fee.

4.4. Where the Fee is based on an estimate, the Fee is an indicative estimate only and may be subject to change. BMT reserve the right to issue invoices for any actual quantities relevant to the provision of the Services.

4.5. Unless other payment terms are agreed in writing, the Client must pay the amounts claimed by BMT, in cleared funds and without set-off, within 14 days from receipt of BMT's invoices.

4.6. The Client is not entitled to demand or withhold any form of security, including retention monies, from BMT.

4.7. Payment of BMT's invoices is the sole and exclusive obligation of the Client and BMT will not enter into any "pay when paid" or "pay if paid" arrangements whereby payment to BMT is contingent on the Client receiving funds from its client or a third party.

4.8. If any of BMT's invoices become overdue then interest will be payable on such invoices at the rate of 12% per annum for each day the invoice is overdue and BMT shall have the right to suspend performance of the Services without liability to the Client until all overdue invoices and interest are paid in full.

5. GST

5.1. Subject to context, a reference in this clause 5 to a term that is defined or used in the GST Act has, when used in this clause, the meaning given to that term in the GST Act.

5.2. Any amount referred to in the Agreement which is relevant in determining a payment to be made by the Client to BMT is exclusive of any GST, unless expressly stated otherwise.

5.3. If the whole or any part of any amounts payable by the Client to BMT under the Agreement is the consideration of a taxable supply, the Client must also pay to BMT an additional amount equal to the GST liability. BMT will set out the GST liability payable by the Client in its tax invoices. The Client must pay any GST liabilities at the same time as all other amounts due under each tax invoice.

6. Client Information

6.1. The Client must provide the Client Information to BMT within the timeframes agreed upon by the parties, or where no time frames have been agreed, within a reasonable time and manner that allows BMT to promptly proceed with the performance of the Services without delay. BMT shall not be liable for any delay or failure to perform the Services if such delay or failure is caused by the Client's failure to provide the required Client Information within the specified timeframe or within a reasonable timeframe.

6.2. The Client is responsible for the completeness and accuracy of the Client Information. BMT may rely on the Client Information to perform the Services and is not obligated to verify it in any way except to the extent that BMT has expressly agreed to do so as part of the Services.

6.3. Where the Services require BMT to utilise or interpret the Client Information to perform its Services, such Client Information must be provided in a complete, clear and accurate state and in a manner that sufficiently enables BMT to efficiently perform the Services. BMT shall not be liable or responsible for any losses, damages, claims, costs or damages to the extent that it is caused by or attributable to Client Information that is inaccurate, incomplete or erroneous.

6.4. Where required, BMT may request from the Client clarification or interpretation of the requirements of any Client Information. These requests will be submitted as 'Requests for Information' ('**RFIs**'). The Client shall ensure RFIs are responded to promptly and satisfactorily. If the quantity of RFIs required to be raised by BMT becomes excessive due to incomplete, conflicting and/or unclear Client Information, then BMT shall be entitled to compensation for BMT's time spent in preparing and submitting such RFIs.

7. Variations

7.1. Where: (a) any services are required which are not specified as part of the Services but which are related to or supplement the Services; or (b) any change, addition, revision, omission or amendment is required or directed to the scope of the Services, these changes or additional services will be treated as a variation to the Services ('**Variation**') and undertaken by BMT at the Variation rates specified in the Proposal. If no Variation rates are specified, then the Variation will be undertaken at reasonable rates as determined by BMT or as otherwise agreed between the parties.

7.2. If a Variation consists of a reduction in the scope of Services, BMT's fees will be reduced by a reasonable amount as determined by BMT taking into consideration factors including loss of efficiency, economies of scale and costs incurred to date.

7.3. BMT is not obligated to carry out any Variation until its scope and value have been agreed in writing between BMT and the Client.

8. Time

8.1. BMT will use all reasonable efforts to perform the Services and provide the Deliverables within the time frame agreed upon by the parties, or where no time frames have been agreed, within a reasonable time.

