Port of Brisbane Mangrove Health Monitoring Program 2019 – Final Report

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BMT Commercial Australia Pty Ltd Level 8, 200 Creek Street Brisbane Qld 4000 Australia PO Box 203, Spring Hill 4004 Tel: +61 7 3831 6744 Fax: + 61 7 3832 3627 ABN 54 010 830 421 www.bmt.org	**Document:**	R.B23621.002.00.Mangrove_2019.docx
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Synopsis:	**A report outlining the mangrove condition at locations around Port of Brisbane between July 2018 and July 2019.**	

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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 norther side of the Brisbane River mouth. These vegetation communities are among the largest of their kind in western Moreton Bay and represent important ecological assets.

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 2019 MMP assessment. The aims of this assessment were to:

- Map changes in mangrove canopy condition indices across the Port of Brisbane test sites and surrounding control sites using remotely-sensed data; and
- Identify potential drivers for mangrove change.

Study Approach

Three mangrove condition indices were mapped using remotely sensed data: normalized difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI) and leaf area index (LAI). NDVI and SAVI are spectral indices that estimate the amount of green biomass while LAI calculates the amount of canopy per unit area. These metrics were calculated for 10 periods between and inclusive of July 2018 to July 2019. Site inspections were carried out in areas where changes in mangrove condition were observed over the twelve-month period.

Findings

Consistent with previous surveys, mangrove canopy condition was typically greatest in the well-flushed seaward fringes of the forest, and lower in areas near the mangrove-saltpan interface. Water stress is a key driver of this spatial gradient.

There was a net increase in mangrove health between 2018 and 2019 at the test sites (Fisherman Island, Whyte Island and Bulwer Island). Some small (<100 m^2) isolated mangrove patches had a reduction in canopy condition over this period, most notably:

- Forests fringing the inner-most claypan in the western portion of Fisherman Islands;
- Isolated patches on the southern seaward fringe of Fisherman Islands;
- Isolated patches on the inland sections of Whyte Island; and
- Isolated patches in eroding areas on the seaward fringe of Bulwer Island.

Most of the die-back areas were also observed in previous years, indicating a continuing long-trend trend of mangrove degradation in these areas. In most cases, the change in canopy condition was due to tree fall or canopy thinning in a few trees.

Consistent with previous years, seasonal changes in vegetation indices were observed within the 2018-19 monitoring period. NDVI (Figure 1), SAVI and LAI declined over late spring/summer 2018, but rapidly improved in autumn 2019, coincident with an increase in two-month cumulative rainfall. Past sampling carried out by BMT found that mangrove condition tracked long-term trends in rainfall, consistent with these results.

Conclusions

The results demonstrate that high-resolution satellite imagery, together with targeted field surveys, provide a robust means of tracking mangrove health. The present study indicates that mangrove condition generally improved over 2018 and 2019, and this trend was consistent across test and control sites. Small areas of mangrove die-back were observed at test sites in areas remote from PBPL activities. Some highly localised bank erosion and mangroves falls were observed at Bulwer Island where works have been conducted to improve fish habitat connectivity.

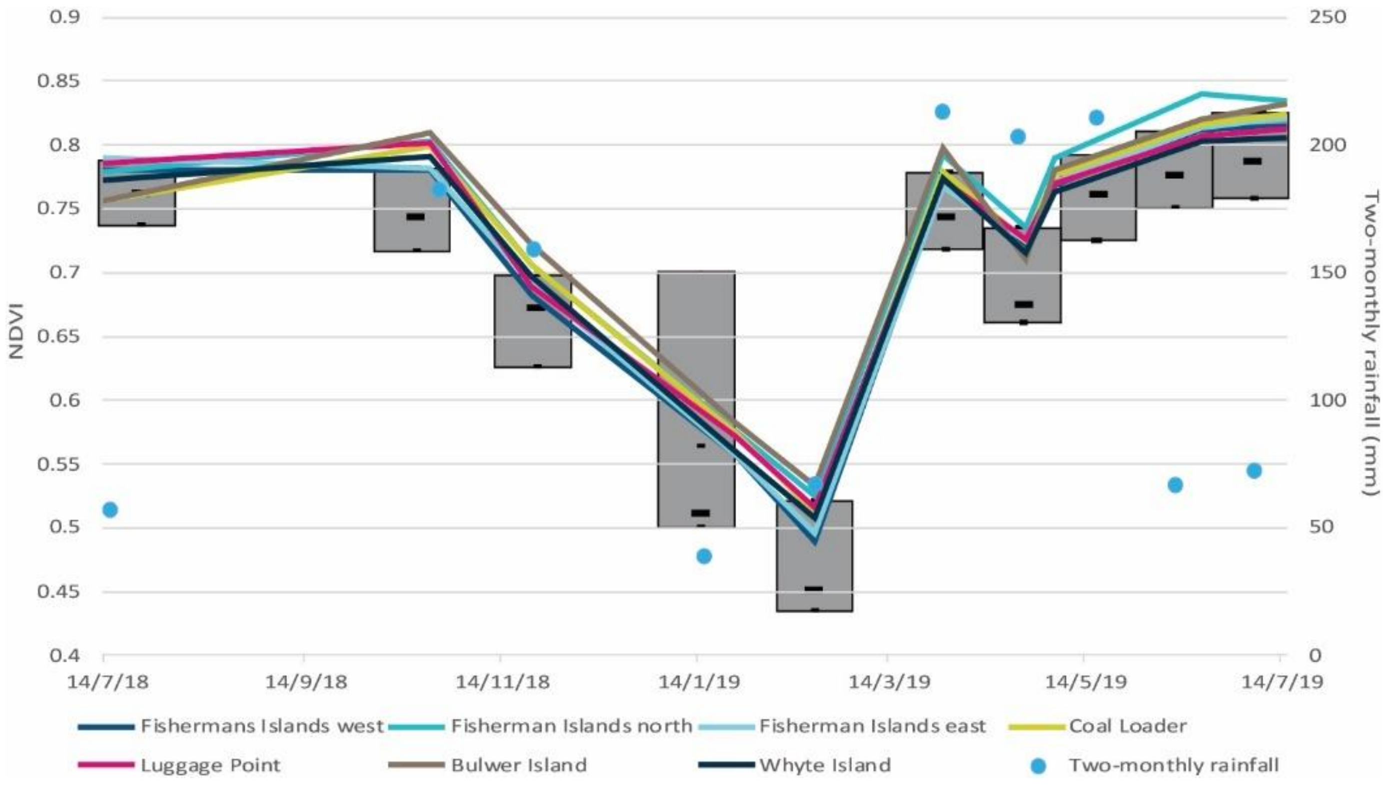

Figure 1 Temporal changes in NDVI and two-month cumulative rainfall at test and control (box plot) sites - July 2018 to July 2019

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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).

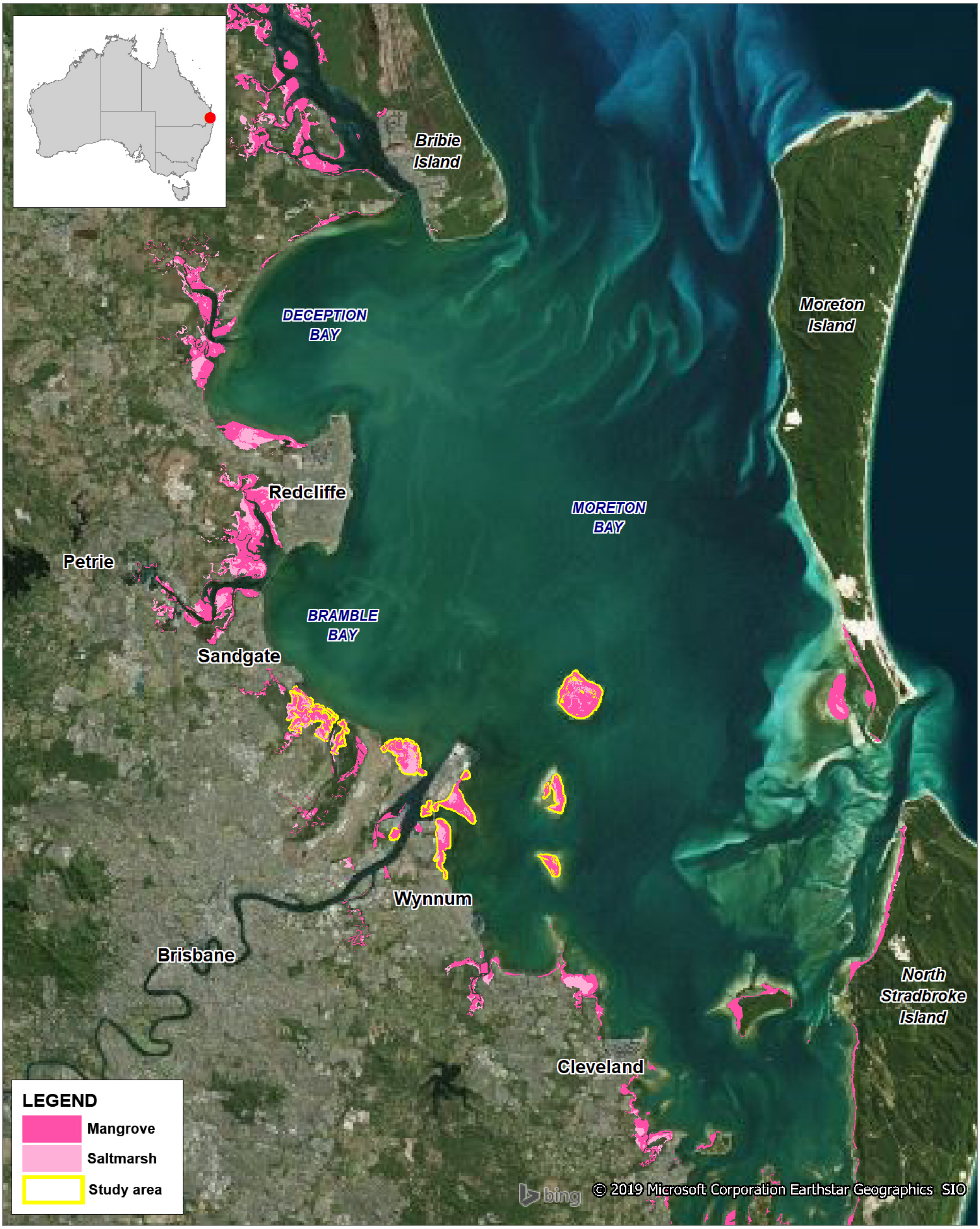
The Port of Brisbane Pty Ltd (PBPL) operates adjacent to these mangrove forests and saltmarsh communities therefore the variation of their health through time and space needs to be monitored and analysed to ensure port activities are not impacting these communities. Monitoring of the mangroves and saltmarsh surrounding the Port of Brisbane has been conducted since the 1990s (WBM 1992; CSIRO 1992; BMT WBM 2016) 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) or during the Millennium Drought (2006-2008). The long-term trend from 1987 to 2018 was decreasing NDVI values, with no evidence of NDVI values recovering to pre-Millennium drought levels.

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:

- Investigate mangrove health using several vegetation indices: NDVI, soil-adjusted vegetation index (SAVI) and leaf area index (LAI).
- Map changes in mangrove health between July 2018 and July 2019 using remotely sensed data and validate using ground surveys.
- Identify potential drivers of mangrove degradation in key investigation areas, namely 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 and Validation

2.1.1 Data Sources

Sentinel-2 imagery (10 m resolution, 12-band) was used to derive vegetation condition metrics for mangrove forests at nine locations (termed investigation areas, refer to Section 2.1.2). Data were acquired for ten periods:

- 14th of July 2018;
- 23rd of October 2018;
- 22nd of November 2018;
- 26th of January 2019;
- 19th of February 2019;
- 31st of March 2019;
- 26th of April 2019;
- 5th of May 2019;
- 19th of June 2019; and
- 15th of July 2019.

Vegetation mapping in Accad *et al.* (2016) was used to identify mangrove forest boundaries. All other vegetation community types were excluded from the analysis.

WorldView2 imagery (2 m multi-spectral, 8-band) was also used to observe finer scale patterns of mangrove health at an individual tree level. The WorldView2 imagery was captured on the 9th of July 2019.

2.1.2 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.

The area (hectares) and pixel counts for mangrove forests in each investigation areas are presented in Table 2-1, 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.

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Test	
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Mangrove health assessment test and control sites

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Table 2-1 Investigation Areas

Treatment type	Investigation area	Area (ha)	Equivalent pixels
Test	Fisherman Islands (main)	181.6	18,161
Test	Fisherman Islands (Coal Loader)	22.9	2,293
Test	Whyte Island/Wynnum	143.9	14,389
Test	Luggage Point	265.8	26,579
Test	Bulwer Island	29.3	29,25
Control	Nudgee Wetlands	366.6	36,667
Control	King Island	68.0	6,803
Control	St Helena Island	126.0	12,596
Control	Mud Island	444.6	44,460
Total		**1648.7**	**164,873**

2.1.3 Spatial Data Processing

2.1.3.1 Vegetation Indices

Atmospherically-corrected bottom-of-atmosphere (BoA) Sentinel-2 data (Level-2A products) were produced using the Sen2Cor processor (Version 2.4.0), developed by the European Space Agency. Level-1C top of atmosphere products were corrected for atmosphere, terrain, and cirrus cloud density using Sen2Cor within the Sentinel Application Platform (SNAP). Three indices were calculated.

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.

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.

