PCPA CHAMP

PORT CURTIS AND PORT ALMA COASTAL HABITAT ARCHIVE AND MONITORING PROGRAM

Final Report

CA14000114 (CA140034): Monitoring the survival and recovery of shorelines, specifically Tidal Wetlands (Mangroves/Saltmarsh/Saltpans)

Norman C Duke, Jock Mackenzie, Adam Canning, John Kovacs, Riley Cormier, Ysabel Castle

Report No. 22/32

5 September 2022

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Final Report
for the
Ecosystem Research and Monitoring Program Advisory Panel
as part of the
Gladstone Ports Corporation's
Ecosystem Research and Monitoring Program

Report No. 22/32
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Prepared by Norman C Duke, Jock Mackenzie, Adam Canning, John Kovacs, Riley Cormier and Ysabel Castle

Centre for Tropical Water and Aquatic Ecosystem Research,
TropWATER
James Cook University
Townsville
Phone : (07) 4781 4262
Email: TropWATER@jcu.edu.au
Web: www.jcu.edu.au/tropwater/

Gidarjil Development Corporation

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"We acknowledge the traditional owners of this land wherever we walk.
We pay our respects to the elders both past and present and to the future generations yet to come."

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This report has been produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. The study was undertaken through a Consultancy Agreement (CA14000114) between Gladstone Ports Corporation (GPC) and James Cook University (JCU) to monitor the condition, survival and recovery of shorelines, specifically tidal wetlands (Mangroves/Saltmarsh/Saltpans) in the Port Curtis and Port Alma region; in field surveys conducted by researchers, traditional owner rangers and community members.

This publication has been compiled by TropWATER, JCU.

For further information on the content, contact:

Dr Norman Duke, Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER)
James Cook University
E: norman.duke@jcu.edu.au
James Cook Drive, ATSIP Building, James Cook University Qld 4811
www.jcu.edu.au/TropWATER

EXECUTIVE SUMMARY

1. **Final Report.** This Final Report documents the key findings of the program of works (commencing mid-November 2014) directed by Prof. Norm Duke with Jock Mackenzie from James Cook University (JCU) including project partners: Prof. John Kovacs of Nipissing University in Canada, and Rangers of the Gidarjil Development Corporation (Fig. 1). The program included monitoring of the condition, survival and recovery of shorelines, specifically tidal wetlands, as outlined in the scope of works for tender CA14000114 (CA140034). As noted in interim Annual Reports, this project forms part of Gladstone Ports Corporation's (GPC) Ecosystem Research and Monitoring Program (ERMP) - a compliance requirement under the Commonwealth approval for GPC to undertake the Western Basin Dredging and Disposal Project (WBDDP).

Figure 1. Partners and stakeholders in the PCPA CHAMP project, from the left at our 2014 launch, representing James Cook University TropWATER Centre (Norm Duke, Jock Mackenzie), Gladstone Ports Corporation (Megan Ellis), Nipissing University (John Kovacs), Gladstone Regional Council (Col Chapman) and the Gidarjil Development Corporation (Richard Johnson).

2. **Report focus.** This 7th and final report presents the overall synthesis of project findings, regards our assessment of issues and the condition of mangrove tidal wetlands of the PCPA (Port Curtis Port Alma) region (Fig. 2). The PCPA CHAMP (Coastal Habitat Archive and Monitoring Program) project commenced around mid-November 2014. The PCPA region extends from Port Alma to Rodds Harbour and includes three subregions of Port Alma, Port Curtis and Rodds Harbour. Western Basin and Gladstone Harbour are included in the central Port Curtis subregion. Over the project period, 2014-2022, the plan was to generate essential baseline data, including comparisons with historical information, as the basis for our evaluations of environmental condition and change in the region. While a current baseline has been established, in several cases the current condition needed further explanation where current conditions were influenced by much earlier changes.

3. **Assessment of PCPA tidal wetlands.** Our assessment of the unique natural environment of tidal wetlands commences with a brief appraisal of the broadly encompassing influences on this highly beneficial habitat. These influences consist of two key pressure

groupings including expanding human development and changes in environmental conditions. The former is largely self-evident in the expansion of the major urban and industrial hub surrounding Gladstone, and its busy international port. These activities had clearly impacted local tidal wetlands within the immediate vicinity. However, while it is important to quantify these impacts, it has also been critically important to evaluate the current condition of the vast area of surrounding tidal wetlands. Our studies show that these surrounding natural areas have been changing also. But, the chief drivers of change include all-encompassing influences of changing global climate and weather conditions, along with the profoundly important changes with rising sea levels. Awareness of all these influences is essential knowledge and lessons needed for effective adaptive management.

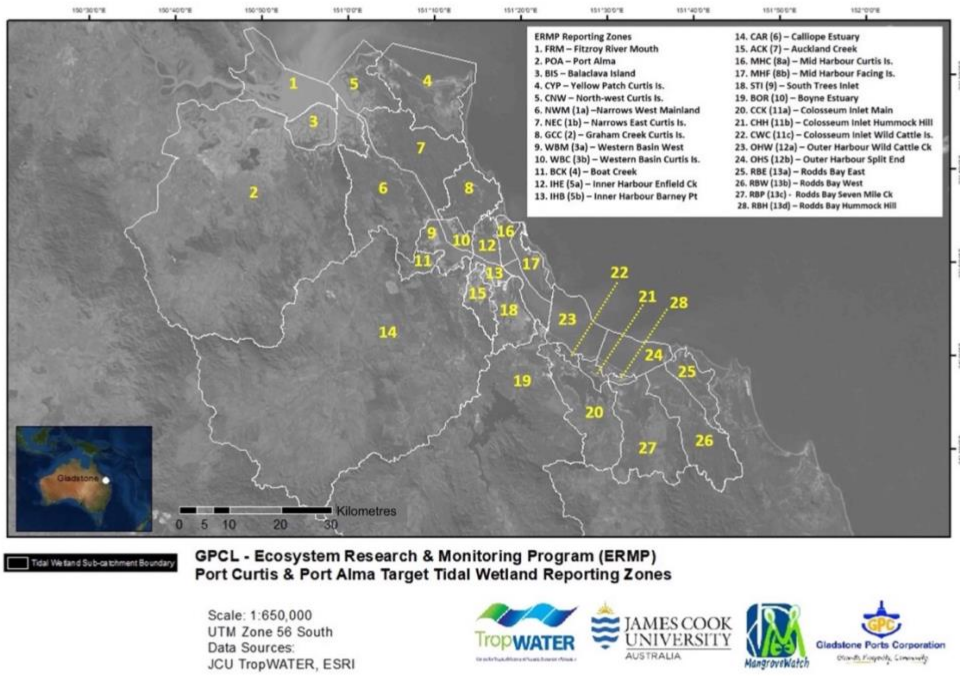


Figure 2. Map of the study area for the PCPA CHAMP program, showing included catchment zone areas from the Fitzroy River mouth and Port Alma to Gladstone, and south to Rodds Harbour. (Source: NC Duke).

4. **Changing climate and sea levels in the PCPA region.** According to records from the Australian Bureau of Meteorology (BOM) some fundamental climate variables are changing. Temperatures are rising, and the rate has increased considerably in recent decades with the current rate of 2.6° C per 100 years (averaged over the last 25 years). Rainfall levels are varying, having declined over the last century (-1.8 mm per year), although rising slightly over the last 25 years. According to port sea level records with the Permanent Service for Mean Sea Level (PSMSL), sea levels have risen at 4.8 mm per year over the last 25 years (Fig. 3). Furthermore, recently recognised, longer-term oscillations in mean sea level have increased in amplitude, recording an event of unusually extreme high sea level in 2011 with severe La Niña conditions. These high sea levels resulted in the sudden loss of a large area of mangroves at the southern mouth of South Trees Inlet (consider Duke et al., 2022). This type of dieback had been unprecedented, and more research is needed.

5. **Changing storm weather conditions.** Storm weather events of various types have become more severe or more frequent in recent decades. In 1994, a large hail storm of unprecedented severity impacted more than 200 ha of mangroves in the Calliope estuary. Severe tropical cyclones *Oswald* in 2013, *Marcia* in 2015 and *Debbie* in 2017 each delivered torrential rains causing severe flood damage and loss of mangroves in the Boyne

and other estuaries across the region. In the Boyne, around 80% of mangroves were severely damaged or lost. The recent frequency of such damaging weather events is considered unprecedented. There is a great need to quantify the accumulative impacts, and the likelihood of recovery.

6. **Tidal wetlands of the PCPA region.** Tidal wetlands of the PCPA region occupy an area of around 59,501 ha, consisting of 24,608 ha of mangrove forests and thickets and 34,892 ha of tidal saltmarsh and saltpan. This remarkable area describes the extent of upper tidal zone lands between mean sea level (MSL) and highest astronomical tide (HAT) levels. This defines the spatial area occupied by this vital habitat in the region. Mangroves and tidal wetlands are of immense ecological importance. In 2016, the total living plant carbon biomass of mangrove trees alone amounted to around 21 Mt. Based on prior studies in the Port Curtis subregion, we estimated the biomass of four key marine fauna of mangrove forests for the entire PCPA region to include: 1.2 billion Grapsid crabs (>11 species) weighing 1,003 tonnes dry weight; 249 million Alpheid shrimp (>2 species) weighing 1,139 tonnes dry weight; 57 million Thalassinid lobsters (1 species) weighing 1,145 tonnes dry weight; and 109 billion Sipunculid worms (1 species) weighing 9,561 tonnes dry weight. However, these numbers represent only a fraction of the total dependent fauna present, considering the abundant presence also of marine mammals, fish, birds, insects and reptiles.

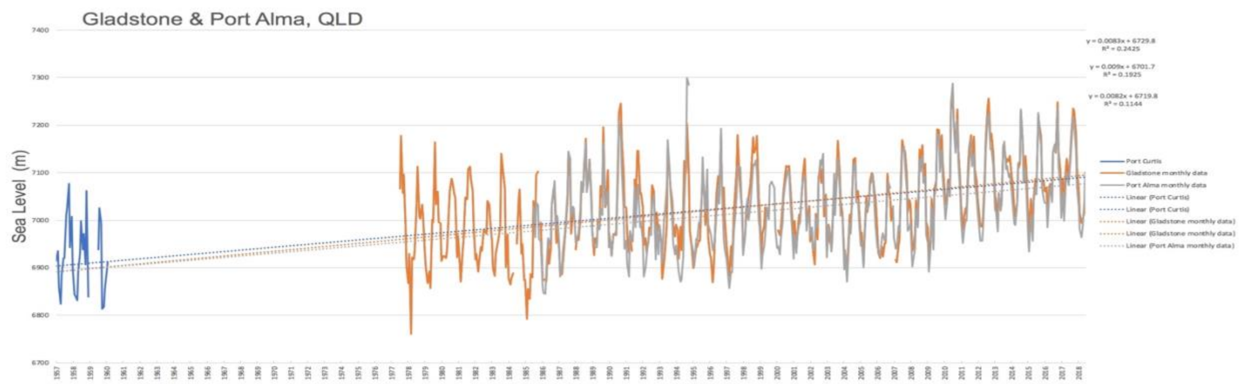


Figure 3. Sea level changes recorded in the PCPA study area (Gladstone and Port Alma tide gauges) showing the steady increasing rise of around 0.16 m over the last 50 years (Source: PSMSL website). These changes are having a notable effect on mangrove and tidal wetland habitat throughout the region. (Source: NC Duke).

7. **Tidal wetland plants and habitat.** Mangroves form the dominant structural element of tidal wetland habitat of the PCPA region, made up of 16 plant species. The most dominant, occupying more than 65% of mangrove areas, is the Stilt-Root Mangrove, *Rhizophora stylosa*. Five other species (31% of the total) occur at their southern-most distributional limits, including *Acanthus ilicifolius, Bruguiera exaristata*, *Bruguiera dungarra*, *Pemphis acidula* and *Xylocarpus moluccensis*. The mean height of mangrove trees in the region is around 4 m, with a maximal height closer to 10 m. The more diminuitive tidal saltmarsh species comprise about 18 macrophyte species.

8. **Assessment of PCPA tidal wetlands.** To quantify the condition of tidal wetland areas across the PCPA region, we undertook an extensive aerial survey in late April 2019. The survey entailed filming the entire shoreline (mangroves, beaches, rocky shores) for all 28 ERMP zone areas. For each zone, we recorded more than 28 condition indicators, noting the severity and extent of each, and developed as condition scores for this assessment. The condition indicators comprised at least 11 human-related and 17 climate-natural issues observed during the aerial survey. It was significant that both groups of indicators had comparable ranges of condition scores.

9. **Human-related indicators.** The human-related indicators that scored most highly, as the top five in this group, included: ‘human altered hydrology’, ‘built structures’, ‘direct loss and damage’, ‘human access damage’, and ‘stock damage’. There were understandably high scores recorded in these indicators in the Port Curtis subregion, given the dominance of industry and port activities there.

10. **Climate-natural indicators.** The climate-natural indicators that scored most highly, as the top five in this group, included: ‘terrestrial retreat’, ‘depositional gain’, ‘pan scouring’, ‘shoreline erosion’ and ‘ecotone shift gain’. These scores were notably maximal in the subregions of Port Alma and Rodds Harbour – a feature consistent with the lesser presence of human-related drivers there.

11. **Development impacts.** A group of human-related indicators identified reclamation areas along with tidal wetland areas lost or noticeably impacted by the expansion of industry and port development. These were characterised mostly by three major indicators of ‘built structures’, ‘direct loss’ and ‘encroachment’. An extreme instance of these kinds of impacts was recorded for estuaries of Auckland Creek-Inlet and South Trees Inlet (Fig. 4). In each case, there had been losses of ~90% of functional tidal wetland areas since 1941. These past changes have longer term consequences affecting the resilience of remaining nearby mangrove and tidal wetland areas.

Figure 4. Development has dramatically removed tidal wetlands from some areas like Auckland Inlet since earlier days. (Source: NC Duke).

12. **Human alterations to normal tidal exchange.** The ‘human altered hydrology’ indicator as a human-related indicator identified alterations to tidal and normal runoff flows which were in part a consequence of development works. However, in addition there were multiple instances of small-scale construction works, like rural tracks and earthen bund walls of ponded pasture lands. As such, this indicator was observed more widely across all subregions.

13. **Sublethal damage from dredging and reclamation.** We briefly evaluated the condition of protected mangrove forests surrounding the Western Basin Reclamation Area (Chapter 6, page 76). We found that while these mangroves were impacted during the period of dredging (~2011 to 2017), there was no noticeable loss of trees, and the trees impacted recovered their lost canopy condition (from ~30% loss) by 2021. However, the fact that these trees displayed some level of impact (not noticed in the contracted monitoring programs) suggests that future monitoring strategies need to be improved upon. In particular, there needs to be closer scrutiny of canopy condition during such works. Our recommendation is to use readily available remote sensing measures of canopy condition, and to use a more appropriate series of reference sites. Both are needed for a more informative risk management monitoring system. Our recommendation is to implement an effective and more informative ‘Alert-to-Action’ monitoring strategy as proposed with this report (Appendix 9).

14. **Damage by vehicles.** The 'vehicle damage' as a human-related indicator identifies potential damage caused by vehicles (2- and 4-wheeled) was indicated by the presence of tracks on tidal wetland areas, particularly the more open areas of tidal saltmarsh and saltpans. This damage was observed in areas across the PCPA region, in every possible area accessible by vehicles. There appeared to be no restrictions on this kind of damage, except the terrain, the tidal channels and the occasional dense vegetation.

15. **Damage by livestock.** The 'cattle damage' indicator as a human-related indicator identifies potential damage caused by cattle and other livestock like horses, and was observed in areas mostly away from densely populated areas. Damage by feral animals was relatively minor and restricted to more remote parts of the region.

16. **Damage by pollutants.** The 'pollutant' indicator as a human-related indicator was not specifically applied in the 2019 survey (Fig. 5). While there were differing responses to past incidents, these were dependent on the particular polluting agent. For example, we refer to four notable past pollution incidents in the region, including: – a) the significant bunker oil spill with the *Global Peace* incident in 2006 which had toxic and suffocation effects on mangrove vegetation and animals; b) herbicides in terrestrial runoff killed mangrove trees of the vulnerable species *Avicennia marina*, exemplified in the Fitzroy River upper and mid estuary in 2008; c) the same species, *A. marina*, was apparently also vulnerable to micro-dust particles clogging normal leaf respiration, as apparently occurred in the Port Curtis subregion in the early 1970s; and, d) the widespread occurrence of mutant, albino-propagules of *Rhizophora stylosa* mangroves (observed during boat and field surveys with this study), associated elsewhere with high levels of petroleum hydrocarbons in mangrove waters and sediment. None of these incidents were appropriately investigated, so explanations and potential lessons have not been utilised. Such an omission emphasises the immense importance and value in conducting immediate, rapid-response surveys and monitoring at the time such incidents occur, or afterwards.

Figure 5. Aerial surveys in 2019 filmed and recorded the condition of tidal wetlands throughout the PCPA study area from the mouth of the Fitzroy River to Rodds Harbour.(Source: NC Duke).

17. **Enhanced growth by excessive nutrients.** The 'nutrients' indicator as a human-related indicator identifies potential damage from excess nutrients enhancing the growth of either mangrove trees, or algae nearby. Enhanced tree growth was not detected in these aerial surveys, but there were multiple instances throughout the region of green algal growth on exposed mud flats bordering mangrove stands. The presence of such growth is considered notable, and worthy of further investigation of the source and likely consequences.

18. **Damage from grass and bushland fires.** The 'fire damage' indicator is relevant to mangrove forests because they are seriously affected by scorching heat, and on occasion mangrove forests do burn. It is considered a human-related indicator, but this is not

always the case. During the 2019 survey, there were a few instances, noting blackened grass and timber in three subregions spread across the PCPA region: the Fitzroy mouth, The Narrows and Outer Harbour.

19. **Damage from storm winds, waves, flooding, hail and lightning.** The 'storm damage' indicator as a climate-natural indicator identifies a diverse group of agents delivering harm from storms impacting mangrove forests. The impacts of these different agents were broadly distinguished in the 2019 aerial survey. Hence this category includes: 'storm damage' when wind and waves have broken, uprooted and damaged trees; 'flood damage' when trees are water swept, muddied and eroded; and 'light gaps' when lightning strikes killed small circular patches of trees without other physical damage. Curiously, 'storm damage' was more severe in zone areas to the north, a feature consistent with a likely association with severe tropical cyclone *Marcia* in 2015. In seeming contrast, 'flood damage' was observed in southern estuaries, Calliope, South Trees and Boyne following the intense flooding from severe tropical cyclone *Oswald* in 2013 in particular. However, severe flooding impacts had been reported in the upper Fitzroy estuary in 2006 – and, this area was outside the study area. So, the distribution of 'flood damage' is possibly more comparable with 'light gaps' which were notably widespread across the region. Another indicator not applied in the aerial survey was 'hail damage'. A one-off severe event in 1994, recorded in mangroves of the Calliope Anabranch severely impacted nearly 30% (~200 ha) of Calliope tidal wetlands, although notably there had been recovery since.

20. **Damage to low elevation (water's edge) mangrove stands.** The 'shoreline erosion' and 'bank erosion' indicators as climate-natural indicators identify the loss of edge trees along seaward and estuarine shorelines. As noted for 'storm damage' and associated indicators, the distribution of these erosion indicators matched the more severe northern influence of severe tropical cyclone *Marcia* in 2015. Hence, these indicators appear to represent a common driver of severe storm impacts.

21. **Damage from shifting sediments burying mangrove roots.** The 'root burial' and 'natural altered hydrology' indicators, as climate-natural indicators, mostly identify the impacts of mobilised sediments that shift and move through and around mangrove stands. As the occurrence of mobilised sediments is probably linked with the erosion indicators (#19), it is likely that these indicators will also relate to severe storm impacts as the common dominant driver.

22. **Rising sea levels and an upland shift in tidal wetlands.** The 'terrestrial retreat' and 'upland migration' indicators, as climate-natural indicators, mostly match the impacts of rising sea levels. These indicators had higher levels in southern zone areas, a pattern that was consistent with southern areas having faster rates of sea level rise. The pattern wth 'pan scouring' was less defined, and it was probably compounded by storm impacts, for example 'shoreline erosion' and 'bank erosion' indicators, as other possible indicators influenced by rising sea levels.

23. **Rising sea levels and a progressive upward shift in mangroves.** The 'ecotone shift gain' indicator, as a climate-natural indicator, defines the recruitment and expansion of mangroves into saltpan areas, likely driven by rising sea levels. This indicator had higher impact levels in southern zone areas, a pattern that was consistent with southern areas having faster rates of sea level rise. This driver therefore has comparable influences as with other indicators like 'terrestrial retreat' and 'upland migration'.