8.2. BMT will not be liable for any failure of or delay in performance of its obligations under this Agreement to the extent such failure or delay is caused by: (a) any act, omission or default of the Client or its employees, agents or contractors; or (b) any other circumstance beyond BMT's reasonable control including but not limited to performance of Variations, delayed receipt of Client Information, delayed receipt of responses to RFIs, delayed approval of Variations, and receipt of Client Information that is incomplete, inaccurate or unclear.

8.3. To the extent that BMT's Services are delayed due to any of the factors described in clause 8.2, BMT shall be entitled to a reasonable extension of time to any date or timeframe for performance of its Services and all reasonable, direct and unavoidable costs or losses arising out of such delays.

9. Limitation of Liability

9.1. To the full extent permitted by law, BMT's total aggregate liability for any costs, losses, damages, fees, claims, actions or other form of liability, whether under or in connection with the Agreement, statute, in tort (including negligence), equity, restitution or otherwise, is limited to the value of the Fee.

9.2. BMT will in no event be liable to the Client for any consequential or indirect financial loss, damage or expense including loss of revenue, loss of profit, loss of use, loss of data, loss of financial opportunity or economic loss whether arising out of a breach by BMT of this Agreement, in tort (including negligence), at law, under any statute or in equity.

10. Intellectual Property

10.1. Each party acknowledges and agrees that each party retains ownership of that party's Background IP.

10.2. Subject to the Client's payment for the Services, all Project IP is vested in the Client as and when created and BMT hereby assigns all rights, title and interest in and to the Project IP to the Client.

10.3. To the extent that BMT needs to use any of the Client's Background IP or Project IP for the purposes of performing its obligations under this Agreement, the Client grants to BMT a non-exclusive, royalty free, non-transferable licence to use and develop (and sub-license its agents to use and develop) the Client's Background IP and the Project IP for the purpose of carrying out BMT's obligations under the Agreement. The Client warrants that it has the right to grant the licence under this clause 10.3 to BMT.

10.4. BMT grants the Client a perpetual, non-exclusive, royalty free, non-transferable licence to use (and sub-license third parties to use) BMT's Background IP to the extent that it is incorporated in or relates to the Project IP.

10.5. Each party must ensure that no IP rights or moral rights of third parties are infringed in the performance of this Agreement and each party indemnifies the other against all losses, liabilities and legal costs arising from any such infringement.

11. Confidentiality

11.1. The parties agree that any information disclosed during the course of this Agreement which is marked as confidential or which ought reasonably be considered confidential ('**Confidential Information**') shall not be disclosed to any third party without the prior written consent of the other party, except that each party may disclose Confidential Information to its employees, officers, agents, delegates, contractors, service providers and its Affiliates who have a need to know such information for the purpose of carrying out the obligations or exercising the relevant rights under this Agreement provided that such persons acknowledge and agree to maintain the confidentiality of such information.

11.2. The obligations of confidence in clause 11.1 do not apply to Confidential Information which is: (a) in or becomes part of the public domain, or is received from a third party, other than through a breach of a party's obligations under this Agreement; (b) required to be disclosed by law or a government authority; or (c) disclosed to legal advisers or auditors who are under a duty of confidence.

11.3. Each party must take all steps and do all such things as may be necessary, prudent or desirable in order to safeguard the confidentiality of the Confidential Information of the other party.

11.4. Without limiting the generality of the above clauses, the Client acknowledges that the Customised Software, Business Methods and documentation and information associated with the Customised Software and Business Methods ('**BMT's Confidential Property Information**') is strictly confidential property of BMT and that its disclosure would cause considerable commercial and financial detriment to BMT such that an award of damages or an account of profits may not adequately compensate BMT if this clause is breached.