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:

$$LAI = \text{leaf area} / \text{ground area}$$

Band-math and atmospheric correction were performed using SNAP 6.0, Sen2Cor, and the Sentinel-2 toolbox (S2TBX). Raster calculations and area of interest queries were performed using ArcGIS 10.5, and presented in MapInfo 15.0.

2.1.3.2 Vegetation Community Mapping

False-colour WorldView2 imagery was used to create community maps of Fisherman Islands. Classification was performed in ArcGIS using maximum likelihood classification. The community classes used for classifying the mangroves were:

- *Avicennia marina* dominated closed to open forest, >10 m canopy height +/- *Aegiceras corniculatum*, *Ceriops australis, Rhizophora stylosa and Bruguiera gymnorhiza;*
- *Avicennia marina* low closed to low open forest, 2-10 m canopy height +/- *A. corniculatum*, *C. australis, R. stylosa and B. gymnorhiza;*
- *Ceriops australis* open to closed to open forest, 2-5 m canopy height +/- *A. corniculatum and A. marina*;
- Saltmarsh; and
- Claypan (including ponded waters).

2.1.4 Rainfall data

Rainfall data was accessed from the Bureau of Meteorology from July 2018 to July 2019. The weather station closest to the study area was 040842 Brisbane Airport. Two monthly cumulative rainfall data were compared with vegetation condition indices.

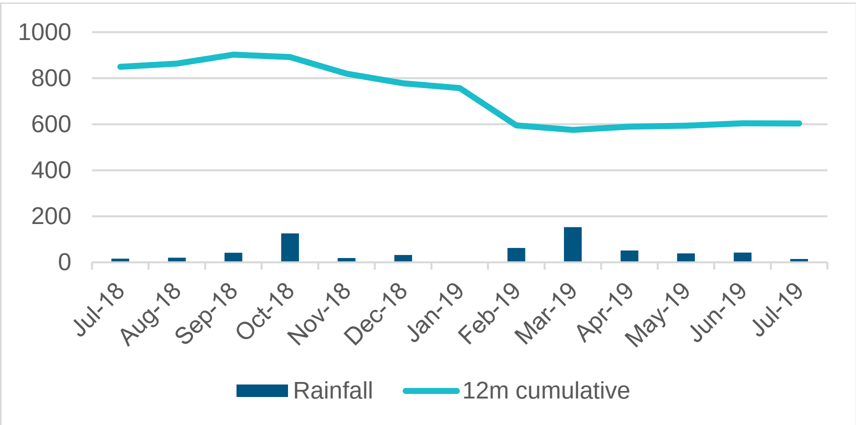


Figure 2-2 Monthly total rainfall and 12-monthly rainfall for the Brisbane Airport (station 040842)

2.1.5 Assumptions and Limitations

The orthorectification of Sentinel-2 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 (salt-pans and dieback regions), variable soil moisture can dominate the signal. Therefore, some interpretation is required in such areas.

3 Results

3.1 Spatial Patterns in Vegetation Indices

3.1.1 High Resolution WorldView2 Imagery - Fisherman Islands

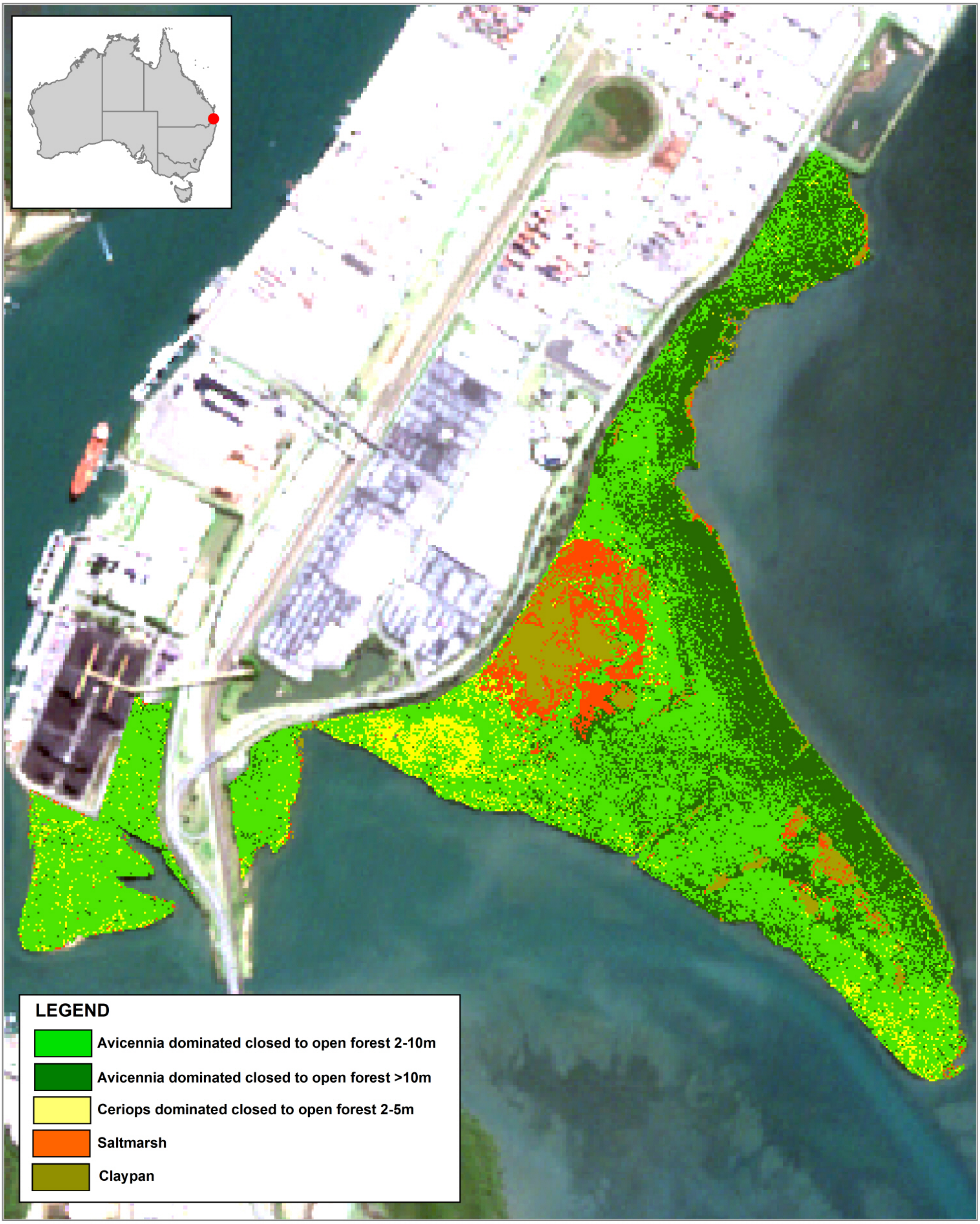
Figure 3-1 is a map of tidal vegetation communities derived using maximum likelihood classification techniques and field survey data presented in BMT WBM (2014; 2016; 2017; 2018). The most extensive mangrove community type at Fisherman Islands was low *Avicennia* dominated forest. Tall *Avicennia*-dominated communities numerically dominate the northern seaward margin of Fisherman Islands, and *Ceriops* copses occur in places. Claypan/saltmarsh communities occur in the central portions of the island. The claypan towards the eastern tip of the island is an area of mangrove die-back that has been converted to ponded waters.

Figure 3-2 is a map of NDVI values for mangrove-dominated communities at Fisherman Islands. NDVI values were highest in tall, closed *Avicennia*-dominated forests and lowest in lowest in the *Ceriops* and *Avicennia* shrublands. There is no evidence of differences in vegetation condition in areas directly adjoining PBPL operational areas (e.g. Coal Loader, Port Drive, Lucinda Drain) and parts of Fisherman Islands distant from operational areas.

3.1.2 Sentinel-2 Imagery – Investigation Areas

Spatial patterns in NDVI, SAVI and LAI are mapped for all investigation areas in Figure 3-4, Figure 3-6 and Figure 3-7, respectively. The three metrics had broadly consistent spatial patterns. The main exception was that SAVI and LAI resolved finer scale differences in mangrove condition than NDVI, most notably between the northern and southern shorelines of Fisherman Islands. The northern side of Fisherman Islands supported taller (BMT WBM 2016) and healthier mangrove forests than the southern shoreline.

The high resolution WorldView2 imagery reveals tree scale patterns in mangrove health WorldView-2 imagery (Figure 3-2) identified fine-scale changes in mangrove condition not discerned through Sentinel-2 imagery (Figure 3-4). In this regard, Worldview2 imagery identified small-scale (individual tree) features of poor health in the northern and western sections of Fisherman Islands, together with greater spatial resolution in term of identifying gaps in the forest canopy. The Worldview2 imagery provided a basis for refining targeted ground inspections described in Section 3.3.



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Mangrove species Fisherman Islands 2019

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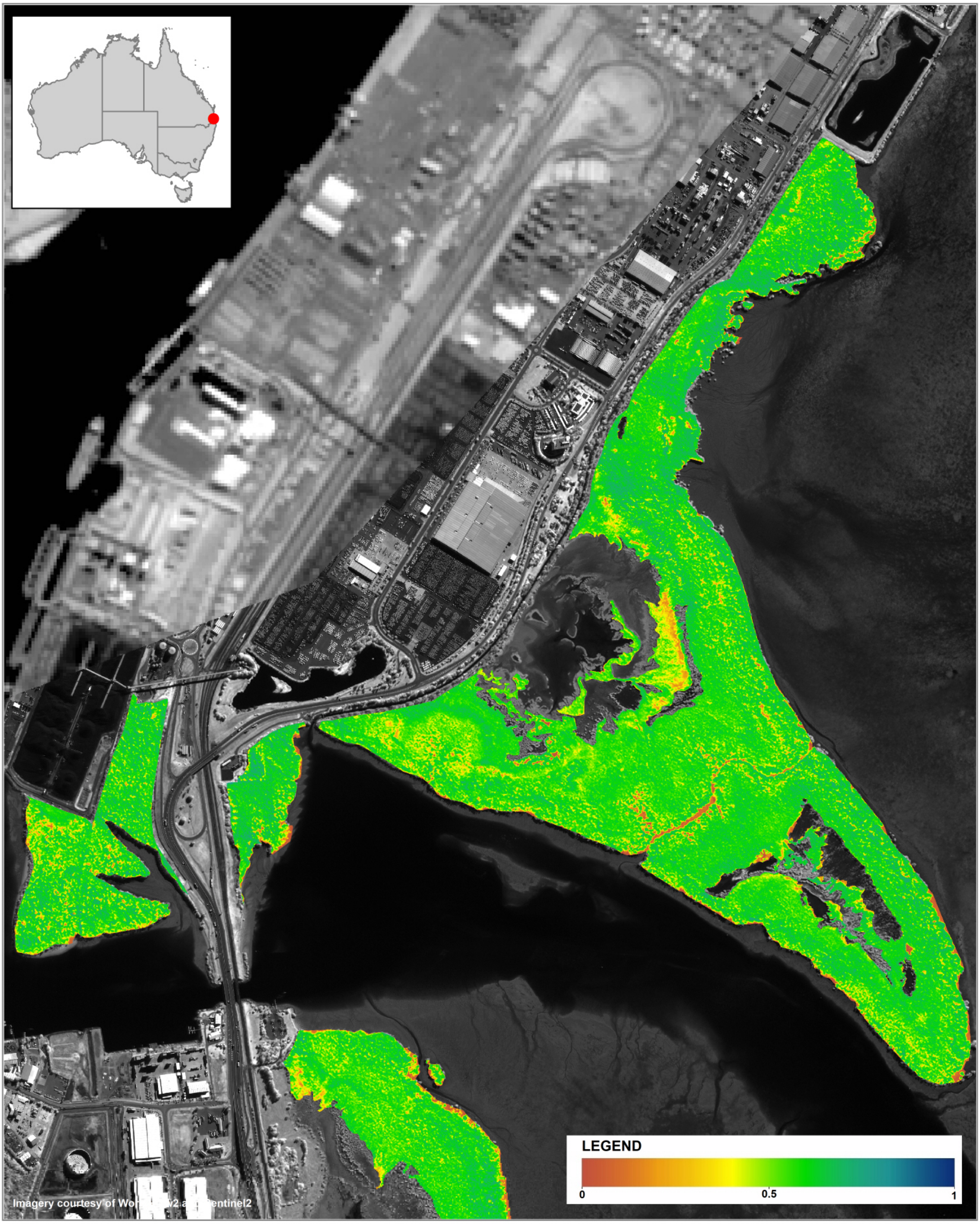

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NDVI WorldView2 July 2019

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3.2 Temporal Trends in Mangrove Condition

3.2.1 NDVI and SAVI

NDVI and SAVI had similar temporal trends, consisting of (Figure 3-3):

- A decline in vegetation condition between winter and spring 2018, extending through to summer 2018-19;
- A minima in vegetation condition during summer 2018-19;
- A rapid improvement in condition in late summer 2019; and
- Gradual improvement in condition throughout autumn and winter 2019, peaking in July 2019.

This temporal pattern was strongest in NDVI and weakest in SAVI.

In all months, NDVI and SAVI values at test sites were consistently within the range or slightly greater than observed at control sites. Mud Island had the lowest overall condition scores whereas Whyte Island and Bulwer Island showed the most marked improvements in condition over time.