24. **Declining longer-term rainfall and mangrove loss.** The ‘ecotone shift loss’ indicator, as a climate-natural indicator, defines the dieback and retreat of mangroves from saltpan areas, likely driven by a longer-term decline in annual rainfall (Fig. 6). This indicator had higher levels in northern areas. Our assessment showed the declines in mangrove condition were incremental over many years – a feature consistent with the overall declining rainfall trend. By contrast, impacts associated with ‘storm damage’ were more abrupt and coincident with the year of impact.

Figure 6. Mangrove dieback in stands fringing saltpans was an indication of longer-term declining rainfall, notable on Balaclava Island near the Fitzroy mouth. (Source: NC Duke).

25. **The unusual occurrence of extreme high sea level and mangrove dieback.** The ‘fringe collapse’ indicator, as a climate-natural indicator, defines the drowning dieback of shoreline mangroves during a La Niña driven event of unusually high mean sea levels in 2011. This was shown in our assessment of the sudden dieback of 3 ha of mangroves at the southern mouth of South Trees Inlet. This previously unexplained dieback was recorded in multiple locations across the PCPA region, and elsewhere in northern Australia. As with ‘terrestrial retreat’, there was a common tendency for greater impacts in southern areas, consistent with higher rates of rising sea levels.

26. **Damage caused by roosting fruit bats.** The ‘bat damage’ indicator, as a climate-natural indicator, defines the damage caused by roosting fruit bats. Colonies of bats congregating in large numbers in mangrove forest canopies cause severe leaf loss and crown dieback. However, because the bats relocate after a few years, damage is minimal and recovery is rapid. Recovery is probably enhanced by the additional nutrients left in bat droppings. At least three colonies were recorded during the 2019 aerial survey, including Auckland Creek, Calliope River mouth and Inner Harbour areas.

27. **Damage caused by excessive insect herbivory.** The ‘insect damage’ indicator, as a climate-natural indicator, defines the damage caused by severe defoliation of mangrove trees. This indicator was not applied in the 2019 aerial survey. However, a detailed account of severe defoliation levels up to 40% of canopy leaves from 1996-1998 identified the great significance of this kind of damage in the Western Basin mangroves of the Port Curtis subregion. It is not known what caused the outbreak, nor how it ended. However, it was clear that this insect was native to the area (notably described by Joseph Banks in this region in 1770), and that it had a peculiar habit of moving between trees after each moult, thus ensuring the survival of impacted trees.

28. **The deciduous mangrove mistakenly appears to be suffering dieback.** The occurrence of the conspicuously deciduous Cedar Mangrove *Xylocarpus moluccensis* is an undoubtedly attractive feature of the PCPA region. Every August, these normally less remarkable trees synchronously produce full canopies of bright orange and red leaves (Fig. 7). After the leaves fall, the branches remain bare for nearly a month until they burst back into life with a full set of bright green new leaves. This natural display has been occasionally misinterpreted as possible dieback and distress of mangrove trees. There is a need to educate locals of this natural and wonderous natural occurrence. Perhaps this event could be useful to make use of by marking it with a day of celebration for tidal wetlands in the PCPA region.

Figure 7. Orange-crowned trees of the uniquely deciduous Cedar Mangrove spotted amongst the green canopy of other mangroves are an attractive annual August event across the PCPA region. (Source: NC Duke).

29. **Concluding environmental observations.** Our studies have identified many significant observations about tidal wetlands of the PCPA region, the changes they are undergoing, and the drivers behind those changes. Clearly, some changes are obvious such as the human-related reclamation areas, but others are much more subtle, and one at least, has only recently been explained. Notably, the cause of 3 hectares of mangrove dieback in South Trees Inlet had been a mystery until this study. This impact was the dramatic consequence of an unprecedented six months of high mean sea levels associated with severe La Niña conditions around 2011. Other similarly abrupt impacts associated with changing climatic conditions included severe cyclones and flooding events in 2013, 2015 and 2017, and the severe hail storm in 1994. However, other less discernible, incremental impacts were those occurring over many years and decades including those driven by steadily rising temperatures which in turn drive the more severe storm events, the overall declining longer-term rainfall, and increasingly more rapid rising sea levels. All these changes have recognisable impacts. However, there are further concerns regards their combined impacts, as their accumulative pressure forms a growing threat to the resilience and functioning of tidal wetlands of the PCPA region.

30. Project outcomes. Our studies have generated a number of publications along with seven annual reports. These are useful research products where they document key aspects of ecosystem functioning for their better-informed management. They also describe our development and application of the aerial and boat-based survey methods we have used in the Port Curtis Port Alma region. In addition, another outstanding and significant outcome from the project has been our partnership with indigenous land and sea rangers of the Gidarjil Development Corporation. Being based in this region, they have demonstrated overwhelming dedication to tidal wetland country. While assisting with our surveys they were always keen observers interested in the monitoring and survey works being conducted. A particular milestone of some note, had been the ability of the rangers to conduct the required monitoring works independently after embracing the training and precise use of survey equipment. We believe this proven capability of Gidarjil rangers, demonstrates their readiness to: a) assist in considered responses to future unexpected events and accidents that impact upon local tidal wetlands; b) assist in investigations of past events and matters like the proposed survey of albino propagules and their association with petroleum hydrocarbons; and c) assist in the proposed 'Alert-to Action' mangrove monitoring of on-going development works.

31. **Project outcomes not fully realised.** ShoreView – the proposed public access and data entry portal for display of shoreline survey imagery, remains incomplete and temporally unavailable to the public. There were unanticipated challenges in developing such a highly innovative facility. While the working platform was developed and demonstrated to the ERMP panel, this has not yet been finalised. Our responsible project partners and the project team are continuing to complete the final stages of this development project. There have been a number of issues, including COVID restrictions and the very large data files were required to be stored offline by the data host. This situation has now been rectified. The ShoreView site is currently being re-installed and the 2019 aerial survey data will be uploaded. As noted, the platform and website were shown to be operational. However, while work on the platform and data management system have been produced, at the time of this final report, the online facility was unavailable.

32. **Alert-to-Action monitoring and response capability.** As part of this assessment of PCPA tidal wetlands, our team specifically developed an innovative and effective program of 'Alert-to-Action' monitoring for monitoring the healthy condition of tidal wetlands surrounding development areas and construction sites. This program was made possible by the combination of newly-devised, assessment tools like the green fraction timeseries plots, along with our newly discovered links between mangrove canopy growth, climate and sea level changes. The capability now identified means that any signs of stress on mangrove plants can be identified using satellite data collected each month. It can then be relayed to project construction teams to amend their work activities accordingly. For example, our assessment of the WBRA of PCPA tidal wetlands (see #13 above), demonstrates the potential effectiveness of the proposed 'Alert-to-Action' monitoring program where there is demonstrable expertise as well as the necessary equipment ready for immediate deployment.

Historical Note …

Figure 8. In 1803, tidal wetlands of the PCPA region were mapped and evaluated.

An early European visitor wrote of the Port Curtis mangroves:

"The country round Port Curtis is overspread with grass, and produces the eucalyptus and other trees common to this coast; yet the soil is either sandy or covered with loose stones, and generally incapable of cultivation. Much of the shores and the low islands are overspread with mangroves, of three different species; but that which sends down roots, or rather supporters from the branches, and interweaves so closely as to be almost impenetrable, was the most common. This species, the Rhizophora Mangle of Linnaeus, is also the most abundant in the East and West Indies; but is not found at Port Jackson, nor upon the south coast of this country."

Matthew Flinders HMS 'Investigator', 1802 (Figs. 8-9).

Figure 9. An early map of the PCPA area drafted by Flinders in 1803 showing the extent of European knowledge at the time.

ACRONYMS USED IN THIS REPORT

ALOS – Advanced Land Observation Satellite
AVNIR – Advanced Visible and Near Infra-Red
BMRG – Burnett Mary Regional Group
CHAMP – Coastal Habitat Archive and Monitoring Program
DNRM – Queensland Department of Natural Resources and Mines
DSITI – Queensland Department of Science, Information Technology and Innovation
DSLR – Digital Single Lens Reflex camera
DSM – Digital Surface Model
ENSO – El Niño Southern Oscillation
ERMP – Ecosystem Research and Management Program
FBA – Fitzroy Basin Association
GBR – Great Barrier Reef
GDC – Gidarjil Development Corporation
GPC – Gladstone Ports Corporation
GPS – Global Positioning System
HAT – Highest Astronomical Tide levels
IPCC – Intergovernmental Panel on Climate Change
JCU – James Cook University
LIDAR – Light Detection and Ranging - a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth
MSL – mean sea level
NDVI – Normalized Difference Vegetation Index
NESP – National Environmental Science Program, Australian Governments Department of Environment and Energy
NRM – Natural Resource Management
PCPA – Port Curtis Port Alma region, includes Port Alma, the Narrows, Western Basin, Gladstone Harbour and Rodds Harbour
SPOT – Satellite for Observation of Earth
S-VAM – Shoreline Video Assessment Method
TropWATER – Centre for Tropical Water and Aquatic Ecosystem Research
TUMRA – Traditional Use of Marine Resources Agreement
WBDDP – Western Basin Dredging and Disposal Project
WCI – Wetlands Cover Index, as the proportion of mangrove area within tidal wetlands.

FINAL REPORT

FACTORS AFFECTING MANGROVE TIDAL WETLANDS OF THE PORT CURTIS PORT ALMA (PCPA) REGION

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

Mangrove tidal wetland shorelines have been surveyed, monitored and assessed as part of a Coastal Habitat Archive and Monitoring Program (CHAMP) led by scientists from James Cook University TropWATER Centre and Nipissing University in collaboration with the Gidarjil Development Corporation. The project formed part of Gladstone Ports Corporation's (GPC) Ecosystem Research and Monitoring Program - a compliance requirement under GPC's approval for the Western Basin Dredging and Disposal Project.

The PCPA CHAMP project commenced with the agreement between Gladstone Ports Corporation Limited (GPC) and James Cook University (JCU) around mid-November 2014. Six annual reports have been produced since then. Each outlined the project achievements made with each year of the assessment and monitoring of mangrove tidal wetlands of the Port Curtis and Port Alma area, including Gladstone Harbour (Fig. 10). Over the years 2014-2022, the plan has been to generate baseline data, including data extending from prior historical baseline information where this was available.

Figure 10. Map of the study area for the PCPA CHAMP projects showing subregions north of Gladstone to Port Alma, Port Curtis and south to Rodds Harbour.

As noted, these works focused on monitoring and assessment of the condition, impacts, survival and recovery of shorelines, specifically tidal wetlands, as outlined in the scope of works for tender.

Briefly, the program devised was structured around five components listed in the project scope of works for the Port Curtis and Port Alma area, as:

1. High resolution maps of tidal wetlands, plus historical assessment (change detection);

2. Normalised Difference Vegetation Index (NDVI) mapping of tidal wetlands;
3. Shoreline condition monitoring using oblique aerial image data acquisition;
4. Shoreline condition monitoring using boat-based video image data acquisition and community volunteers; and
5. Public access and data entry portal (ShoreView) for display of current and past mapping.

To complete these tasks, the program was led by science specialists in tidal wetlands, who characterised the shoreline environmental components and values of the PCPA area. While TropWATER were the lead agent for managing the contract with GPC, we collaborated with specific organisations through individual sub-contracted/partnership arrangements, as required:

a. Gidarjil Development Corporation (GDC) indigenous sea rangers along with community volunteers in the Gladstone region, are assisting in the monitoring and assessment of coastal tidal wetland habitats (Component 4 chiefly, plus 3);
b. Collaboration with Prof John Kovacs of Nipissing University, Canada, for specialist remote sensing assessments and mapping of tidal wetland habitats in the region (Components 1 & 2 primarily, plus using 4 for opportunities in ground truth and data validation);
c. Partnership with Queensland Cyber Infrastructure Foundation and the JCU e-Research Centre for the development and implementation of the planned online facility (Component 5 primarily, plus all other components eventually).

Project Outcomes

A range of outcomes were presented in 6 annual reports (see Duke & Mackenzie 2015, 2020; Duke at al., 2016, 2017b, 2018, 2019c), as follows:
2014-2015 – GDC meetings, project launch, set-up mapping, aerial & field surveys.
2015-2016 – first aerial survey Aug 2015, boat surveys Sept 2015, ShoreView.
2016-2017 – mapped 2016 tidal wetland areas, processed aerial & field data, ShoreView.
2017-2018 – mapped veg indices & structure, carbon, ShoreView presentation.
2018-2019 – field validation of maps, second aerial survey Apr 2019, rapid long plots.
2019-2020 – preliminary assessments, aerial surveys, rapid long plots, leaf counts.

These reports and related research articles published are listed in Appendix 1.

Public presentations made are listed in Appendix 2.

This Report

The new information presented in this final report includes key outcomes deduced from a newly-developed method using a Landsat remote-sensing vegetation index (NDVI) to construct monthly timelines for the period from 1987 to 2022. We refer to this technique as the ‘green fraction’ method. This methodology enabled us to make fundamental observations about the longer-term condition at any chosen location, to meet several major objectives for this program. Specifically, the technique allowed us to greatly enhance our understanding of temporal change at specific points of interest. Using this knowledge, we were able to unravel and resolve a number of mangrove mysteries, like the dieback of mangroves at the southern mouth of South Trees Inlet in 2011, and to confirm the severe hail storm event in 1994. The method offers valuable benefits, supported by our accompanying recent findings concerning the influences of normal and extreme oscillations in mean sea level (Duke et al., 2022). The method has been adapted for use in a future ‘Alert-to-Action’ management monitoring strategy (Appendix 9).

This project is considered to have been an important opportunity to achieve a more refined compilation of data and expert advice gathered during field surveys and with key stakeholders from industry, government, universities and with indigenous rangers and community volunteers. The outcomes provide a comprehensive foundation assessment of ecological condition and health of tidal wetland mangroves for the region (building on prior surveys like Duke et al. 2003; 2005). The public archive created with this project is intended for future use; being a tangible, permanent resource for regional managers, industry stakeholders and community members wishing to maximise conservation benefits while maintaining environmentally appropriate coastal development works.

These outcomes are intended to educate managers and communities by raising public awareness of coastal tidal wetlands as beneficial vital natural ecosystems while they are also provide essential indicators of environmental health for these threatened coastal and estuarine ecosystems. By assisting in the monitoring of these valuable but fragile ecosystems, we believe local human communities can help not only in the preservation of coastal nursery habitat and shoreline buffering from erosion and deposition, but also towards the protection of highly-prized neighbouring coastal habitats, such as seagrass meadows and coral reefs.

The mangroves and tidal wetlands of the PCPA region are vital and highly-valued ecosystems. They have immense benefits, and they deserve the greatest consideration and protection.

CHAPTER 2

TIDAL WETLAND HABITAT AND CONDITION CRITERIA

Mangrove and Saltmarsh Plants

Mangrove and saltmarsh vegetation are an important habitat but this ecosystem often has a problem with public perception (Dahdouh-Guebas et al., 2020). The benefits are summarised in various publications (such as Duke et al., 2007). The diversity of plant types growing in the tidal wetlands of the PCPA region borders on tropical in character with at least 10 plant families represented in mangrove species alone (Duke 2006). Broadly, there are two distinct macrophyte groupings in tidal wetlands, including mangroves and saltmarsh plants.

There are 16 species of mangroves and 18 species of tidal wetland saltmarsh plants (see Appendix 3).

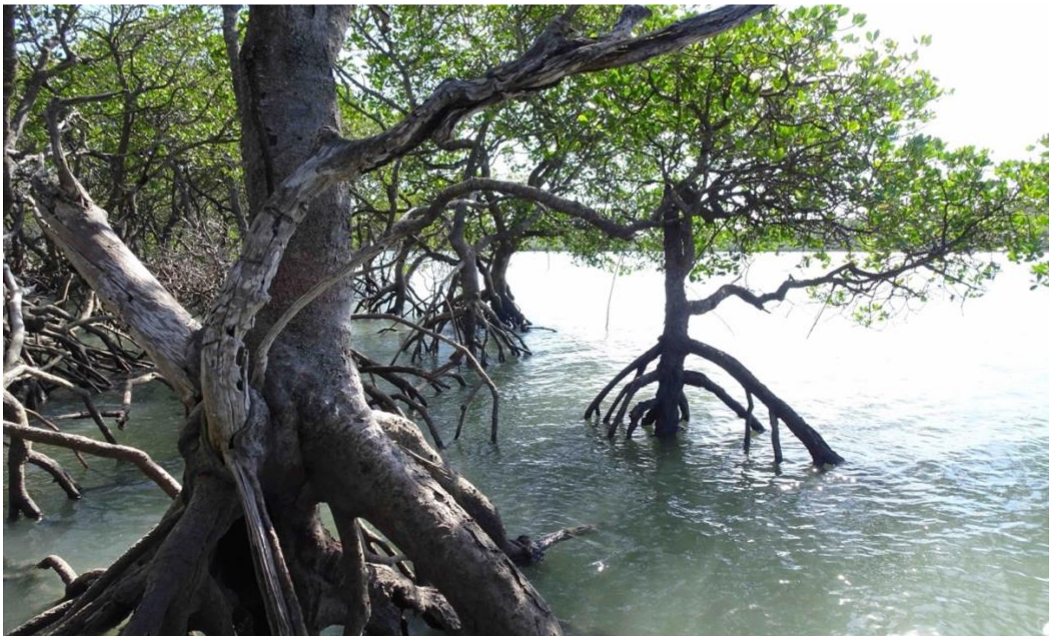


Figure 11. The dominant Stilt-rooted Mangrove, *Rhizophora stylosa*, in the PCPA study region. (Source: NC Duke).

A number of mangrove species (5 being 31%) are at their southern-most distributional limits, including *Acanthus ilicifolius, Bruguiera exaristata, Bruguiera dungarra, Pemphis acidula* and *Xylocarpus moluccensis*. This is consistent with the tropical affinities of the PCPA region.

As aptly described by Flinders in 1803 (see page 11), the dominant of mangrove species throughout the region was then, and still is, *Rhizophora stylosa* (Fig. 11). The proportion of this dominance of *Rhizophora* was quantified at around 65% of mangrove area in the region by Danaher et al. (2005).

Discovery of a Rare Mangrove Leaf Oyster Reef

During the field survey in May 2019, a rare Mangrove Leaf Oyster Reef was discovered by the project team at the southern end of the PCPA study area (Fig. 12). The species name is *Isognomon ephippium*. The location of this intertidal bivalve reef is Rodds Harbour, south of Port Curtis at: 24° 4' 47.69" S; 151° 33' 32.808" E.

These reefs are now extremely rare since they were extensively harvested for the shell in years gone by. The site is surrounded by mangrove forests and tidal estuaries.

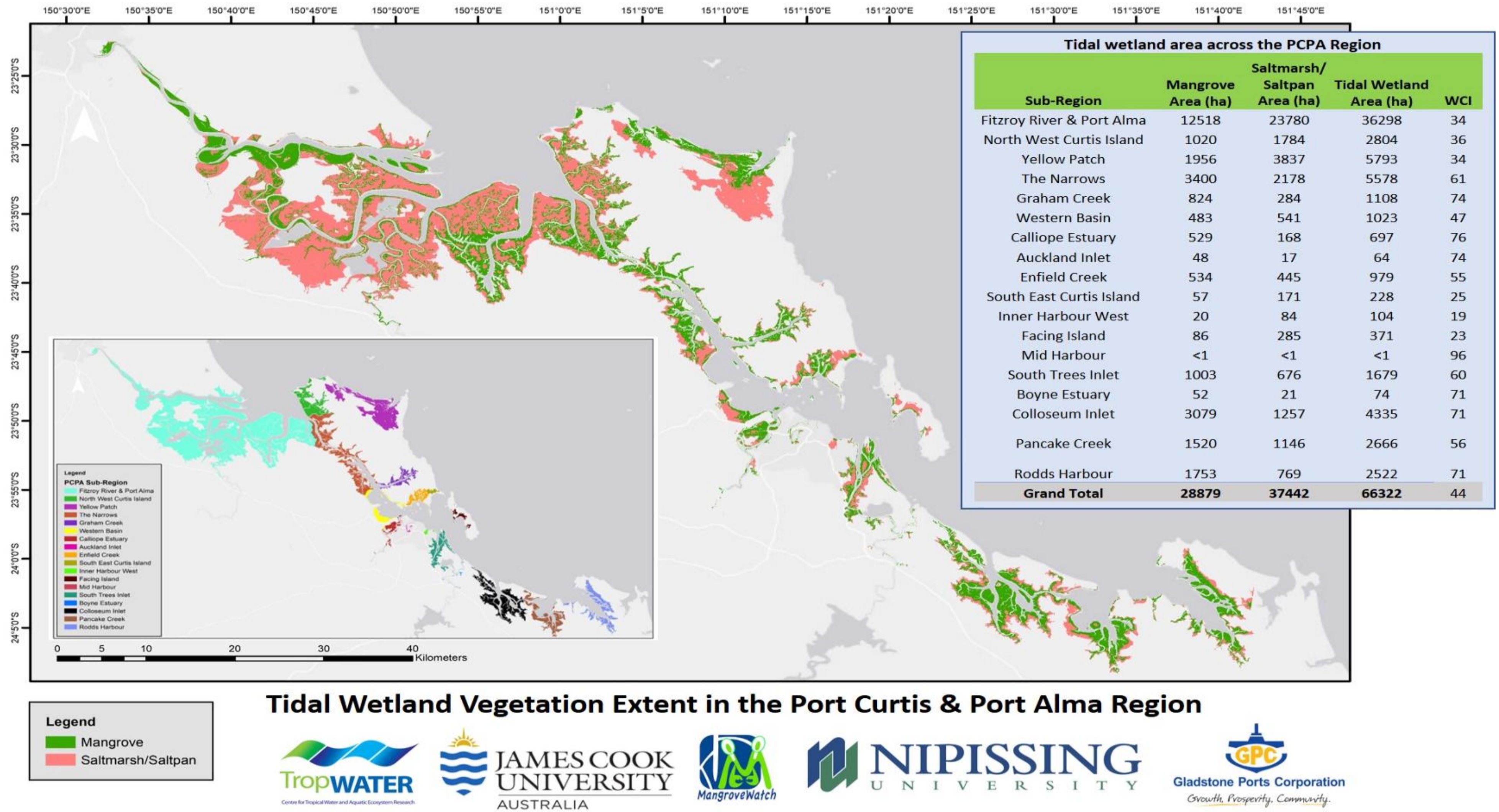
Researcher Rory Mulloy, at Central Queensland University, has commenced a detailed study of the rare reef.

