Port of Brisbane Mangrove Monitoring Program - 2021

Customer	Port of Brisbane Pty Ltd
Project	B23621
Deliverable	012
Version	01
	29 July 2022

Document Control

Document Identification

Title	Port of Brisbane Mangrove Monitoring Program - 2021
Project No	B23621
Deliverable No	012
Version No	01
Version Date	29 July 2022
Customer	Port of Brisbane Pty Ltd
Customer Contact	Penelope Webster, Craig Wilson
Classification	BMT (OFFICIAL)
Synopsis	An assessment of mangrove condition at the Port of Brisbane and adjacent environments.

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Project Manager	Darren Richardson

Amendment Record

The Amendment Record below records the history and issue status of this document.

Version	Version Date	Distribution	Record
00	30 May 2022	Port of Brisbane Pty Ltd	Draft report
01	29 July 2022	Port of Brisbane Pty Ltd	Updated report

Executive Summary

Background

Extensive mangrove forests and saltmarsh communities occur at and near the Port of Brisbane at Fisherman and Whyte Islands, and on the northern side of the Brisbane River mouth. These vegetation communities are important ecological assets and are among the largest in western Moreton Bay.

Port of Brisbane Pty Ltd (PBPL) has implemented a mangrove monitoring program (MMP) to measure trends in the condition and extent of mangroves potentially affected by Port activities. This report outlines the findings of the 2021 MMP assessment.

MMP Aims

- Map wetland types for the 2021 period based on vegetation community composition
- Quantify long-term changes in the spatial extent of mangrove and saltmarsh/saltpan between 1950s and 2021 based on analysis of aerial photography and satellite data
- Map and quantify temporal patterns in mangrove green biomass (NDVI) using satellite data at the following temporal scales:
  - seasonal patterns for 2021 monitoring period
  - contemporary changes for the period 2020-21, based on remotely sensed data and validate using high resolution aerial imagery.
  - long-term patterns between 1988 and 2021
- Identify potential drivers of mangrove degradation in key investigation areas (Fisherman Islands, Whyte Island and Bulwer Island).

Study Approach

The MMP was comprised of three elements:

- Quantification of patterns in mangrove canopy condition using satellite data. Three mangrove condition indices were mapped using remotely sensed data: NDVI, SAVI and LAI. NDVI and SAVI are spectral indices that estimate the amount of green biomass using red and near infrared spectra while LAI calculates the amount of canopy per unit area. These metrics were calculated from Landsat and Sentinel-2 satellites for the periods of 1988-2021 and 2015-2021, respectively using analysis-ready data (ARD). Relationships between NDVI and rainfall, Southern Oscillation Index, and temperature were examined for the Landsat data, while NDVI, SAVI, and LAI were assessed using Sentinel-2. Aerial imagery was used to investigate and validate areas where changes in mangrove condition were observed over the twelve-month period.
- Fine-scale mapping of community types. Building on existing historical mangrove mapping data-sets, remote sensing was used to map wetland community types in 2021. Changes in wetland community extent for the period 2018-21 and 1997-21 were mapped. The historical mapping (pre-

2021) was based on aerial photograph interpretation and was of lower spatial resolution than the fine-scale 2021 mapping data.

Findings

Changes in Wetland Extent

- In the period 2018-21, there were minor (<1 ha) changes in tidal wetland community extent at Fisherman Islands and Bulwer Island. Mangrove extent increased and saltmarsh/saltpan extent decreased during this period at Whyte Island, mostly due to colonisation of mangroves in saltpan areas.
- Over longer timeframes (1997-21), the following was observed:
  - a long-term net decrease in mangrove extent at Fisherman Islands. This was mostly due to die-back at the saltpan-mangrove interface (ecotone) and mangrove erosion on the seaward margin in places.
  - mangrove forests expansion occurred in places, especially on the northern seaward fringe of Fisherman Islands and in the saltmarsh/saltpan environments of Fisherman Islands and Whyte Island. The mangrove encroachment into saltpan varied spatially, and there has also been mangrove retraction (i.e. replacement by saltpan) in places.
- These results demonstrate that tidal wetland communities are highly dynamic, varying inconsistently over time and space.
- Several processes likely interact long-term patterns in intertidal wetland dynamics, long-term rainfall-drought cycles, sea level rise and geomorphological processes. These processes likely varying from place to place (e.g. due to local topographical variations, local hydraulics) and over time.

Long-Term Trends in Condition

- NDVI measured from 1988 to present exhibited a strong seasonal pattern as well as significant inter-annual variability (Figure 1).
- These patterns were consistent among sites suggesting that climatic processes, especially rainfall, are key drivers of mangrove condition.
- Observable patterns include the reduction in NDVI through the early 1990's and mid to late 2000's, and a general improvement at most sites more recently.
- In more recent times there has been a consistent reduction in variation between sites, where peaks in NDVI in highest performing sites become more modest, and troughs in worst-performing sites become less severe.
- There has also been a gradual improvement in mangrove condition at most sites, except for Whyte Island, Nudgee Wetlands, and Mud Island, which historically had higher NDVI peaks pre 2000 than post 2000. Long-term improvement may be the result of mangrove colonisation within the mangrove area polygons.

Seasonal Patterns

- All of the sites exhibited the strongest NDVI signal in July apart from St Helena Island, where the June signal was slightly higher.
- The summer minima occurred in December and/or February, often as a double-trough.

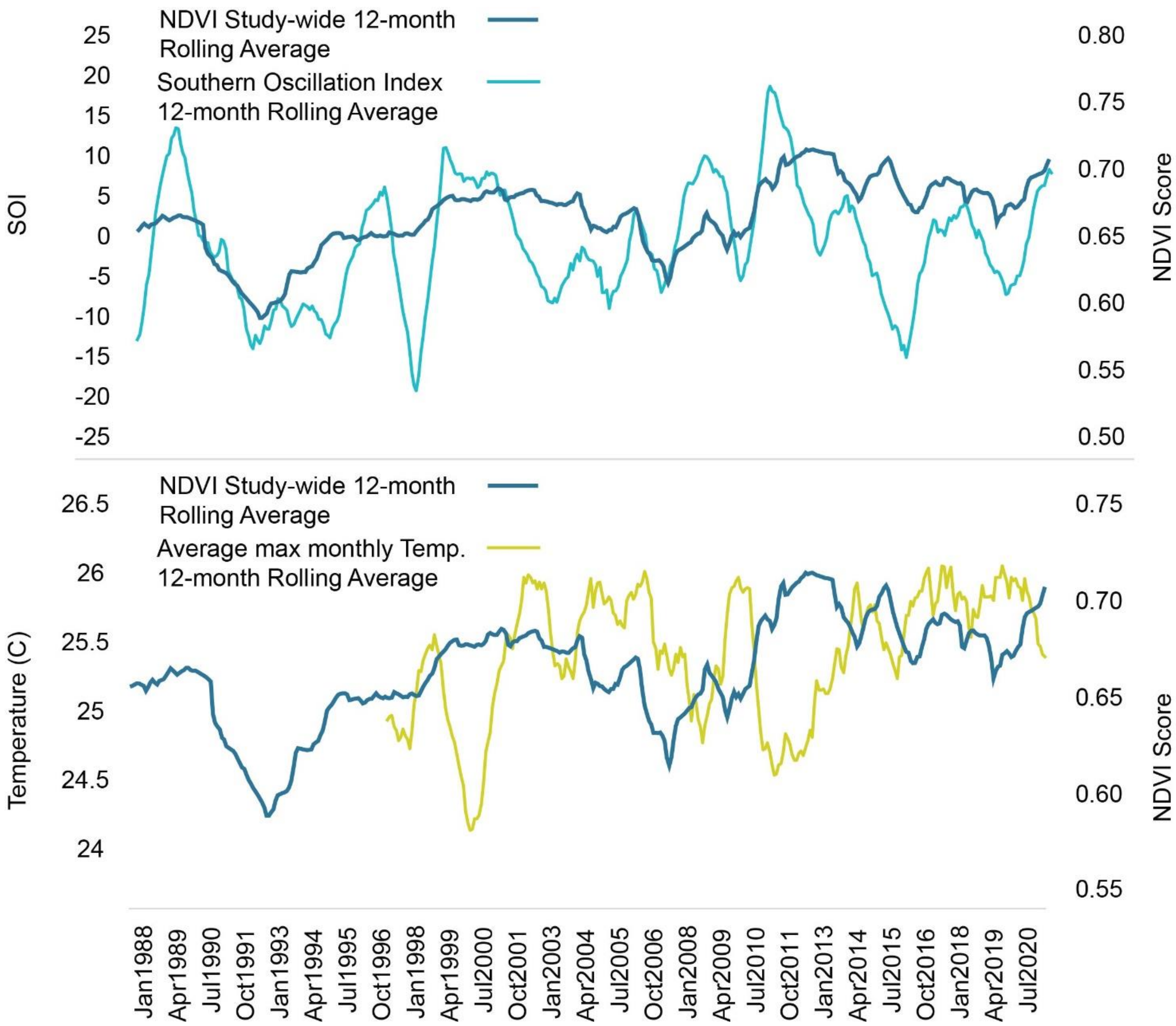

Figure 1. Study-wide, de-seasonalised NDVI and SOI (above) and with average maximum monthly temperature (below) between 1988 and 2021

Spatial Patterns

- A comparison of images taken during July between 1988-2021 identified there recent changes in NDVI (mangrove canopy condition), most notably:
  - reductions in NDVI score in mangroves along Boat Passage and towards the south-east tip of the forest and in the *Ceriops* forest at Fisherman Islands
  - improvements in health surrounding the central saltmarsh and along the northern extent of Fisherman Islands.
  - At Whyte Island, improvements in NDVI tended to centre around the mangroves adjacent to saltmarshes, with a decline in health observed peripherally.
- These changes were consistent with observed patterns in wetland extent.
- Differences in NDVI between July 2021 and July 2020 (Figure 2) show that most of the test sites apart from the Coal Loader have generally improved, with some small areas of reduced scores at

the north of Fisherman Islands, surrounding the *Ceriops* forest, and in two small patches in central and southern Whyte Island.

- Recent (2020-2021) NDVI score reductions are consistent with canopy thinning or a reduction in greenness rather that due to tree falls, except at central Whyte Island.

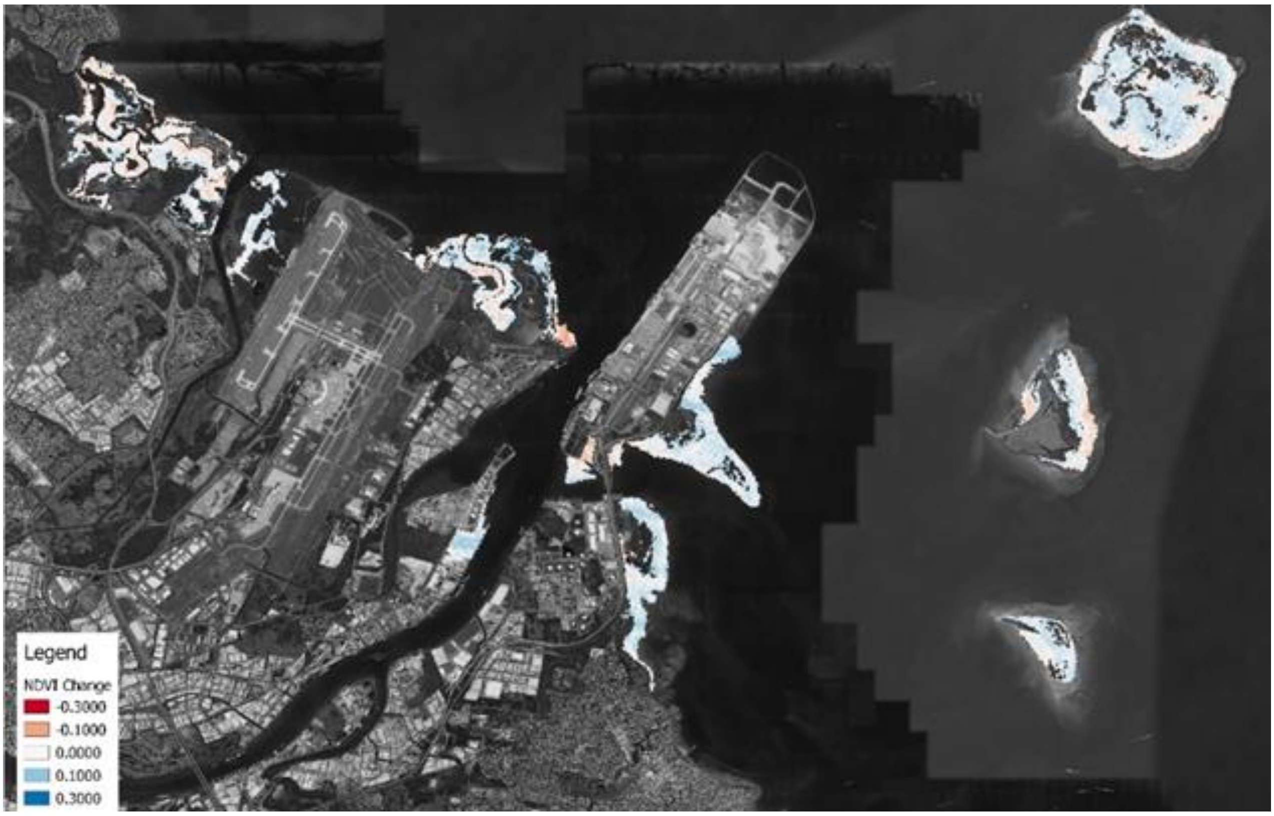

Figure 2. Differences between July 2021 and July 2020 geomeans (Landsat)

Monitoring Implications

- Landsat ARD provided a valuable tool for investigating long-term trends in vegetation condition and creating long-term geomeans. Sentinel-2 ARD was affected by excessive cloud-masking and will require additional work to extract valid masked data adjacent to infrastructure
- July is the most important period to monitor spatial changes due to the spatial and temporal consistency in the annual maxima, and due to the abundance of cloud-free scenes
- The July 2020 to July 2021 period was characterised by a slight improvement in vegetation indices after a broadscale decrease in vegetation health was observed July 2019 and July 2020. While the overall pattern was of improvement, some reductions in scores were observed.
- NDVI typically improved slightly in most community types apart from *Avicennia* at the Coal Loader and the western extremity of Fisherman Islands, adjacent to the Coal Loader.
- Future monitoring will include a recent (12 monthly) time-series analysis of all sites using Landsat ARD, geomean comparisons against the July long-term average, and against the previous July. High-resolution (Sentinel-2) July captures should continue to be assessed to monitor fine scale changes such as tree falls, dieback and dieback improvements.

Contents

Tables

Figures

1 Introduction

1.1 Background

Extensive areas of mangrove forests and saltmarsh communities are located at the mouth of the Brisbane River. 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).

The Port of Brisbane Pty Ltd (PBPL) operates adjacent to these mangrove forests and saltmarsh communities therefore the variation of their health through time and space needs to be monitored and analysed to ensure port activities are not impacting these communities. Monitoring of the mangroves and saltmarsh surrounding the Port of Brisbane has been conducted since the 1990s (WBM 1992; CSIRO 1992; BMT WBM 2016, BMT 2017, BMT 2018, BMT 2019, BMT 2020) but variable assessment techniques and observer bias made long-term health assessments difficult. The Port of Brisbane Mangrove Monitoring Program was revised in 2016 to provide a more robust objective means for mapping and characterising patterns in mangrove condition (BMT WBM 2016).

Previous monitoring programs have found strong associations with weather and climate variations and changes in mangrove health. Cumulative rainfall has been found to relate to normalized difference vegetation index (NDVI) while longer term health has been associated with the El Niño–Southern Oscillation (ENSO) cycle (BMT WBM 2016). The medium-term trends show a decrease in mangrove health that coincided with strong La Niña conditions (1987-1989) and during the Millennium Drought (2006-2008).

1.2 Aims and Objectives

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

- Map tidal wetland types (mangroves, saltmarsh/saltpan) for the 2021 period based on vegetation community composition and elevation
- Quantify long-term changes in the spatial extent of mangrove and saltmarsh/saltpan between 1950s and 2021 based on analysis of aerial photography and satellite data
- Map and quantify temporal patterns in mangrove green biomass (NDVI) using satellite data at the following temporal scales:
    - seasonal patterns for 2021 monitoring period
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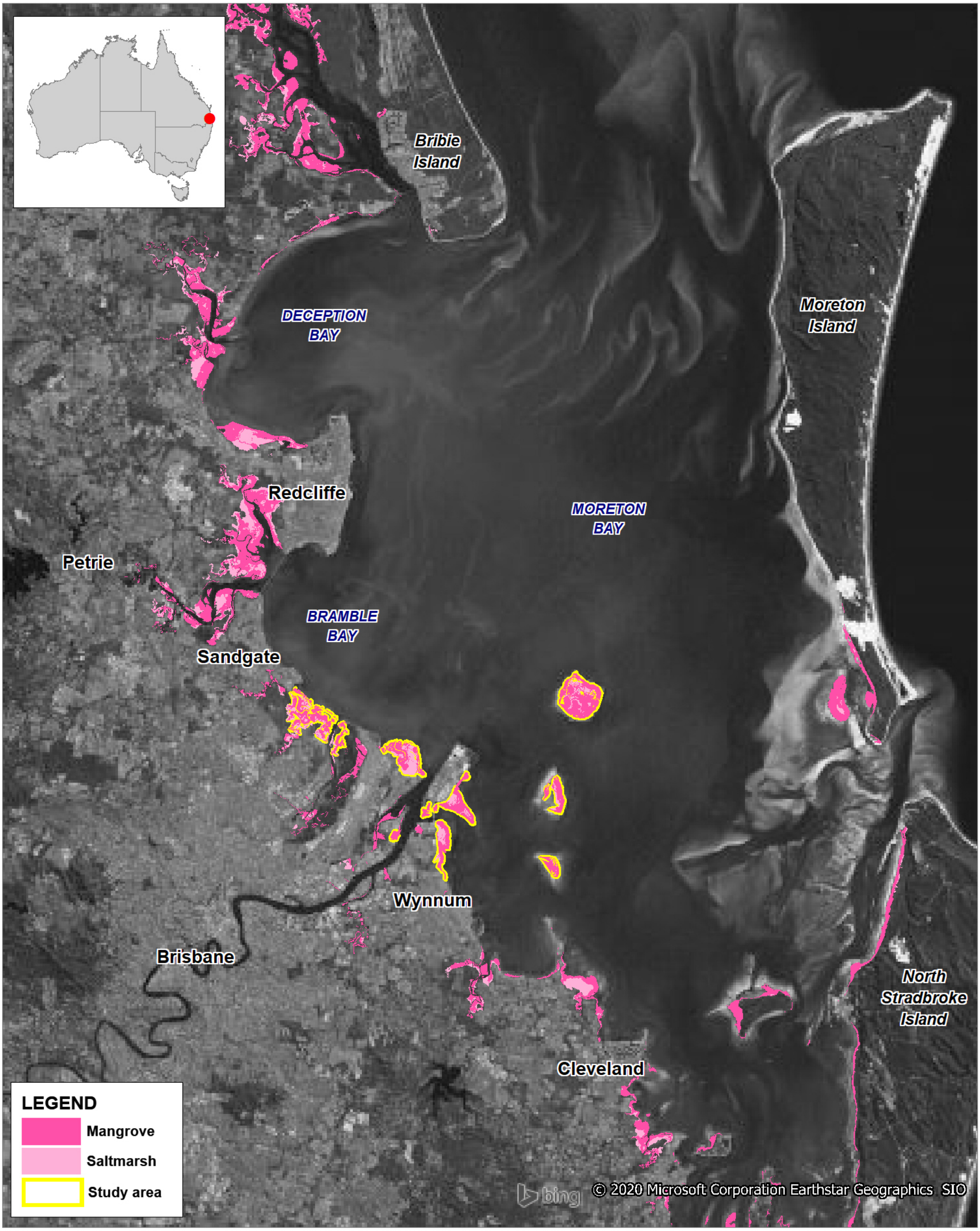
- Identify potential drivers of mangrove degradation in key investigation areas (Fisherman Islands, Whyte Island and Bulwer Island).