The magnitude of temporal change varied within investigation areas. The largest changes in condition among time periods (both declines and improvements) occurred in central portions of mangrove forests, especially mangroves located adjacent to saltpan/saltmarsh areas (see Appendix A and Appendix B).

3.2.2 LAI

LAI time series are shown in Figure 3-3 and spatial representations are mapped in Figure 3-7.

Consistent with NDVI and SAVI, LAI was higher July 2019 than July 2018 at all test locations and most control locations (except St Helena Island). Also consistent with NDVI was the seasonal trend in LAI, with high LAI occurring in spring 2018, a decline over summer 2018-19, and an improvement in late autumn and winter 2019. LAI was uniform between November 2018 and early autumn 2019, unlike the rapid increase observed during early autumn 2019 in NDVI and SAVI.

Temporal differences in LAI are mapped in Figure 3-7 and Appendix C. Like NDVI and SAVI, the magnitude of temporal change varied within locations. In particular, between July 2018 and February 2019 (Figure C-1) there an increase in LAI occurred along seaward and creek fringes while LAI tended to decline in central areas. Mud Island had the greatest reduction in LAI while Bulwer Island and Coal Loader both had an increase in LAI.

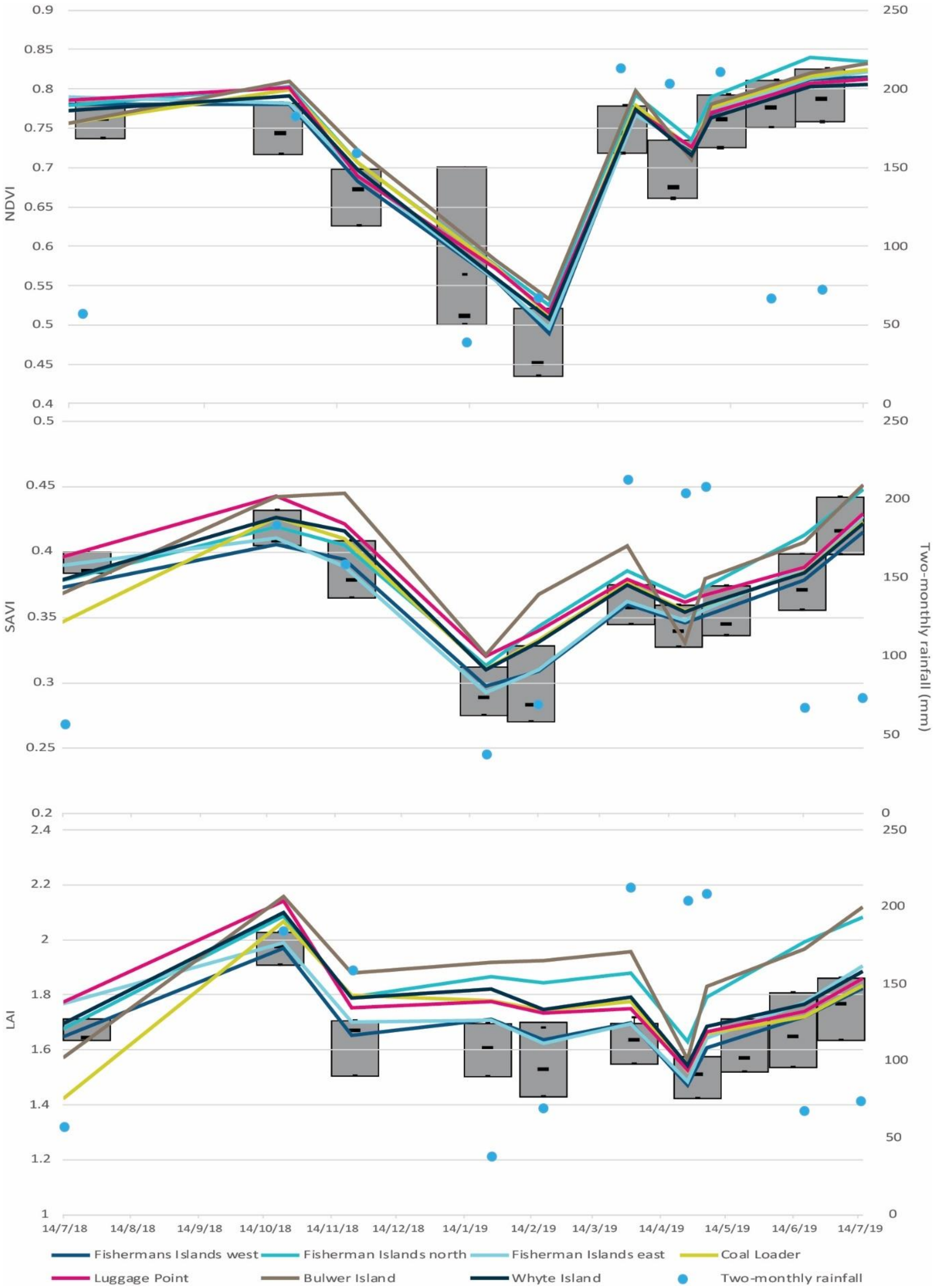
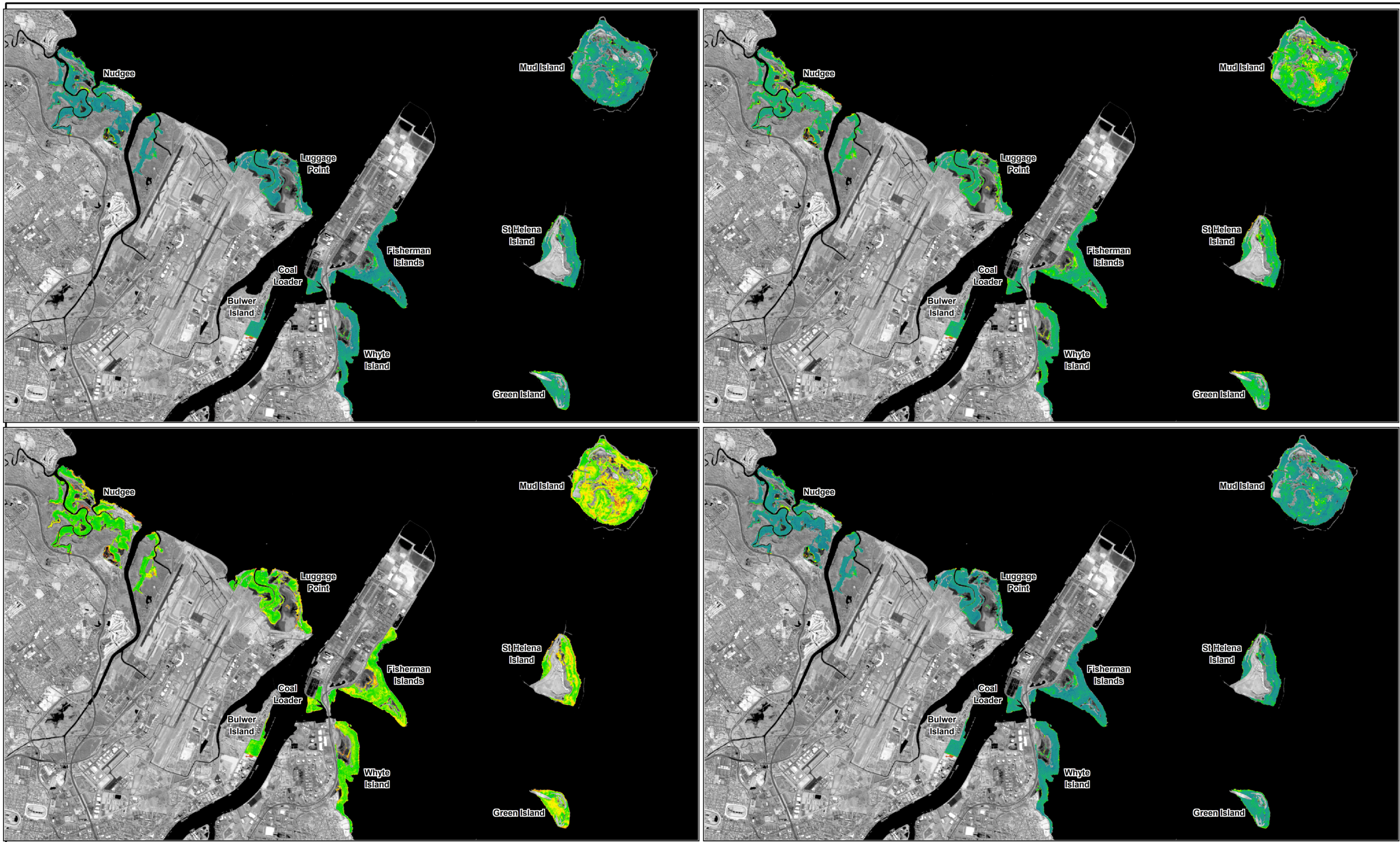


Figure 3-3 Temporal changes in NDVI, SAVI and LAI at Test sites and Control sites (box plots), from July 2018 to July 2019 and two-month cumulative rainfall



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NDVI Score

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NDVI at investigation sites in July 2018, November 2018, February 2019, and July 2019

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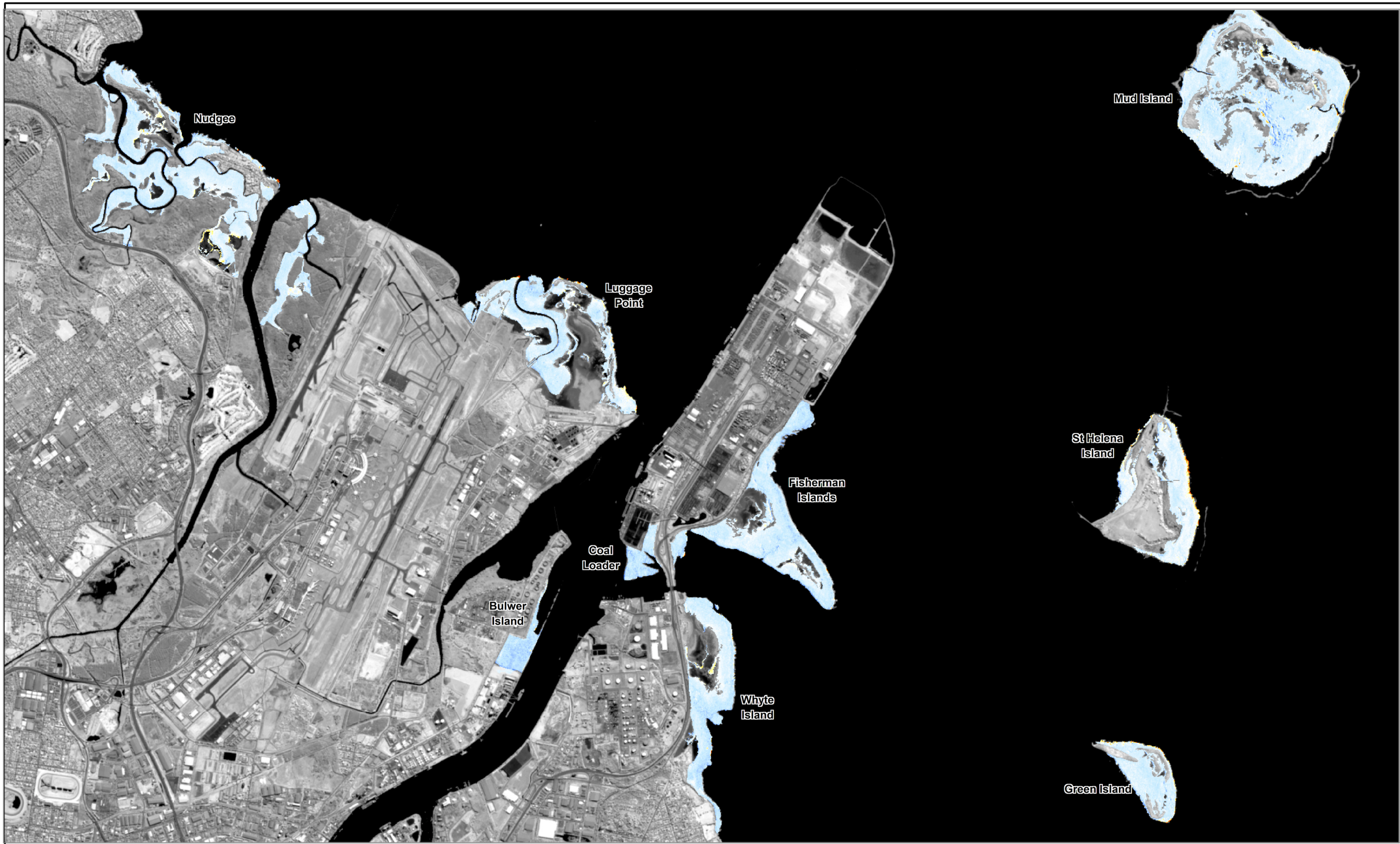

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Changes in NDVI between July 2018 and July 2019