Figure 12. A rare occurrence discovered in Rodds Harbour of a reef of Mangrove Leaf Oysters. (Source: NC Duke).

Other wildlife in PCPA mangroves and saltmarsh are not reviewed in this treatment. However, these are documented in various studies (Saenger 1988, 1996; Saenger et al., 1982) including that by Duke and Burns (1999). Based on the latter study in the Port Curtis subregion, we have roughly estimated the numbers and biomass of four key marine fauna of mangrove forests in the PCPA region – an area of 27,316 ha in 2016. These fauna include: 1.2 billion Grapsid crabs (>11 species) weighing 1,003 tonnes dry weight; 249 million Alpheid shrimp (>2 species) weighing 1,139 tonnes dry weight; 57 million Thalassinid lobsters (1 species) weighing 1,145 tonnes dry weight; and, 109 billion Sipunculid worms (1 species) weighing 9,561 tonnes dry weight. However, while these numbers appear large, they represent only a fraction of the total dependent fauna present in PCPA mangrove tidal wetlands. There is also an abundant of fish, birds, insects, reptiles and mammals – all reliant on this valuable ecosystem of mangrove tidal wetlands.

Areas of Mangrove and Saltmarsh-Saltpan

The respective areas of mangrove and saltmarsh grouping are depicted in the regional map (Fig. 13). Note that northern areas had lesser proportions of mangroves. These areas were drier than those areas to the south (see the Section on Environmental Conditions). A global relationship between the proportionate mangrove area (the Wetland Cover Index) and longer-term rainfall has been described in detail by Duke et al. (2019a).



Sub-Region	Mangrove Area (ha)	Saltmarsh/ Saltpan Area (ha)	Tidal Wetland Area (ha)	WCI
Fitzroy River & Port Alma	12518	23780	36298	34
North West Curtis Island	1020	1784	2804	36
Yellow Patch	1956	3837	5793	34
The Narrows	3400	2178	5578	61
Graham Creek	824	284	1108	74
Western Basin	483	541	1023	47
Calliope Estuary	529	168	697	76
Auckland Inlet	48	17	64	74
Enfield Creek	534	445	979	55
South East Curtis Island	57	171	228	25
Inner Harbour West	20	84	104	19
Facing Island	86	285	371	23
Mid Harbour	<1	<1	<1	96
South Trees Inlet	1003	676	1679	60
Boyne Estuary	52	21	74	71
Colloseum Inlet	3079	1257	4335	71
Pancake Creek	1520	1146	2666	56
Rodds Harbour	1753	769	2522	71
Grand Total	**28879**	**37442**	**66322**	44

Figure 13. The broad extent of mangrove (green) plus saltmarsh and saltpan (pale red) vegetation throughout the Port Curtis Port Alma (PCPA) region mapped from SPOT 2016 imagery (Appendix 6). Note the dominance of saltmarsh and saltpan areas in the north around the mouth of the Fitzroy River estuary (top left). The inset table lists subregion areas and their Wetland Cover Index (WCI). The WCI is the ratio of mangrove area to the total area of tidal wetlands (Duke et al., 2019a). (Source: J. Mackenzie).

The total area of tidal wetlands throughout the PCPA study region in 2016 was around 59,501 hectares, with 24,608 ha of mangroves, and 34,892 ha of saltmarsh-saltpan (Fig. 13, noting that mid and upstream areas of the Fitzroy River estuary were not included; see Appendix Table 3). Notably, these areas and their relative proportions varied both within the region, and over time. The differences between spatial and temporal factors conforms mostly with key environmental variables, although they are often further altered by human influences.

As noted by Danaher et al (2005), the dominant mangrove species in at least the Port Curtis subregion of the study area was the Stilt-rooted Mangrove *Rhizophora stylosa* (Table 1). It's proportionate area exceeded the area of saltmarsh habitat.

Table 1. Tidal wetland component areas of the Port Curtis region (Danaher et al., 2005; Connolly et al., 2006). The wetland cover index (WCI) is the overall proportion of mangrove to tidal wetlands (Duke et al., 2019a).

Tidal Wetland Types	Area (ha)	Mangrove	Saltp/m	WCI
Closed Rhizophora	4396	1		
Closed Avicennia	100	1		
Open Avicennia	85	1		
Closed Ceriops	309	1		
Open Ceriops	35	1		
Closed Avicennia/Ceriops	745	1		
Open Avicennia/Ceriops	13	1		
Closed Rhizophora/Avicennia	350	1		
Open Rhizophora/Avicennia	1	1		
Closed Aegiceras	96	1		
Closed Aegiceras/Rhizophora	38	1		
Closed Aegiceras/Avicennia	23	1		
Closed mixed mangroves	520	1		
Dead Rhizophora	3	1		
Dead Ceriops	14	1		
Dead Ceriops with emergent Avicennia	8	1		
Saltflat	3894		1	
Samphire	486		1	
Saline grass	193		1	
	11309	6736	4573	0.60

It is also useful to consider that mangroves in the PCPA region occur in 18 major catchment areas (Fig. 14). These areas have markedly varied influences affecting tidal wetlands where some are notably larger riverine catchments such as estuaries of the Fitzroy River, the Calliope River, the Boyne River and South Trees Inlet. Others were less associated with larger land catchments, and more influenced by tidal factors, and other changes in sea level, such as The Narrows, Western Basin, Facing Island and Rodds Harbour.

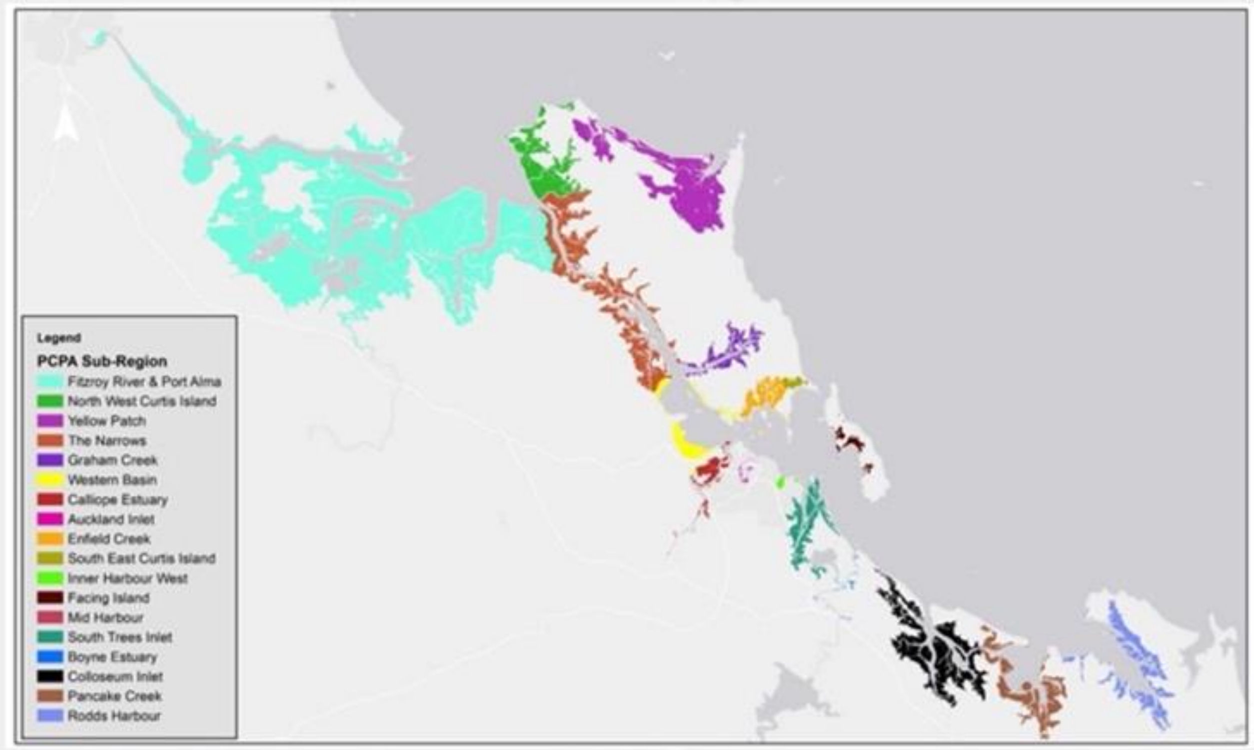


Figure 14. Distribution of mangrove and saltmarsh/saltpan in 18 key catchment areas within the Port Curtis Port Alma region. (Source: J. Mackenzie).

Canopy Height of Mangroves

A notable trend in mangrove canopy height. Mangrove canopy heights overall vary notably from north to south, although average canopy height was around 4 metres (Fig. 15). Those in the north range were shortest, around 1-3 m tall. Those in the Port Curtis area were 3-5 m tall, and those around Rodds Harbour, ranged around 5-7 m tall. The taller canopy heights were indicative of the influences of higher levels of longer-term rainfall (see Chapter 3; Table 3).

Vegetation Density. Knowing that the NDVI describes the relative density of vegetation canopy, we used this index as a proxy for vegetation condition, at a spatial scale of 30 m^2, low NDVI represents low mangrove canopy cover and high values depict dense healthy mangrove cover. Low NDVI values may be attributed to either low vegetation stem density (stems m^{-2}) or low canopy density, where each relate to aspects of physiological stress. Both instances represent poor mangrove ‘condition’ as healthy mangrove areas are characterised by having continuous canopies with moderately dense canopy cover.

Observations were consistent with earlier observations, where mangrove habitat in the north had lower canopy densities and heights compared to those in central areas, and those in the south. Canopy condition was quantified using the NDVI estimated from the Landsat Thematic Mapper for 1980 data. The overall trend was the same as that shown for 2016. Those in the north were more stressed, compared with those in the central area, and those in the south.

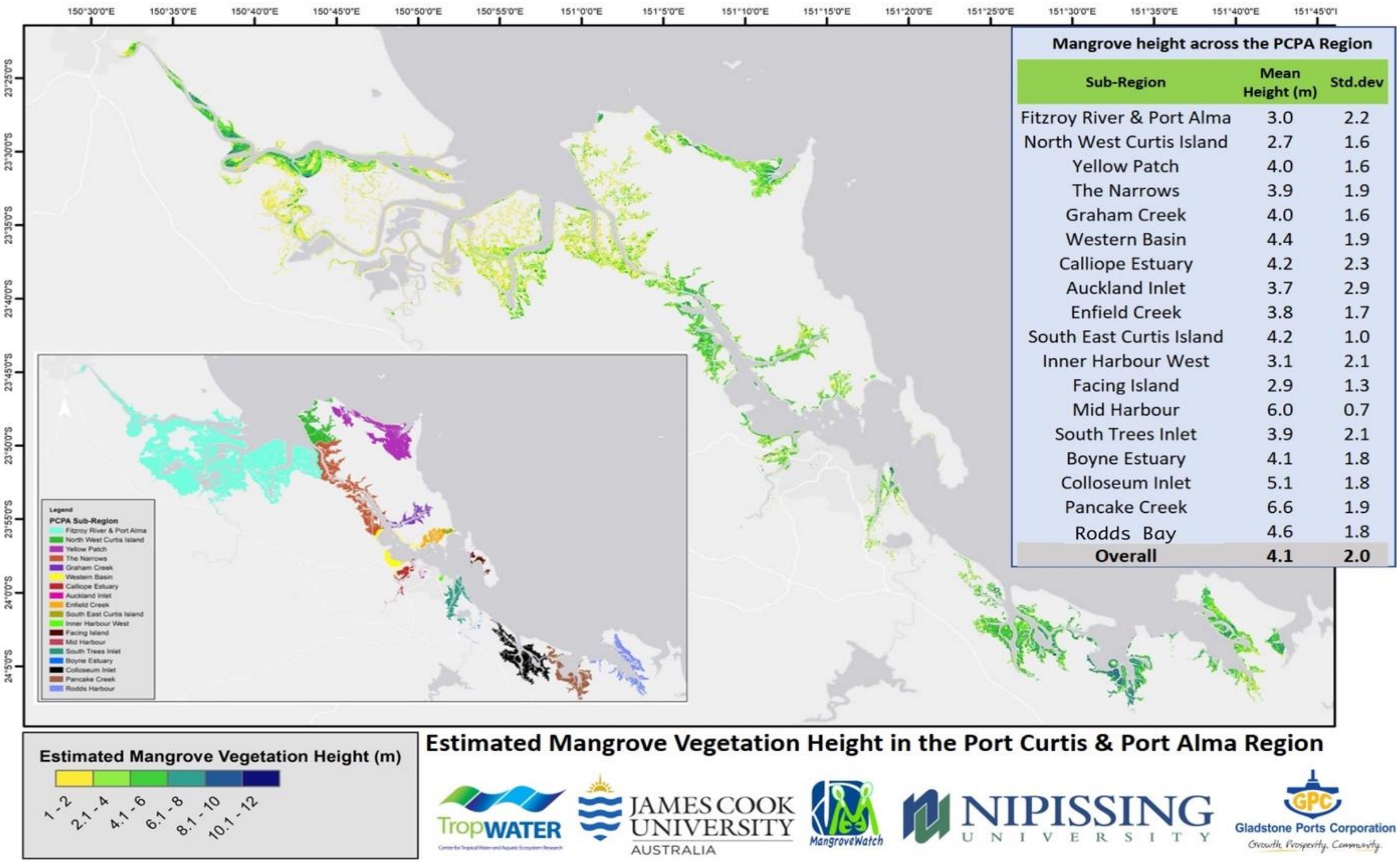
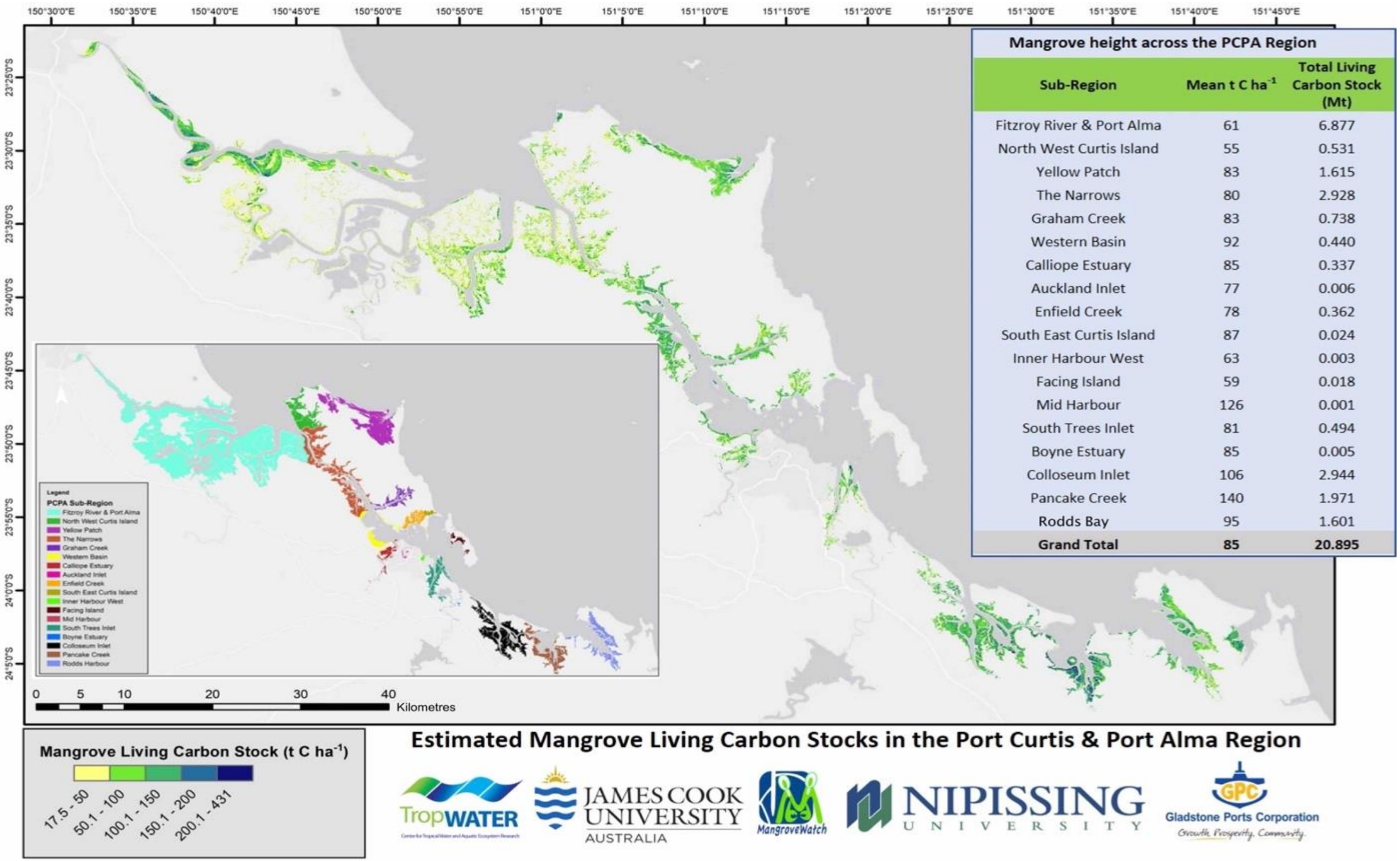


Figure 15. Mangrove vegetation height (yellow-green-blue) mapped from AVNIR 2016 – Port Curtis and Port Alma study area (see Appendix 5). (Source: J. Mackenzie).



Sub-Region	Mean t C ha^{-1}	Total Living Carbon Stock (Mt)
Fitzroy River & Port Alma	61	6.877
North West Curtis Island	55	0.531
Yellow Patch	83	1.615
The Narrows	80	2.928
Graham Creek	83	0.738
Western Basin	92	0.440
Calliope Estuary	85	0.337
Auckland Inlet	77	0.006
Enfield Creek	78	0.362
South East Curtis Island	87	0.024
Inner Harbour West	63	0.003
Facing Island	59	0.018
Mid Harbour	126	0.001
South Trees Inlet	81	0.494
Boyne Estuary	85	0.005
Colloseum Inlet	106	2.944
Pancake Creek	140	1.971
Rodds Bay	95	1.601
Grand Total	**85**	**20.895**

Figure 16. Carbon accumulated stocks (Mt) in living mangrove forests of the Port Curtis Port Alma study area (see Appendix 6). (Source: J. Mackenzie).

Mangrove Biomass and Carbon Stocks

Where canopy density was quantified using the NDVI estimated from the Landsat Thematic Mapper for 2016 data, these data (Fig. 16) showed a trend in tree height and biomass from north to south. These may be taken as measures of condition but this conclusion must be considered approximate.

In any case, the area map (Fig. 13) shows the baseline presence of habitat that defines the extent of mangrove and saltpan habitat distributions in each subregion. It has been important to accurately map the distribution of mangroves upstream in estuarine systems. Mangrove stands in these locations are difficult to discriminate in low (coarse) resolution imagery because trees are often small in size, and they often occur in very narrow zones, just a few trees wide. In other locations, mangroves at the landward fringes are sometimes hard to distinguish where they border sometimes dense supratidal upland forest vegetation.