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

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2 Methodology

2.1 Remote Sensing

2.1.1 DEA Data Cube

Analysis was performed on the Open Data Cube, where Sentinel, Landsat and other freely available remote sensing data are available for the Australian continent, catalogued by Digital Earth Australia (DEA). The DEA open data cube was accessed and analysed using code modified from Krause et al (2021). The data cube contains analysis-ready datasets (ARD) for Sentinel 2A, 2B and Landsat 5, 7 and 8 sensors. ARD datasets have been geometrically corrected and stacked consistently so that sequential observations can be used to track changes over time. Surface reflectance are corrected for sensor gains, biases and offsets, and include adjustments for terrain illumination, atmosphere and sensor viewing angle per pixel.

Nadir-corrected, Bidirectional reflectance distribution function, Adjusted Reflectance with Terrain illumination (NBART) imagery was used from Landsat and Sentinel-2 sensors.

2.1.2 Data Sources

Sentinel-2 imagery (10 m resolution) and Landsat 5, 7, and 8 (30 m resolution) were gathered for individual study sites and the combined mangrove region. Sentinel-2 masking near port infrastructure reduced the number of available scenes at the Coal Loader (13 scenes) and Bulwer Island (32 scenes) otherwise a large number of scenes were available for analysis (Table 2.1). For Landsat 5,7, 9, a minimum of 98% good data was used as a filter. For Sentinel-2, data quality filters were relaxed to between 50% and 90% to increase temporal coverage due to a large number of masked pixels.

Table 2.1 Scene availability for different sensors and time periods

Site	Sentinel 2 (July 2017-July 2021))	Sentinel-2 (July 2020-July 2021)	Landsat 5,7, 8 (Aug 1988 – July 2021)
Pelican Banks / Coal Loader	13	-	361
Nudgee Wetlands	283	-	294
Luggage Point	326	-	362
Bulwer Island	32	-	359
Whyte Island	268	-	437
St Helena Island	318	-	560
Green Island	289	-	576
Mud Island	341	-	512
Fisherman Islands	237	-	395
Entire Area		47	469

2.1.3 Investigation Areas

Two treatments were adopted:

- Test treatment – which are mangrove areas direct adjacent to Port operations (i.e. Fisherman Islands, Coal Loader and Whyte Island/Wynnum foreshore) or occur in the vicinity of operational works undertaken by PBPL (i.e. habitat restoration works at Bulwer Island, cruise ship construction works at Luggage Point).
- Control treatment – these are mangrove areas outside the direct influence of PBPL activities and provide contextual information on background variability. These sites encompass minimally disturbed environments (e.g. St Helena Island) and areas subject to historical (e.g. coral dredging at Mud Island) and/or ongoing human disturbance.

The area (hectares) and pixel counts for mangrove forests in each investigation areas are presented in Table 2.2, and the extent of these areas are shown in Figure 2.1. Sentinel-2 images provided between 2,293 and 44,460 pixels per investigation area (depending on size of the investigation areas), which provided sufficient resolution to assess broad temporal trends in the vegetation health indices.

Due to its large size, Fisherman Islands was further stratified into four segments (Figure 2.2).

Table 2.2 Investigation Areas

Treatment type	Investigation area	Area (ha)	Pixel Count (Sentinel-2)	Pixels Count (Landsat)	Scene Count (Sentinel2)	Scene Count (Landsat)
Test	Fisherman Islands (North, Central and South Point)	131	18,161	2,018	237	395
	Fisherman Islands (Pelican Banks / Coal Loader)	19	2,293	255	13	359
	Whyte Island/Wynnum	89	14,389	1,599	268	437
	Luggage Point	123	26,579	2,953	386	294
	Bulwer Island	24	29,250	3,250	32	362
Control	Nudgee Wetlands	243	36,667	4,074	283	512
	Green Island	49	6,803	756	289	560
	St Helena Island	78	12,596	1,400	318	576
	Mud Island	301	44,460	4,940	341	361
Total		1648.7	164,873	21,244		

LEGEND

- Test
- Control

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Mangrove health assessment test and control sites

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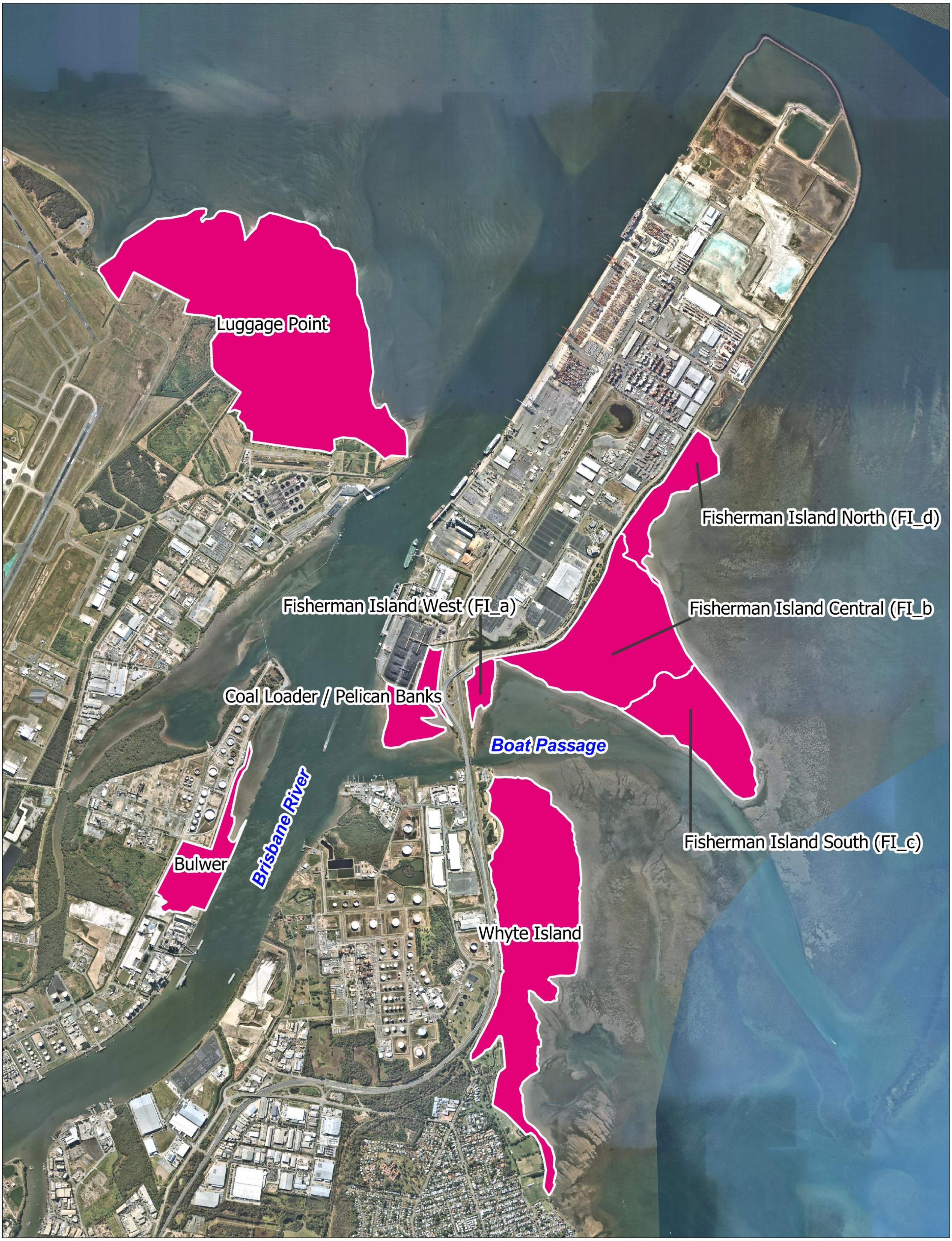

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Reporting boundaries for mangrove community vegetation indices

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2.1.4 Spatial Data Processing

Vegetation Indices

Atmospherically-corrected bottom-of-atmosphere (BoA) analysis-ready products for Sentinel-2 and Landsat 5, 7, and 8 products were used to derive the following three vegetation indices, using the calculate indices function within the DEA data cube:

1. The normalized difference vegetation index (NDVI), which is the difference between near-infrared (which chlorophyll in vegetation strongly reflects) and red light (which chlorophyll absorbs), and essentially represents greens (i.e. chlorophyll found in leaves). NDVI for each of the pixels was calculated using the following formula:

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

   Where *NIR* is the near-infrared BOA reflectance and Red is the BoA reflectance of the red band.

2. Like NDVI, the soil adjusted vegetation index (SAVI) is based on the difference between red and near infrared wavelengths, and therefore provides a measure of chlorophyll content in leaves. SAVI also compensates for the confounding effects of soil moisture and soil colour (i.e. changes in ‘soil brightness’). SAVI was calculated for each pixel using the following formula:

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

   Where *NIR* is the near-infrared BOA reflectance, Red is the BoA reflectance of the red band and L is the vegetation correction factor.

3. Leaf area index (LAI) is a biophysical index that as the name suggests measures the area of leaves in the visible canopy. LAI was calculated for each pixel using the following formula from Boegh et al. (2002) utilising the Enhanced Vegetation index of Huete et al. (2002):

   $$LAI = (3.618 * 2.5 * (Green * ((NIR - Red) / (NIR + SWIR * Red - 7.5 * Blue + 1))) - 0.118$$

Only NDVI was applied to the Landsat dataset due to its relative consistency across sensors, and similarity to other indices.

Vegetation Community Mapping

Vegetation communities were mapped using a combination of recent aerial imagery and known species locations. Previous field surveys of mangrove condition have shown distinct community areas across Fisherman Islands. This data was used as training data within QGIS Orpheo Toolbox to classify Nearmap Imagery of Fisherman Island and Whyte Island. Nearmap imagery from the 10th of June 2021 was used for classification. This image was classified into the following classes:

- *Avicennia marina* dominated community;
- *Ceriops australis* dominated community;
- *Rhizophora stylosa* dominated community; and
- Saltmarsh/saltpan.

2.1.5 Rainfall data

Rainfall data was accessed from the Bureau of Meteorology from January 1988 to July 2021. The weather station closest to the study area was Brisbane Airport (040842), but this provided an incomplete record of rainfall. Missing data were filled using nearby Fort Lytton (040320). Twelve monthly cumulative rainfall data were compared with vegetation condition indices.

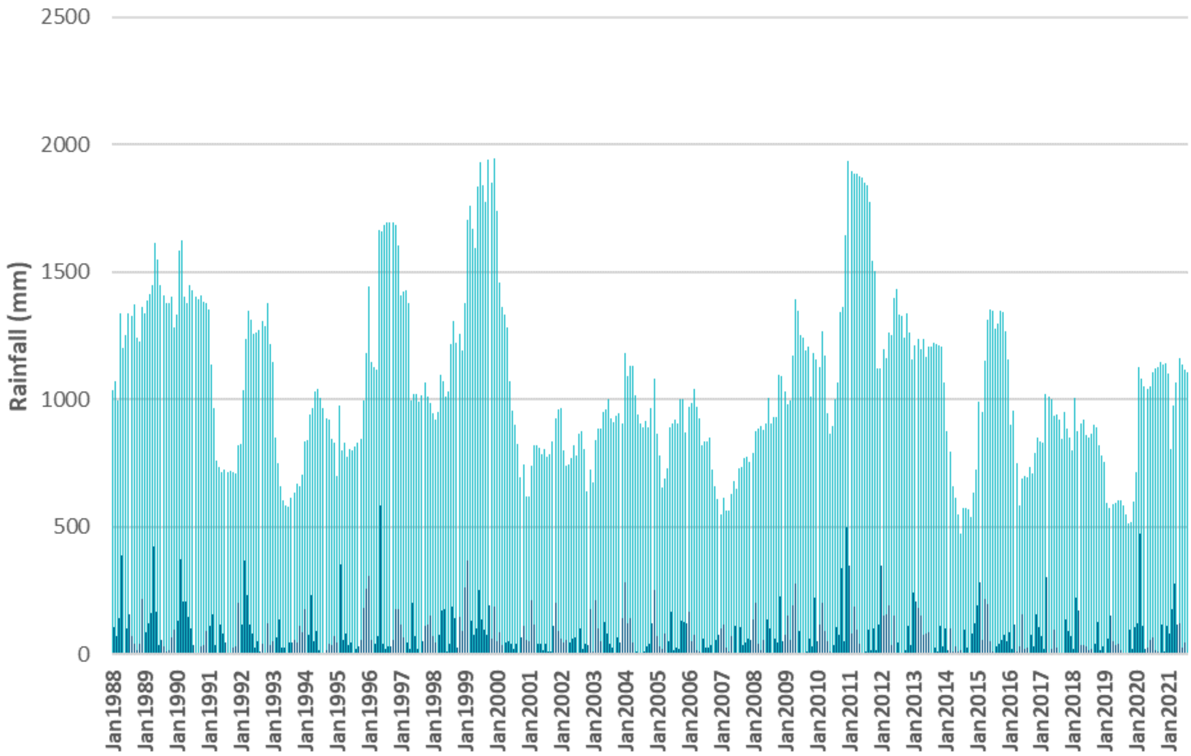


Figure 2.3 Monthly total rainfall (dark blue) and 12-monthly rainfall (light blue) for the study area in millimetres (based on Brisbane Airport station 040842 and Fort Lytton station 040320)

2.1.6 Assumptions and Limitations

Analysis-ready Sentinel-2 and Landsat imagery can have up to 12.5 m geolocational error, meaning that up to two 10 m pixels from each capture may be misaligned. Therefore, rectification errors can occur within two pixels and contribute to errors along edge of mangrove forests. It is also noted that where the canopy is sparse (saltpans and dieback regions), variable soil moisture can dominate the signal. Therefore, some interpretation is required in such areas.

Various minimum-good data thresholds (based on cloud filtering) between 70 and 98% were applied to each analysis based on the availability of data. For long-term Landsat analyses, scene counts were always relatively high and minimum good data thresholds were maintained at 98%. Some of the Landsat ARD scenes included heavy clouds that had not been effectively filtered. These were removed by filtering out mean NDVI scene values less than 0.40.

For Sentinel-2, ARD pixel masking tended to be adversely affected by nearby infrastructure, particularly near the Coal Loader and at Bulwer Island. At these locations, where scene counts were low, the thresholds of minimum good data were lowered to 70%. Despite this, scene counts for Sentinel-2 data were relatively low at these two sites.

NDVI represents and extremely robust vegetation index for long-term comparisons in vegetation community due its relative simplicity and similarities in central wavelengths for the red and NIR bands among sensors. Inter-sensor comparisons (AVHRR, SPOT, MODIS SeaWiFS, Landsat) typically differ by less than 0.05 NDVI units over most of the non-polar regions of the world (Brown et al 2000).

Comparisons of NDVI among various Landsat sensors since 1988 are potentially prone to small changes in sensors, orbit and sensor drift. Orbit changes in Landsat 5 over the 27 year record resulted in 0.0006 NDVI / year, equivalent to about a 0.016 NDVI change over the entire Landsat 5 TM data record (Zhang and Roy 2016). These issues for long-term assessments have been resolved by the introduction of analysis-ready data where atmospheric correction, spatial alignment and radiometric calibration allow estimation of the remotely sensed surfaces without sensor, atmospheric, or geolocation artefacts (Dwyer et al 2018).

2.2 Unmanned Aerial Vehicle Data Collection

2.2.1 Data Capture

A small UAV was used to collect data over several days in 2021 and April 2022. 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.

Images were collected with a 75% forward and lateral overlaps. The UAV was flown by a Civil Aviation Safety Authority (CASA) certified operator. The flights were within the 5 km Brisbane Airport exclusion zone, therefore, flight plans were pre-approved by CASA and limited to 50-80 m was observed depending on the area.

2.2.2 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.

2.2.3 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.

There are limitations with the UAV data resulting from the low altitude of the flights (80 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 80 m and compressed flight windows were not sufficient for a higher than normal level of image overlap.

3 Findings

3.1 Patterns in Wetland Community Extent

3.1.1 Wetland Community Types and Elevation

Figure 3.1 maps vegetation community types and extent in 2021. *Avicennia*-dominated forest was the most extensive community type at the Fisherman Islands, Coal Loader, Whyte Island and Bulwer investigation areas. Mangals at both Fisherman Islands, Whyte Island and Bulwer 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 at Fisherman Islands. Large areas of saltmarsh/saltpan occurred at Whyte Island, Fisherman Islands – Central (Area FI_b) and Fisherman Islands - South Point (Area FI_c). These patterns in community structure were consistent with those previously reported by BMT WBM (2016).