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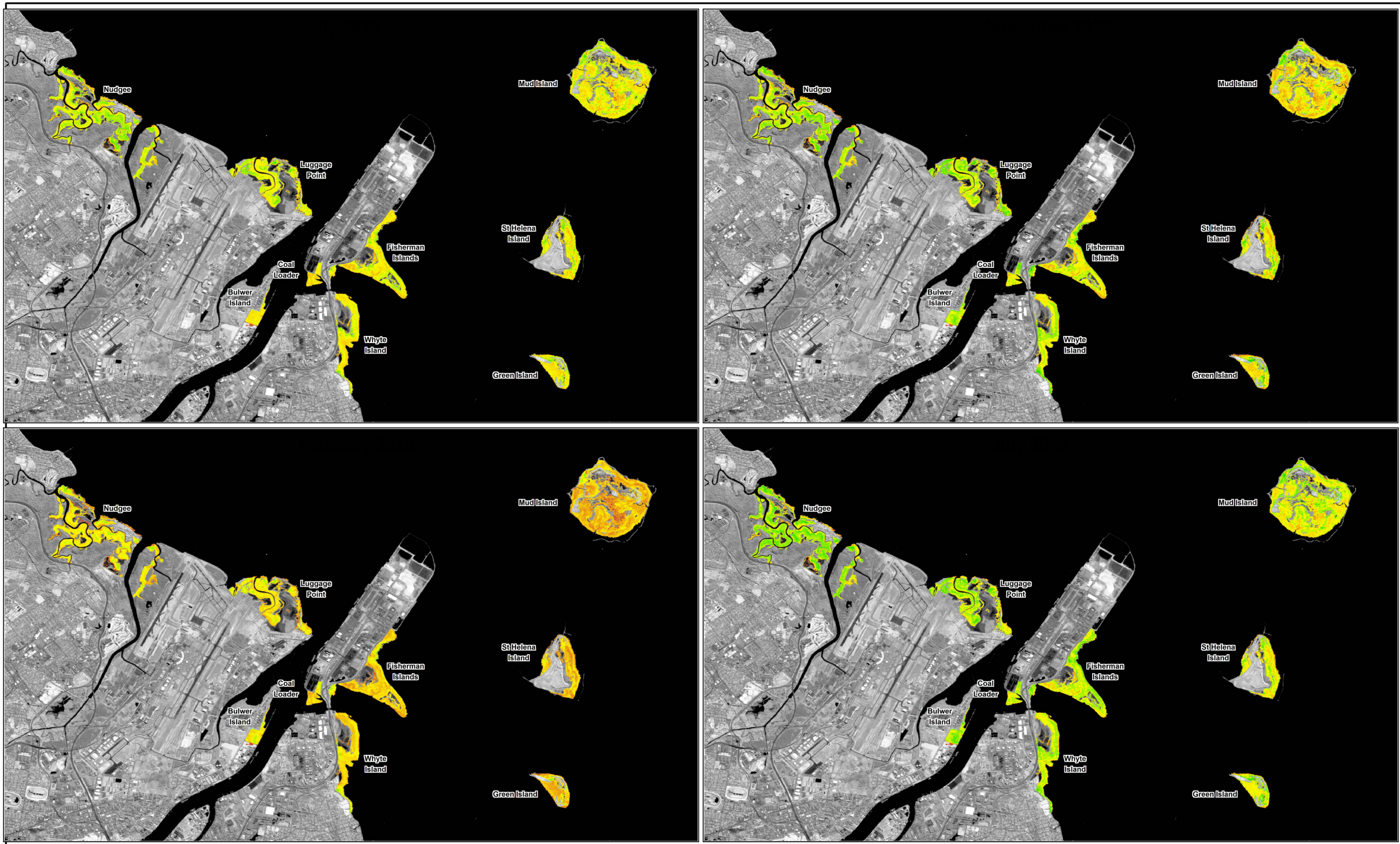

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SAVI at investigation sites in July 2018, November 2018, February 2019, and July 2019

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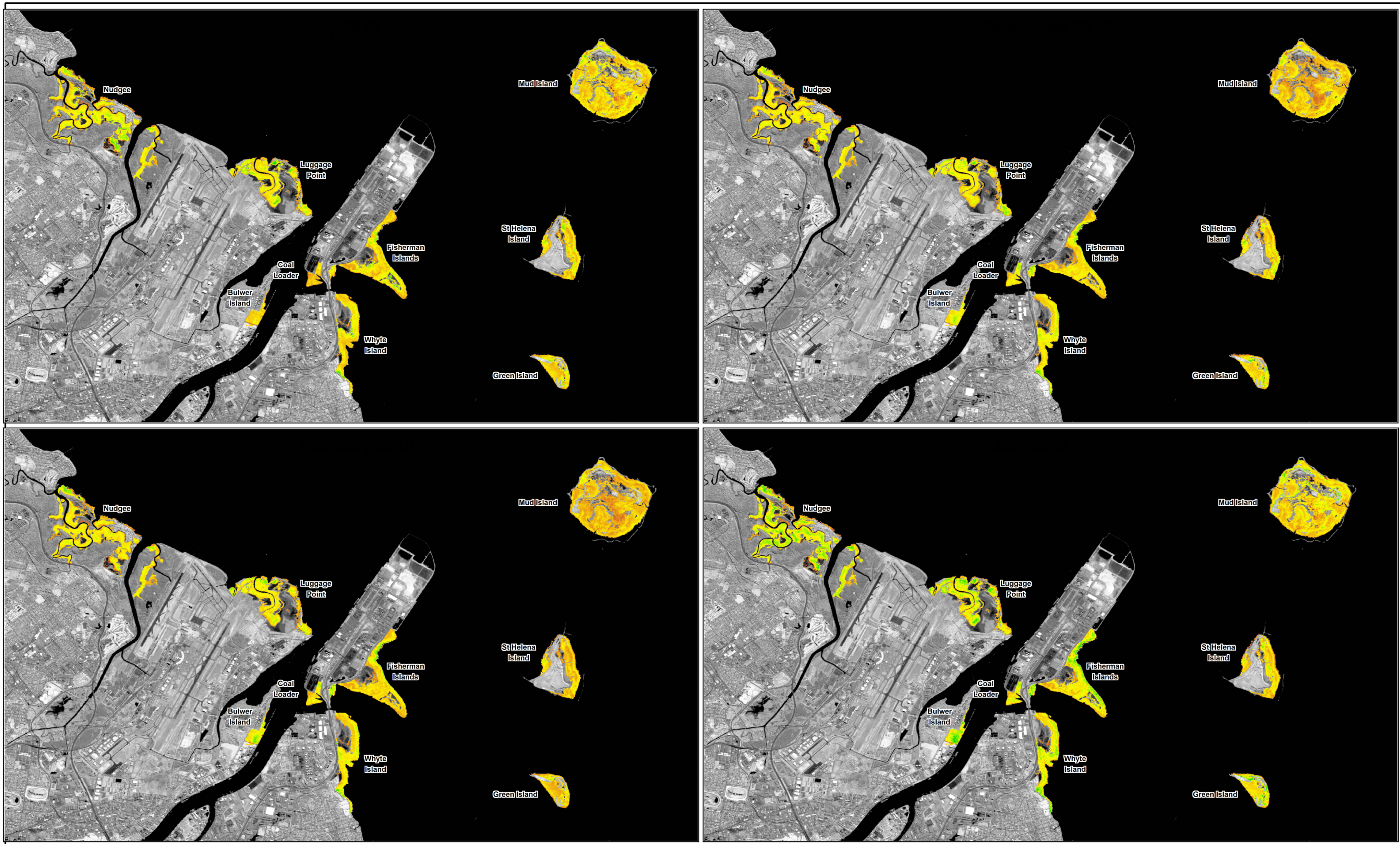

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LAI at investigation sites in July 2018, November 2018, February 2019, and July 2019

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3.3 Site Inspections

Ground-truthing was conducted on the 1st of August at 20 sites (Figure 3-8) where vegetation condition indices indicated a decline or improvement in mangrove condition. There was excellent agreement between remotely sensed data and site observations, as summarised in Table 3-1 (Fisherman Islands) and Table 3-2 (Whyte and Bulwer islands). Declines in mangrove condition were a response to tree-fall, die-back and canopy thinning. Improvements in mangrove condition were a response to seedling recruitment and new growth on mature trees.

3.3.1 Fisherman Islands

3.3.1.1 Areas of Improved Mangrove Health

Fisherman Islands site 1

Site F1 is located on the northern end of Fisherman Islands. In previous years mangrove condition in this patch was in poor condition, but there was improvement over 2018-19. Ground-truthing identified mangrove seedling recruitment had occurred, resulting in a dense mat of seedlings across the site. In addition, established trees had new growth and there the presence of several saplings indicated that recruitment from the previous year was successful.

Coal Loader site 1

In the previous year, mangrove condition at this site was poor. There was a broad-scale improvement in vegetation condition in 2018-19 at the Coal Loader, especially along the seaward fringe. Ground-truthing indicated that the improvement in condition was mainly due to new growth on existing trees.

3.3.1.2 Areas of Decreased Mangrove Health

Fisherman Islands site 2

F2 is located near the landward fringe of the western claypan. Similar to the previous survey, this area experienced an overall decrease in mangrove health. During the ground-truthing survey it was observed that multiple trees had low levels of defoliation.

Fisherman Islands site 3

F3 is located in the mangrove forest adjoining the western claypan. Mangrove health here declined between 2017 and 2018, which continued in the 2018-19 period. Trees were displaying partial and complete die-back, and recent leaf-browning was observed on a few individuals.

Fisherman Islands site 4

F4 is located near F3, near the western claypan. This area was in good condition in 2017-18 but declined in condition during 2018-19. The reduced mangrove condition was due to defoliation.

Fisherman Islands site 5

F5 is located near the edge of the western claypan. This area was in good condition in 2017-18 but declined in condition during 2018-19. *Avicennia* regrowth observed in 2017-18 was experiencing both partial and complete die-back in 2018-19.

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NDVI field validation sites 2019

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Table 3-1 Site inspection results – Fisherman Islands

Location	2019 Site	2017-18 Trend	2018-19 Trend	Observation
FI – northern end near remnant Whyte Is.	F1	Decline	Improvement	Mangrove seedling recruitment
Coal Loader – seaward fringe	C1	Decline	Improvement	New growth on existing trees
FI – edge of western claypan	F2	Decline	Decline	Defoliation/canopy thinning of several trees
FI – edge of western claypan	F3	Decline	Decline	Defoliation/canopy thinning, tree death
FI – edge of western claypan	F4	No change	Decline	Defoliation/canopy thinning
FI – edge of western claypan	F5	Improvement	Decline	Defoliation/canopy thinning, tree death
FI – eastern tip near ponded waters	F6	Improvement	Decline	Tress death, recruitment failure
FI – eastern tip seaward edge	F7	No change	Decline	Minor die-back, but ‘change’ most likely a rectification (measurement) error
FI – eastern tip near ponded waters	F8	No change	Decline	Defoliation/canopy thinning
FI - Boat Passage	F9	Decline	Decline	Treefall (individual tree)
FI - Boat Passage near Port Drive	F10	Variable	Decline	Treefall in response to bank erosion
FI - Boat Passage near Port Drive	F11	Variable	Decline	Treefall in response to bank erosion
FI - Boat Passage near Port Drive	F12	Variable	Decline	Treefall in response to bank erosion

Fisherman Islands site 6

F6 is located adjacent to ponded waters on the eastern tip of Fisherman Islands. This area was in good condition in 2017-18 but declined in condition during 2018-19. Death of mature trees was observed, and unlike in 2017-18, no seedlings were observed in this area.

Fisherman Islands site 7

F7 is located on the seaward fringe of the eastern tip of Fisherman Islands. Unlike trends in previous years, this site had a decrease in mangrove health in 2018-19. Some die-back along the edge but not enough to explain the large area of decrease in mangrove health and therefore may have been a result of rectification error.

Fisherman Islands site 8

F8 is located near Fisherman Islands site 6. This area was in good condition in 2017-18 but declined in condition during 2018-19. Minor defoliation was observed in the upper and lower canopy, however new regrowth was also observed on several trees.

Fisherman Islands site 9

F9 is located on the southern margin of Fisherman Islands, near the mouth of the unnamed channel that intersects the island. Mangrove health here declined between 2017 and 2018, which continued in the 2018-19 period. The decline in NDVI was a result of a tree fall.

Fisherman Islands site 10

F10 is located on Boat Passage. This site displayed no clear trend in condition in the previous period but declined in condition over 2018 and 2019. The decline in condition was due to tree fall (three individuals) resulting from bank erosion.

Fisherman Islands site 11

F11 is located on Boat Passage. This site displayed no clear trend in condition in the previous period but declined in condition over 2018 and 2019. The decline in condition was due to tree fall. Numerous cable roots were present, indicating changes in sediment erosion and accretion processes.

Fisherman Islands site 12

F12 is located on Boat Passage. This site displayed no clear trend in condition in the previous period but declined in condition over 2018 and 2019. The decline in condition was due to tree fall resulting from bank erosion.

3.3.2 Whyte Island

3.3.2.1 Areas of Improved Mangrove Health

Whyte Island site 1 is located on the northern side of the central Whyte Island claypan. In previous years mangrove condition in this patch was in poor condition, but there was improvement over 2018-19. Ground-truthing identified that recovery of trees previously in poor condition, and seedling recruitment.

Table 3-2 Site inspection results – Whyte Island and Bulwer Island

Location	2019 Site	2017-18 Trend	2018-19 Trend	Observation
WI – northern end of the claypan	W1	Decline	Improvement	Mangrove seedling recruitment, regrowth
WI – eastern margin	W2	Variable	Decline	Defoliation/canopy thinning, leaf yellowing, tree death
WI – western margin of claypan near Port Drive	W3	Variable (some regrowth)	Decline	Defoliation/canopy thinning of several trees
WI – central claypan	W4	Improvement	Decline	Defoliation/canopy thinning, tree death
WI – central claypan	W5	Improvement	Decline	Defoliation/canopy thinning
WI – southern shoreline	W6	Improvement	Decline	Defoliation/canopy thinning, leaf browning
BI – northern fringe	B1	Decline	Decline	Defoliation/canopy thinning, tree fall
B2 – entrance opening	B2	Decline	Decline	Defoliation/canopy thinning, tree fall in response to erosion

3.3.2.2 Areas of decreasing mangrove health

Whyte Island site 2

W2 is located on the eastern fringe of Whyte Island. This site displayed no clear trend in condition in the previous period but declined in condition over 2018 and 2019. Mangroves in this area were in poor condition, manifested as leaf yellowing, canopy thinning, and tree death.