CHAPTER 3

THE CHANGING TIDAL WETLAND ENVIRONMENT

Environmental Conditions Influencing Tidal Wetlands. The natural environmental influences on tidal wetlands of Port Alma, Port Curtis and Rodds Harbour are changing. These changes are having notable impacts on: the area of mangrove, saltmarsh & saltpan vegetation units. Key factors changing include: air temperature, rainfall, storms, sea level and fluctuations in mean sea level.

Temperature Rise

In the Gladstone and the PCPA region generally, average air temperatures mostly range between 15°C and 31°C throughout the year, with moderately distinct seasonal variations in temperature rarely below 11°C or above 34°C. However, temperature levels have been gradually increasing over many years as the effects of accumulating greenhouse gases take effect around the world. The situation for the PCPA region is displayed in Figure 17. While there are slightly different rates of rising mean temperatures in the three subregions of Port Alma, Port Curtis and Rodds Harbour, it is notable that all have risen since 1970.

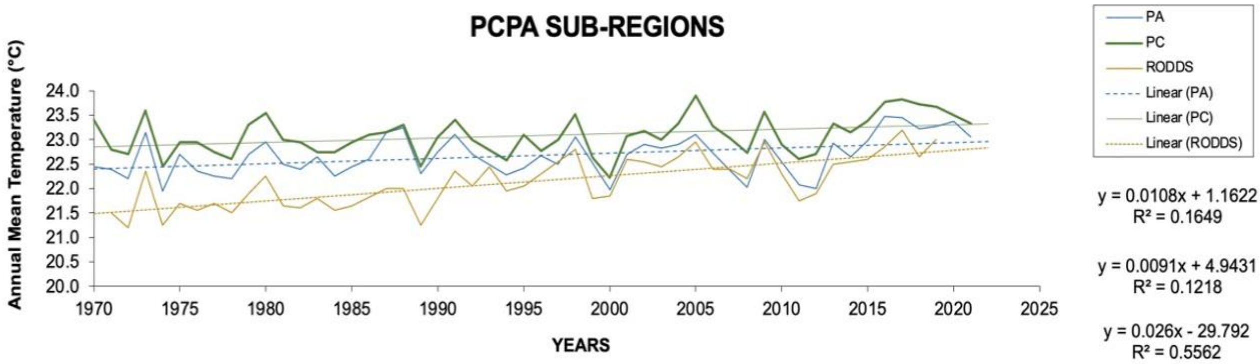


Figure 17. Long term trends in annual mean temperature for Port Alma, Port Curtis and Rodds Harbour subregions – 1970-2022 (Sources: see Appendix 4).

Specific rates of change in the PCPA subregions over a range of recent time periods are shown in Table 2. These data quantify differences to the rates of change. For example, this is depicted in values for Rodds Harbour having increased more than twofold between the averaged rate over the last century (1.09 degrees centigrade over 101 years) compared with the averaged rate over the last 27 years (2.54). Overall, for the region, the average rate was 2.63 for the last 27 years, up from 1.53 for the 51-year average.

Table 2. Varying rates of change in mean temperature (degrees centigrade per 100 years) between subregions and over time. Rates have more than doubled in recent years (Appendix 4).

Change Period	Port Alma	Port Curtis	Rodds Harbour	PCPA Mean
1994-2021 (27)	2.64	2.72	2.54	2.63
1970-2021 (51)	1.08	0.91	2.60	1.53
1920-2021 (101)	No data	No data	1.09	No data

This upward trend is predicted to worsen. In Figure 18, the light shaded areas represent uncertainties in changes based on the consideration of the response of the models to the emissions scenarios and uncertainty in carbon cycle feedbacks in the climate system. The coloured lines indicate changes based on the mean average response of the models and mid-range assumptions about carbon cycle feedbacks. The black line indicates observed changes recorded during the 20th Century. Source: Meehl et al. (2007).

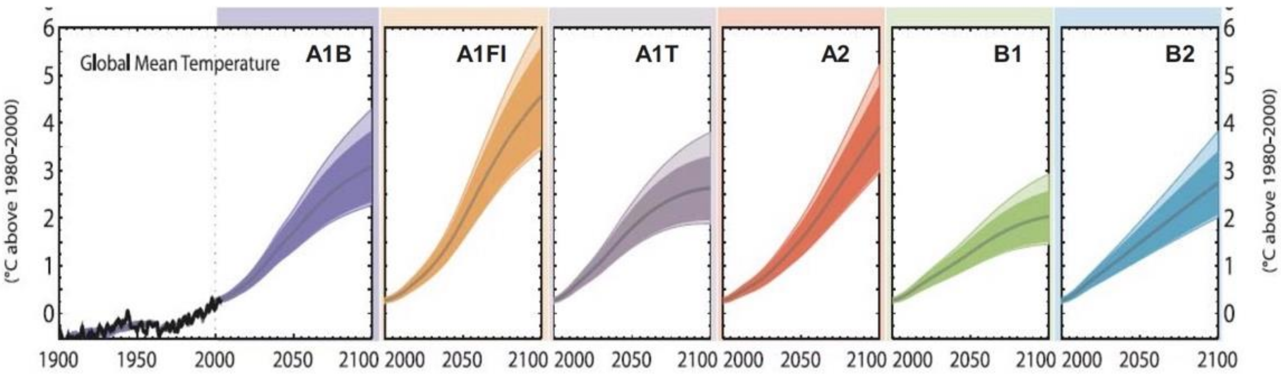


Figure 18. Changes, relative to the average for the period 1980-2000 in global average surface temperature for the 21st Century for the A1B, A1FI, A1T, A2, B1 and B2 SRES emissions scenarios. The dark shaded areas represent uncertainties in changes based on the consideration of the response of 19 climate models to the emissions scenarios.

Rainfall Decline

In the PCPA region, the mean annual rainfall is around 949 mm averaged over the last century, with a range of 333-2227 mm. There are moderately distinct seasonal variations. The wetter season lasts around 5 months, from November to March, with February being the wettest month. The drier season lasts around 7 months, from April to October with the driest month in July.

Table 3 displays differences between subregions with Port Alma being the driest (855 mm), Port Curtis (916 mm) in between, and Rodds Harbour the wettest (1076 mm). Rainfalls have also changed over time within each subregion, with a common trend towards drier conditions as the effects of greenhouse gases take effect around the world. The situation for each of the PCPA subregions is displayed in Figure 19. While having slightly different rates of mean annual rainfalls, the rates in all three subregions of Port Alma, Port Curtis and Rodds Harbour declined.

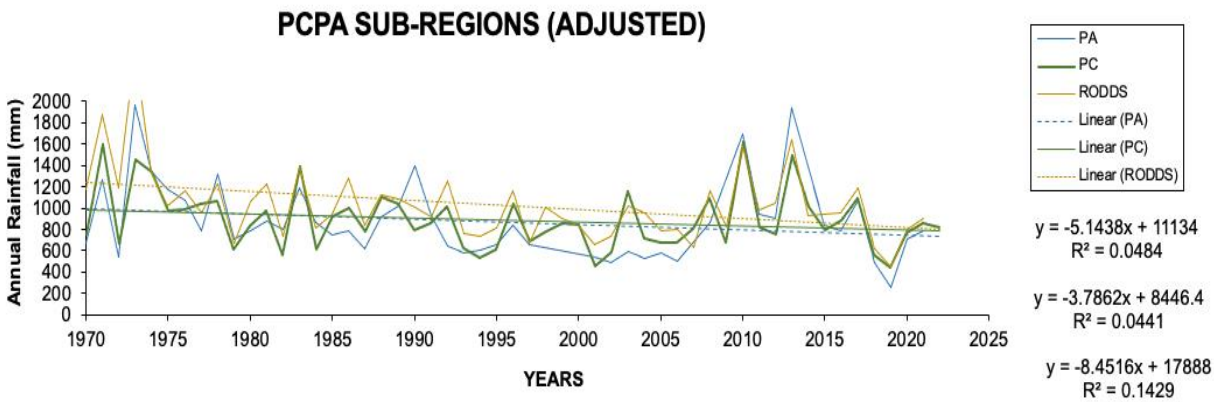


Figure 19. Long-term trends in annual rainfall for Port Alma, Port Curtis and Rodds Harbour subregions – 1970-2022 (see Appendix 4).

Table 3. Mean annual rainfall (mm) and rates of change in annual rainfall (mm per year; in brackets) for PCPA subregions and over time. While rates had risen in recent years, there was an overall decline in annual rainfall over the last 100 years, although less so for Port Alma (Appendix 4).

Change Period	**Port Alma**	**Port Curtis**	**Rodds Harbour**	**PCPA Mean**
1994-2021 (27)	868 (8.8149)	851 (5.1232)	946 (3.0349)	**888** **(5.65767)**
1970-2021 (51)	893 (-5.1438)	912 (-3.7862)	1029 (-8.4516)	**945** **(-5.79387)**
1920-2021 (101)	855 (-0.6751)	916 (-1.2637)	1076 (-3.3534)	**949** **(-1.76407)**

Sea Level Rise

Sea levels rising due to climate change are one of the biggest threats to the survival of mangrove communities (Gilman et al., 2008). The observed sea level rise (Fig. 20) is ~5 mm per year (Table 4), based on measurements between 1994 and 2021. Moreover, this estimate is greater than the global value of ~3 mm per year (Church & White 2011). Changes in global sea level is nonlinear and projected to be 0.8 m by 2100. There is still great uncertainty associated with the expected scale and timing of rises in sea level due to the highly dynamic nature of major ice sheets. Current warming of the oceans and atmosphere is likely to drive further increases in global sea level for centuries, even if there are drastic reductions in current greenhouse gases emissions.

Measured rates from PCPA sea level data have been greatest in southern subregions. And, rates appear to have more than doubled in recent years.

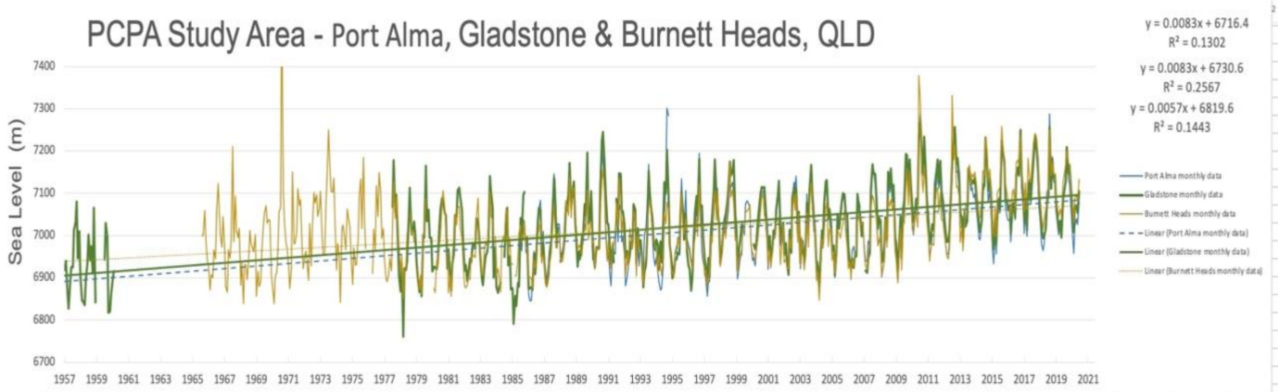


Figure 20. Long-term trends in monthly mean sea levels for Port Alma, Port Curtis and Rodds Harbour subregions – 1970-2022 (see Appendix 4).

Table 4. Increasing rates of mean sea level rise (mm per year) amongst subregions, and over time.

Change Period	Port Alma	Port Curtis	Rodds Harbour	PCPA Mean
1994-2021 (27)	4.0024	4.4506	5.9964	4.83573
1970-2021 (51)	No data	No data	2.2787	No data

More Extreme Oscillations in Mean Sea Level

El Niño-Southern Oscillation (ENSO) phenomenon: ENSO is the major driver of the inter-annual variability of climate of the Southern Pacific region. ENSO is linked to several large-scale climate drivers that influence both land and oceanic environments.

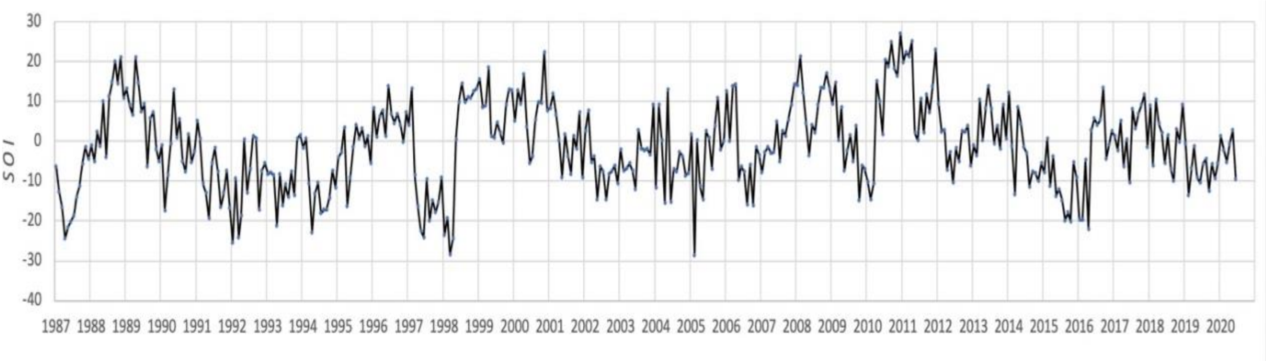


Figure 21. Long term trend in monthly SOI levels for Port Alma, Port Curtis and Rodds Harbour subregions – 1970-2022 (see Appendix 4).

A graph of the Southern Oscillation Index (SOI) is displayed in Figure 21. This graph identifies the two acknowledged climatic periods of El Niño (negative value troughs) and La Niña (positive value peaks). The strengths and consequential impacts of either period depends on either the trough depth, or peak height, respectively (for more details, see: http://www.bom.gov.au/climate/updates/articles/a008-el-nino-and-australia.shtml). A direct correlate with SOI in tropical latitudes is mean sea level (SOI (cp. Figs. 20 & 21).

Mean sea levels oscillate at two or more amplitude periods including: annual highs and lows; and, multiple-year periods of highs and lows (see Fig. 21). The relationship between means sea level and the SOI indicates how the periods of high and low extremes in sea level correspond with the oscillations defined by the severity of El Niño and La Niña events.

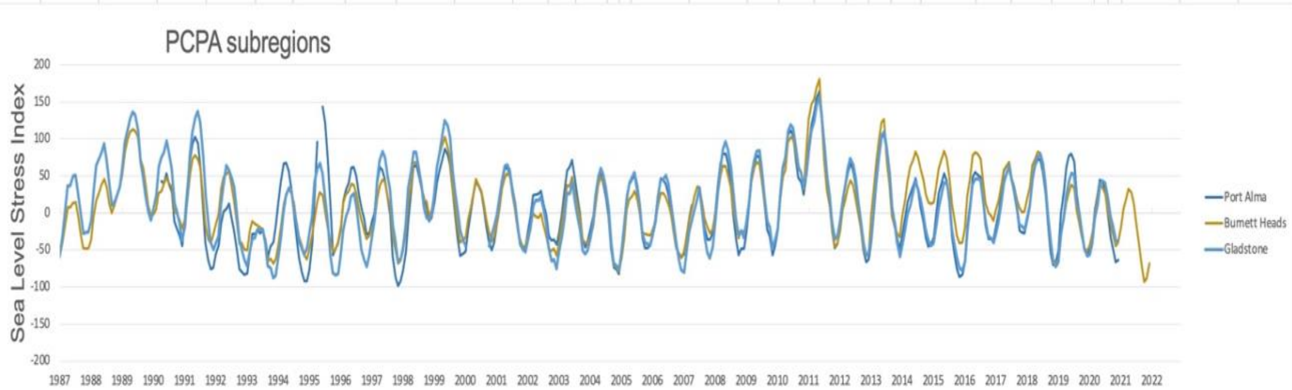


Figure 22. Sea level stress index developed by Duke et al. (2022) to depict threshold limitations in mean sea level on intertidal mangrove stands (see Appendix 4).

The extremes in oscillations in mean sea level have catastrophic impacts on 'moisture-dependent' tidal wetlands (Duke et al. 2021; Duke et al. 2022). For example, in Australia's Gulf of Carpentaria in 2015, a particularly severe period of low sea levels caused 76 km^2 of mangrove forests to die (Duke et al., 2017a). Detailed subsequent investigations of the incident (see Fig.

23) derived the Sea Level Stress Index (SLSI; see Fig. 22) linking and quantifying changes in mean sea level as a useful indicator of mangrove ecosystem stress.

Notably, the SLSI derived from PCPA sea level data was significantly correlated with the SOI (Fig. 24). Accordingly, periods of low sea levels corresponded with El Niño periods of low SOI six months earlier, and conversely, periods of high sea levels correspond with La Niña periods of high sea levels. In the PCPA region, SLSI levels were relatively minor compared to the devastating low levels (< -400) recorded in the Gulf. However, a notable incident of mangrove dieback in South Trees Inlet (see the Fringe Collapse indicator, page 112), was explained by the coincidence of maximal values >150 (156.7) SLSI, in May 2011, and with SOI levels >27 a few months earlier in Dec 2010. Such occurrences were recently described by Duke et al (2022).

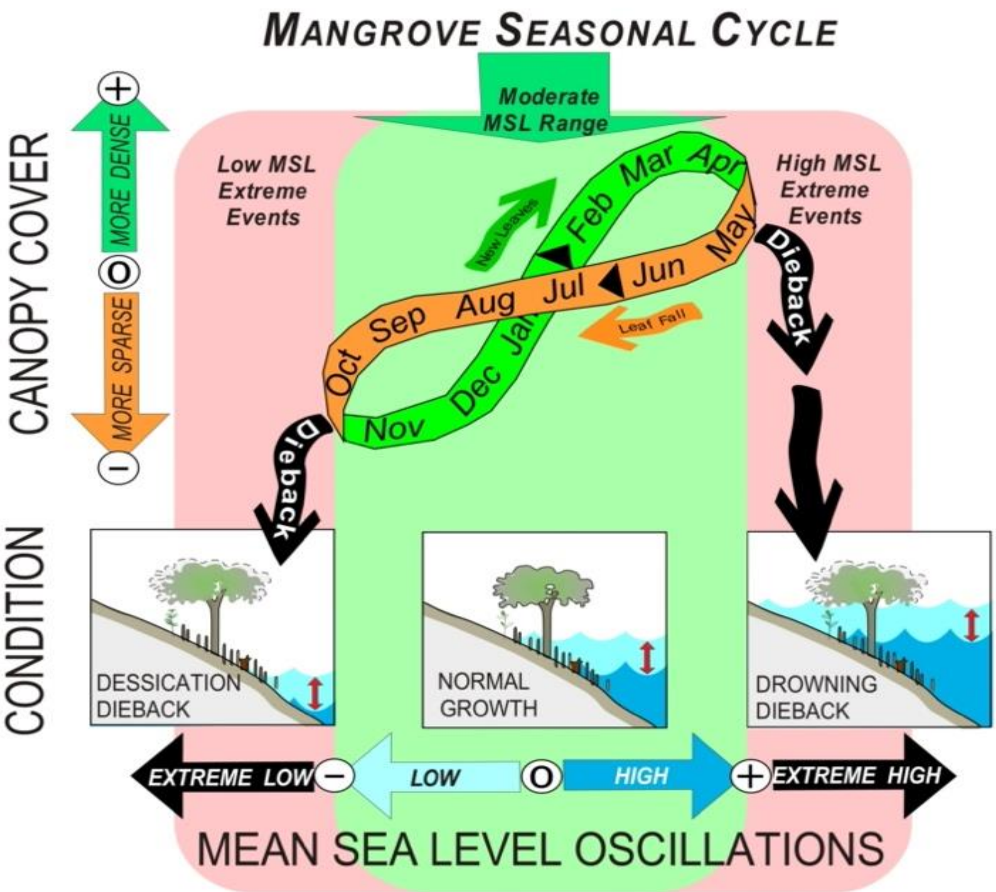


Figure 23. Relationships between canopy condition of tropical shoreline mangroves and mean sea level. When sea level conditions exceed the mangrove Goldilocks zone (central green shaded block) of normally moderate annual oscillations in mean sea level, there are severe destructive impacts from extreme high or low events (drowning or desiccation dieback respectively; pink shaded side blocks). Moderate oscillations appear to drive natural seasonal cycles of leafing and leaf fall (Image source: Duke et al. 2022).