0 is a surface elevation map showing heights of the vegetation canopy and bare ground. 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 in the inland portions of South Point also contain ponded water, which is still retained at low tide, depending on the amplitude of successive tides. Davie (1984) reported that canopy height in mangals progressively declines from approximately mean high water tide level in Moreton Bay, consistent with the patterns observed in the present study.

The elevation trends noted in 2016, remain true for the 2021 elevation data in that:

- The tallest canopy areas are in fringing *Avicennia marina* communities; and
- The dense stand of *Ceriops australis* is shorter than surrounding *Avicennia marina*.

Although elevation trends were consistent between 2016 and 2021, a direct comparison of elevations was not possible due to the low flight restrictions resulting in anomalies in the data. A side by side comparison of the data is shown in Annex C.

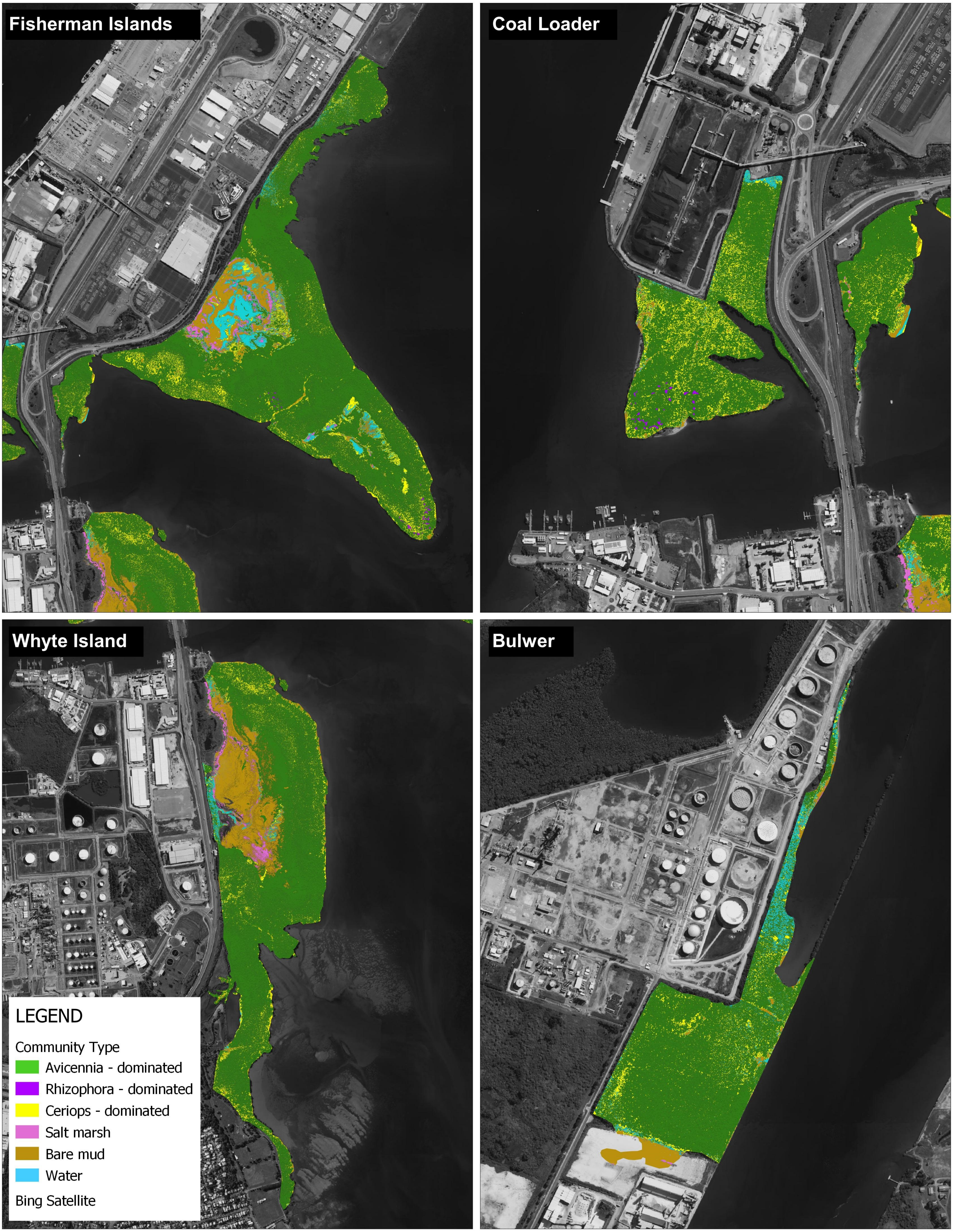
3.1.2 Temporal Patterns in Wetland Community Extent

BMT (2018) mapped mangroves and saltmarsh/saltpan extent between 1955 and 2018, and the 2021 wetland community map (Figure 3.1) extends this time-series. Figure 3 3 presents mangrove and saltmarsh/saltpan total extent at Fisherman Islands, Whyte Island and Bulwer in each year. A difference plot showing changes in mangrove and saltmarsh/saltpan are shown for 2018-2021 (Figure 3.4) and 1997-2021 (Figure 3.5).

Contemporary Changes (2018-2021)

The following changes to mangrove and saltmarsh/saltpan extent were recorded between 2018 and 2021:

- Fisherman Islands – There were minor (<1 ha) changes in mangroves and saltmarsh/saltpan extent during the period, mostly associated with mangrove colonisation in ponded areas in the centre of South Point and Fisherman Islands – Central saltmarsh/saltpan, but mangrove retraction on the seaward margin of Fisherman Islands - North and around Coal Loader/Pelican Banks. Overall, there was a net increase in mangroves of 0.4 ha, and net decrease in saltmarsh of 0.7 ha (replaced by mangroves and ponded water).



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Mangrove Community Mapping 2021

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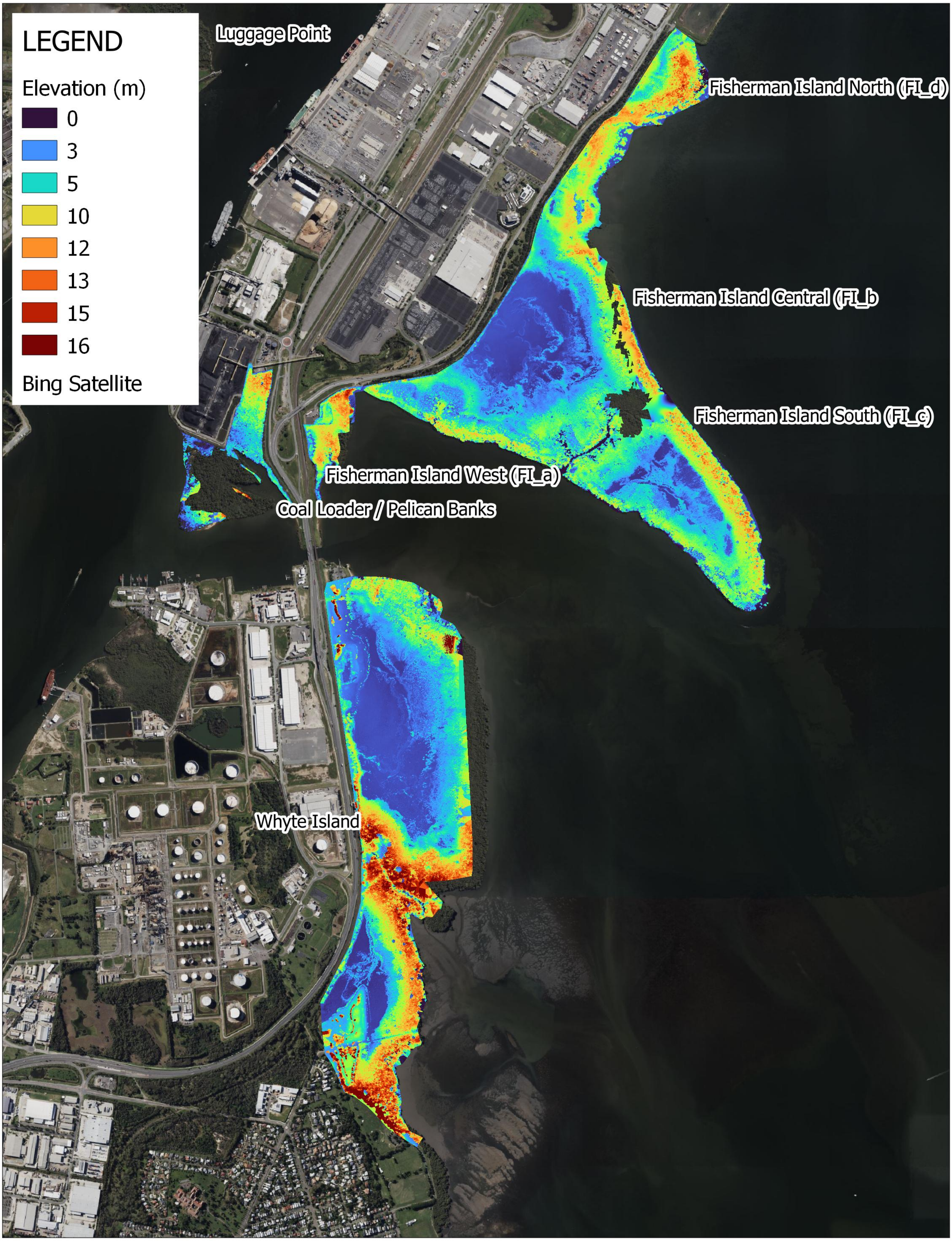

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High resolution mapping of canopy elevation based on UAV survey – 2021

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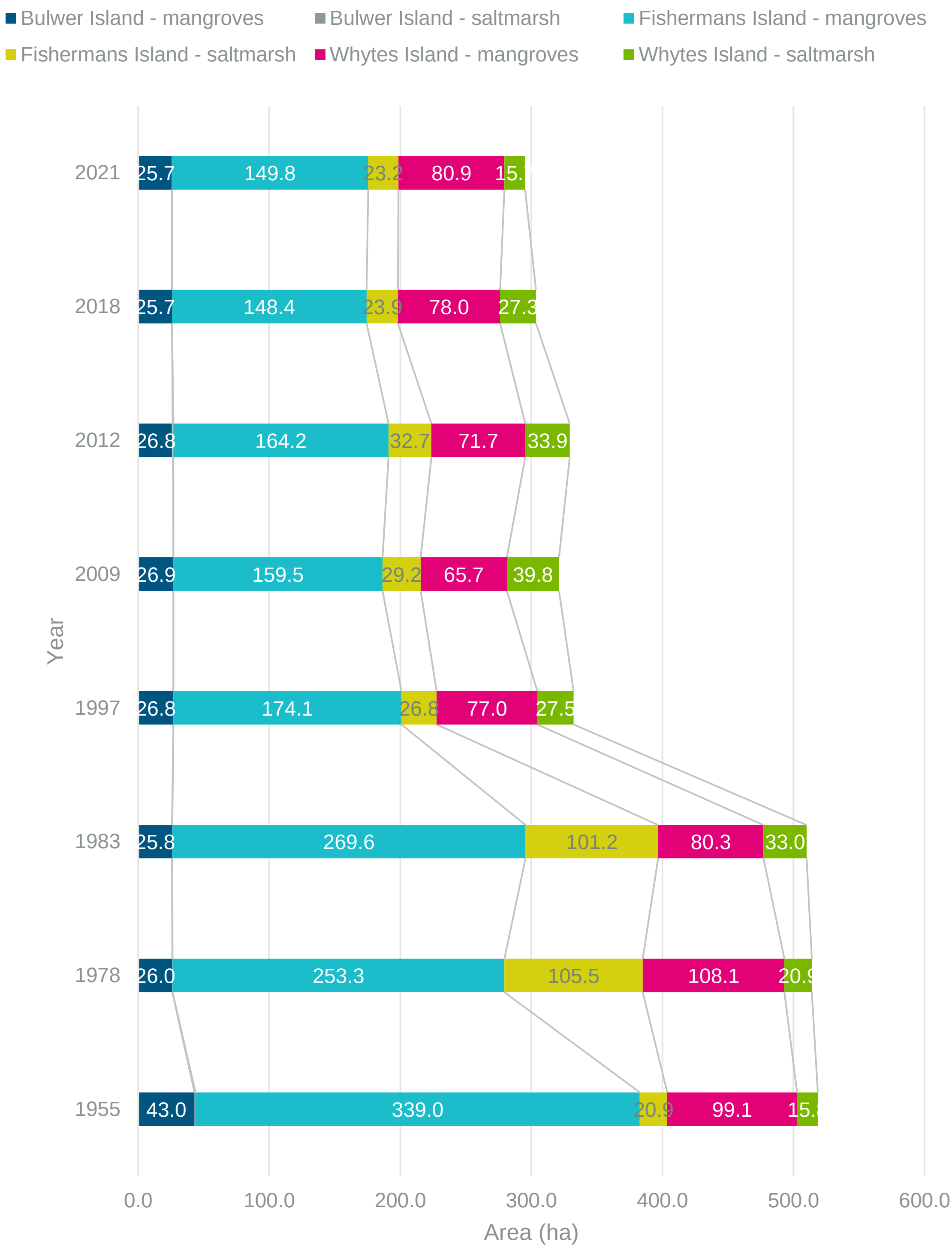

Figure 3.3 Area of mangrove and saltmarsh at Fisherman Islands, Bulwer Island and Whyte Island through time

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Change in mangrove extent between 2018 and 2021

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Change in mangrove extent between 1997 and 2021

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- Whyte Island - parts of the saltmarsh/saltpan habitat were colonised by mangroves during this period, but there was also mangrove retraction (replacement by saltpan) in other areas. Part of the area colonised by mangroves between 2018-21 supported mangroves in 1955 and 1978, but not in subsequent years (BMT 2018). Overall, there was a net increase in mangroves of 2.9 ha between 2018-21. There was a net decrease in the mapped extent of saltmarsh/saltpan of 12 ha, most of which was due an expansion of mangroves in 2021.
- Bulwer – <0.5 ha change between 2018-21.

Long-term Changes (1997-21)

Port expansion and foreshore development works between the 1950s and early 1990s resulted in large-scale losses in mangrove and saltpan/saltmarsh (see Figure 3.3 and BMT 2018). In the subsequent period (post 1990s), the following long-term trends were observed (Figure 3.4):

- Fisherman Islands mangroves – there was a net decrease in mangroves of 24 ha (average loss of 1 ha/year), most of which occurred between 1997 and 2009. The largest changes were recorded at:
  - losses within the Coal Loader area
  - losses in the central portion of South Point and Fisherman Islands – Central (conversion to saltpan and ponded waters)
  - minor losses on the seaward fringe along Boat Passage (Central, Pelican Banks/Coal Loader and South Point sites)
  - gains in mangrove area were recorded along the Fisherman Islands – North and Fisherman Island - Central saltmarsh/saltpan.

  The 1997-2009 period coincided with the Millennium Drought, which saw major declines in mangrove condition due to water stress (see Section 3.2.1).
- Fisherman Island saltmarsh/saltpan – there was a net decrease in saltmarsh/saltpan of 3.6 ha. Losses occurred in Fisherman Island – Central saltmarsh/saltpan (replacement by mangroves and ponded water), and both losses and gains were recorded in the central portion of South Point.
- Whyte Island – there was a net gain in mangroves of around 4 ha, and net reduction in saltmarsh/saltpan of around 12 ha. Mangrove gains were recorded in the north-eastern portion of the saltpan, and losses were mainly recorded on the far northern, southern and western margins of the saltpan, and the northern seaward mangrove fringe. The reduced saltmarsh/saltpan extent was a result of the mangrove expansion into saltpan.
- Bulwer – there was a net 1 ha decrease in mangrove extent. Saltmarsh/saltpan extent was <0.5 ha over time.

3.1.3 Summary

The results of this study indicate that intertidal wetland dynamics vary at a landscape scale. In summary:

- Parts of the mangrove fringe on Boat Passage and Pelican Banks have been eroding since at least 1997, and mangrove die-back has occurred in the central portion of South Point. This has resulted in a long-term net decrease in mangrove extent at Fisherman Islands. There has also been minor retraction in the seaward mangrove fringe at Whyte Island
- By contrast, mangrove forests have expanded along the northern seaward fringe of Fisherman Islands and the saltmarsh/saltpan environments of Fisherman Islands and Whyte Island. The mangrove encroachment into saltpan varies spatially, and there has also been mangrove retraction (replacement by saltpan) in places

- Bulwer mangals have remained relatively stable over time.

Several processes likely interact long-term patterns in intertidal wetland dynamics. Historical port expansion works have likely altered local coastal dynamics around Fisherman Islands, including more quiescent conditions in the northern sector of Fisherman Islands. Other processes operating at the landscape scale, such as long-term rainfall-drought cycles (see Section 3.2.1.3) and sea level rise (BMT 2018), are also likely to influence long-term wetland dynamics, varying from place to place (e.g. due to local topographical variations, local hydraulics) and over time.

3.2 Mangrove Condition

3.2.1 Temporal Patterns in NDVI

Seasonal Patterns for the 2021 Monitoring Period

Temporal analysis on 2021-22 data shows a NDVI minima in summer (December or February), and a winter peak occurring in July (Figure 3.5). The July peak was observed at all sites except for St Helena Island, where June NDVI values were slightly higher than July. This seasonal cycle was consistently observed over time (BMT 2016; 2021).

From a monitoring program design perspective, sampling in July is desirable as: (i) it coincides with mangrove maximal vegetation condition, and (ii) is typically cloud free. For long-term spatial analyses, July represents the most consistent time to measure anomalies from the previous year or from the long-term average, as described below.