11.5. Each party acknowledges that, without in any way compromising its right to seek damages or any other form of relief in the event of a breach of this clause 11, a party may seek and obtain an interlocutory or final injunction to prohibit or restrain the other party or its advisers from any breach or threatened breach of this clause.

12. Termination

12.1. Either party may immediately terminate this Agreement by written notice to the other party if that other party: (a) breaches a material term of this Agreement, where that breach is not capable of remedy; (b) breaches a material term of this Agreement which is capable of remedy and has not been remedied within 30 days' written notice to do so by the first party; or (c) commits an act of insolvency or bankruptcy, comes under any form of insolvency administration, ceases or resolves to cease to carry on business, or is unable to pay its debts when due.

12.2. The Client may terminate this Agreement for its convenience after giving 14 days' written notice to BMT. If this Agreement is terminated under this clause 12.2, the Client must pay BMT for the Services (including any Variations) performed up to and including the date of termination plus all reasonable direct and unavoidable costs arising from termination of the Services.

12.3. Termination under this clause 12 shall not affect any claim for loss or damage available to the terminating party or for costs or fees accrued up to the date of termination.

13. Dispute Resolution

13.1. If any dispute, difference or controversy between the parties arises out of or in connection with this Agreement ('**Dispute**'), then any party may give the other party a written notice of dispute adequately identifying and providing details of the Dispute.

13.2. On receipt of a notification under clause 13.1 the parties must arrange for their respective representatives to meet within 14 days to attempt to resolve the Dispute in good faith. The respective representatives must have the authority to bind each party.

13.3. If the Dispute is not resolved within 30 days of receipt of the notification under clause 13.1, either party may initiate legal proceedings in relation to the Dispute.

13.4. Nothing in this clause shall prejudice the right of a party to seek injunctive or urgent declaratory relief.

14. Force Majeure

14.1. Neither party will be liable to the other party for any delay or failure to fulfil obligations to the extent that such delay or failure arises from any significant and unforeseen events or circumstances that are beyond the first-mentioned party's control including fire, floods, terrorism, strikes, lock out, war, riot, epidemic, pandemic, or any governmental act or regulation, except that such event or circumstance does not relieve a party from liability for an obligation which arose before the occurrence of that event, nor does that event affect the Client's obligation to pay any money under this Agreement in a timely manner.

15. General

15.1. This Agreement is governed by the laws of Queensland, Australia and the parties submit to the exclusive jurisdiction of the courts of Queensland. A dispute or legal proceeding in relation to the Agreement must be held in Brisbane, Queensland.

15.2. No failure to exercise, or any delay in exercising, any right, power or remedy by BMT operates as a waiver.

15.3. The Client may not assign any of the Client's rights or obligations under this Agreement without the written permission of BMT.

15.4. BMT is an independent contractor and not an employee or agent of the Client. Neither BMT, nor any employee, contractor, representative or agent of BMT will by virtue of this Agreement be deemed to be an employee of the Client.

15.5. No variation or amendment of this Agreement will be effective unless it is made in writing and signed by an authorised representative of each party.

15.6. The Client is responsible for complying with all applicable law including any applicable statute, regulation, by-law, ordinance or subordinate legislation in force from time to time in the relevant jurisdiction(s) where BMT provides the Services.

15.7. BMT may subcontract its performance of any part of the Services and the Client hereby consents to such subcontracting.

15.8. This Agreement is the entire agreement and understanding between the parties on everything connected with the subject matter of the Agreement and supersedes any prior agreement, representation, promise or understanding of the same.

15.9. The clauses that by their nature should remain in force on expiry or termination of this Agreement do so, including clauses 1, 4, 5, 9 ,10, 11, 12.2, 12.3, 13 and clause 15.

15.10. Should any clause or part of any clause of this Agreement be held as void, unlawful or otherwise unenforceable for any reason, then this Agreement shall be read and enforced as if such clause or part of such clause has been deleted and the remaining clauses shall continue in full force and effect.