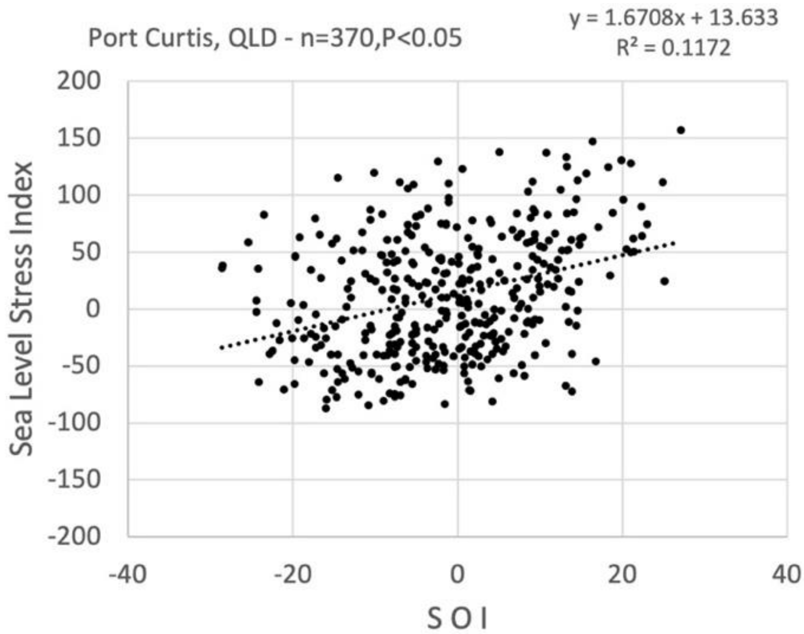


Figure 24. The relationship between SOI and SLSI for Port Curtis area. The overall relationship was highly significant (95%) compared with SOI levels 6 months earlier. (see Appendix 4).

More Frequent Severe Tropical Cyclones

Severe tropical cyclones are relatively rare in the Port Curtis Port Alma (PCPA) region. As for the wider Australian region, tropical cyclones are highly seasonal and mostly confined to the summer months, although, tropical cyclones do form in late spring and early autumn. Severe tropical cyclones (Categories 3-5) are known to cause severe physical damage to shoreline mangrove stands. A distinctive feature of monsoon depressions (lows) and tropical cyclones which form along the monsoon trough is that they are responsible also for large amounts of rainfall and flooding damage during summer months.

While there is considerable uncertainty about recent changes to tropical cyclone behaviour due to enhanced greenhouse conditions, a recent review of tropical cyclone characteristics (Knutson et al. 2010) suggested there will be an increase in globally averaged tropical cyclone intensity of 2-11% by 2100. This would result in an increase of ~20% for the precipitation rate within 100 km of the storm. These models also suggest a decrease in the frequency of tropical cyclones in the Southern Hemisphere with mixed changes in northern Australia. Solomon et al. (2007) posited that the intensity of tropical cyclones will increase globally under enhanced greenhouse conditions. However, a lack of regionally-specific information means it is difficult to state how changes in tropical cyclone activity may impact the PCPA region.

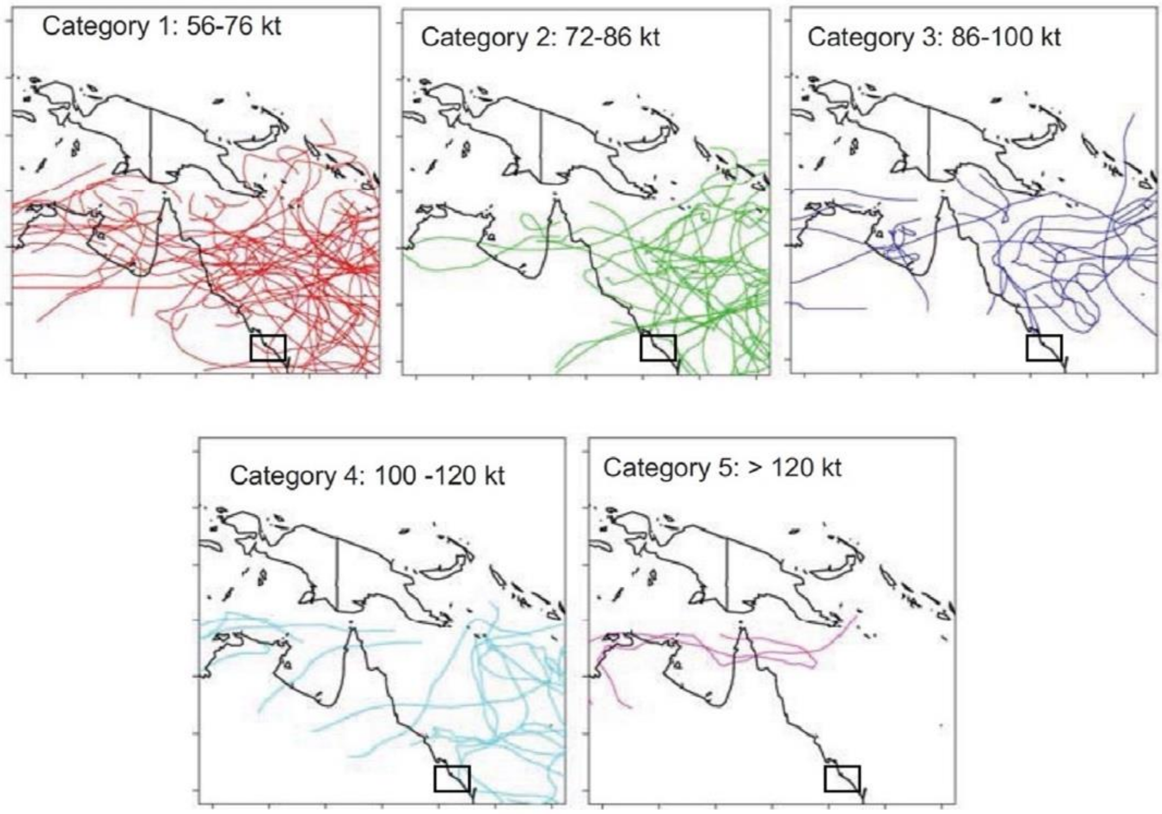


Figure 25. Tropical storms and cyclones that fall between Category 1 and 5 in the vicinity of the PCPA area (see Inset Box). Only tracks from 1970 and 2008 are plotted. Source: US National Climate Data Center, Ashville (https://www.ncdc.noaa.gov/cdo-web/search).

Figure 25 shows tracks of storms that include Category 1 to Category 5 cyclones between 1970 and 2008 (US National Climate Data Center, US. https://www.ncdc.noaa.gov/cdo-web/search). Most of the storms (Category 1 to Category 5) crossed over north-eastern Australia, but only a few affected the PCPA region. Prior to 2007, there are reports of severe storm damage (Table 5). The Figure shows the incidence of direct hits by severe tropical cyclones is low, but the indirect effect of cyclones moving along the coast of Australia can be significant as storm surges generated by these storms, along with torrential flooding rains. Ocean inundation is also a common hazard impacting many communities in the affected regions associated with tropical cyclones and tropical depressions that formed over Coral Sea and elsewhere.

Twelve tropical cyclones have been recorded having crossed the coast in the vicinity of the PCPA study area since 1913 (Table 5). While there have been four category 3-4 cyclones, it is notable that over the last 50 years, they have been category 2 or less. While this is consistent with the global modelled trends mentioned above, this does not diminish the amount of destruction caused by sometimes torrential rains and devastating flooding.

Descriptions of 7 recent cyclones and the types of impacts caused in the PCPA region
(Source: http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/history/past-tropical-cyclones/)

1972 April. Tropical cyclone *Emily* crossed the Queensland coast just to the southeast of Gladstone while rapidly weakening. Wind damage was confined to trees and sheds. The cyclone had been very severe and generated huge seas. It claimed the lives of 8 seaman in three separate incidents off the southern and central Queensland coasts. Flooding occurred with Kingaroy being isolated for a time and Breakfast Creek flooded houses in Brisbane.

1976 March. Tropical cyclone *Dawn* developed on the north Queensland coast and moved down the coast crossing Fraser Island. Two homes were unroofed in North Mackay and trees were uprooted on Heron Island. Rainfalls up to 230 mm between Proserpine and Bundaberg caused flash flooding.

Table 5. Tropical cyclones and notable low pressure systems recorded affecting the PCPA region (Port Alma, Port Curtis and Rodds Harbour) between 1913 and 2022. Source: BoM.

Year	Date	Name	TC Cat. PCPA	Direction	Press	Likely Impact Location Sub-regions (1,2,3)
1913	7 Jan	AU191213_01U	4		1000	
1917	15 Dec	AU191718_01U	4			
1929	9 Jan	AU192728_06U	1		1002	
1947	10 Feb	AU194647_04U	3		1002	
1949	2 Mar	AU194849_07U	2		972	
1971	21 Feb	*Fiona*	4	South east	994	1,2,3 - Offshore close
1972	2 Apr	*Emily*	2	South west	974	2 - Port Curtis, Boyne
1976	5 Mar	*Dawn*	1	South east	988	1,2,3 - Offshore eastward
1985	22 Feb	*Pierre*	0	South east	999	1,2,3 - offshore
1992	15 Mar	*Fran*	2	South	980	3 - Offshore, Rodds south
2013	26 Jan	*Oswald*	0	South		1,2,3 - Far inland
2015	20 Feb	*Marcia*	2	South	975	1,2,3 - Inland Mt Larcom
2017	30 Mar	*Debbie*	0	South		1,2,3 – Far Inland

1985 February. Tropical cyclone *Pierre* formed about 160 km east of Cooktown. The central pressure was 995 hPa during the morning of 21 February, rising to 986 hPa at about 0600 UTC 21 February. Decay was fairly rapid after landfall in Shoalwater Bay. The resulting low went out to sea again near Yeppoon. The maximum reported wind speed was 102 km/h reported from Hayman Island at 0600 UTC 21 February. Damage was minimal with only minor temporary flooding occurring.

1992 March. Tropical cyclone *Fran* was the second cyclone to cross the Queensland coast in that year. *Fran* moved from the south western Pacific before reaching the Queensland coast, where it reached estimated mean winds of 40 m/s approximately 650 km away. The weakening cyclone crossed the Queensland coast near the Town of Seventeen Seventy at 1700 UTC 15 March, with an eye diameter of approximately 80 km and maximum sustained winds estimated at 28 m/s. *Fran* moved inland and weakened to a tropical depression before recurving to the southeast and moving back over water. In southeast Queensland, winds and flooding caused minor property damage and heavy crop losses along the coast, particularly in the Bundaberg district. Insurance losses were estimated to be $A2.5 million.

2013 January. Tropical cyclone *Oswald* formed as a category 1 cyclone while tracking eastward across the Gulf of Carpentaria on January 21. While the cyclone had little impact on its landfall near Kowanyama, as a low, it subsequently delivered severe weather over nearly all of eastern Queensland (Fig. 26) and northern New South Wales. Destructive winds were recorded at Hay Point, near Mackay (a gust of 140 km/h was measured). The low also stalled west of Rockhampton for two days on January the 25 and 26, producing over 1000 mm of rainfall with major flooding. Record flooding occurred also in the Burnett and Mary Rivers. At least five tornadoes, the largest number known in Australia, occurred near Bundaberg on January 26, causing serious damage in Bargara and Burrum Heads. Afterwards, the system moved towards further south, heavily impacting south-eastern Queensland and north-eastern New South Wales, with damaging destructive winds, torrential rain, dangerous surf and prolonged tidal inundation.

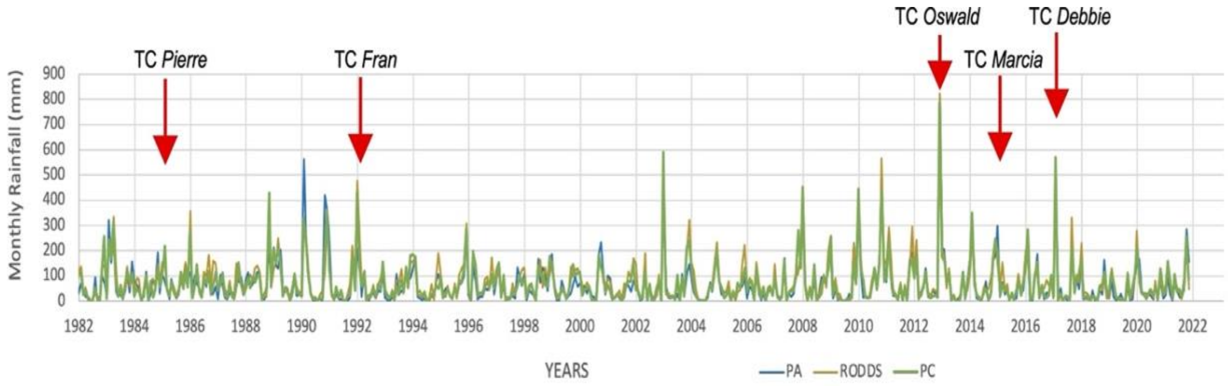


Figure 26. Tropical cyclone *Oswald* in January 2013 was notably accompanied by extremely high rainfall and flooding in the PCPA region (see Table 5; data source: Appendix 4).

2015 February. Severe tropical cyclone *Marcia* formed in the Coral Sea and crossed the coast at Shoalwater Bay (north northwest of Yeppoon) at category 5 intensity during the morning of 20 February 2015. The increase in intensity prior to landfall was well above the average rate of intensification for tropical cyclones anywhere in the world. The automatic weather station on Middle Percy Island recorded a maximum sustained (10-minute average) wind speed of 84 knots (156 km/h) and a maximum wind gust of 112 knots (208 km/h). Significant damage was recorded at Yeppoon and Rockhampton as the system weakened (Fig. 27). Winds were heaviest (category 3) around Port Alma (south of Yeppoon), decreasing to the south.

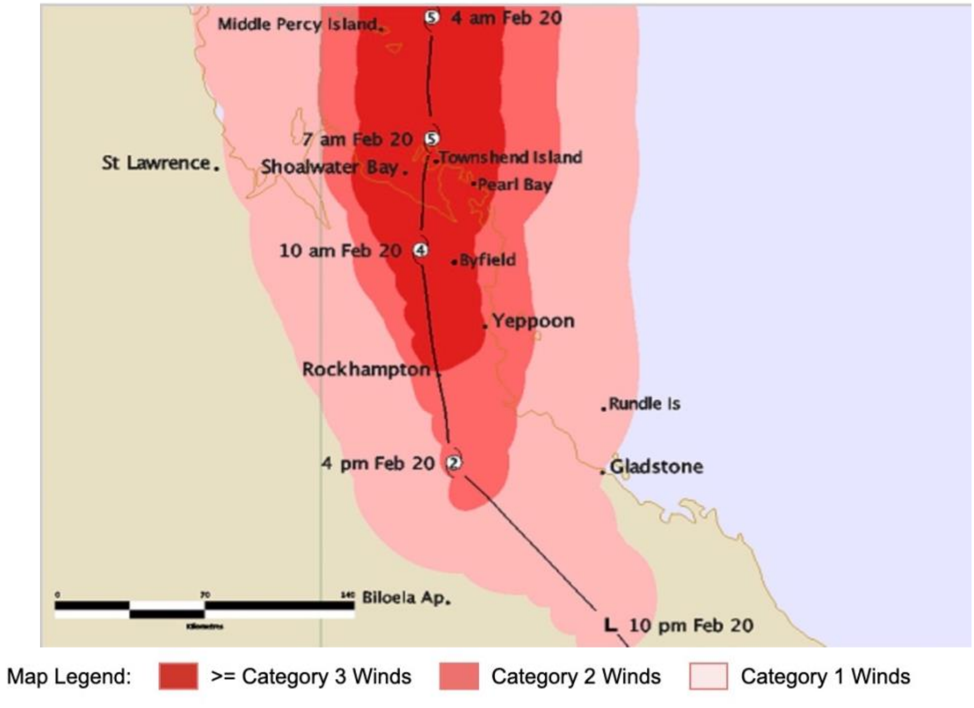


Figure 27. Track of severe tropical cyclone *Marcia* in February 2015, showing estimated areas affected by winds at associated categories of intensity in the PCPA study area (Gladstone). (Source: http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/history/past-tropical-cyclones/)

2017 March. Severe tropical cyclone *Debbie*, having formed in the Coral Sea, made landfall near Airlie Beach on Tuesday, 28 March 2017. It crossed the Whitsunday islands as a large and powerful category 4 strength system, devastating resort islands in the Whitsunday group (peak wind gusts of 263 km/h), as well as the towns of Airlie Beach, Proserpine, Bowen and Collinsville (many hours of category 2 strength winds). A 2.6 m storm surge was recorded by the Laguna Quays storm tide gauge (south of the location the cyclone made landfall), which exceeded the Highest Astronomical Tide (HAT) by 0.9 metres. After 29 March, the remnant low moved southeast and produced major flooding in central and southeast Queensland and northeast New South Wales during the following few days. Several locations in the Fitzroy River basin received up to 1000 mm in rainfall over two days, and the Fitzroy River went into major flood warning at Rockhampton, extending south to Agnes Waters during the following week.

CHAPTER 4

ECOSYSTEM INDICATORS OF CHANGE IN TIDAL WETLANDS

The state, condition and health of shorelines can be classified and quantified according to a series of indicators as potential drivers of change (Fig. 28). Their identification provides an improved capability to monitor change affecting tidal wetlands on a broad scale. These observations may be used to monitor habitat condition associated with identified drivers, as well as providing an assessment benchmark for local and national management priorities.

The assessment protocol quantifying these processes compliments pre-existing mapping of coastal environment and tidal wetland habitats based on remote sensing of oblique and vertical imagery. In the following section and in reference to Figure 28, selected major drivers of change are described. While there have been substantive impacts from direct human development, we also include drivers from climate-natural processes as these have also impacted tidal wetlands and shorelines (Duke et al., 2021). This is not withstanding that climate-natural influences may also be indirectly affected by anthropogenic drivers associated with increased greenhouse gas emissions.

Mangrove Condition as Indicators of Drivers

Tidal wetlands of mangrove ecosystems are ancient ecosystems having evolved over more than 50 million years. During this time, the earth, sea level and climate have changed dramatically. Mangroves of today are comprised of plants that are the survivors of previous changes through time. These ecosystems consequently have well developed life history strategies for survival with an enhanced capacity for dealing with change. As tidal wetlands ecosystems respond to changing environmental conditions they rely on their inherent adaptive capacities (Duke et al. 1998).

Where changes can be identified, described, measured and monitored they form the basis for a more enlightened monitoring and assessment strategy. For example, if a tidal wetland habitat had shifted upland, this might demonstrate, identify and quantify the effects of sea level rise. Two deductions to be made from such observations are that mangroves responded to sea level rise, and that we might evaluate the rate of net change. The value in this approach in combination with direct instrument measures, like sea level elevation stations, is that mangrove plants integrate daily and seasonal term fluctuations. These changes, when viewed from above, are significantly enhanced along sometimes characteristically low profile slopes in many locations. Furthermore, the exaggerated shifts can be readily determined retrospectively based on interpretation of vegetative condition and specific location from historical aerial imagery.

There are also questions about what causes such changes. This would be better understood if we were able to expand our general knowledge and monitoring of the full complement of forces or drivers that influence mangrove coasts. Such drivers act at local and global levels, with some delivered directly, others indirectly, and of course, some are natural. In all situations, tidal wetlands are responding to changing influences in characteristic ways that are useful as indicators of change. With systematic identification of the different types of change in tidal wetlands (Fig. 28), we are able to identify the responsible drivers and quantify their importance – and anticipated consequences.