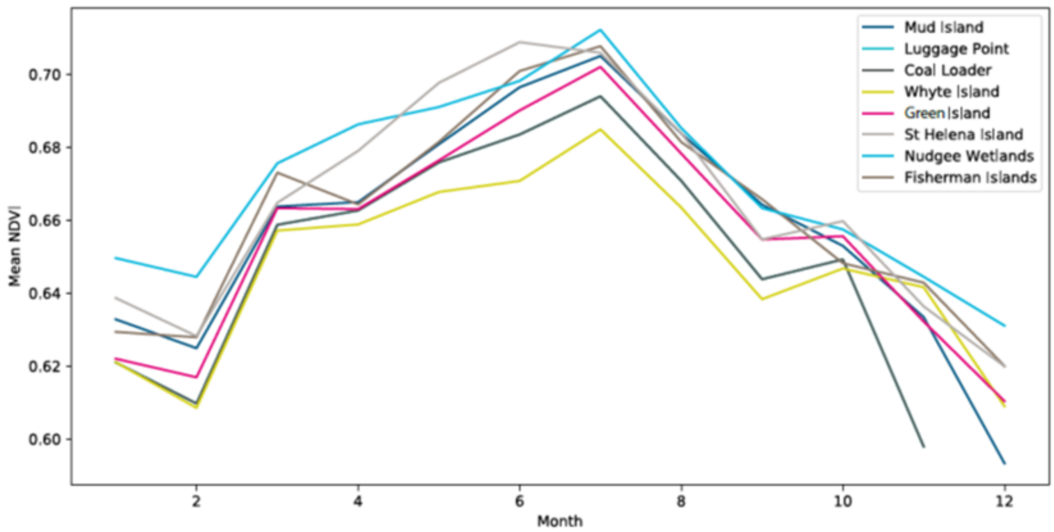


Figure 3.6 Long-term average scene NDVI scores in each month for each investigation area (2021-22)

July 2020 and 2021 Monitoring Period

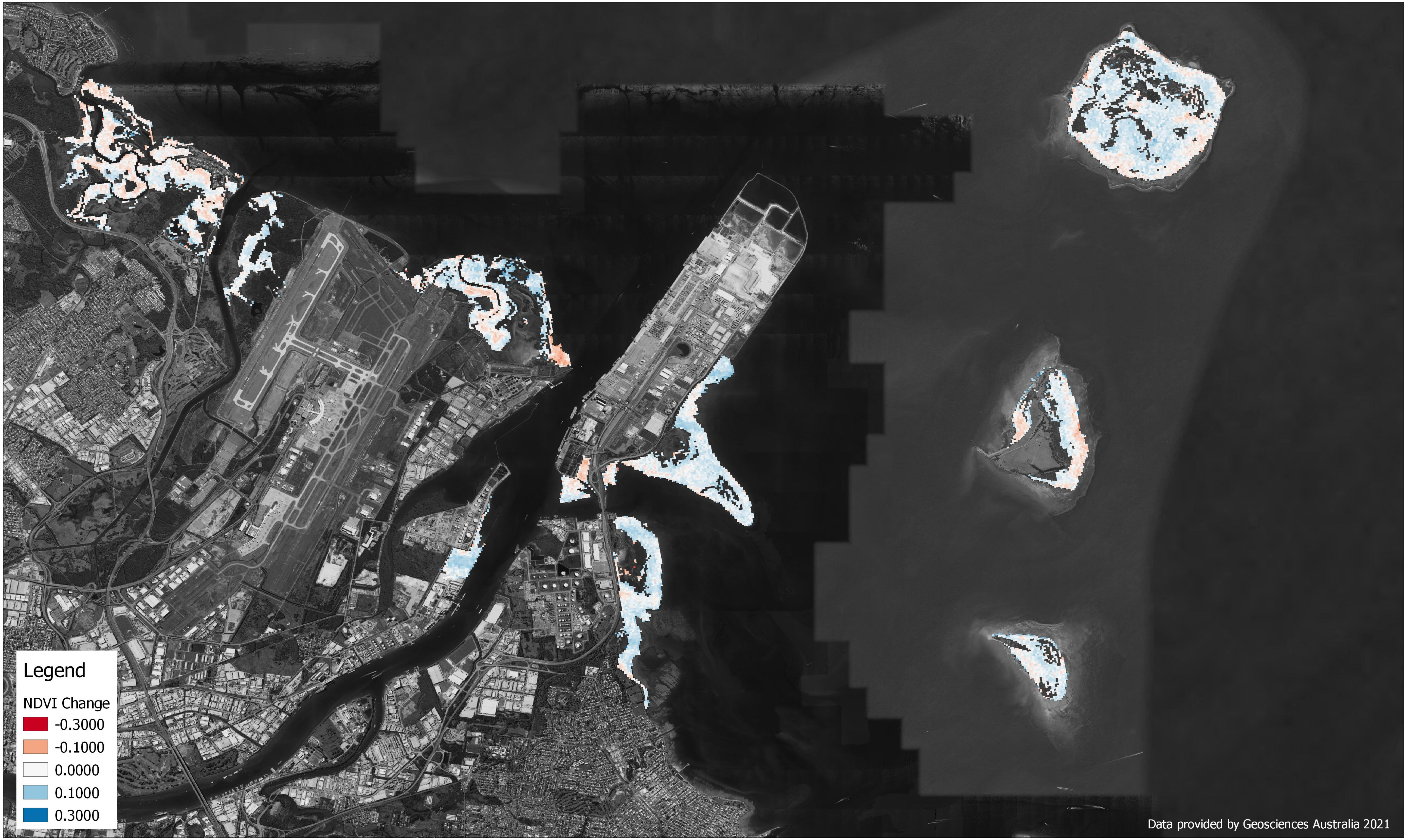
Figure 3.6 shows differences in NDVI values between July 2020 and July 2021, based on Landsat data[1]. Minor changes (±0.1 NDVI change) in NDVI were recorded at both test and background sites. Most test sites had slightly higher NDVI values in July 2021 than July 2020, with the following exceptions:

- Coal Loader (Pelican Banks) – This site had a broad-scale reduction in NDVI values between July 2020 and 2021. An inspection of aerial photography identified canopy thinning across the site, but no large-scale tree falls. NDVI changes of similar magnitude (spatial extent and degree of change) were also recorded at background sites (e.g. Juno Point, Serpentine Creek). Notwithstanding this, given the recent adjacent road upgrade directly east of the Coal Loader site, future monitoring should focus on this area, as even minor alterations to hydrology can lead to mangrove dieback.
- Fine-scale changes in mangrove patches at: (i) Fisherman Islands adjacent to and north of the Port administration office; (ii) Fisherman Islands *Ceriops* forest and along Boat Passage; and (iii) small mangrove patches in central and southern portions of Whyte Island. Nearmap aerial imagery indicates that most areas with reduced NDVI scores were a result of canopy thinning rather than tree falls. The exception to this was central Whyte Island where some fallen trees were also present (Figure 3.7).

Average changes in NDVI values between July 2021 and July 2020 geomeans for different community types in each location are shown in Figure 3.8 (refer to Figure 2.2 for locations). Patterns in average NDVI in each community type were largely inconsistent among locations with an overall increase in NDVI observed in most community types. The observed changes in most locations were of small magnitude (within 0.05 mean NDVI units). The largest variations in NDVI change occurred in saltmarshes at the Coal Loader, Bulwer Island, and most of Fisherman Islands. Consistent improvement in saltmarsh occurred in Fisherman Islands – Central (FI_b) and consistent worsening occurred at saltmarshes at Whyte Island.

Areas of Avicennia, *Ceriops*, and Rhizophora underwent small improvements in NDVI, and the only mangrove areas to worsen were *Avicennia* at the Coal Loader and the Fisherman Islands site adjacent to Pelican Banks/Coal Loader (FI_a).

[1] Sentinel-2 quality flags in the ARD prevent the assessment of the Coal Loader area and parts of Bulwer Island. While less spatially resolved, Landsat ARD is far less prone to quality flag issues and can be used to assess differences in these areas.



Title:

Differences Between July 2021 and July 2020 (Landsat Geomeans)

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Figure 3.8 Examples of defoliation in central Whyte Island in July 2020 (above), and July 2021 (below)

Figure 3.9 Examples of defoliation in central Bulwer in July 2020 (above), and July 2021 (below)

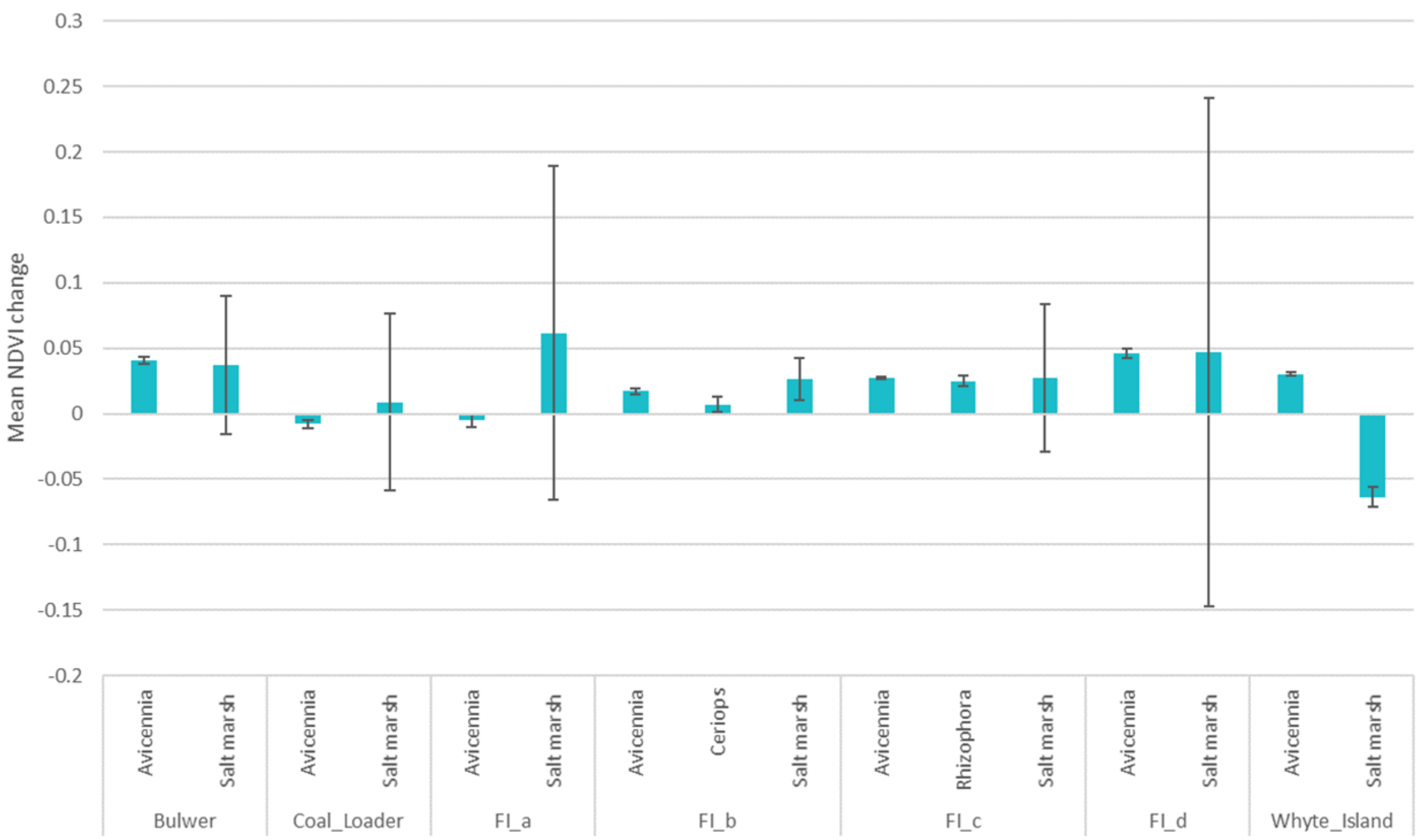


Figure 3.10 Average (± SE) NDVI in July 2020 at each location for community types (saltmarsh, *Avicennia* shrub (2-3 m), *Avicennia* tall (3-10 m), *Avicennia* very tall (>10 m) and *Ceriops* communities)

Long-term Temporal Patterns Among Sites

Figure 3.10 is a time-series of NDVI values for control (upper plot) and test (lower plot) investigation sites. Long-term patterns in NDVI among sites were remarkably consistent among the investigation sites. All sites displayed the same seasonal cycle as described in Section 3.2.1.1, with the intensity of peaks and troughs similar among sites and between test and control sites.

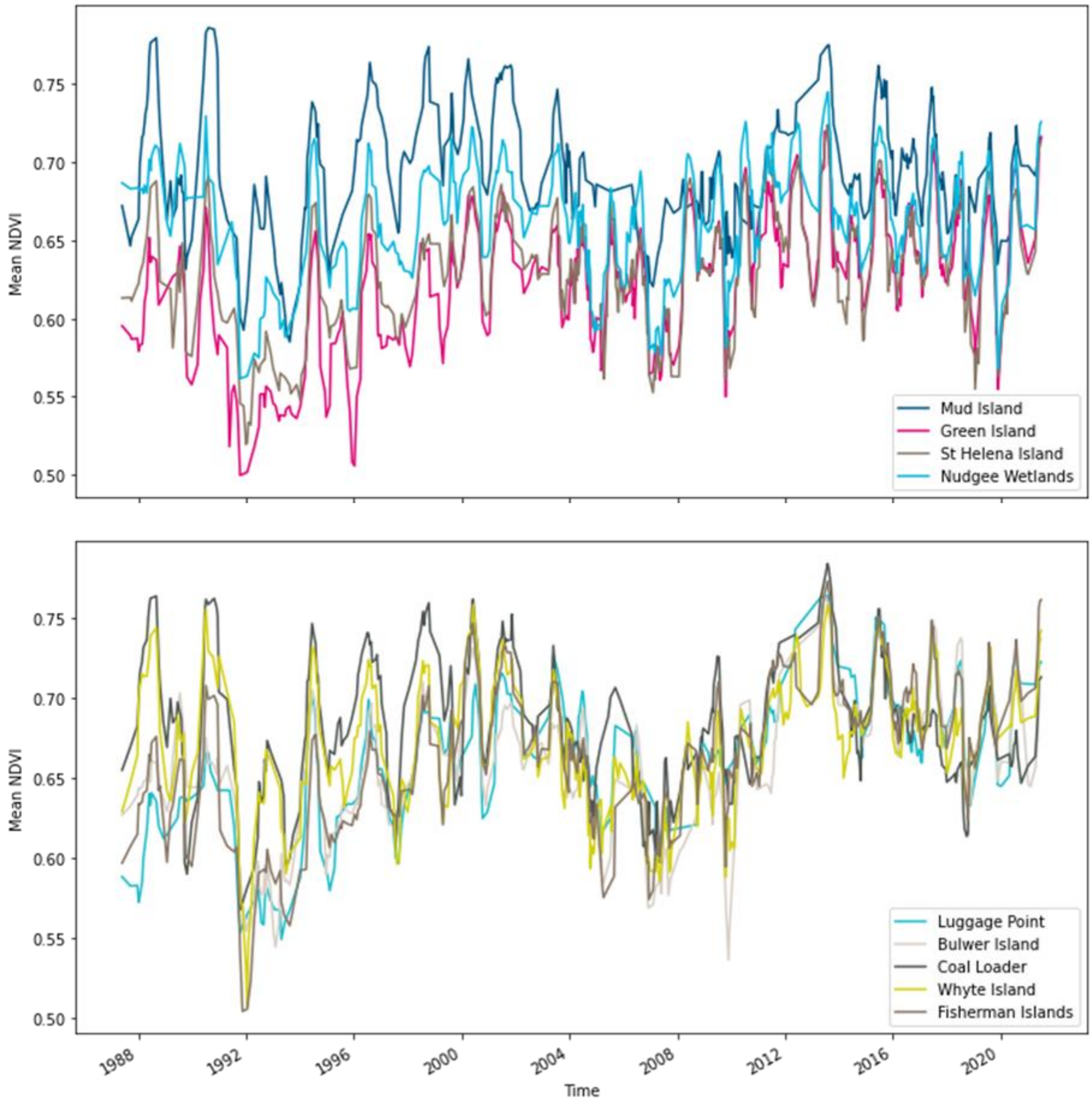


Figure 3.11 Mean NDVI scores for control (above) and test sites (below) from 1988 to July 2021

Figure 3.11 shows NDVI values for mangrove forests at a study area-wide scale presented in two ways: raw time series data (upper plot) and 12 month rolling average over time (lower plot). The historical long term (33 year) average NDVI and 12 monthly rolling average are also presented. The key temporal trends were:

1. a decline between 1989-1992. NDVI values were generally well below the long-term historical average (i.e. lower than average mangrove condition). The 1992 samples had the lowest NDVI values on record, and were coincident with low antecedent rainfall.
2. mangrove recovery between 1992-1999. NDVI values were below the long-term historical average up to 1998, and thereafter were higher than average. The rolling average rainfall was variable in this period, increasing between 1996-1998.
3. relatively stable mangrove condition between 1999-2004, which was above the long-term historical average. A period of high rainfall occurred between 1999-2001, whereas extended drought conditions (with periodic rainfall events) prevailed between 2001-2011.
4. a general decline in mangrove condition between 2006-2007, coincident with extended dry conditions.
5. mangrove recovery between 2008-12. NDVI was higher than the long-term average from 2010 onwards. The improvement to mangrove condition was coincident with wetter conditions, most notably the 2011 Brisbane River flood.
6. instability between 2012-21, but higher than average NDVI over the period. Flood events occurred immediately prior (2011) and during (2013) this period, coincident with peak NDVI values. Thereafter mangrove condition and rainfall were highly variable over time, but displayed similar temporal trends.

These results are consistent with BMT WBM (2016), however additional data from DEA data cube has increased sample replication and provided a more robust assessment of long-term trends.

There was a positive association between mangrove condition and rainfall. A strong positive correlation was found between rainfall ranks and rolling average NDVI ($r = 0.57$, $p < 0.0001$). The relationship between the rolling 12-month average rainfall and average NDVI score was only weakly correlated, but statistically significant ($r = 0.18$ $p = 0.0003$). This indicates that while there was a positive relationship between rainfall and mangrove condition, it was not strongly linear, suggesting that other factors may interact with rainfall to control mangrove condition.

Water availability is the key driver of mangrove condition and community structure (Hutchings and Saenger 1987), and rainfall is just one factor determining water availability. As discussed by BMT WBM (2016), water availability is a function of tidal inundation, ground water recharge, surface water runoff, and the relationship between these processes varies in time and space. Ground water tables are often recharged in the magnitude of months, depending on soil type, vegetation community structure, rainfall and ground water (Alongi 2009). Consequently, there may be a lag between rainfall, groundwater recharge and mangrove response measured in months. Superimposed on this groundwater process are (i) regular tidal flushing (diurnal near sea level, less frequent higher in the profile); (and (ii) irregular surface water runoff. Both processes affect soil salinity and nutrient delivery, and may influence mangrove condition over shorter timescales. Refer to BMT WBM (2016) for a review of these processes.