Whyte Island site 3

Whyte Island site 3 is located on the landward side of Whyte Island. Several old dead trees were present indicating historical die-back. Mangrove condition declined during 2018-19, a result of canopy defoliation.

Whyte Island site 4

Whyte Island site 4 is located on the southern edge of the main claypan. Unlike trends in previous years, this site had a decrease in mangrove health in 2018-19. A stand of mature trees had die-back and leaf loss. This die-back area was slightly more elevated than the surrounding mangroves and was surrounded by a dense stand of saplings. This stand of saplings appears to have constricted water flows to the die-back area.

Whyte Island site 5

W5 is located near W4, on the southern side of the claypan. Unlike trends in previous years, this site had a decrease in mangrove health in 2018-19. Minor canopy thinning and leaf-browning was observed at this site.

3.3.3 Bulwer Island

Bulwer Island site 1 and 2 were located on the seaward fringe of Bulwer Island and both had a decrease in mangrove condition, continuing trends observed in 2017-18. Newly fallen *Avicennia* were observed at site B1 along with some defoliating trees. Fallen and newly dying trees were also observed at site B2, and the presence of exposed cable roots suggest that the area was eroding.

4 Discussion

4.1 Temporal Patterns in Mangrove Health

The present study identified cyclic changes in NDVI, SAVI and LAI over the 2018-19 monitoring period:

- From July 2018 to October 2018 there was an improvement in all condition metrics, but less so in NDVI. Two-month cumulative rainfall also increased over this period.
- From October 2018 to January-February 2019 there was a gradual decline in NDVI and SAVI, whereas LAI displayed an initial decline but remained stable over summer. The decline in mangrove condition over summer was consistent with the seasonal trends (winter-peak, summer-decline) reported by BMT WBM (2016; 2017; 2018). Superimposed on this long-term seasonal cycle, this period also experienced below average low rainfall.
- From February 2019 to March 2019 there was a rapid improvement in all vegetation indices across the investigation sites, and a steady improvement in most months thereafter. The February-March period experienced a spike in two-month cumulative rainfall coincident with the rapid improvement in mangrove condition.
- LAI differed to the other indices in that its lowest point was observed in April across all investigation sites, this is a two-month lag to the decrease in 12-month cumulative rainfall.

As discussed in BMT WBM (2016), temporal cycles in plant health are complex and the drivers not fully resolved. The key temporal trends are:

- The summer-minima/winter-peak seasonal cycle. This cycle is consistent from year to year (BMT WBM 2016; 2017; 2018; present study). This seasonal cycle is not explained by rainfall, as the seasonal rainfall pattern is the reverse of this trend. Potential drivers include increased temperature (e.g. heat stress) and solar irradiance (e.g. increased photosynthetically active radiation available for photosynthesis reducing energy demands) during summer.
- Short to medium term responses to rainfall. While mangrove condition tends to improve following rainfall events, patterns are complex and vary over time (Figure 4-1). In some month's mangrove condition shows rapid response to rainfall (e.g. peaks >150 mm in November 2018 and March 2019), whereas in other months there was a lag of several months between rainfall peaks and changes to mangrove condition (peaks >150 mm in April 2017 and May 2018). These complex patterns are likely driven by temporal variations in ground water recharge and surface water runoff (BMT WBM 2016). Depending on soil type, vegetation community structure, rainfall and ground water, ground water tables are often recharged in the magnitude of months (Alongi 2009). Surface water runoff, which can reduce soil salinity and deliver nutrients, likely influences mangroves over shorter time-scales.
- Long-term responses to rainfall. BMT WBM (2016) found that inter-annual patterns in NDVI tracked El Niño–Southern Oscillation (ENSO) cycle. The period of July 2018 to July 2019 represented weak El Niño conditions (Figure 4-2Figure 4-1). Despite this, the rainfall peak during late summer 2019 appears to have sustained mangroves over late autumn to winter 2019.

Mangrove condition during the July 2019 measurement period was higher than observed in July 2017 and 2018, which came off the back of strong El Niño period (Figure 4-1).

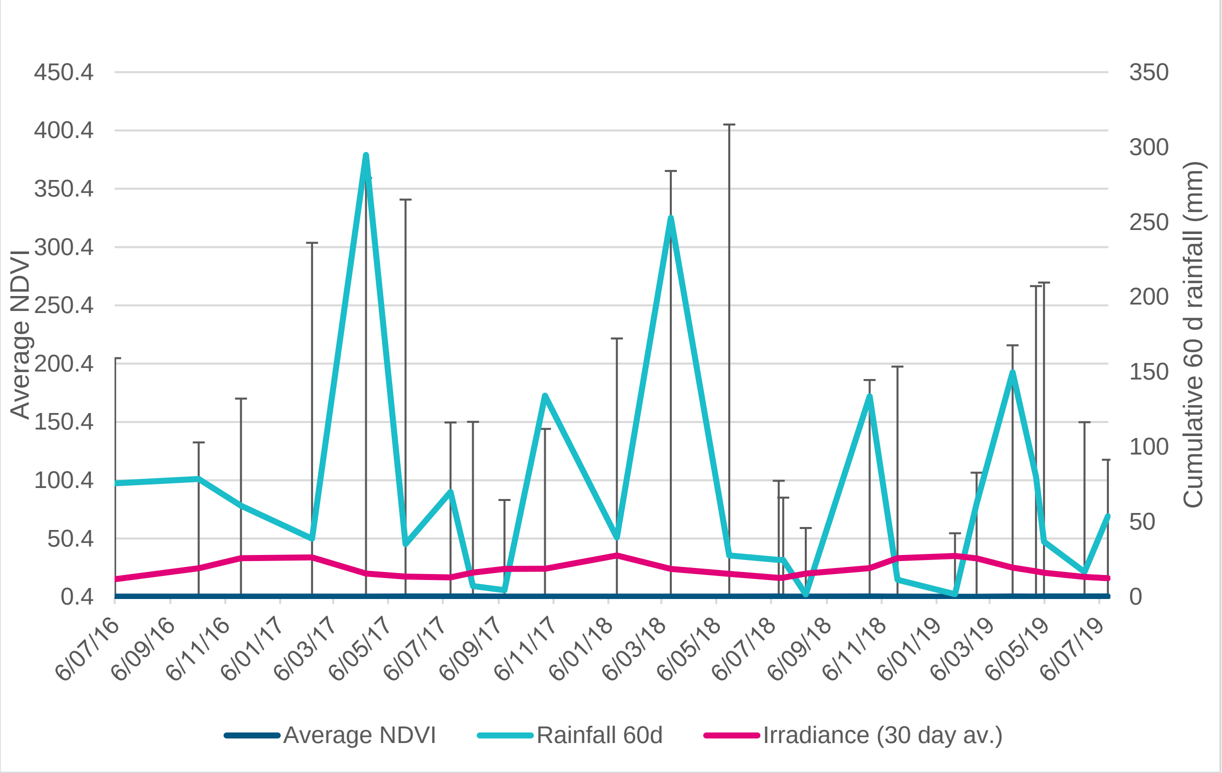

Figure 4-1 Average (± S.E.) NDVI based on Sentinel2 data, and cumulative 60 day rainfall and 30 day average irradiance MJ m^{-2} (Bureau of Meteorology station 040842)

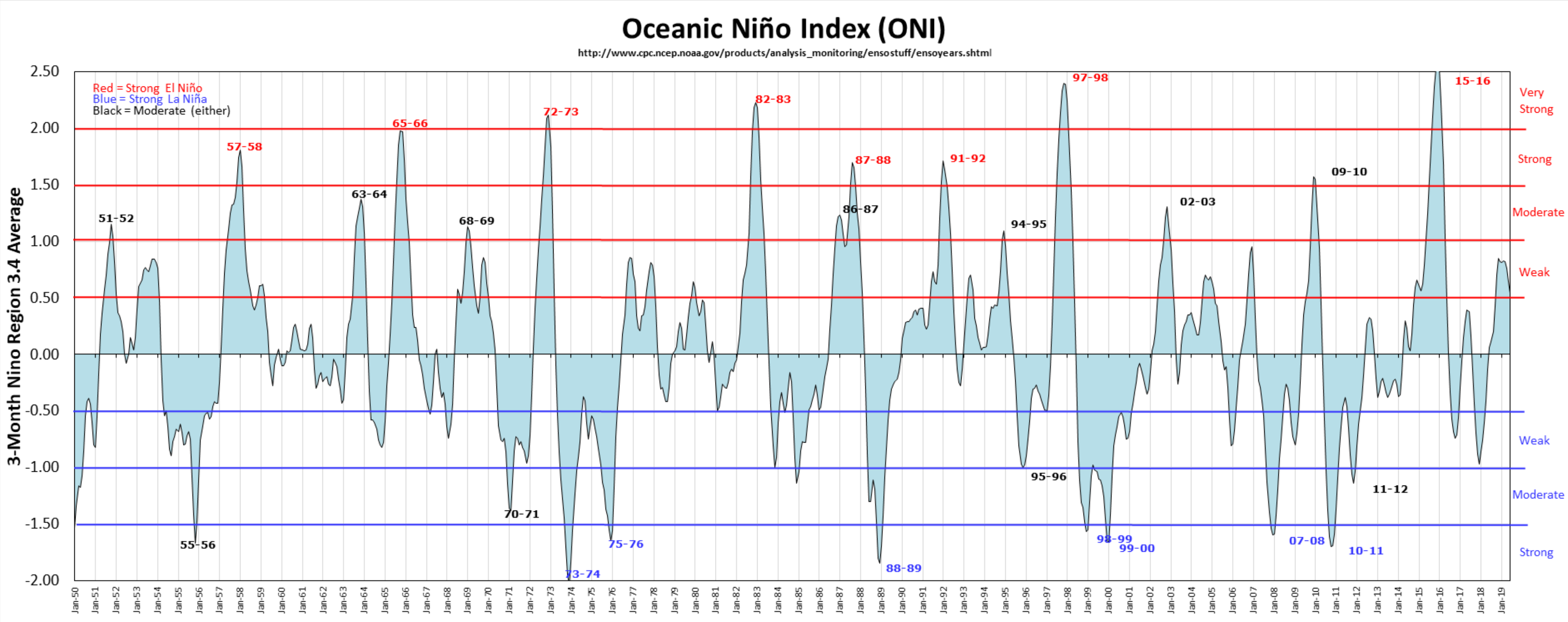

Figure 4-2 Oceanic Nino Index 1955-2019 (NOAA)

4.2 Local Scale Spatial Patterns in Mangrove Health

Vegetation community metrics were higher in July 2019 than July 2018 at a study area wide scale, however there were several mangrove patches which declined in condition over this period. Spatial patterns in mangrove condition are described below.

Mangrove forests along the seaward margins tended to be good condition, as evidenced by high canopy chlorophyll levels and the tall growth form of trees. The seaward mangrove areas are well-flushed by tides and therefore not subject to high levels of water (salinity) stress. Some degraded mangrove patches were detected along the seaward margins, and in all cases the cause appeared to be bed and bank erosion. Key areas of mangrove loss were:

- the mangrove fringe along Boat Passage near Port Drive. This area has eroding banks, resulting in exposure of mangrove roots and localised instances of tree fall. This erosion has been occurring since at least the late 1990s (WBM 2000), however it is not certain whether the rate of change has changed over time.
- mangrove fringe at Bulwer Island near entrance opening works. This area was also subject to bed erosion, most likely in response to capital works (i.e. partial wall removal) to improve connectivity between the Brisbane River and the mangrove forest. This erosion is highly localised, with only a few trees adversely affected.

Highly localized mangrove defoliation and die-back was observed in the interior portions of mangrove forests during the measurement period. Areas that are not regularly flushed (i.e. inland portions of forests, saltpans) accumulate salts, which can lead to physiological stress to plants. This is termed 'water' stress and is the key control of tidal vegetation community structure, especially at the mangrove/saltpan interface (see review by BMT WBM 2016). Extended drought conditions are forecast over the summer 2019-20, which is predicted to result in further mangrove die-back in the interior forest portions.

There was no evidence that PBPL activities were impacting mangrove health at Fisherman Islands. While Sentinel2 imagery identified a small area of degraded mangroves near port facilities, this appears to be a rectification issue as it is not observable on the high resolution WorldView2 imagery.

4.3 Recommendations

The three vegetation indices show broadly similar spatial trends in mangrove health across all investigation areas. Previous research has found similar relationships between both NDVI and SAVI with LAI (Green *et al.* 2018; Diaz and Blackburn 2003). LAI is more sensitive to canopy gaps than the other indices which was evident in areas of *Avicennia* shrubland and *Ceriops* forests which have sparser canopy cover. SAVI appears to be more sensitive to the change in health between different communities.

On this basis, it is recommended that all three indices are considered in future monitoring.