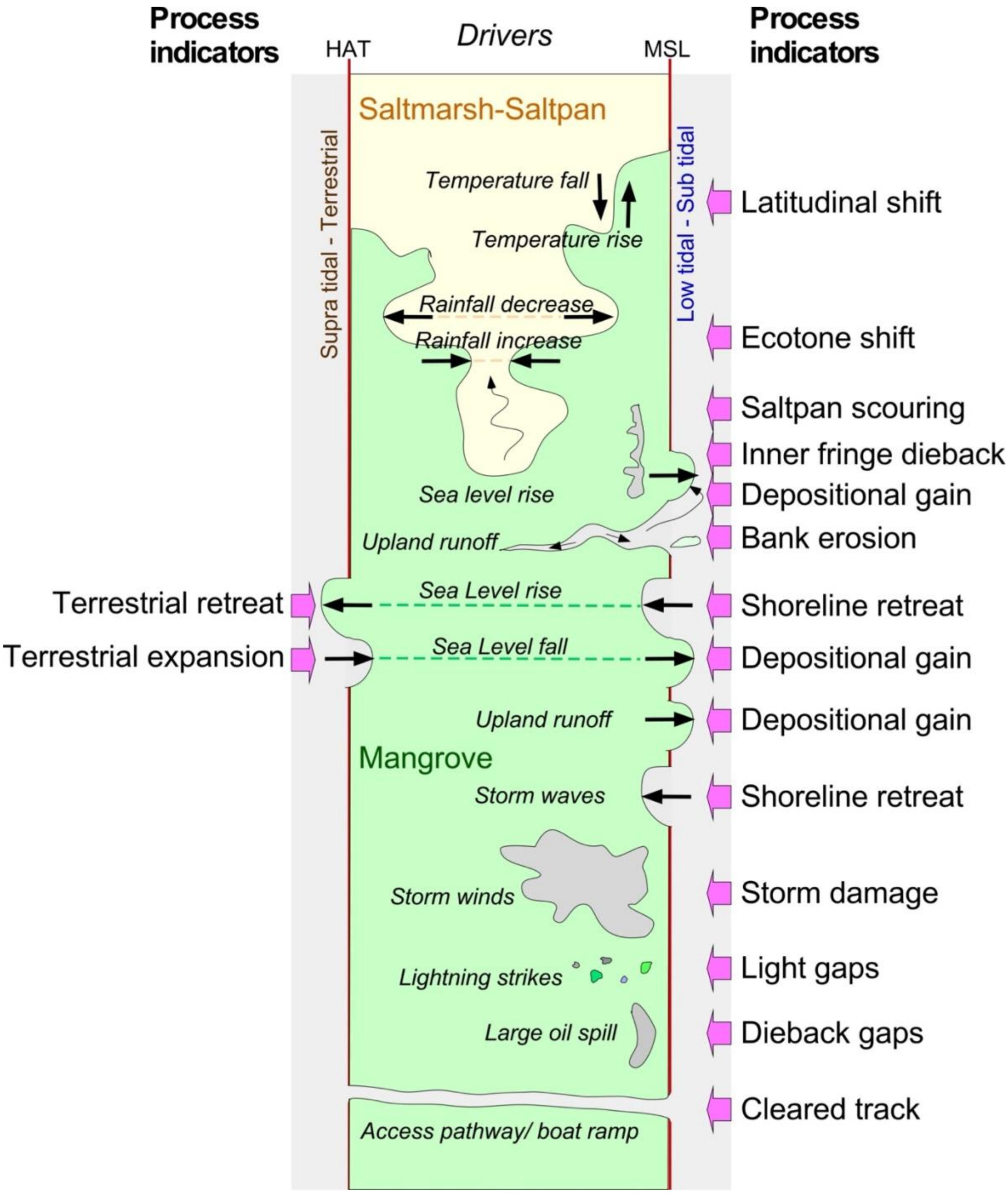


Figure 28. An illustrative schematic showing process response indicators associated with respective drivers acting at specific ecotone locations regarding their respective tidal profile positions (Source: Duke et al., 2021).

Key Pressures on Mangrove Tidal Wetlands

Pressures on mangrove tidal wetlands can be conveniently grouped under two broad headings:

- **Human-related,** as direct and indirect human pressures, as mostly intended and obvious, plus unintended and less obvious; and,
- **Climate-Natural**, as not obviously human-influenced, if at all.

These broad categories are useful when making decisions about sustainable management of coastal and estuarine ecosystems and they form the basis for classification of all types of observed change. As it happens, the direct human influences are those that are more easily mitigated, resulting in relatively rapid, improved environmental outcomes. By contrast, it has been inherently difficult to differentiate between some human and natural influences, like global temperatures. This accepts that some drivers might be somewhat subjective with overlaps and partial ambiguity.

Indicators of Change

Changes are usually measured in terms of ecosystem responses to external pressures. Estuarine, coastal and marine ecosystems are influenced by a number of key factors acting as primary stressors and drivers. The responses of affected habitats are often unique and distinctive making them useful indicators of the key drivers.

Our evaluation of the tidal wetlands across the PCPA region relied upon a total of at least 28 indicators of condition and change. These were considered the majority if not all of the indicators, as might be scored during an aerial survey. These observations consisted of 11 human-related indicators (Table 6), and 17 climate-natural indicators (Table 7). With each, we scored severity and extent according to the presence of defined features and which mangrove zone was likely affected.

Table 6. Indicators of 11 human-related environmental changes and the ecosystem responses observed during aerial surveys of shoreline intertidal wetlands.

Human-related Driver	Driver Code	Field Survey Feature and Indicator of Change	Tidal Wetland Zone most Affected
Built structures	STRT	rockwalls, wharf, ramps, roads	any zone
Direct Loss/Damage	DLOS	clearing, dead trees, landfill, reclamation	any zone
Human Altered Hydrology	HAHD	bunds, drains, impounded areas	mostly upper zones
No Buffer	NBUF	ag/urban encroachment, cut-off tributaries	upper edge zone
People Access	ACES	vehicles, tracks, foot pathways	mostly saltpans - saltpans + high tide edge
Stock Damage	STOC	cattle, horses, goats, tracks	mostly saltpan-upper. saltpans + high tide edge
Feral Animals	PIGS	pigs, tracks, wallows, diggings	mostly saltpan-upper. inner mangrove + freshwater wetlands
Pollutants	POLL	oil spill, scum, dump site, dieback & oil	any zone
Nutrients	NUTS	enhanced growth, expansion	any zone
Fire	FIRE	fire damage, blackened dieback	upper edge zone. Terrestrial margin - fringing mangroves
Weeds	WEED	smothering, weeds, dieback	mostly edge zone. Beach ridge veg. - to mangrove upper edges

Table 7. Indicators of 17 climate-natural environmental changes/responses observed during aerial shoreline surveys of shoreline intertidal wetlands.

Climate-Natural Driver	Driver Code	Field Survey Feature and Indicator of Change	Tidal Wetland Zone most Affected
Storm Damage	STRM	Broken trees, forest damage	Mangrove zones - closed canopies
Shore Erosion	SERO	Fallen trees, steep bank, dieback	Seaward zone. seaward + main channel edge stands of mangroves
Bank Erosion	BERO	Fallen trees, steep channel bank	Channel edges. lower estuary banks
Root Burial	ROOT	Fallen trees, steep bank, dieback	Mostly seaward zone. shoreline and sea-edge mangroves
Fringe Collapse	IFCO	Irregular dieback, canopy gaps	Sea-edge mangroves
Pan Scouring	PSCR	Sheet erosion, scoured surface, missing saltmarsh	Saltpan zone. upper saltpans
Ecotone Shift Loss	ESLO	Dead trees, fringe loss, retreating	Saltpan-mangrove. Avicennia + Ceriops closed canopies
Ecotone Shift Gain	ESGA	Young trees, fringe/ecotone gain, encroaching	Saltpan-mangrove
Depositional Gain	DGAN	Young trees, bank & edge expansion	Water edge. Waters-edge margin
Flood Damage	FLOD	Wash damaged trees; debris; unidirectional fallen stems	Riverine estuary; narrow fringing stands
Terrestrial Retreat	TRTT	Back edge dieback, scouring erosion	Upper zone. Terrestrial fringe
Upland Migration	UPLM	Young mangroves amongst dead terrestrial trees	Along terrestrial margin of saltpans
Light Gaps	LIGP	Circular canopy holes/dieback	Mangrove zones. mangrove closed canopies
Natural Altered Hydrology	NAHD	Naturally impounded, ponded water, dead trees	Shoreline and sea-edge mangroves
Hail Damage	HAIL	Standing dead or damaged trees and shrubs, a grey hue of dead wood	Any mangrove zone
Bat Damage	BATS	Presence of bat (flying fox) colony, canopy loss & damage	Mangrove forest canopy
Deciduous Mangrove	XMRE	Distinctive orange-red foliage, or bare stems having lost all foliage	Edge to mid zone mangrove forests, mid estuary

Assessment of Environmental Change

In April 2019, the PCPA region was surveyed from a small helicopter. The survey systematically recorded a set of observed features considered indicators of environmental change. As noted, for this assessment of tidal wetland condition, zones in the PCPA region were arbitrarily grouped into three subregions, Port Alma, Port Curtis and Rodds Harbour (Fig. 29; Table 8). These broad subregions conveniently encapsulated the dominant features of each subregion, evident for example in the high concentration of industry and port facilities, as likely to be influencing the condition of tidal wetlands in the Port Curtis subregion.

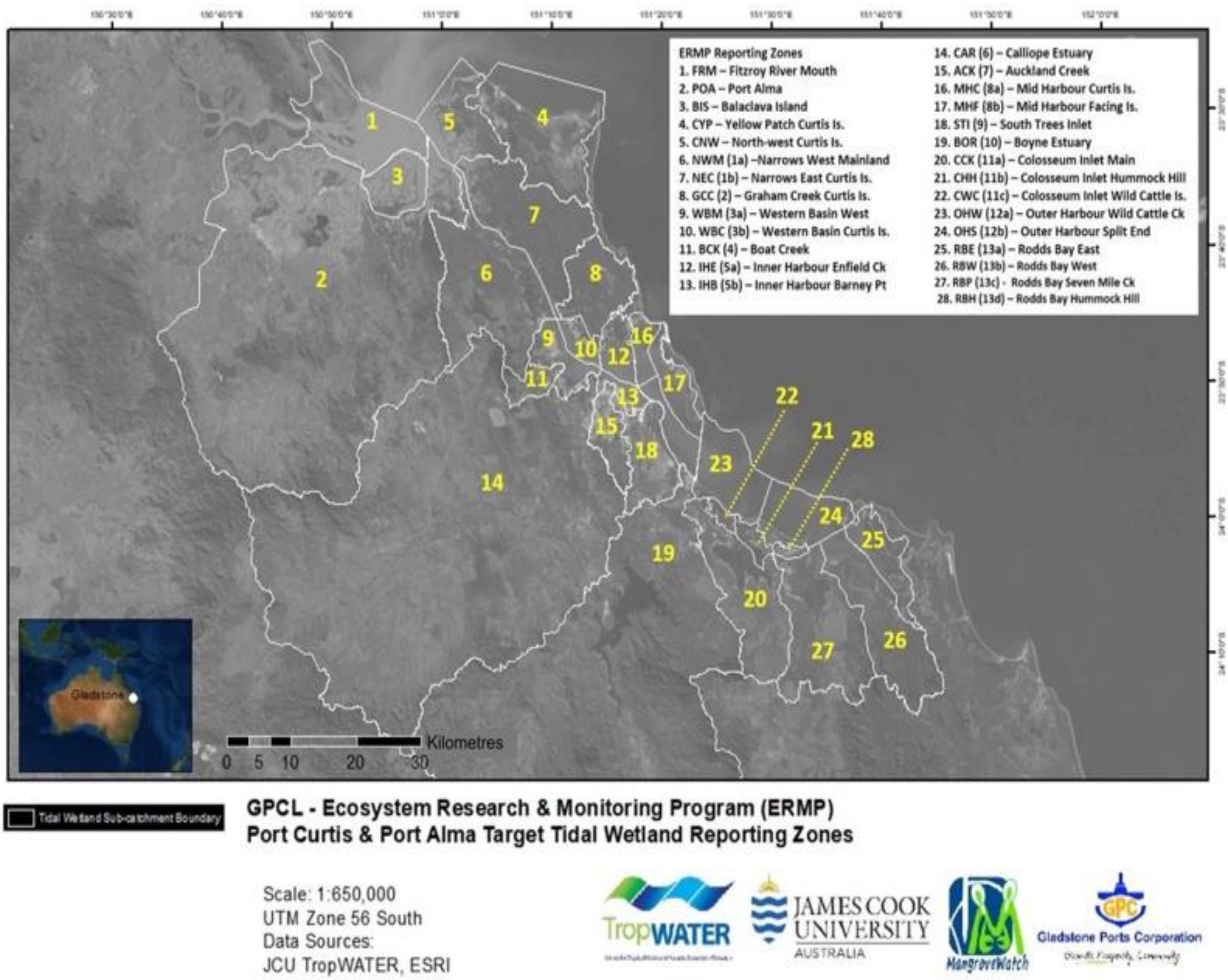


Figure 29. Map of the study area for the PCPA region showing the 28 zone areas extending south from the Fitzroy River mouth (1) and Port Alma (3) to Gladstone, and south to Rodds Harbour (26). (Source: J. Mackenzie).

Table 8. The 28 subzones and 18 zones of the three subregions of the PCPA region, Port Alma (PA), Port Curtis (PC) and Rodds Harbour (Rodds). Refer to Figure 29 for a map showing the location of each zone.

PCPA#	PCPA Zones	PCPA Sub-zone Areas	PA	PC	Rodds
1	1_Fitzroy mouth	Fitzroy mouth	1		
2	2_Port Alma	Port Alma	1		
3	3_Balaclava	Balaclava	1		
4	4_Yellow Patch	Yellow Patch Curtis Island	1		
5	5_NW Curtis	Northwest Curtis Island	1		
6	6_Narrows	The Narrows West		2	
7	6_Narrows	The Narrows East		2	
8	7_Graham	Graham Creek		2	
9	8_Western Basin	Western Basin West		2	
10	Western Basin	Western Basin East		2	
11	9_Boat Creek	Boat Creek		2	
12	10_Inner Harb.	Inner Harbour - Enfield Creek		2	
13	10_Inner Harb.	Inner Harbour - Barney Point		2	
14	11_Calliope	Calliope Estuary		2	
15	12_Auckland	Auckland Inlet		2	
16	13_Mid Harb.	Mid Harbour - Curtis Island		2	
17	13_Mid Harb.	Mid Harbour - Facing Island		2	
18	14_South Trees	South Trees Inlet		2	
19	15_Boyne	Boyne Estuary		2	
20	16_Outer Harb.	Outer Harbour - Wild Cattle			3
21	16_Outer Harb	Outer Harbour - Split End			3
22	17_Colloseum Ilt.	Colloseum Inlet - Main			3
23	17_Colloseum Ilt	Colloseum Inlet - Hummock Hill Is.			3
25	18_Rodds Harbour	Rodds Harbour East			3
26	18_Rodds Harbour	Rodds Harbour - West			3
27	18_Rodds Harbour	Rodds Harbour - Pancake Creek			3
28	18_Rodds Harbour	Rodds Harbour - Hummock Hill Island			3

CHAPTER 5

THE PCPA STUDY AREA AND SUBREGIONAL INFLUENCES

PCPA Subregions

Based on the catchments displayed in Figure 29 and Table 8, the larger area was divided into three subregions (Fig. 30):

1) **Port Alma** – including downstream Fitzroy Estuary & Port Alma, North West Curtis Island, Yellow Patch and the northern portion of The Narrows.
2) **Port Curtis** – including the southern portion of The Narrows, Graham Creek, Western Basin, Calliope Estuary, Auckland Inlet, Enfield Creek, South East Curtis Island, Inner Harbour West, Facing Island, Mid Harbour, South Trees Inlet and Boyne Estuary.
3) **Rodds Harbour** – including Colloseum Inlet, Pancake Creek and Rodds Harbour.

Figure 30. The PCPA study area noting (in yellow font) the three subregions of Port Alma, Port Curtis and Rodds Harbour.

As noted, the key vegetation groups of tidal wetlands of the PCPA region include mangroves and saltmarsh-saltpan (see Chapter 2). The areas of each are listed for each of the three subregions in Table 9. Historical areas (in hectares) of tidal wetlands including mangrove and saltmarsh-saltpan are listed where available for 1941, 1988, 1997, 1999, 2016 (see Bruinsma 2000; Duke et al., 2003; Danaher et al, 2005; Appendix 5). There is uncertainty in these data regards interpretive and methodological differences for respective study years. This means we don't have great confidence in being able to compare regional changes over time from this compilation of area data.

However, while subregion mangrove and saltmarsh area estimates were likely to be in the same proportions within studies, the Wetland Cover Index (WCI) estimates were taken to be representative of the relative proportions of mangrove to total tidal wetlands for respective subregions. Accordingly, we note common estimates of WCI in data for Port Curtis collected by Danaher et al. (2005), and with this study (Table 9). The WCI amount indicated that rainfall influences were likely to be proportionately comparable (Duke et al., 2019a).

Taking this view of WCI values, we also considered estimates for each of the subregions. We note these followed a similar trend across subregions, with estimates being consistent with drier conditions in Port Alma, and wetter in Rodds Harbour (see Duke et al., 2019a for details). This trend matched longer-term annual rainfall averages for these subregions (see Table 9).

Table 9. Tidal wetland areas in the Port Curtis Port Alma region for each of the three subregions showing different measurements (where available) between 1941 and 2016. WCI = Wetlands Cover Index (% mangrove). Asterisk (*) indicates the subregion under greatest anthropogenic influence. Tree heights and carbon (C) stock determined in a biomass assessment with this study (Appendix 6). Also see Appendix Table 3 for each of the 28 PCPA zone areas in 2016.

PCPA Subregion	Acquisition Year	Mangrove (ha)	Saltmarsh (ha)	Tidal Wetland (ha)	WCI %	Tree Hgt. (m)	C Stock (Mt)	Map Data Source
Port Alma	1997	14781	26265	41046	36			Bruinsma 2000; Danaher et al., 2005
	1999	16591	27458	44049	38			Duke et al., 2003
	2016	13087	26658	39745	33	3.2	9.0	This study
Port Curtis*	1941	3843	3851	7694	50			Duke et al., 2003
	1988	3241	2918	6159	53			Duke et al., 2003
	1997	6736	4573	11309	60			Danaher et al., 2005
	1999	5013	3490	8503	59			Duke et al., 2003
	2016	6068	5156	11224	54	3.8	5.4	This study
Rodds Harbour	2016	5454	3078	8532	64	5.4	6.5	This study
PCPA Region	2016	24608	34892	59501	41	4.0	20.9	This study

Mangrove canopy heights overall varied from north to south (Fig. 15). Those in the northern subregion of Port Alma were shortest, around 1-3 m tall. While those in the Port Curtis area were 3-5 m tall, and those around Rodds Harbour range around 5-7 m tall.

Port Alma

The larger scale maps (Figs. 31-33) show built areas around Rockhampton upstream along the Fitzroy River estuary. Within the PCPA study area. notable developed areas exist around Port Alma (lower centre) within tidal wetland areas. These areas however represented a relatively small proportion of the overall area. As noted, this subregion is the most arid of the three subregions (Table 3), and this was consistent with the lowest WCI (33%; see Duke et al., 2019a) and lower tree heights (3.2 m). Carbon stocks were however the largest since the total mangrove area was roughly double that of the southern subregions (see Table 9).

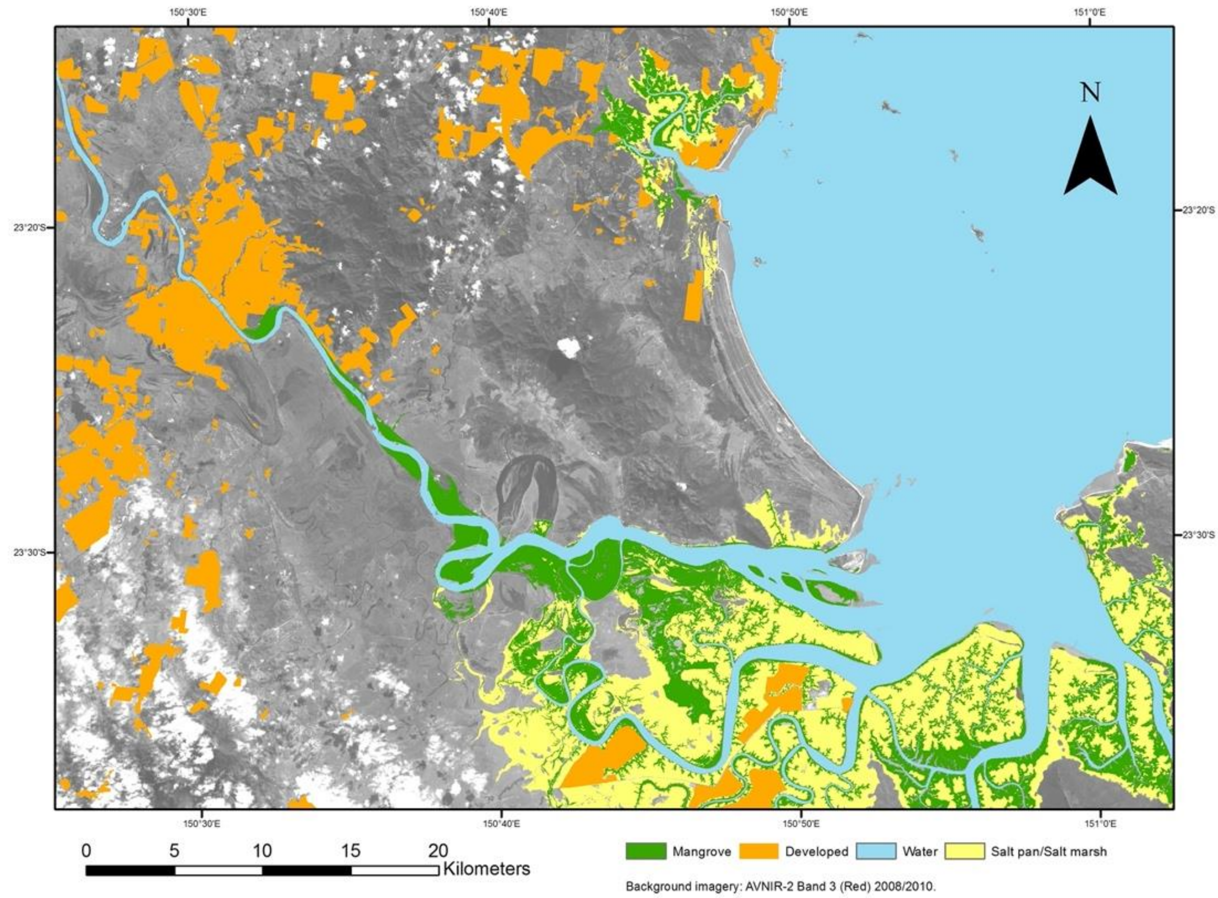


Figure 31. Port Alma subregion based on the 2010 map of Fitzroy River and Port Alma showing the extent of tidal wetlands (mangroves, saltmarsh and saltpans) and the presence of developed areas. The subregion is dominated by the Fitzroy River estuary extending diagonally north-west. (Source: J. Kovacs).