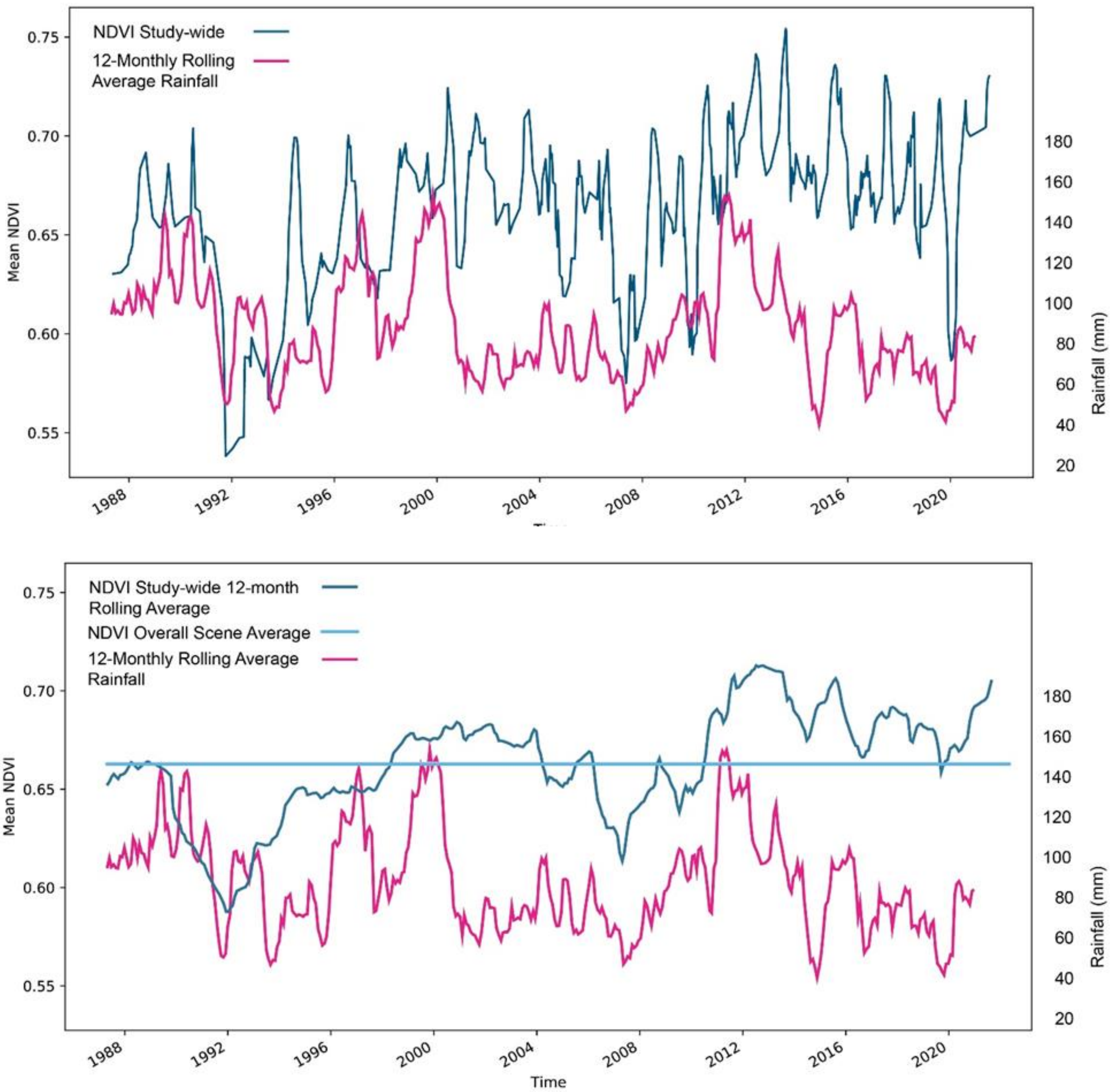


Figure 3.12 Study area wide NDVI time series (upper plot) and 12-month rolling average NDVI (lower plot), shown with rolling average 12 month rainfall

The El Niño - Southern Oscillation (ENSO) is a key driver of rainfall in the region, therefore relationships between mangrove condition and the Southern Oscillation index (SOI) were explored. For the period of 1988 to July 2021, 12 month rolling averages of monthly SOI and NDVI were positive correlated (Figure 3.12, $r = 0.44$, $p < 0.0001$). BMT WBM (2016) did not find a correlation between these variables, as only linear associations were examined, and sample sizes were smaller.

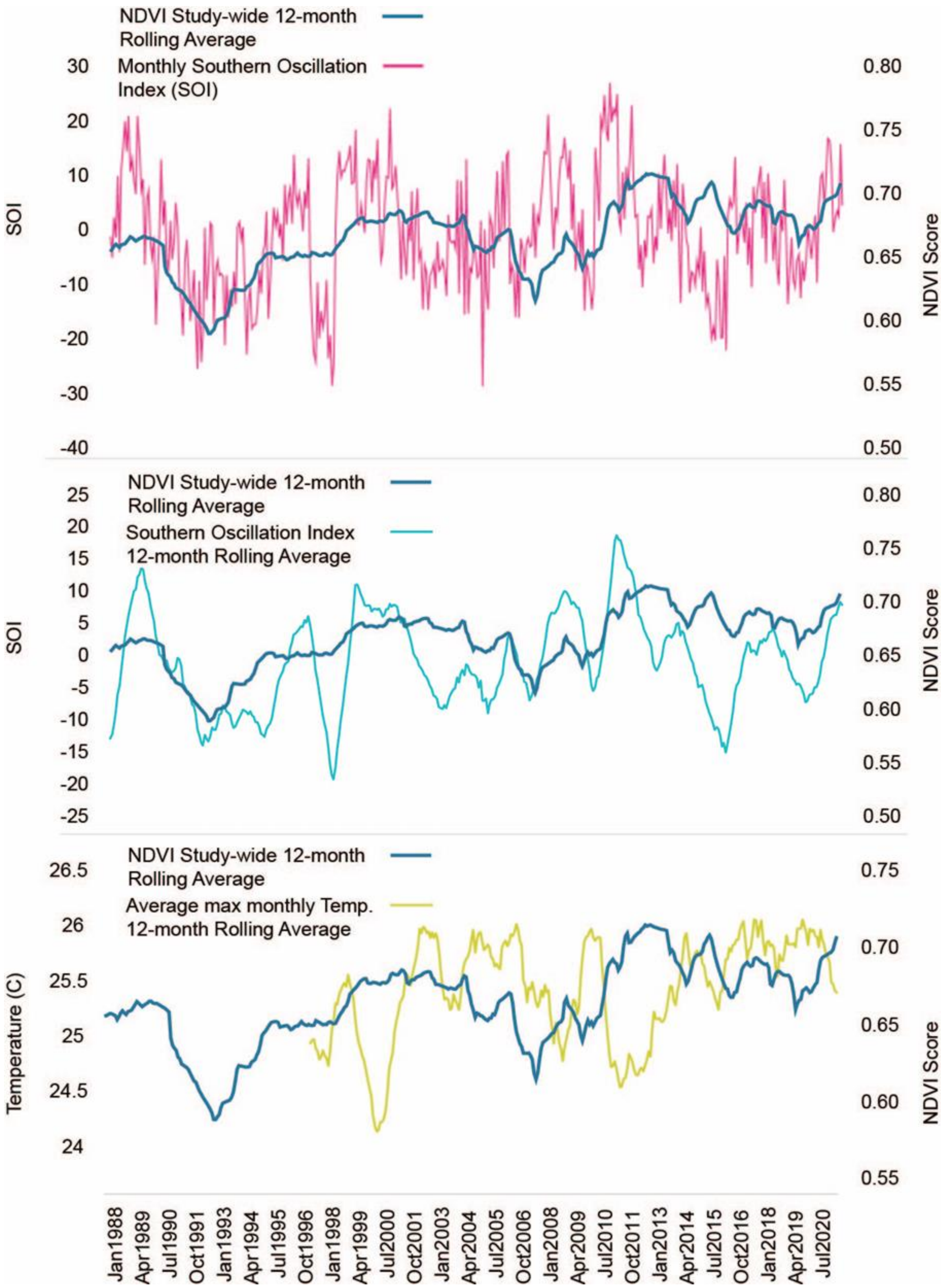


Figure 3.13 Relationships between the 12 month rolling average of NDVI score and: monthly Southern Oscillation Index (SOI) (top); 12 month rolling average of SOI (middle); and the rolling average of maximum monthly temperature (bottom)

SOI is linked to rainfall and temperature with periods of positive SOI bringing higher than average rainfall, and lower temperatures. Conversely, lower SOI results in warmer drier conditions. The relationship between the average monthly maximum temperature (maximum daily temperatures averaged across each month) was weakly inversely correlated to the 12-month rolling average of NDVI across the study area NDVI (Figure 3.12, $r = -0.14$, $p < 0.02$).

Of the correlation coefficients investigated, the strongest relationship was detected between ranked 12-monthly rainfall and NDVI scores. The relationships with monthly and rolling averages of SOI, and maximum monthly temperature, were not as strongly correlated with NDVI, suggesting that recent and antecedent rainfall was the most influential variable of those investigated.

Long-term Temporal Patterns Within Sites

Long-term trends in mangrove condition were examined in the port area using data from July periods, which represents the NDVI maxima (see Section 3.2.1.1). Data sources were medium-resolution Landsat 5,7, and 8 series (1988-2021), and high-resolution Sentinel-2 (dataset beginning in 2015) data. The geospatial averages for both data sets were calculated to identify areas where mangrove condition departed from long-term average conditions.

Landsat

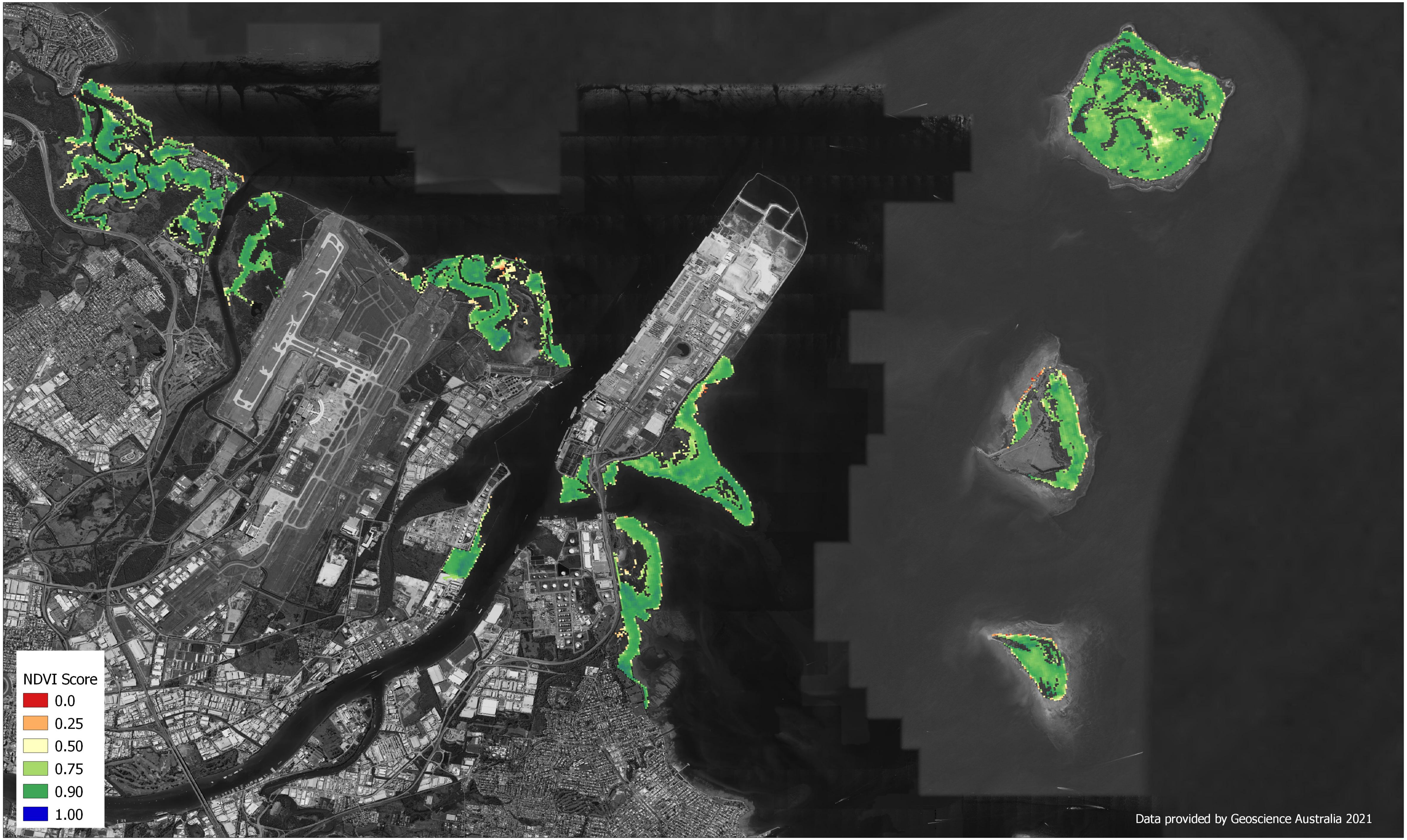
The average pixel value from every July Landsat scene taken from 1987 to 2021 is shown in Figure 3.13, and the Sentinel-2 capture history from 2015 to 2021 is shown in Figure 3.14. The geomeans from Sentinel imagery (2015-2021) and Landsat imagery (1988-21) were compared and a difference plot is shown in Figure 3.15.

The following areas at Fisherman Islands and Whyte Island experienced a >0.1 change in NDVI value (positive to negative) between the 2015-21 average and the long term average (Figure 3.15):

- reductions in NDVI scores at (i) Fisherman Islands along Boat Passage, including the Coal Loader, Fisherman Islands – Central and South Point; (ii) the *Ceriops* forest and nearby landward Avicenna-dominated forest at Fisherman Islands - Central; and (iii) patches at the mangrove/saltpan interface at Fisherman Islands – Central.
- reductions in NDVI scores along the seaward margins of Whyte Island
- improved NDVI on the landward margin of mangrove forests at Fisherman Islands and Whyte Island; and the northern seaward margin of Fisherman Islands.

Trends in mangrove condition on the seaward margins of Fisherman Islands appear to be a response to different sedimentary processes. Parts of the southern margin of Fisherman Islands (along Boat Passage) have been eroding, resulting in tree fall and mangrove retreat (see Section 3.1). By contrast, parts of Fisherman Islands – North have been accreting, resulting in long term seaward expansion.

Bulwer island experienced a >0.1 change in NDVI value (positive to negative) between Landsat scene taken from 1987 to 2021. The general trend observed was a slight decrease in NDVI on the edges and an increase in NDVI in the central locations of Bulwer.



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Average Landsat July NDVI Score (1988-2021)

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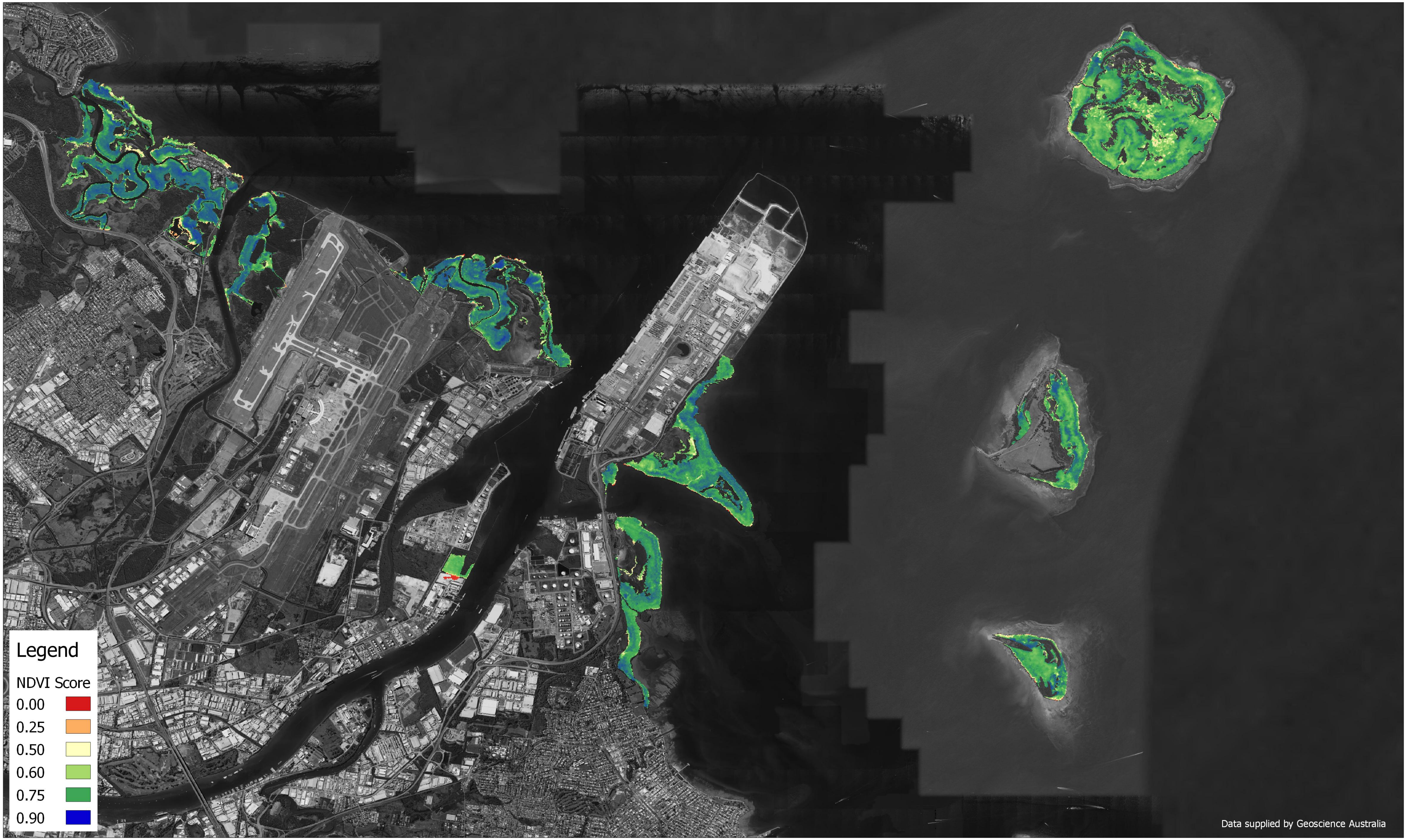

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Average Sentinel-2 July NDVI Score (2015-2021)