5 Conclusions

The present study found that:

- Different vegetation indices are generally complementary in that they found similar mangrove health patterns both temporally and spatially.
- Key locations of poor mangrove health were identified by remote sensing and verified by ground-truthing.
- Mangrove condition during July 2019 was higher than July 2017 and 2018.
- While there was a broad-scale improvement in mangrove condition over the period, small areas of mangrove degradation were recorded.
- The drivers of mangrove degradation varied spatially. Mangrove loss in seaward fringes were a result of bank erosion. Mangrove degradation further inland appear to be a response to water stress caused by prolonged dry conditions.
- It is predicted that further mangrove degradation will occur over summer 2019-20 in response to the (forecast) low rainfall conditions.
- There is no evidence that PBPL activities are impacting mangrove health at Fisherman Islands. Habitat restoration works at Bulwer Island appear to have resulted in highly localised bed erosion and the loss of several trees.

6 References

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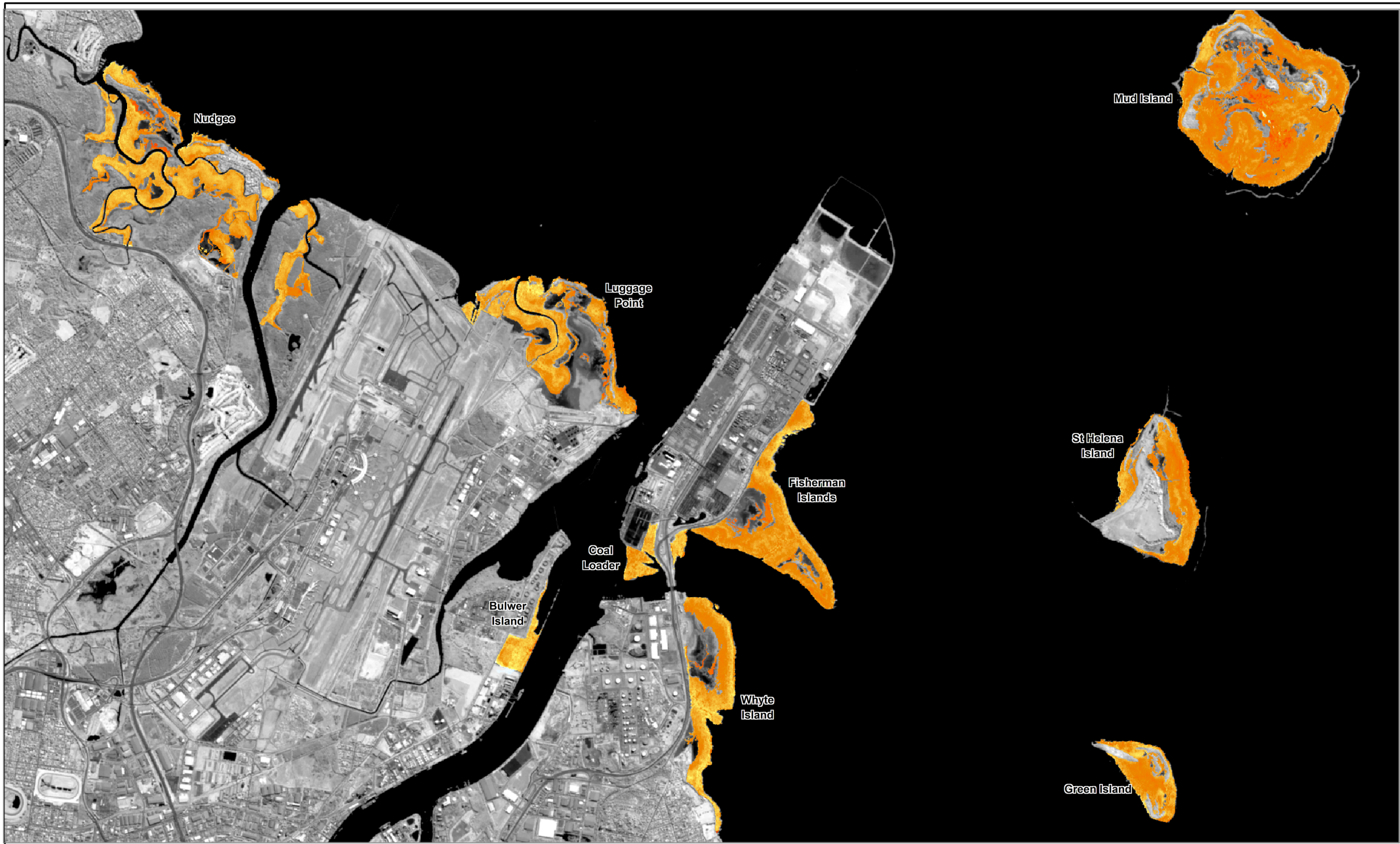
Appendix A Changes in NVDI



LEGEND

NDVI Change Score

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Title:

Changes in NDVI between July 2018 and Feburary 2019

Figure: **A-1**

Rev: **A**

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Approx. Scale

BMT

www.bmt.org

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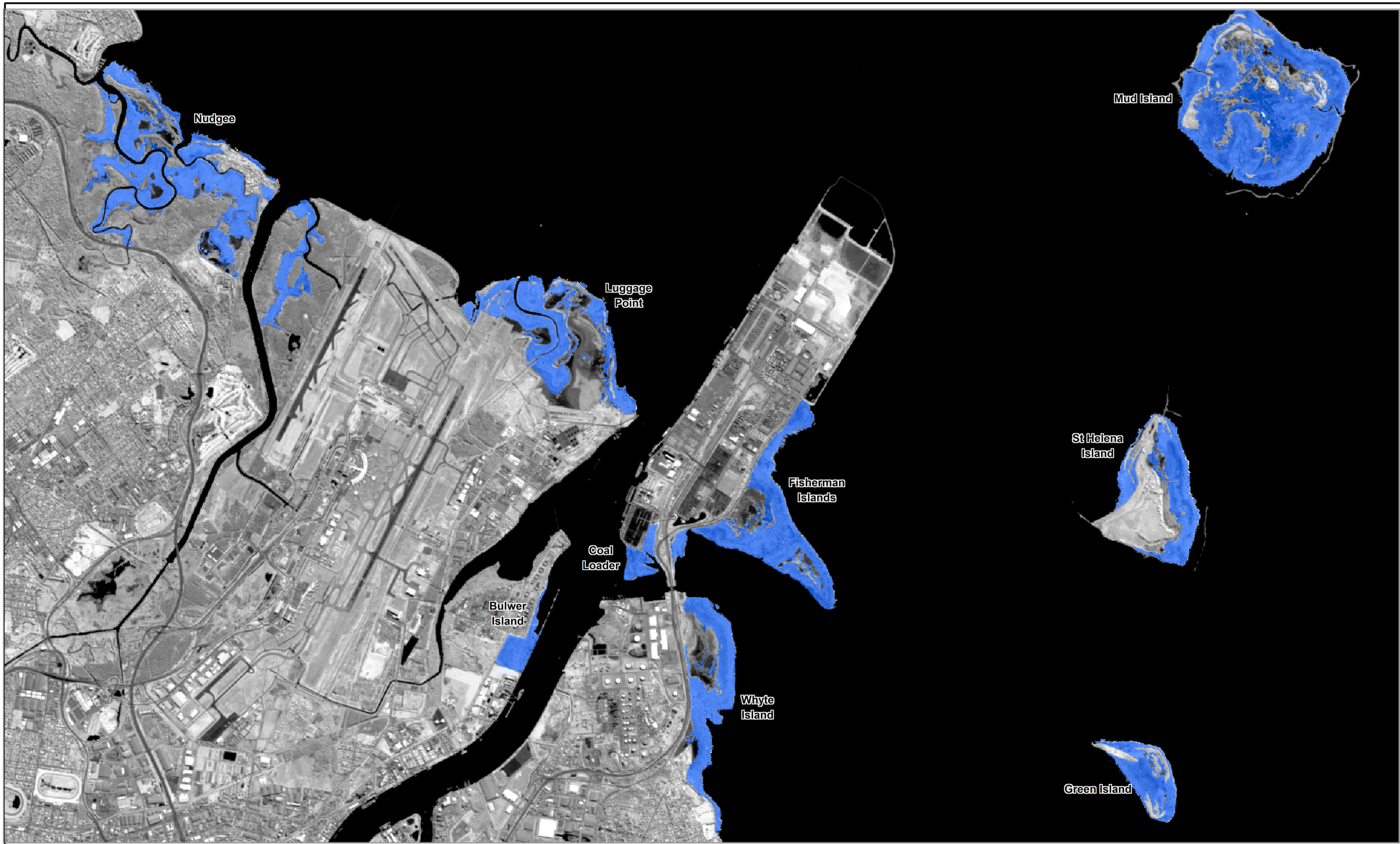

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Figure: **A-2**

Rev: **A**

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Approx. Scale

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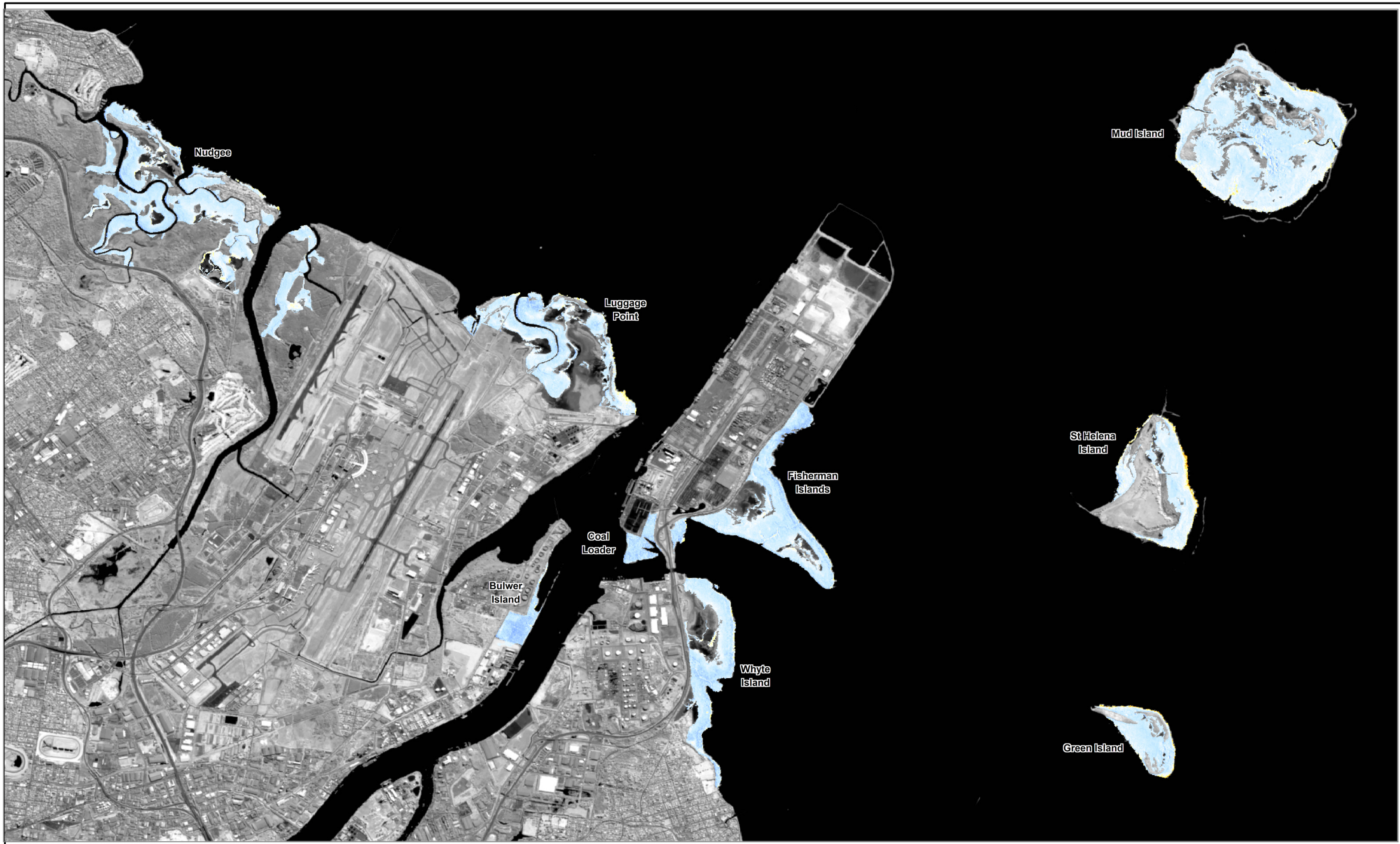
Appendix B Changes in SAVI