Canopy density was roughly quantified using the NDVI estimated from the Landsat Thematic Mapper for 2016 data. At the spatial scale of 30 m^2, low NDVI represents low mangrove canopy cover and high values depict dense healthy mangrove cover. Note that low NDVI values may be attributed to either low vegetation stem density (stems.m^{-2}), or low canopy density from physiological stress. Both instances represent reduced mangrove condition, but shorter stands maybe relatively healthy mangrove areas since condition is often characterised more by canopy density.

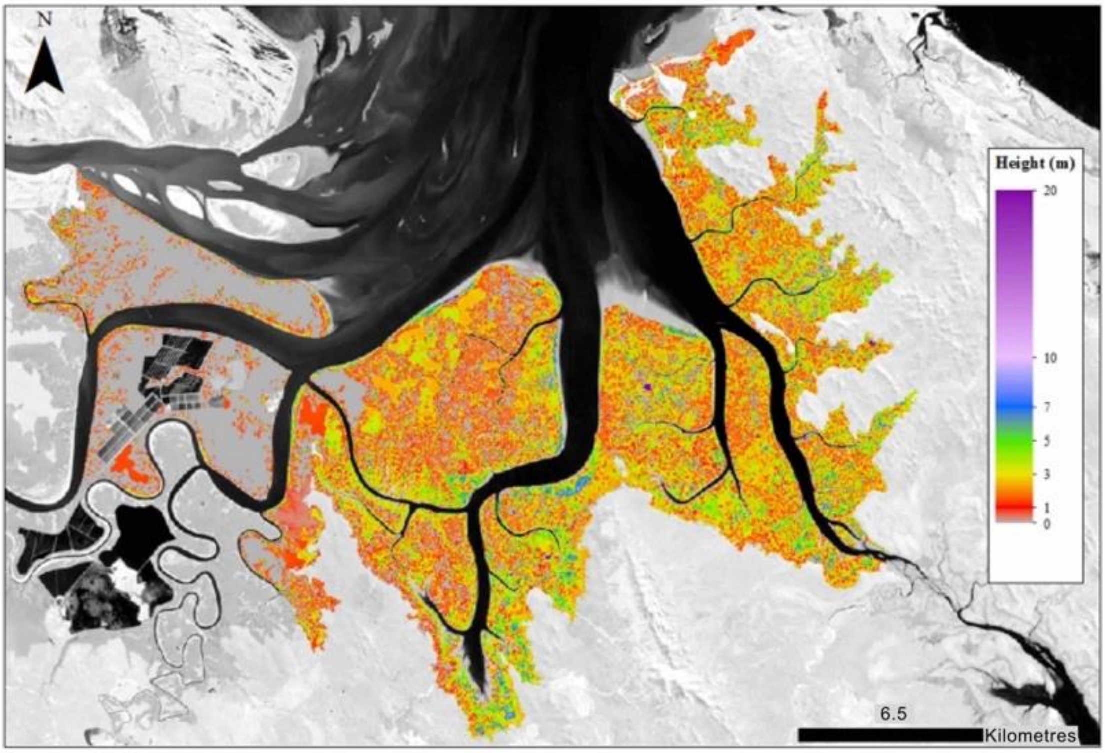


Figure 32. Vegetation height from ALOS DSM 2016 – Port Alma in the northern part of the PCPA study area. (Source: J. Kovacs).

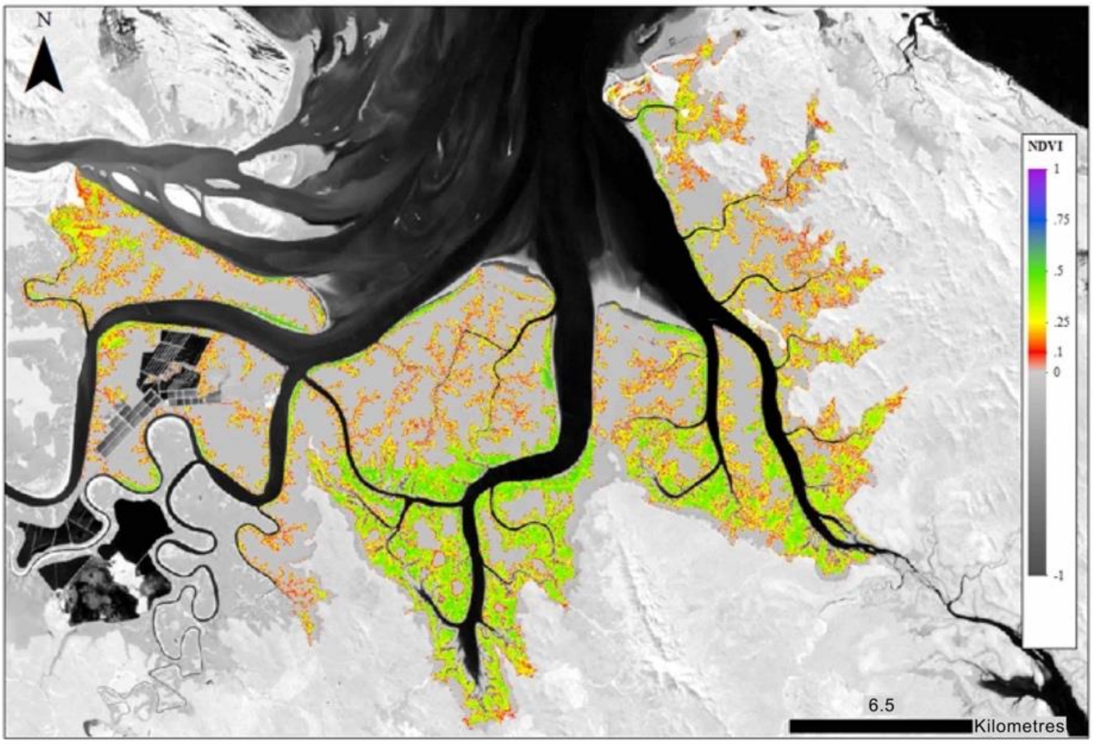


Figure 33. Canopy condition from Landsat NDVI 2016-08-07 – Port Alma in the northern part of the PCPA study area. (Source: J. Kovacs).

Port Curtis

The larger scale maps (Figs. 34-36) show built areas around Gladstone (notably the Calliope and Auckland estuaries) were largely within tidal wetland areas, noting that these areas represent a notable proportion of the overall area. As noted, the subregion has intermediate aridity compared to the other subregions (Table 3). This was consistent with the areas intermediate WCI (59%; see Duke et al., 2019a) and moderate height trees (3.8 m). Carbon stocks were the lowest (5.4 Mt) since the total mangrove area was relatively low with the moderate height canopies.

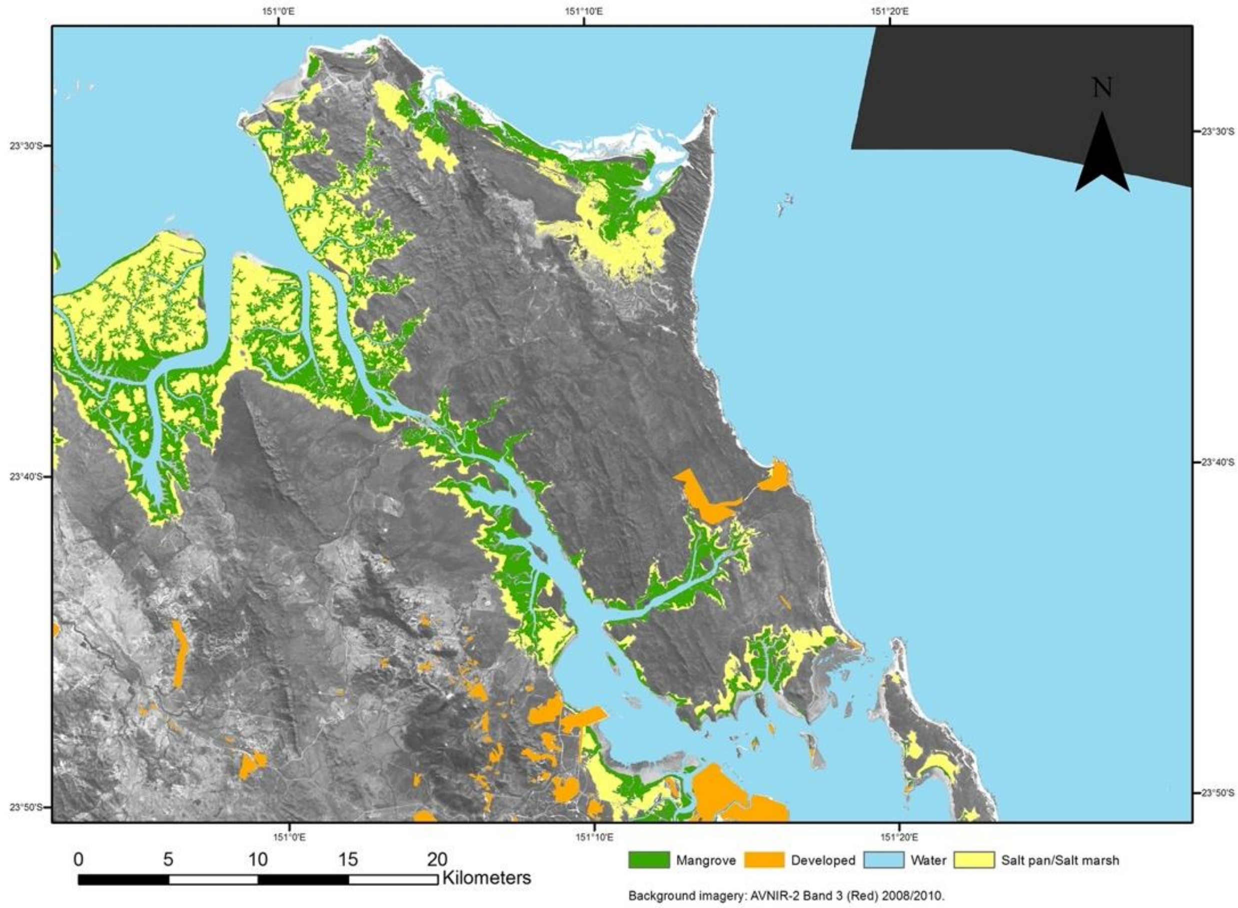


Figure 34. Port Curtis subregion based on the 2010 map of Curtis Island and northern Port Curtis showing the extent of tidal wetlands (mangroves, saltmarsh and saltpans) and the presence of developed areas. (Source: J. Kovacs).

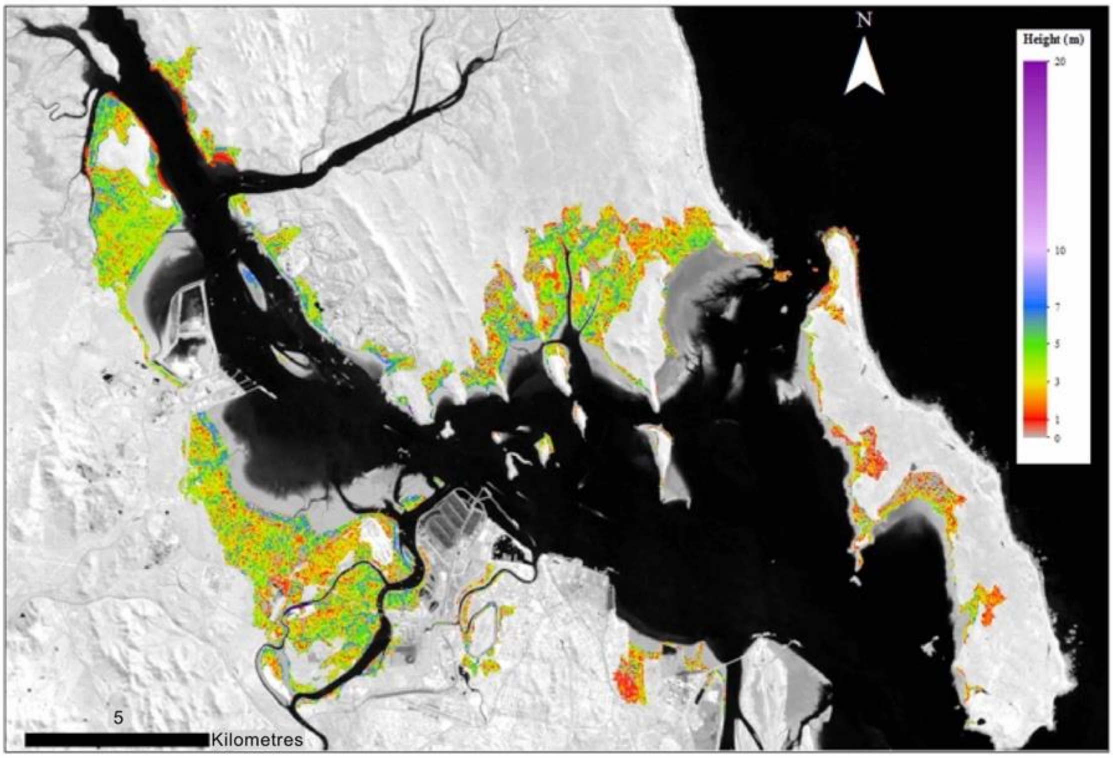


Figure 35. Vegetation height from ALOS DSM 2016 – Port Curtis and Western Basin in the central part of the PCPA study area. (Source: J. Kovacs).

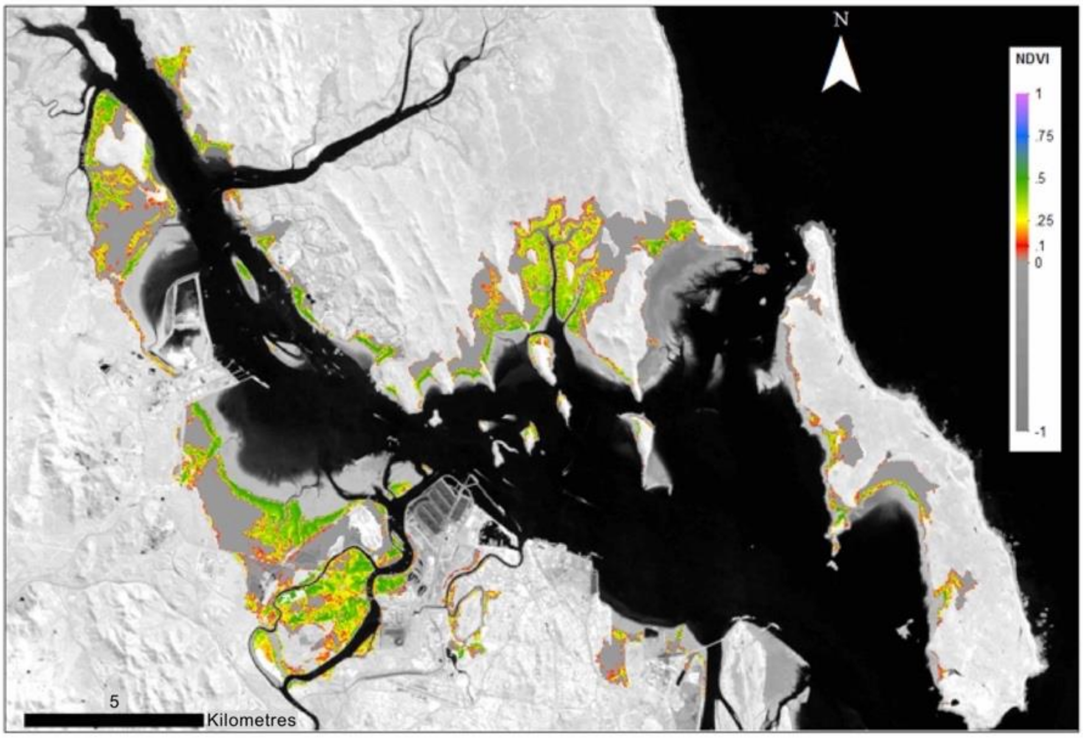


Figure 36. Canopy condition from Landsat NDVI 2016-08-07 – Port Curtis and the Western Basin in the central part of the PCPA study area. (Source: J. Kovacs).

Rodds Harbour

The larger scale maps (Figs. 37-39) show the heavily built areas around Gladstone (in the Port Curtis subregion) were much greater than in the more southern Rodds Harbour subregion. As noted, the subregion is the wetter of the three subregions (Table 3), and this was consistent with the high WCI (67%; see Duke et al., 2019a) and the moderate tree heights (5.4 m). Carbon stocks were the relatively greater (6.5 Mt) since the mangrove trees were relatively tall for the same area of mangroves.

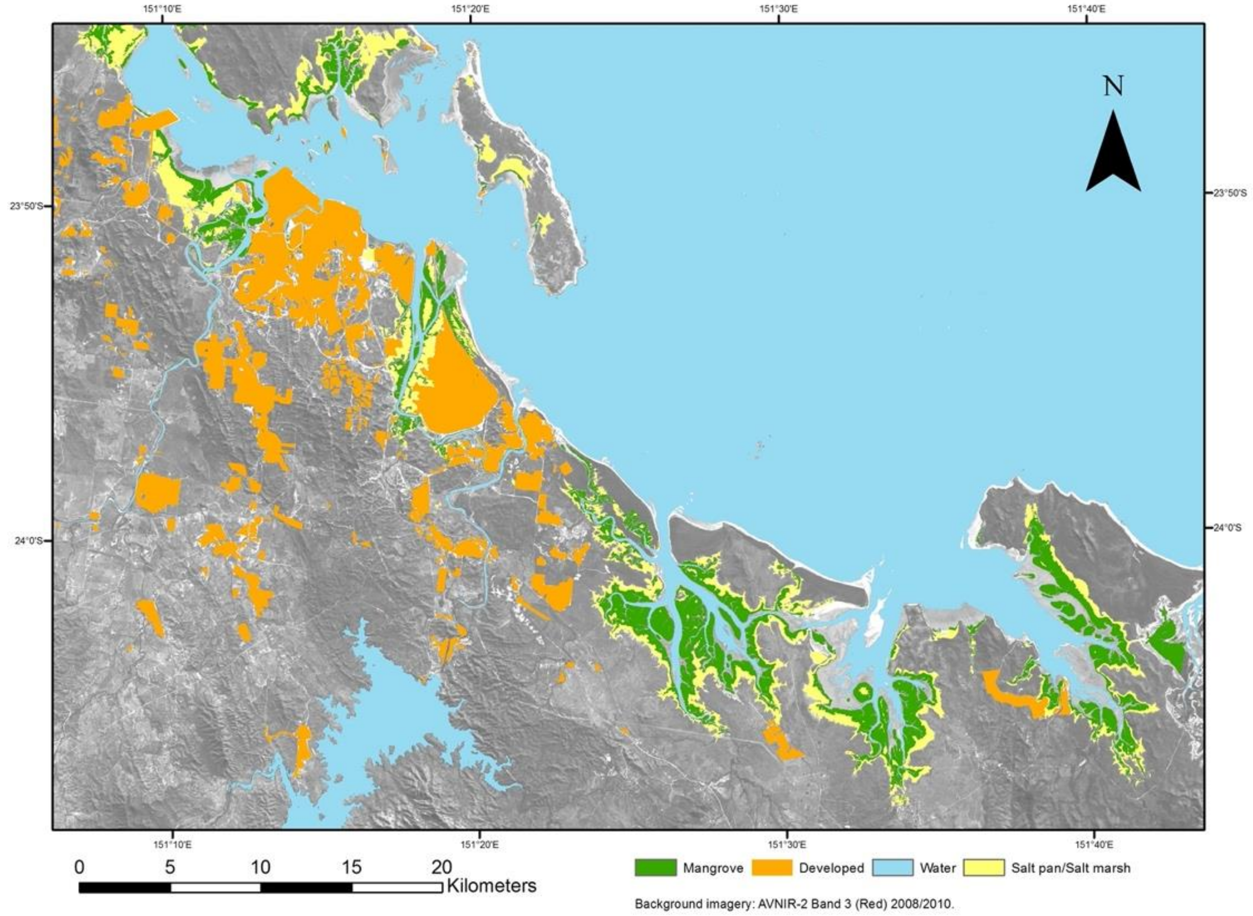


Figure 37. Rodds Harbour subregion based on the 2010 imagery of Port Curtis and Rodds Harbour showing the extent of tidal wetlands (mangroves, saltmarsh and saltpans) and the presence of developed areas. (Source: J. Kovacs).