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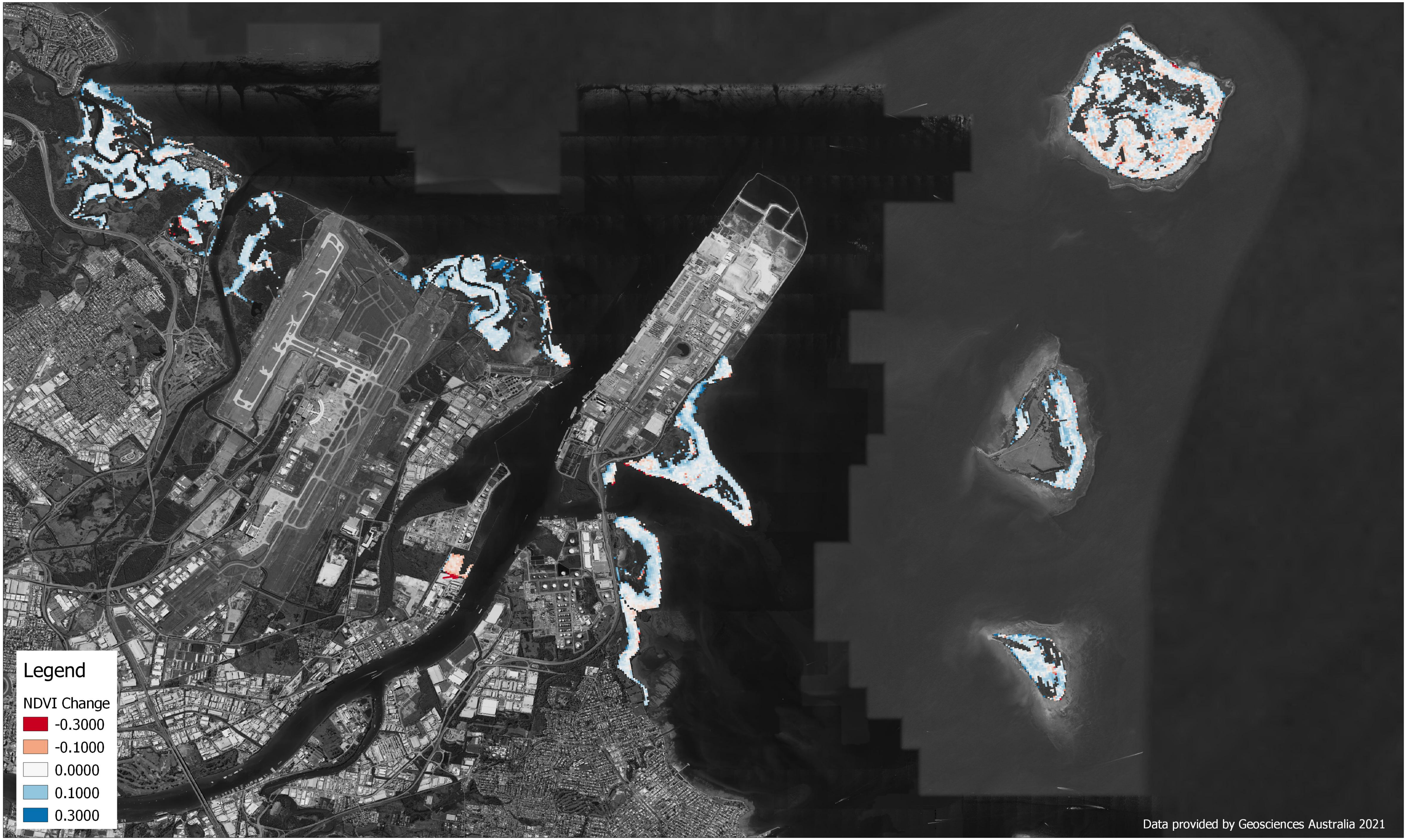

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Differences in July Landsat and Sentinel-2 Geomeans

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Sentinel-2 Imagery (2015-21)

The Sentinel-2 ARD included many quality flags preventing inclusion of many scenes from Bulwer Island and the Coal Loader. This is due to the presence of highly reflective or absorptive surfaces, such as coal stockpiles and infrastructure, incorrectly flagged as cloud or cloud shadow.

Time series of NDVI, SAVI, and LAI for the entire Sentinel-2 capture history (2015-2021) show the same annual patterns observed in recent Landsat data. Each site shows a relatively consistent pattern with strong correlations among all three indices, a generally flat to slightly inclined trajectory, and the most recent overall minima occurring late in 2019 coinciding with very low rainfall and high temperatures.

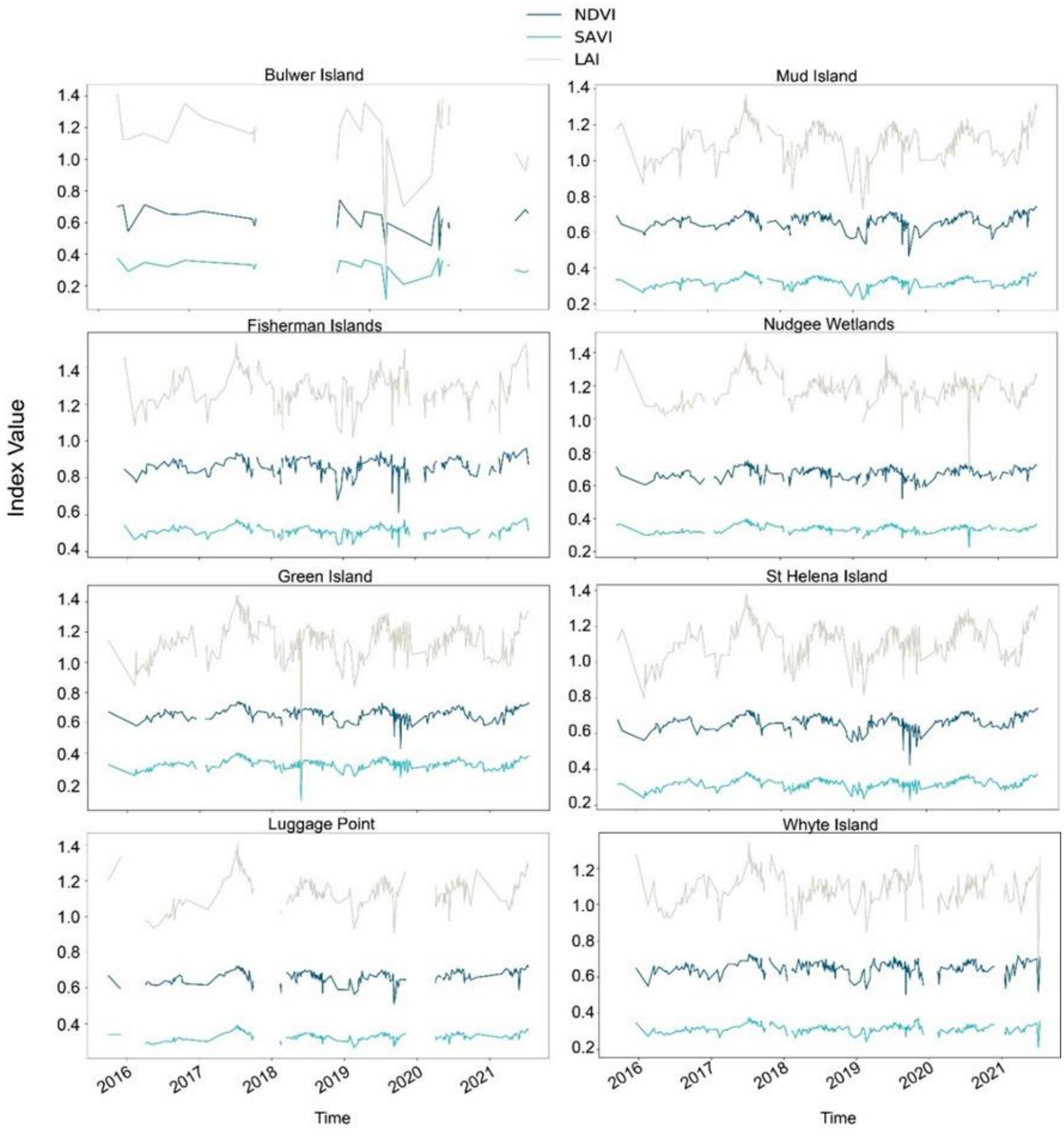

Figure 3.17 Time-series of NDVI, SAVI, and LAI for all sites derived from Sentinel-2 between 2015 and 2021

In the previous monitoring year, mangrove defoliation and die-back were observed in the interior portions of mangrove forests, and vegetation community metrics slightly decreased in July 2020 compared to July 2019. It was suggested that this dieback was consistent with water stress induced by drought conditions and above average temperatures in late 2019. The current monitoring period showed either a neutral response (returning to the 2020 maxima) or in many cases a slight increase in vegetation indices likely stemming from increased rainfall associated with positive SOI index (la Nina) conditions into the start of 2020.

Sentinel-2 geomeans for each month are shown in Annex B.

4 Conclusions

The present study found that:

- In the period 2018-21, there were minor (<1 ha) changes in tidal wetland community extent at Fisherman Islands and Bulwer Island. Mangrove extent increased and saltmarsh/saltpan extent decreased during this period at Whyte Island, mostly due to colonisation of mangroves in saltpan areas, and a greater area of ponded water.
- Over longer timeframes (since 1997), there has been a long-term net decrease in mangrove extent at Fisherman Islands due to die-back at the saltpan-mangrove interface (ecotone) and erosion on the seaward margin in places. However, mangrove forests have also expanded along the northern seaward fringe of Fisherman Islands and the saltmarsh/saltpan environments of Fisherman Islands and Whyte Island. The mangrove encroachment into saltpan varies spatially, and there has also been mangrove retraction (replacement by saltpan) in places.
- Several processes likely interact long-term patterns in intertidal wetland dynamics, long-term rainfall-drought cycles, sea level rise and natural geomorphological processes. These processes likely varying from place to place (e.g. due to local topographical variations, local hydraulics) and over time.
- Long-term temporal analysis of NDVI based on Landsat 5, 7, and 8 sensors allowed up to 576 scenes to be analysed from 1988 to present. This analysis supports the preliminary findings of BMT WBM (2016) and highlighted the importance of annual rainfall in determining mangrove health. With additional data, complex temporal cycles in plant health are evident and include seasonal growth cycles, responses to annual rainfall, and responses to longer-term climate, such as the Southern Oscillation Index (SOI).
- NDVI measured from 1988 to present exhibited a strong seasonal pattern that was significantly correlated with the preceding 12 months of rainfall, the SOI index, and inversely related to average maximum temperatures. The strongest association was with ranked rolling average of 12 monthly rainfall ($r = 0.57$, $p < 0.0001$).
- All of the sites exhibited the strongest NDVI signal in July apart from St Helena Island, where the June signal was slightly higher. The summer minima occurred in December and or February. This suggests that July is the most important period to monitor spatial changes due to the spatial and temporal consistency in the maxima, and due to the abundance of cloud-free scenes.
- The July 2020 to July 2021 monitoring period was characterised by a slight improvement in vegetation indices after a broadscale decrease in vegetation health was observed July 2019 and July 2020. While the overall pattern was of improvement, some reductions in scores were observed within the Fisherman Islands, at the Coal Loader, and the southern central part of Whyte Island. These were associated with a reduction in greenness at all locations except for southern central Whyte Island, where some trees had completely defoliated.
- NDVI typically improved slightly in most community types apart from *Avicennia* at the Coal Loader and Fisherman Islands area A (adjacent to the Coal Loader).
- Landsat ARD provided by the DEA data cube was a valuable tool for investigating long-term trends in vegetation condition and creating long-term geomeans. Sentinel-2 ARD was affected by excessive cloud-masking and will require additional work to extract masked data adjacent to infrastructure.
- Our recommended future monitoring includes a recent (12 monthly) time-series analysis of all sites using Landsat ARD, geomean comparisons against the July long-term average, and against the

previous July. High-resolution (Sentinel-2) July captures should continue to be assessed to monitor fine scale changes such as tree falls, dieback and dieback improvements.

- *Avicennia marina* mixed communities on the northern fringe of Fisherman Island, adjacent to Coal Loader and along the fringe of Whyte Island remain the tallest vegetation stands between 2016 and 2021.

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Annex A Monthly Geo-mean Maps

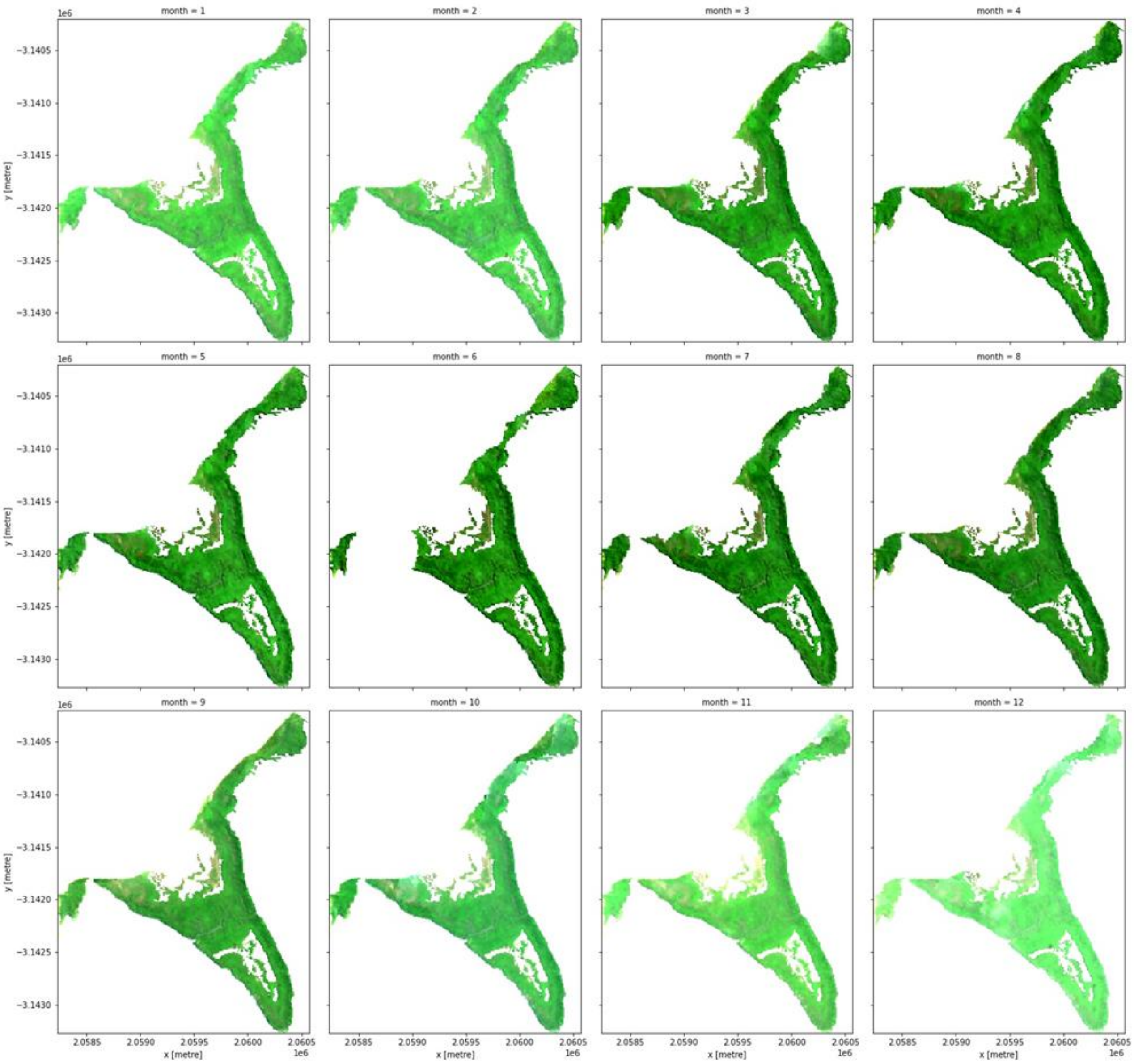


Figure A.1 RGB geomean images of Fisherman Islands for each month based on Sentinel-2 (2015-2021)

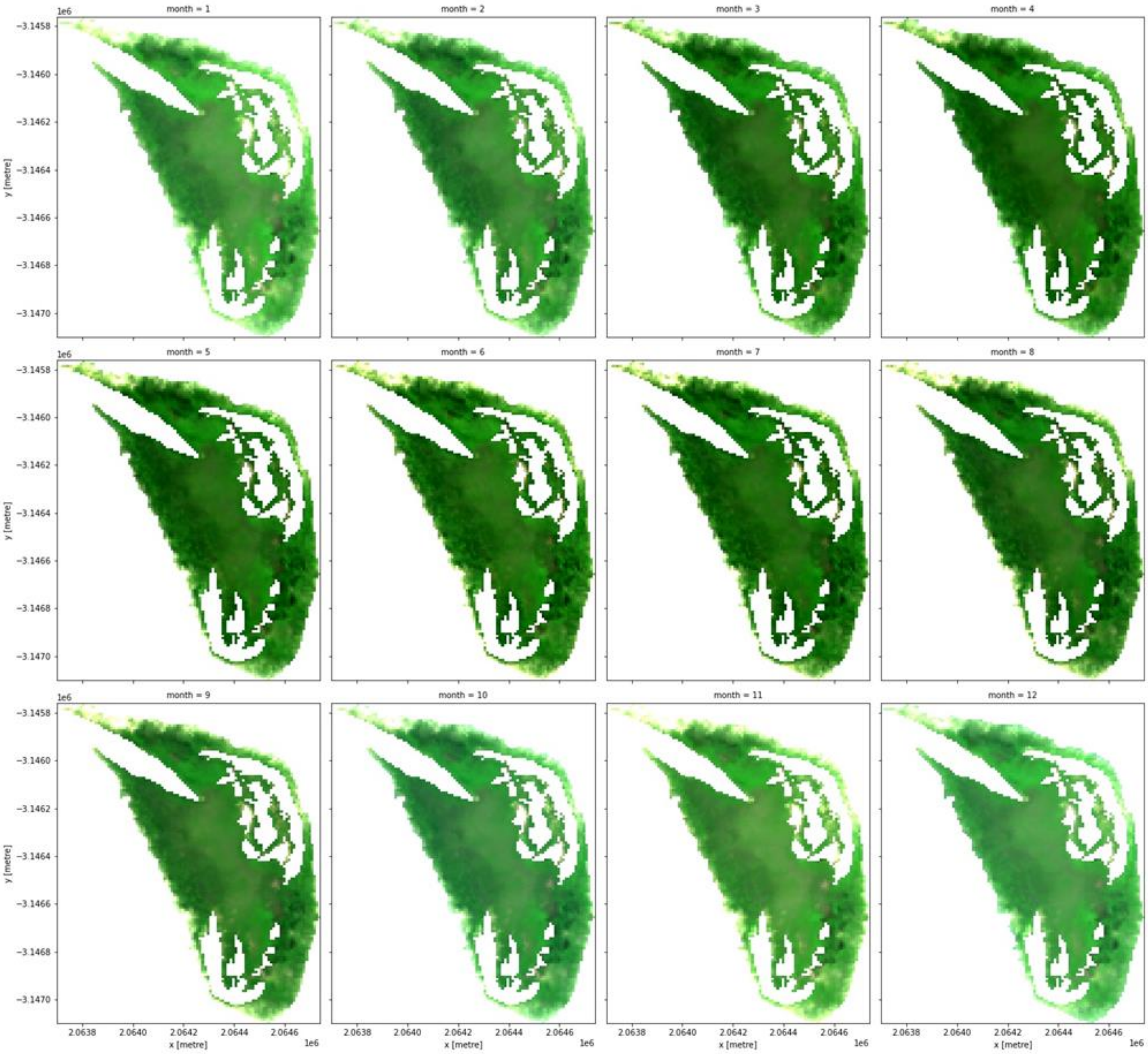


Figure A.2 RGB geomean images of Green Island for each month based on Sentinel-2 (2015-2021)