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Rev: **A**

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Approx. Scale

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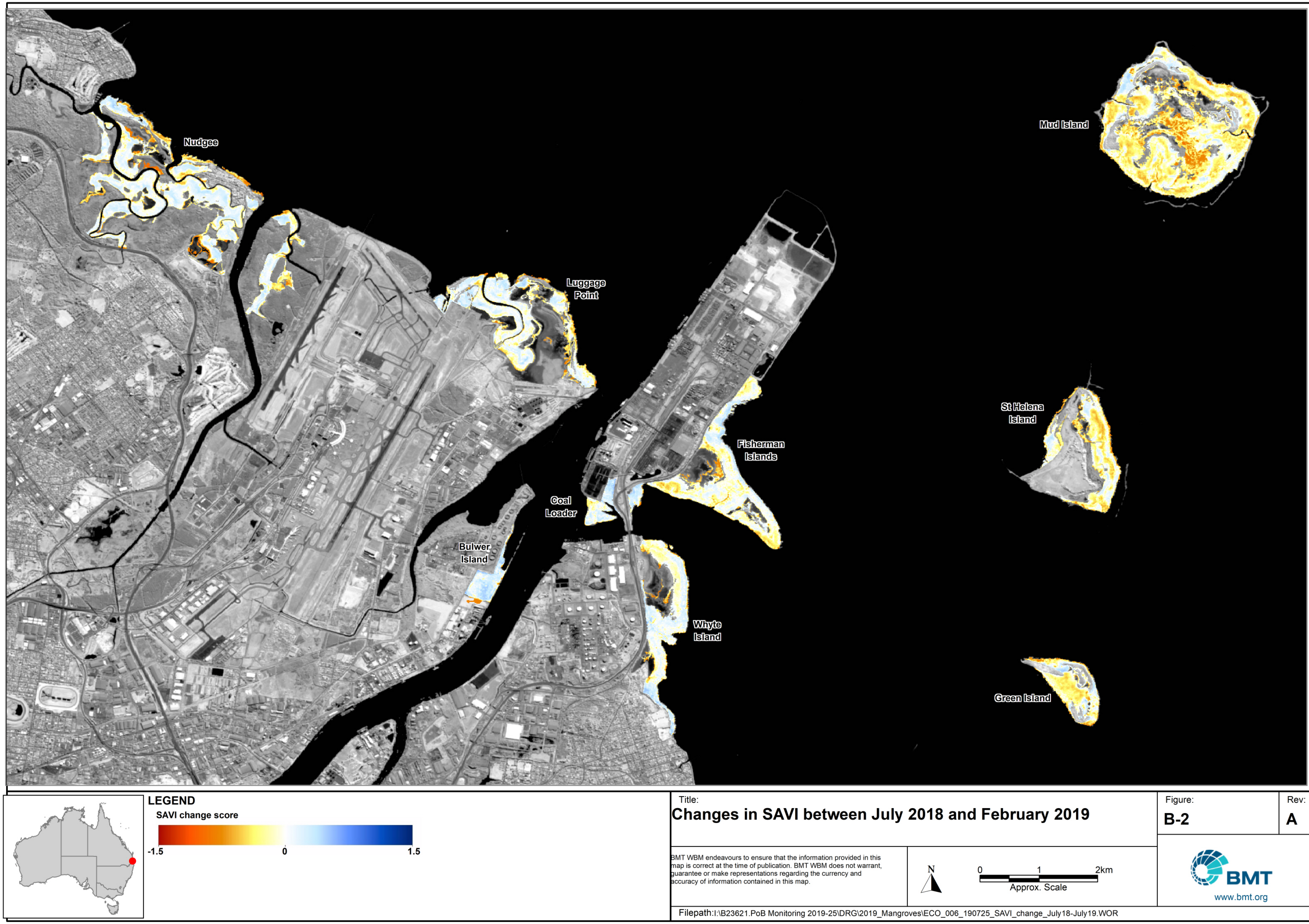

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Rev: A

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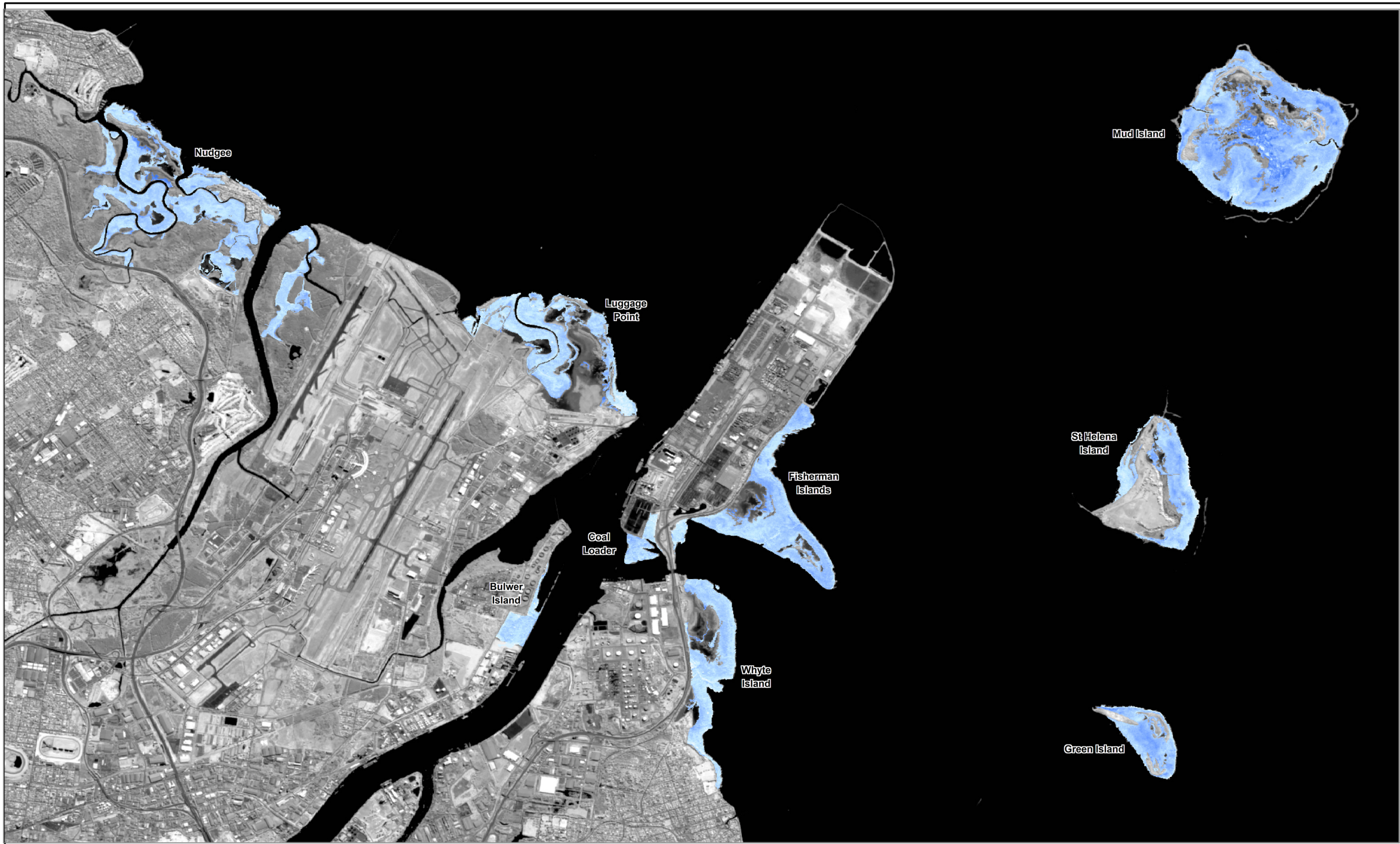

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Title:

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Figure: **B-3**

Rev: **A**

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Approx. Scale

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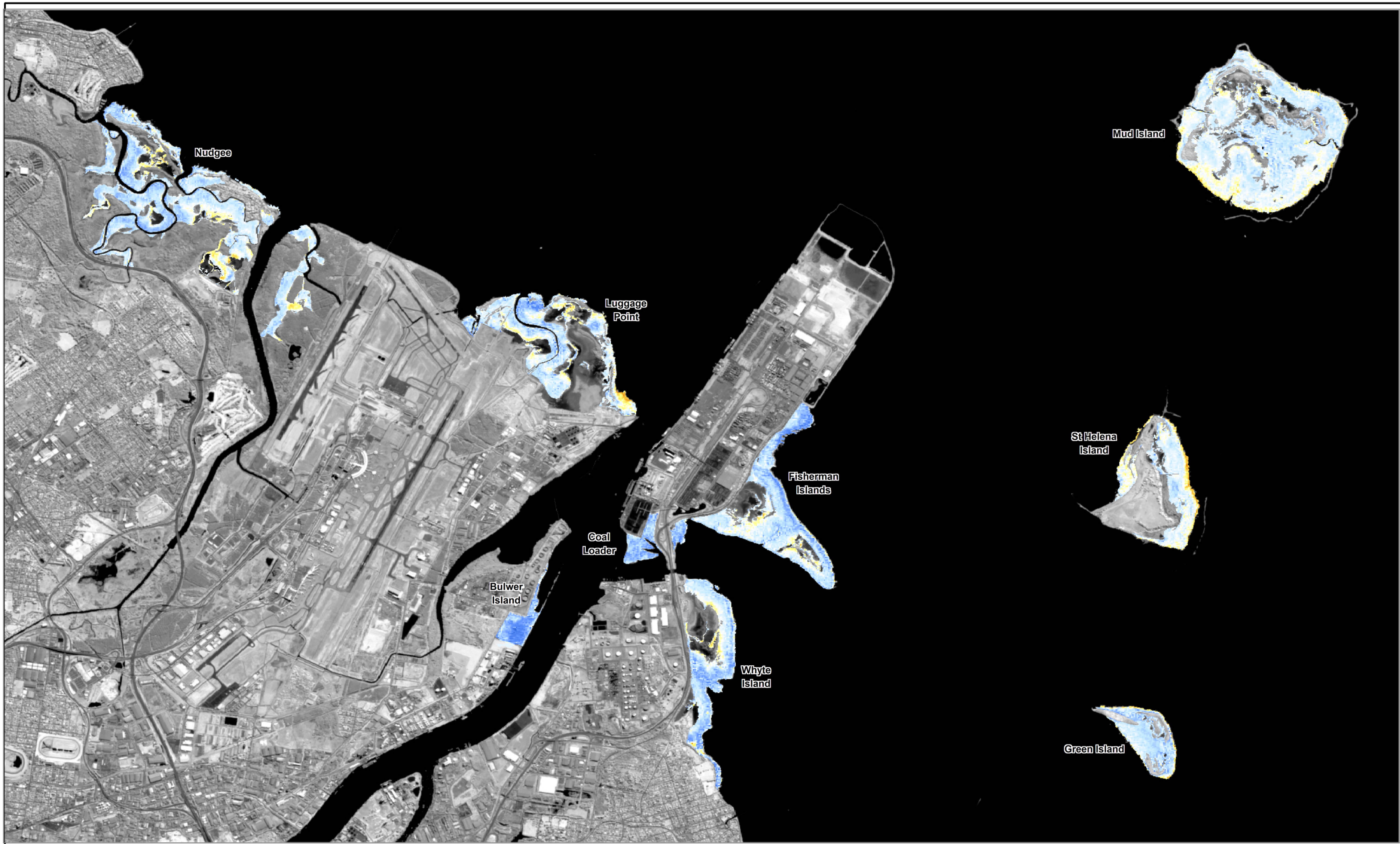
Appendix C Changes in LAI



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LAI Change Score

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Title:

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Figure: C-1

Rev: A

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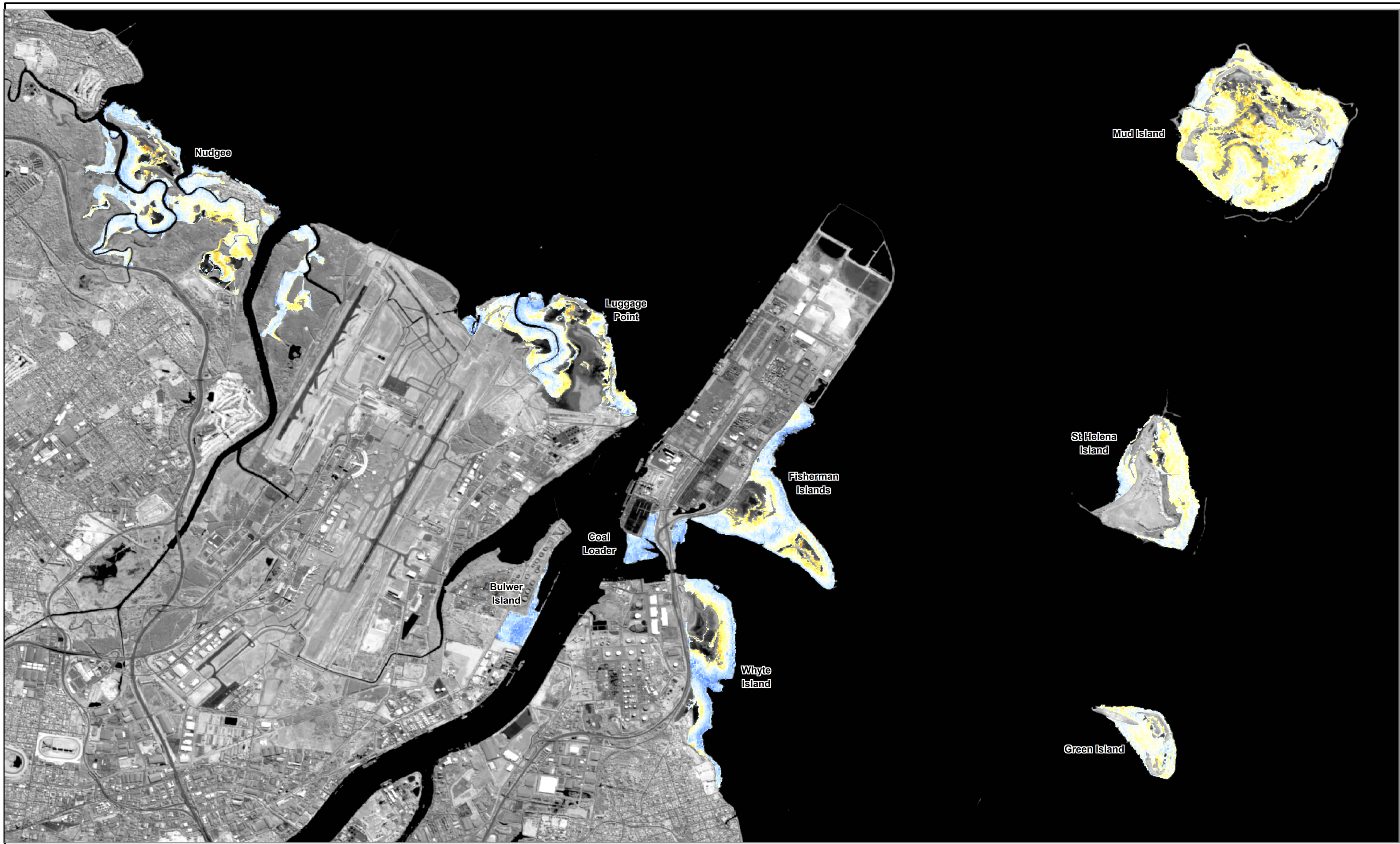

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Figure: C-2

Rev: A

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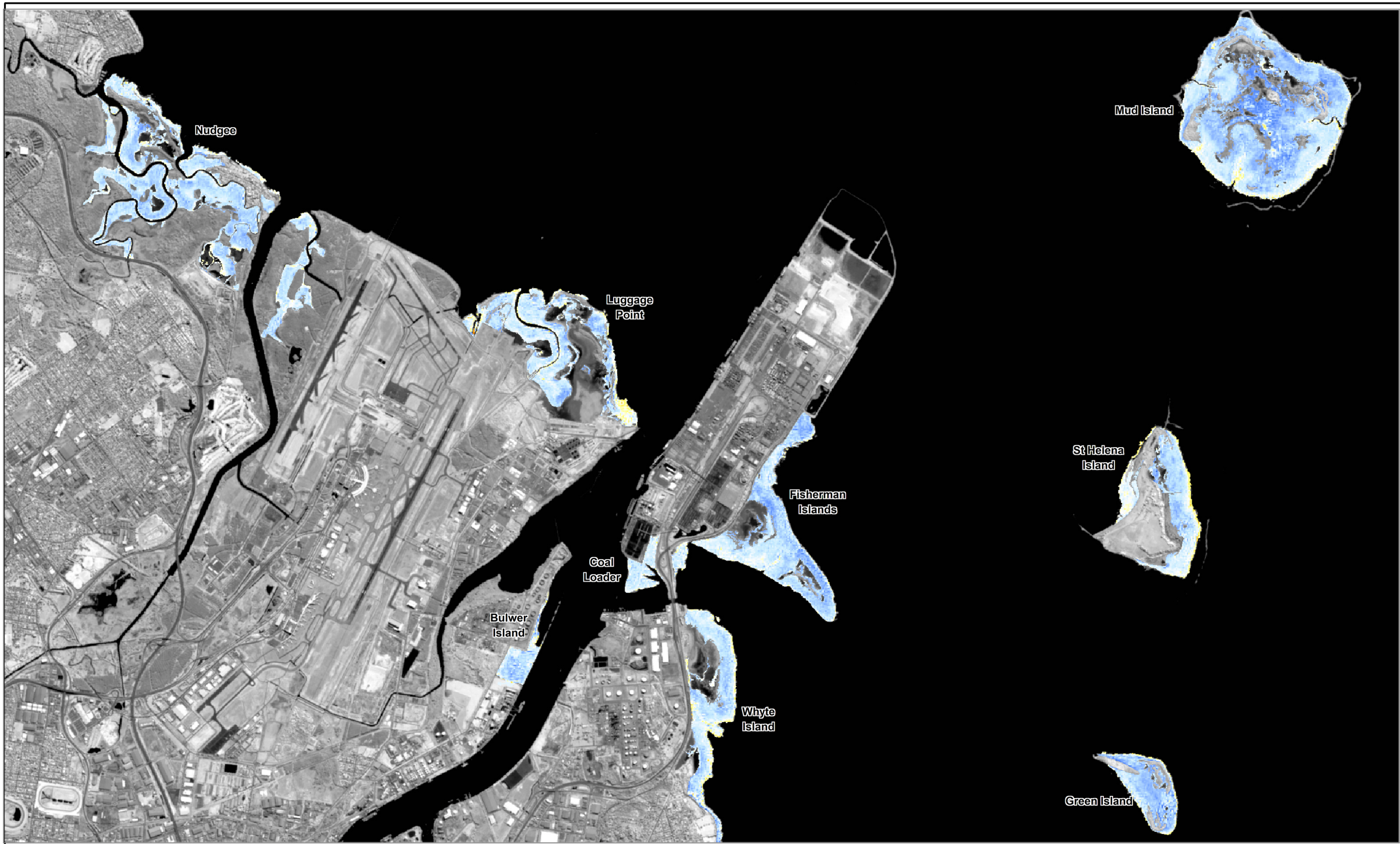

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Title:

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Figure: C-3

Rev: A

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Appendix D Field Validation Images

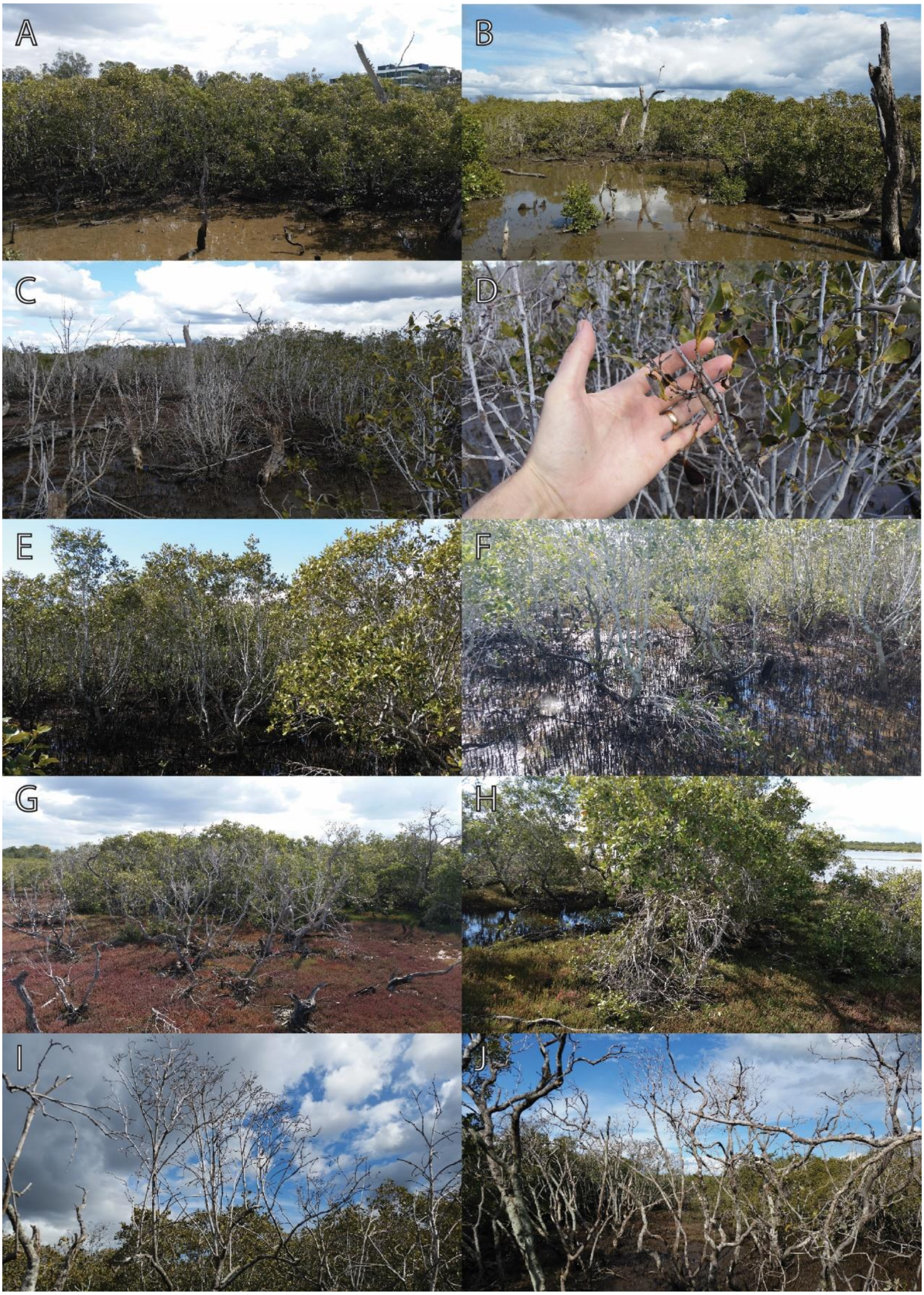

Figure D-1 Areas of decreased mangrove health at Fisherman Islands site 2 (A and B), site 3 (C and D), site 4 (E and F), site 5 (G and H) and site 6 (I and J).

Figure D-2 Ground-truthing site photos at: Fisherman Islands site 7 (A and B), site 8 (C and D), site 9 (E and F), site 10 (G and H) and site 11 (I and J).

Figure D-3 Ground-truthing photos from: Fisherman Islands site 12 (A and B), Whyte Island site 2 (C and D), site 3 (E and F), site 4 (G and H) and site 5 (I and J).

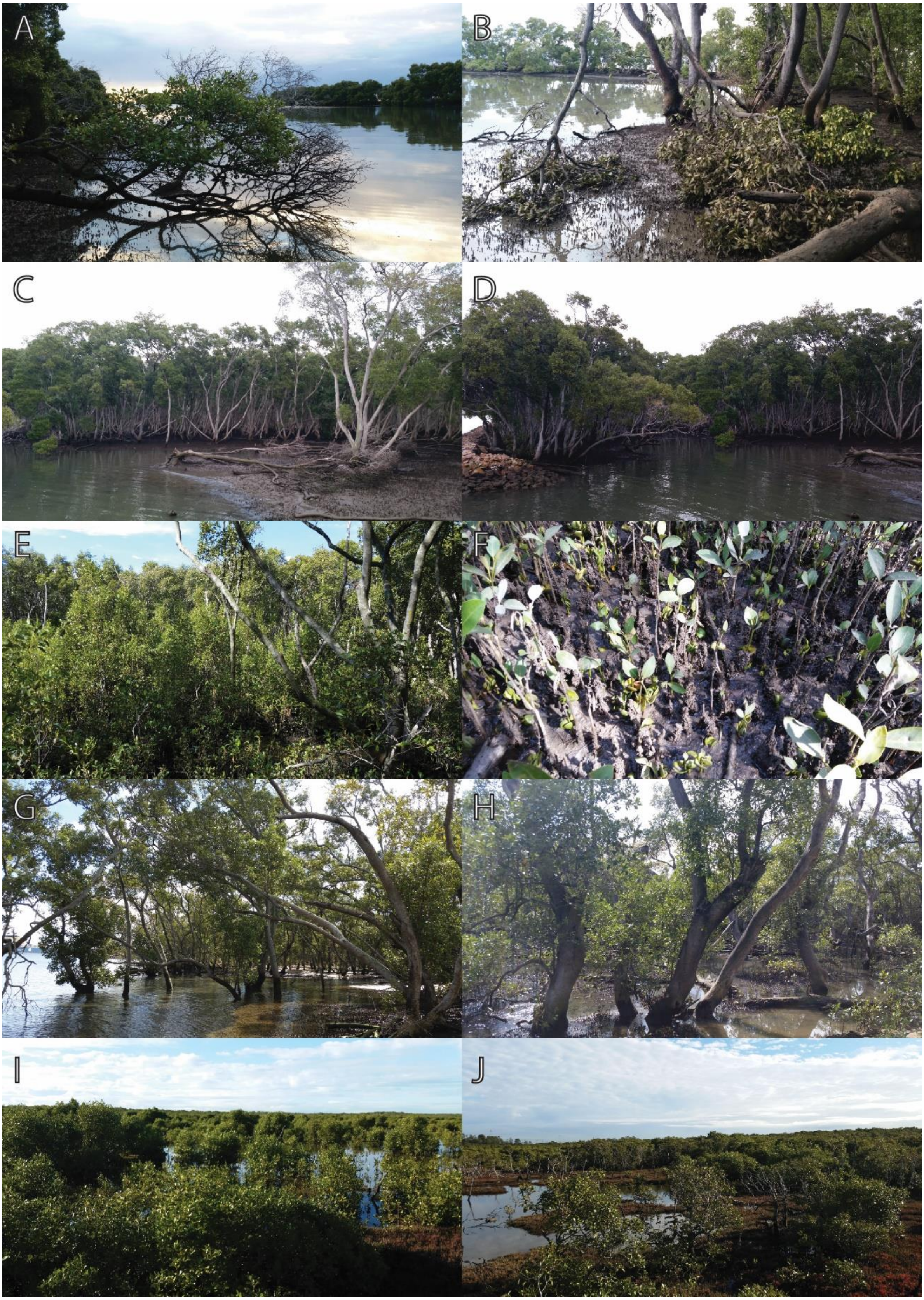

Figure D-4 Ground-truthing from: Bulwer Island site 1 (A and B), site 2 (C and D), Fisherman Islands site 1 (E and F), Coal Loader (G and H) and Whyte Island site 1 (I and J).

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