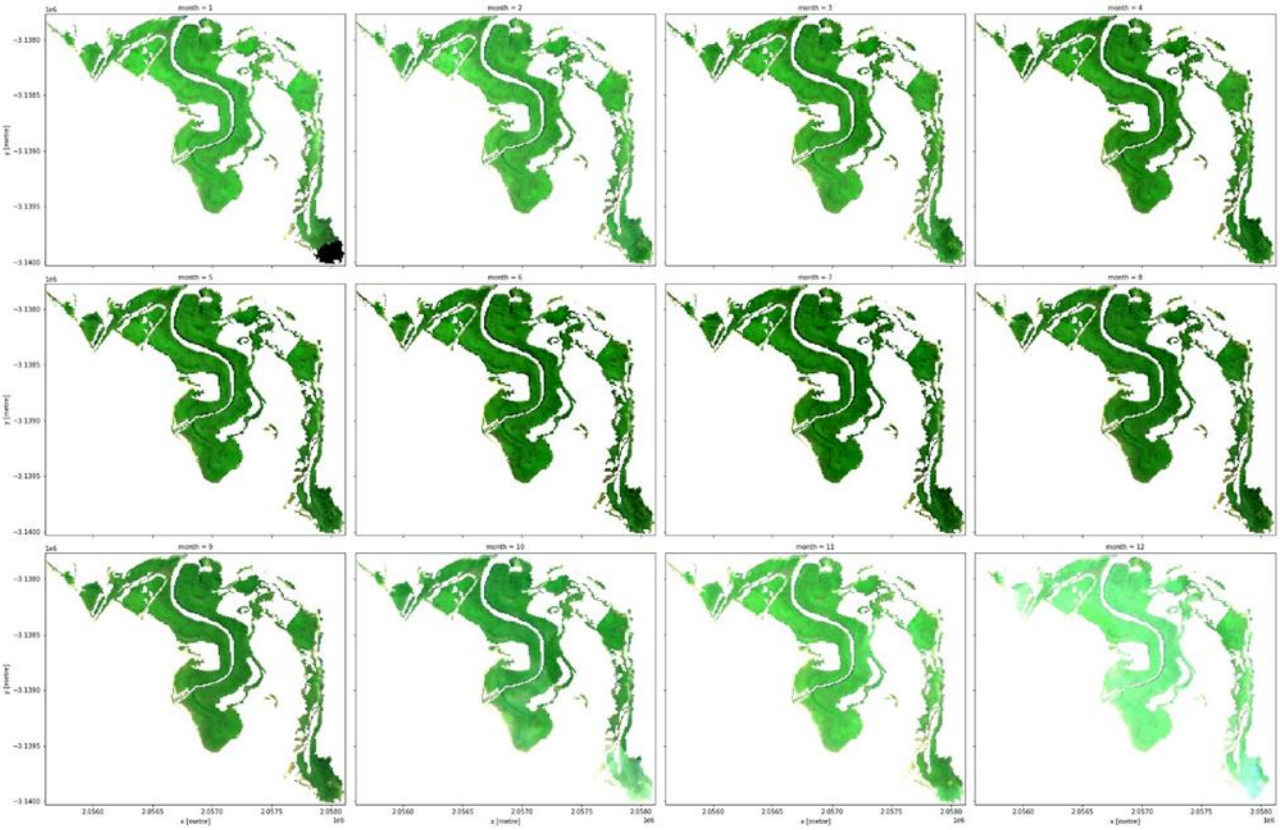


Figure A.3 RGB geomean images of Luggage Point Wetlands for each month based on Sentinel-2 (2015-2021)

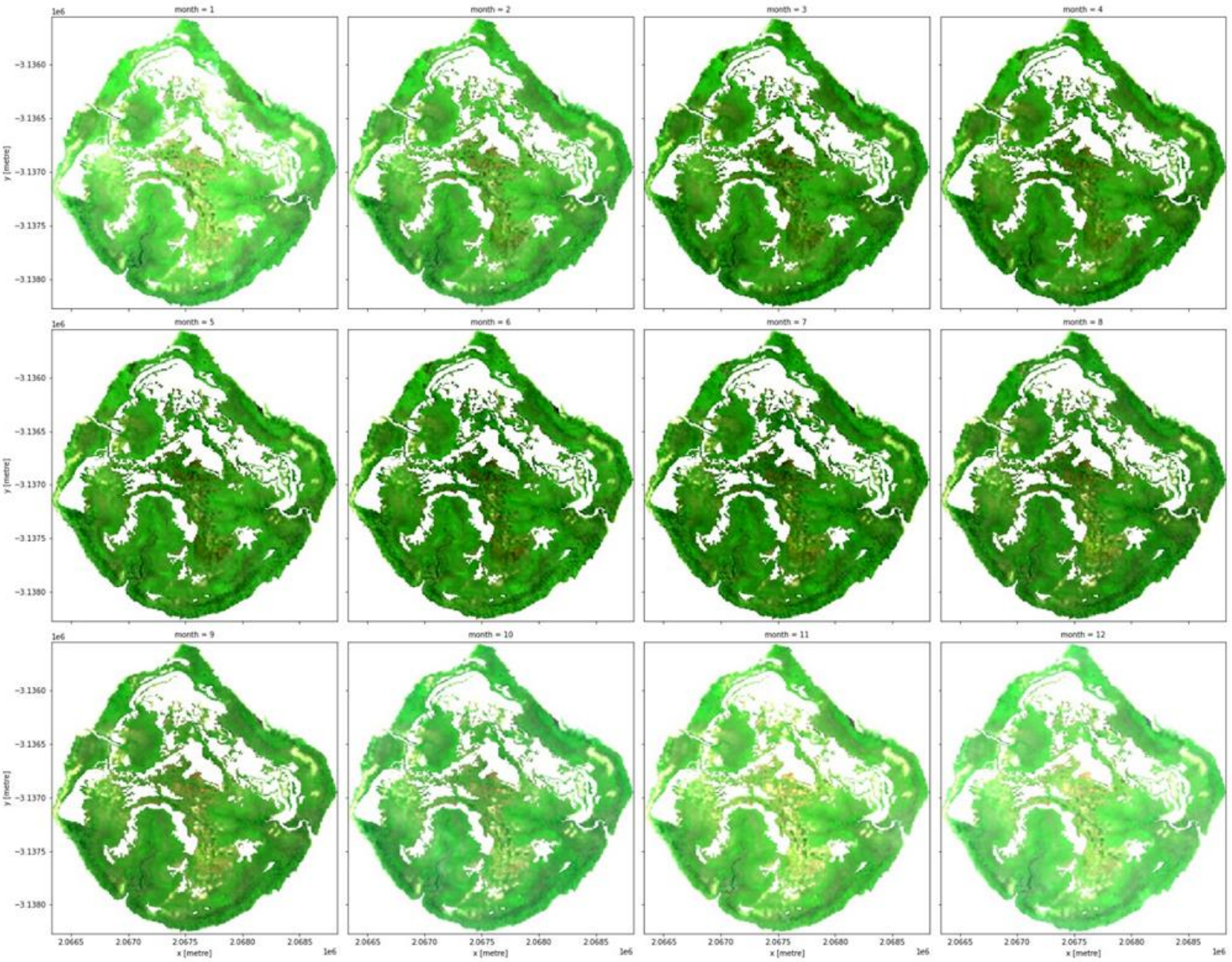


Figure A.4 RGB geomean images of Mud Island for each month based on Sentinel-2 (2015-2021)

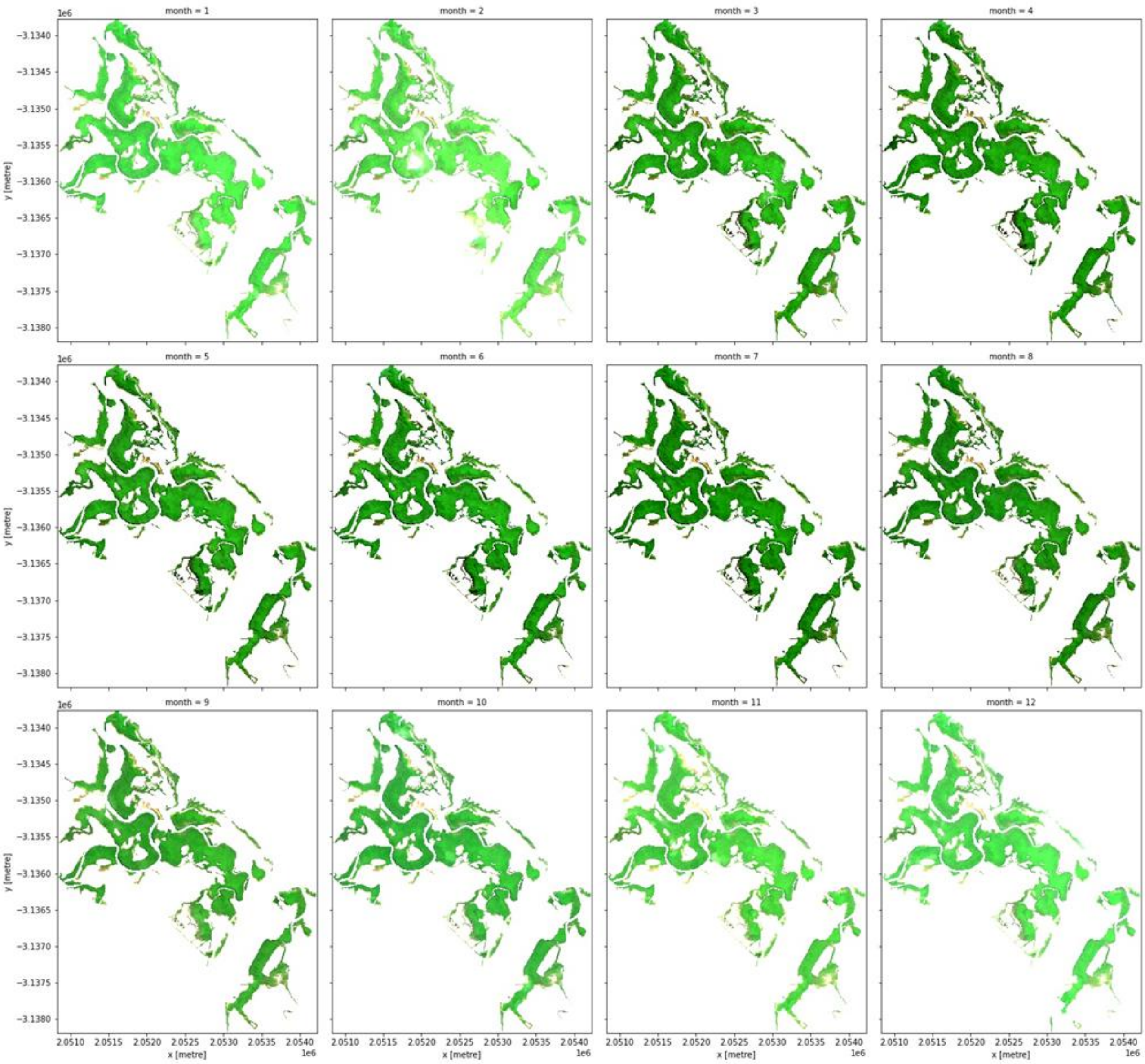


Figure A.5 RGB geomean images of Nudgee Wetlands for each month based on Sentinel-2 (2015-2021)

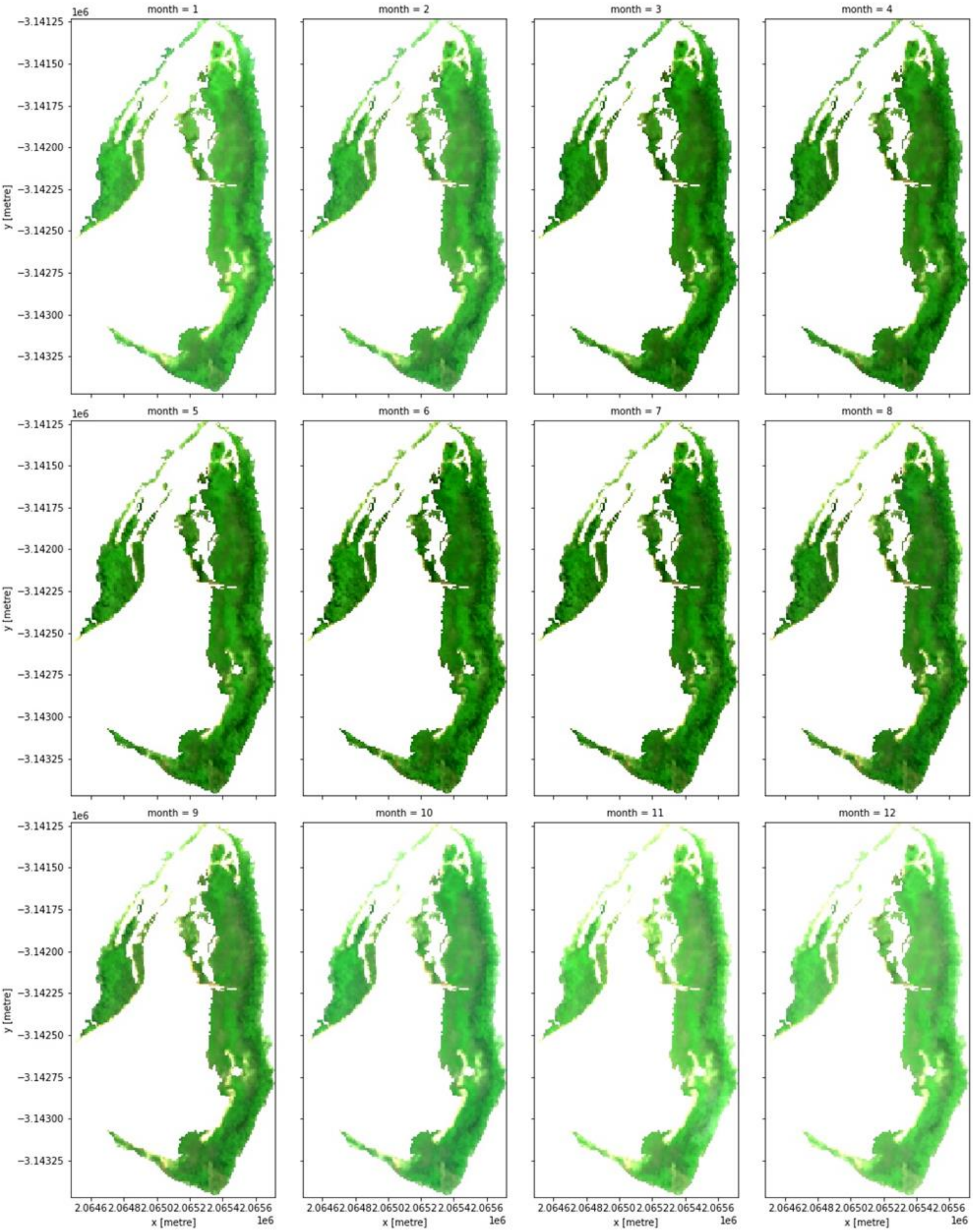


Figure A.6 RGB geomean images of St Helena Island for each month based on Sentinel-2 (2015-2021)

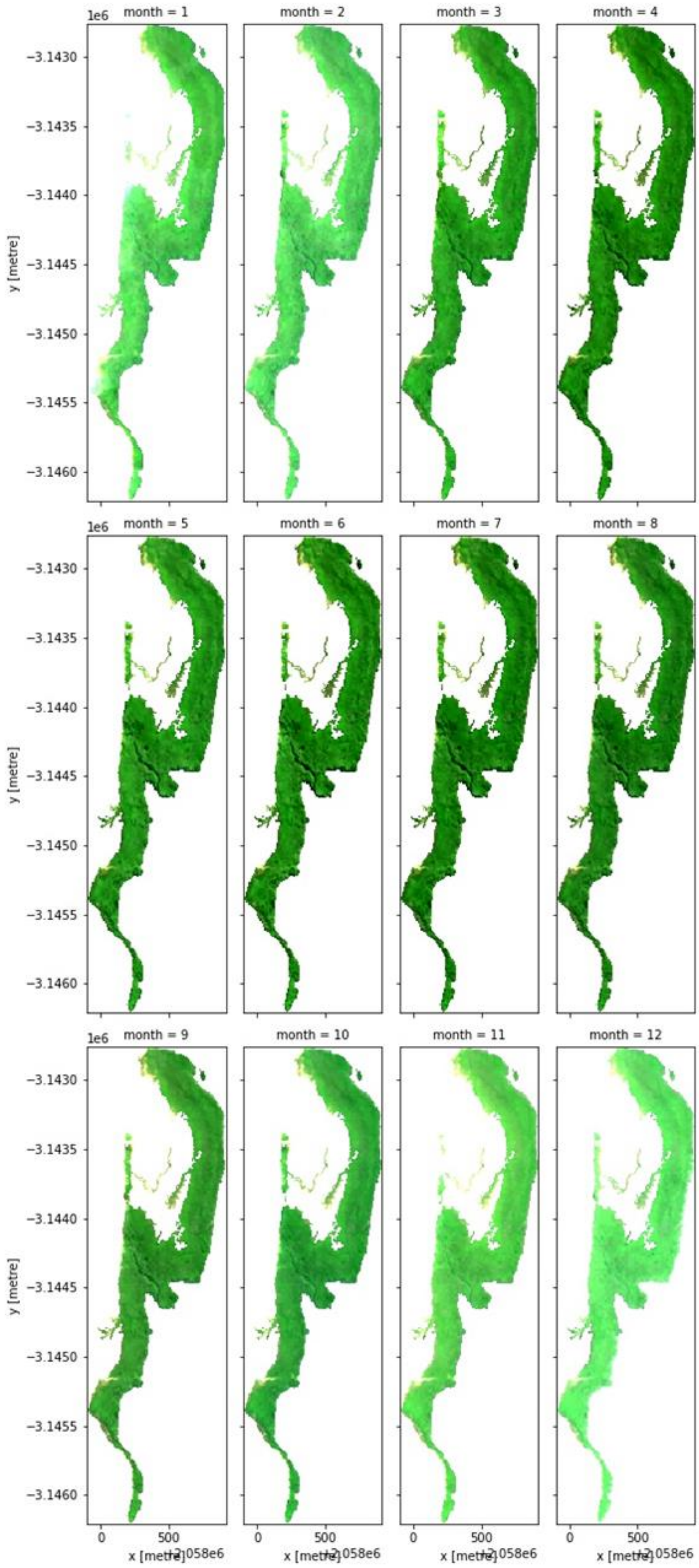


Figure A.7 RGB geomean images of Whyte Island for each month based on Sentinel-2 (2015-2021)

Annex B Vegetation Health Per Community Type

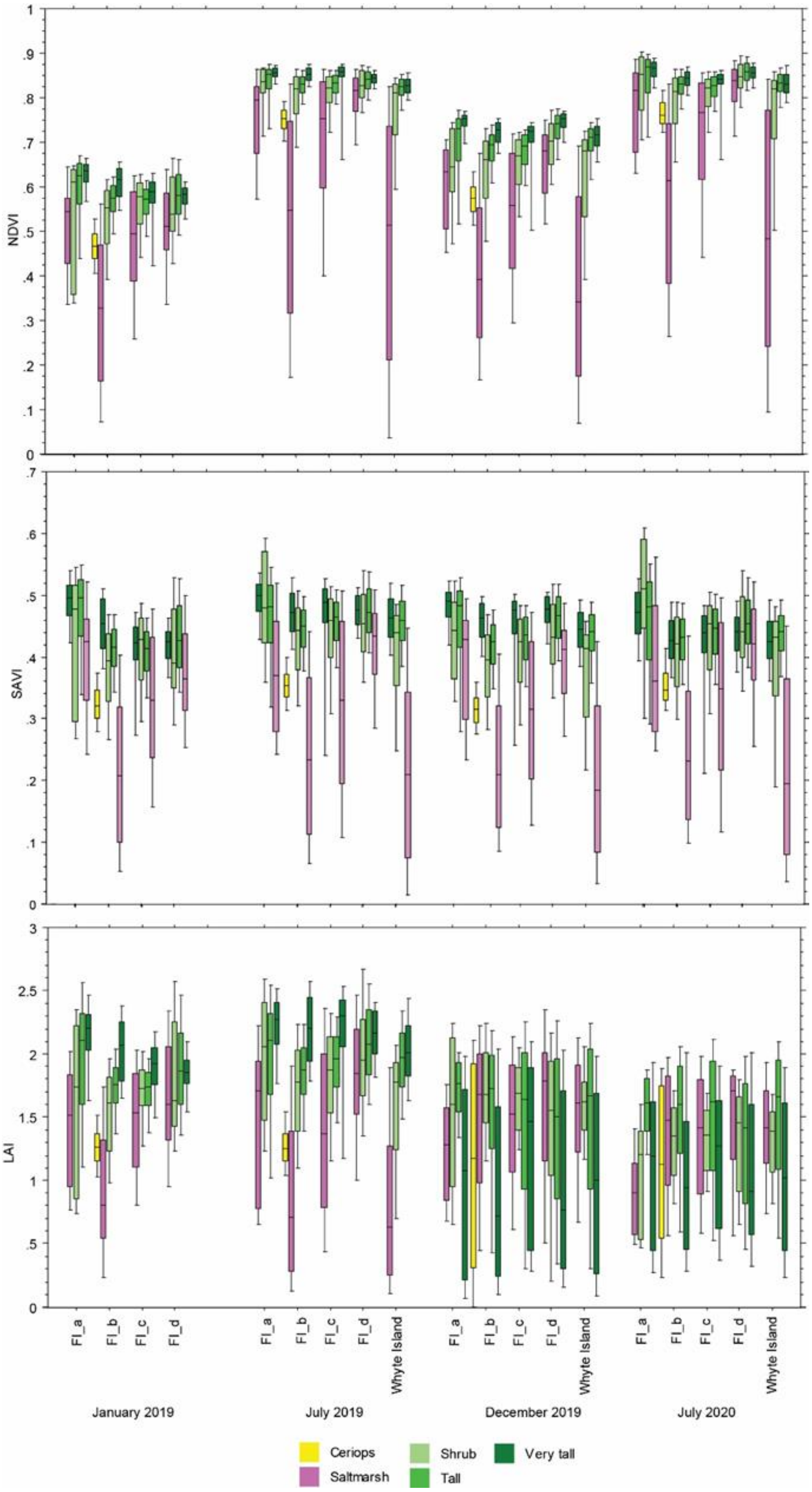
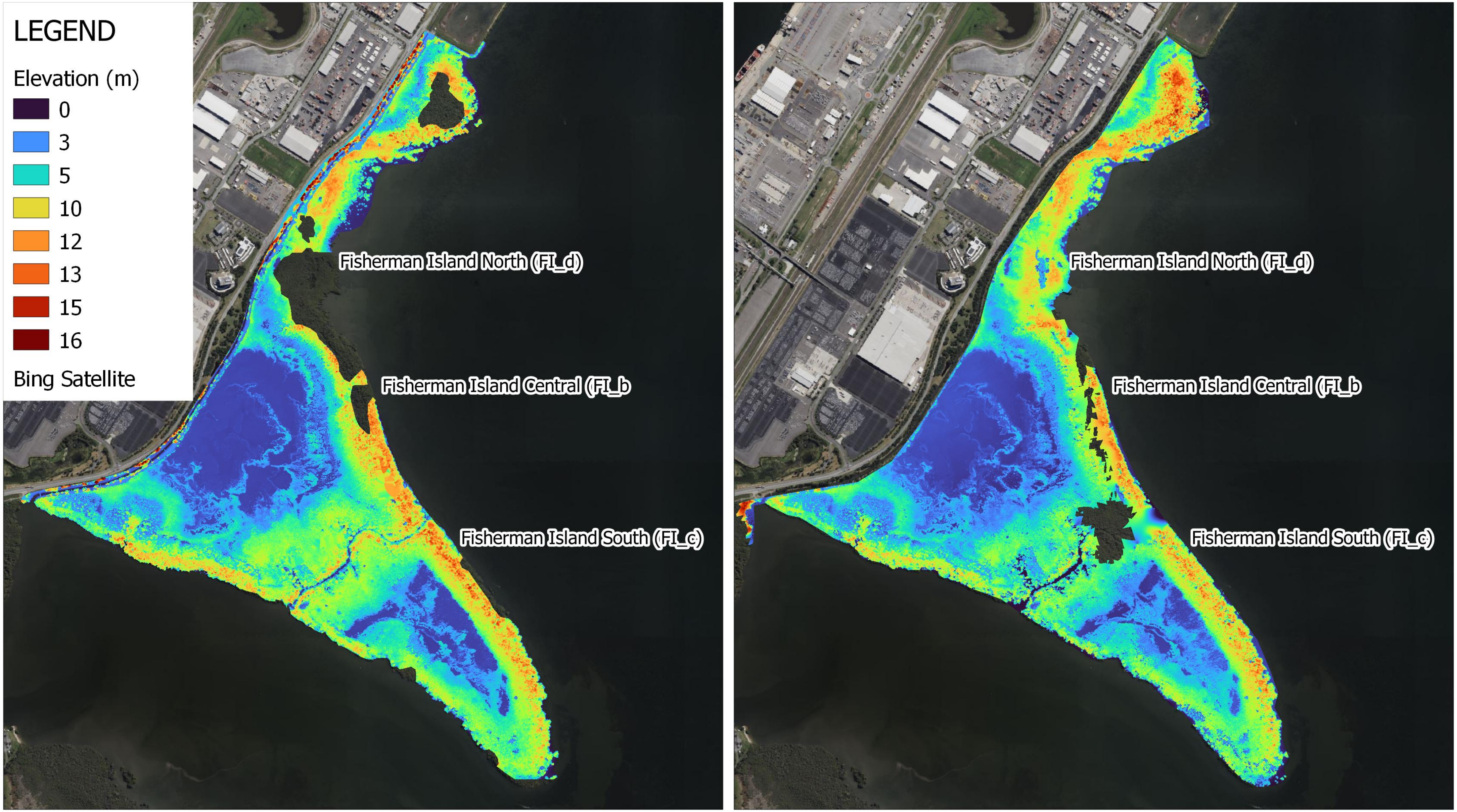


Figure B.1 Vegetation Indices Per Community Type at Fisherman Islands and Whyte Island

Annex C Elevation Data 2016 vs 2021



Title:

Fisherman Island Elevation 2016 (left) and 2021 (right)

Figure: **C.1**

Rev: **A**

N

0 250 500 m

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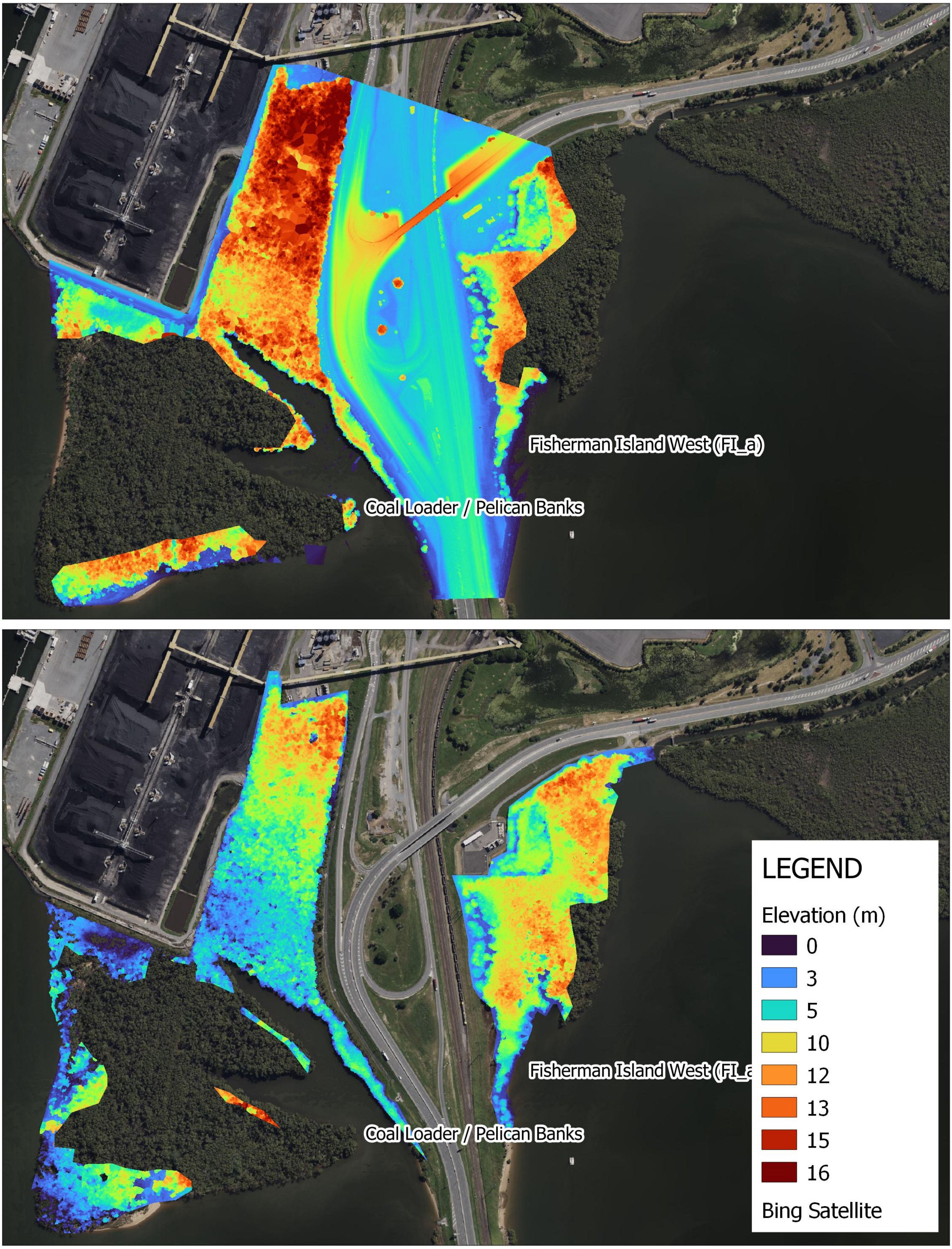

Title:

Coal Loader Elevation 2016 (left) and 2021 (right)

Figure: C.2

Rev: A

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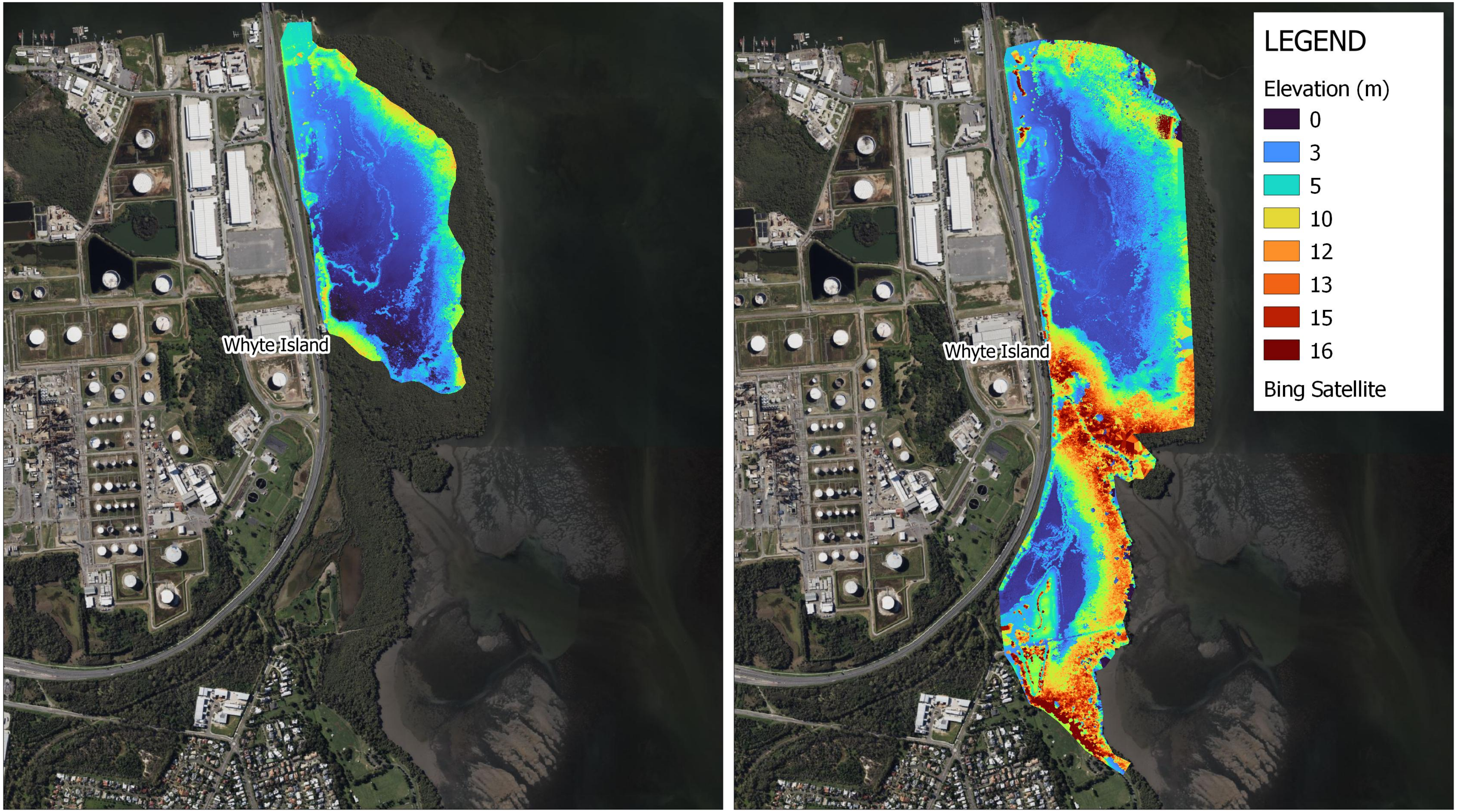

Title:

Whyte Island Elevation 2016 (left) and 2021 (right)

Figure: C.3

Rev: A

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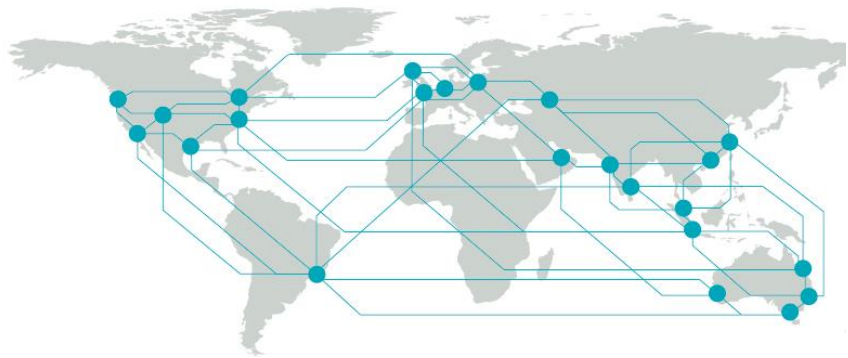

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