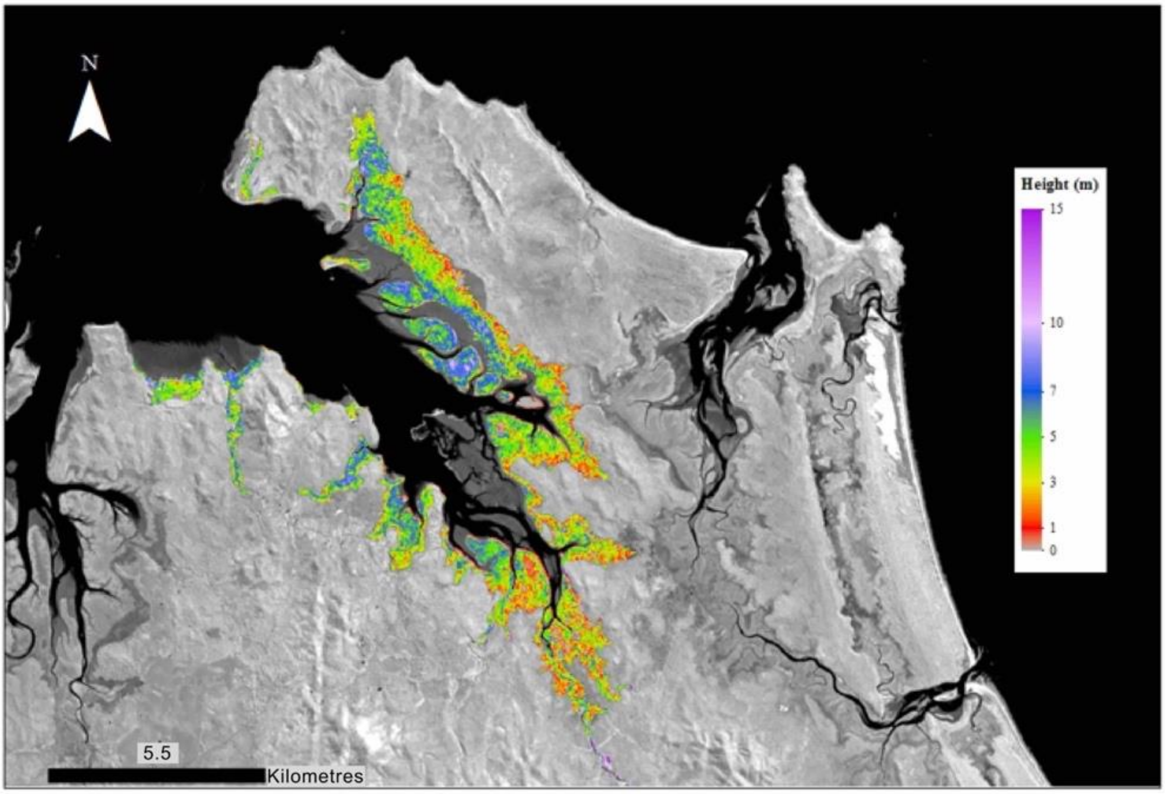


Figure 38. Vegetation height from ALOS DSM 2016 – Rodds Harbour in the southern part of the PCPA study area. (Source: J. Kovacs).

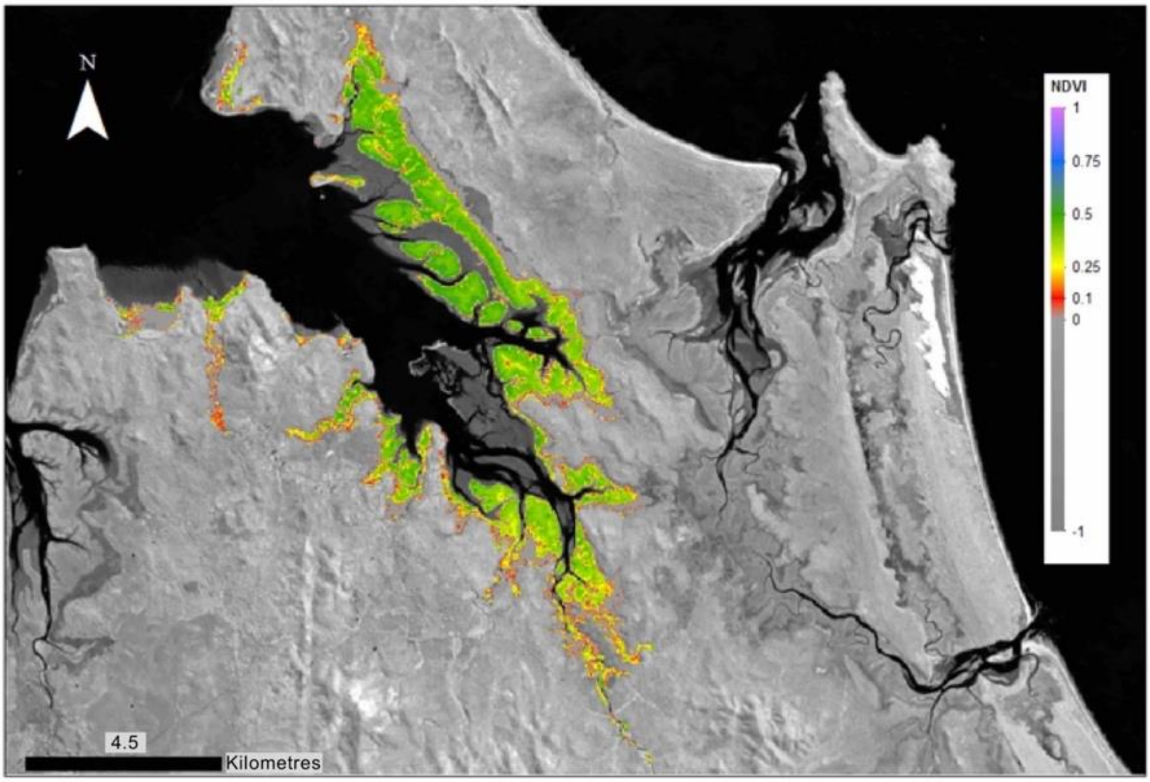


Figure 39. Canopy condition from Landsat NDVI 2016-08-07 – Rodds Harbour in the southern part of the PCPA study area. (Source: J. Kovacs).

Overall condition of tidal wetlands and key influences

The 2019 aerial survey results showed that tidal wetlands had been notably impacted by a range of factors from both human-related and climate-natural groupings. Note that each indicator is described in detail (Tables 6 & 7) along with case studies (Chapters 6 & 7). For our current overall assessment, scores from the 2019 survey provides a useful broad overview of the major changes taking place (Table 10). The overall findings show that climate-natural factors outweigh human-related factors, being 4.3:10.6, or 0.4 overall; showing that natural factors were scored 2.5 times greater overall.

Table 10. For human-related and climate-natural drivers, 28 indicator mean scores made during 2019 aerial surveys of the three PCPA subregions, Port Alma (PA), Port Curtis (PC) and Rodds Harbour (Rodds). Scores with moderate presence >0.6 highlighted orange, and with greatest presence >1.0 highlighted pink. 'Note 1' refers to the single area of hail damage in PC. Asterick refers to indicator not observed being only visible around August each year. Refer to Appendix 7 for the summary of methods and estimated scores of each indicator.

Driver Grouping	#	Indicator	PA	PC	Rodds
Human-related	1	Structures	0.44	1.40	0.31
	2	Direct Loss	0.40	1.27	0.39
	3	Human Altered Hydrology	1.04	1.35	0.27
	4	Encroachment	0.04	0.44	0.09
	5	People Access	0.08	0.78	0.57
	6	Livestock Damage	0.32	0.23	0.27
	7	Feral Animals	0.00	0.09	0.03
	8	Pollutant	0.00	0.32	0.03
	9	Nutrient	0.16	0.16	0.16
	10	Fire	0.08	0.01	0.09
	11	Weeds	0.12	0.15	0.03
Climate-Natural	1	Storm Damage	0.80	0.63	0.24
	2	Shore Erosion	2.80	0.73	0.61
	3	Bank Erosion	1.08	0.82	0.52
	4	Root Burial	1.50	0.27	0.64
	5	Fringe Collapse	0.48	0.55	0.74
	6	Pan Scouring	1.76	0.73	1.27
	7	Ecotone Shift Loss	1.80	0.41	0.23
	8	Ecotone Shift Gain	0.92	0.64	1.46
	9	Depositional Gain	1.56	1.17	1.02
	10	Flood Damage	0.00	0.48	0.00
	11	Terrestrial Retreat	1.20	1.12	2.38
	12	Upland Migration	0.00	0.05	0.87
	13	Light Gaps	0.38	0.25	0.41
	14	Natural Altered Hydrology	0.44	0.21	0.40
	15	Hail Damage	0.00	Note 1	0.00
	16	Bat Damage	0.00	0.15	0.00
	17	Deciduous Mangroves	*	*	*

Of the 11 human-related indicators scored, the most dominant were recorded in the central Port Curtis subregion (Table 10). These included ‘built structures’, ‘human altered hydrology’ and ‘direct replacement losses for urban, industrial and port expansion surrounding the very busy port, and the city of Gladstone. It is therefore not surprising also that ‘people access’ also scored highest in this subregion, albeit at a moderate level.

Of the 17 climate-natural indicators scored, there was a much larger number of changes observed, and these tended to be greatest in Port Alma and Rodds Harbour subregions. However, such indicators were most likely obscured in the Port Curtis subregion by the dominating presence of human-related factors. Dominant climate-natural indicators include ‘shoreline and bank erosion’, ‘root burial dieback’, ‘saltpan scouring’, ‘ecotone shifts losses and gains’, ‘depositional gain’ and ‘terrestrial retreat’. Appreciable regional trends in some of these indicators were recorded with ‘storm damage’, ‘lower edge erosion’, ‘depositional gain’ and ‘ecotone shift loss’. It is of interest that these changes are associated with storm events, flooding and low rainfall (see Table 10) – all having greater impacts in the northern subregion with lesser levels to the south. Four other indicators, ‘fringe collapse’, ‘ecotone shift gain’, ‘terrestrial retreat’ and ‘upland migration’ each showed opposite trends with greatest presence towards the southern subregion. It is notable that these indicators were each associated with rising sea levels which were most rapid in the southern subregion (see Table 10). While individual indicators will be described with local case studies in the next section, beforehand we make some overall observations.

In Figure 40, the marked high levels of human-related factors in the Port Curtis subregion are depicted in the aggregated severity scores showing the appreciably lower levels scored in Port Alma and Rodds Harbour subregions. The inverse pattern was recorded for climate-natural indicators, although this is likely to be an artifact of the overwhelming and masking of climate-natural indicators by human-related indicators in the Port Curtis subregion.

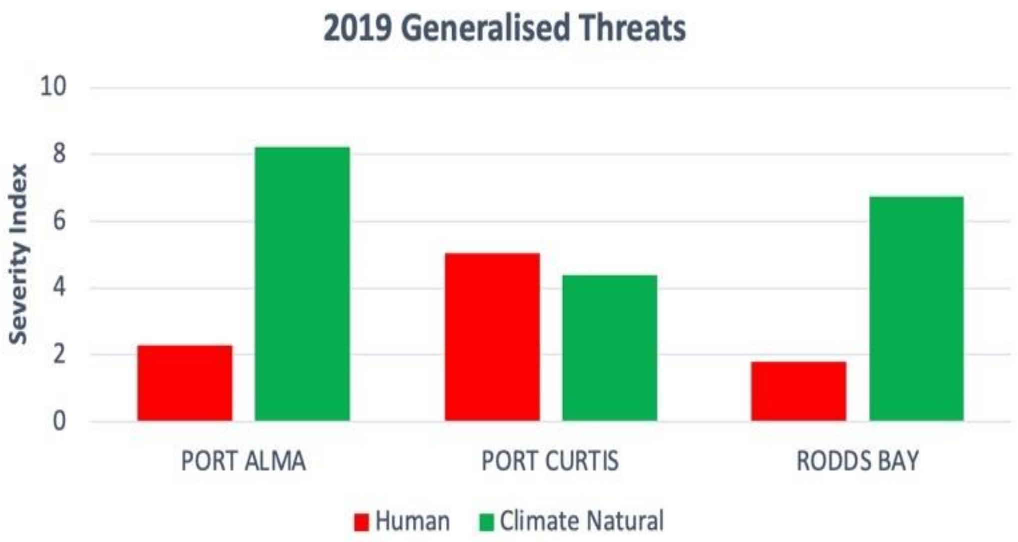


Figure 40. Aggregated scores recorded in 2019 of severity and extent of human and climate-natural driver indicators of tidal wetland condition in the three PCPA subregions. See Appendix Tables 6-8.

As expected, these patterns were focused on specific areas, noting firstly that relative scores where human-related features outweigh climate-natural features occurred in 6 zones in the Port Curtis subregion (see Table 10; Fig. 41), including Western Basin, Inner Harbour, Calliope Estuary, Auckland Creek, South Trees Inlet and Boyne River.

Regarding climate-natural features, as noted, it is likely these would be more uniformly distributed if they were not masked by the more dominating human-related impacts.

For the entire PCPA region, the dominant top-ranking, five features from each these subregion groupings are ranked as follows:

1) Human-related indicators – 'human altered hydrology', 'built structures', 'direct loss and damage', 'human access damage', and 'stock damage'; and
2) Climate-natural indicators – 'terrestrial retreat', 'depositional gain', 'pan scouring', 'shoreline erosion' and 'ecotone shift gain'.

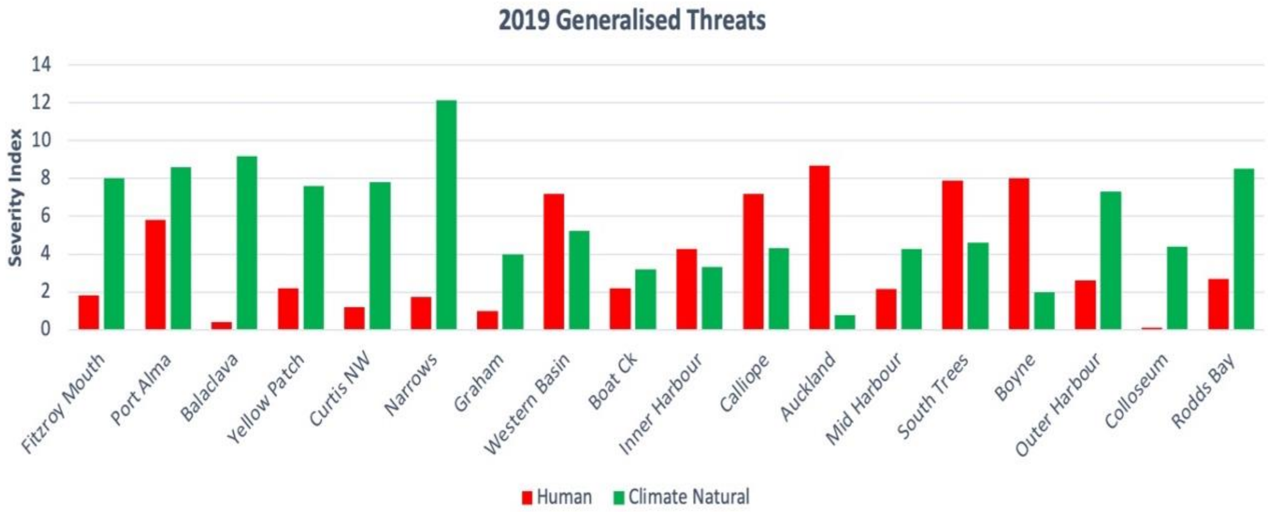


Figure 41. Scores made in 2019 of severity and extent of human and climate-natural driver indicators in the 18 PCPA zones. See Appendix Tables 6-8.

For human-related indicators (Fig. 42), while 'stock damage' was relatively uniform across all subregions, the four major human-related scores were each 4-5 times greater in the Port Curtis region. Rodds Harbour had the lowest levels of human-related threats. 'Human altered hydrology' was distinctly high in both Port Curtis and Port Alma subregions.

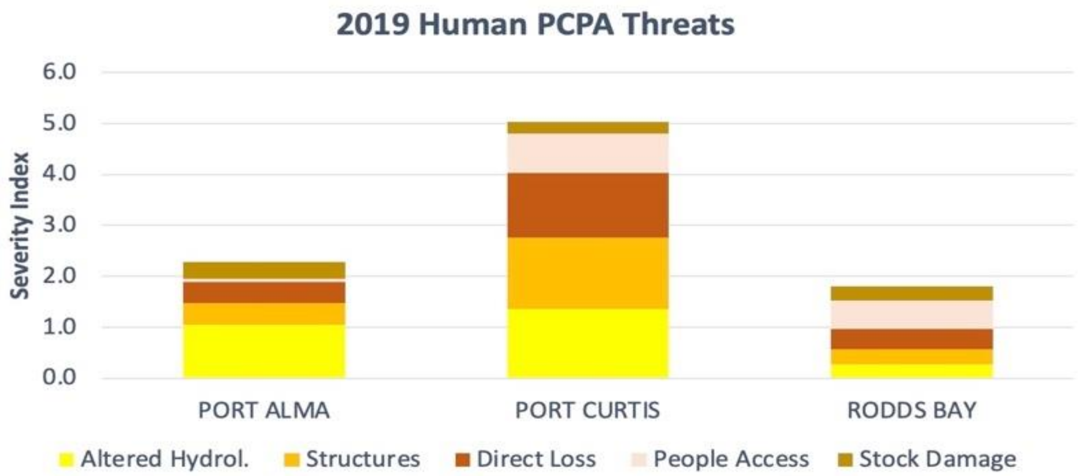


Figure 42. Aggregated scores made in 2019 of severity and extent of the 5 most prevalent human-related driver indicators in the three PCPA subregions. See Appendix Tables 6-8.

Again, a closer focus on specific zones helps orientate the overall observations (Fig. 43). Regards 'Human-altered hydrology' in the Port Alma subregion, understandably relate to the port area in Port Alma and the massive area under salt extraction ponds, but it is seemingly odd that Yellow Patch and NW Curtis Island appear so high. In these zones, there were large areas altered with ill-advised roads and ponded pastures.

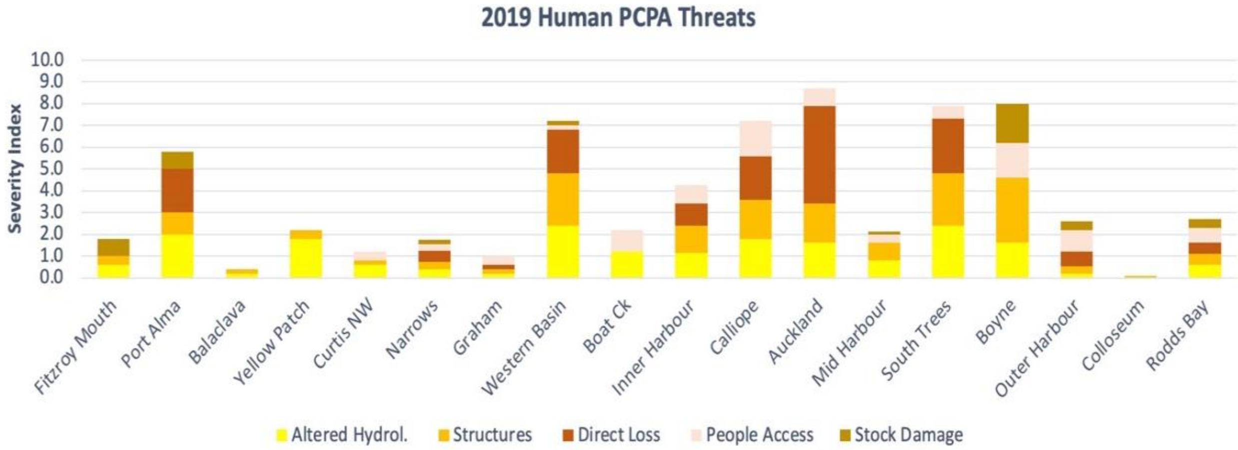


Figure 43. Scores made in 2019 of severity and extent of the 5 most prevalent human driver indicators in the 18 PCPA zones. See Appendix Tables 6-8.

For climate-natural indicators (Fig. 44), three of the dominating indicators followed a latitudinal trend, as noted above, with 'terrestrial retreat' increasing to the south, while 'depositional gain', 'saltpan scouring' and 'shoreline erosion' are greatest in the north. While most of these indicators are associated with rising sea levels (noted to be at around 4.8 mm/year in the PCPA region, see Table 5), one indicator, 'depositional gain' is associated with river flows, rainfall (see Table 4) and sediments from catchment erosion. Individual trends for each indicator will be discussed further in the sections on each indicator (Chapters 6 & 7).

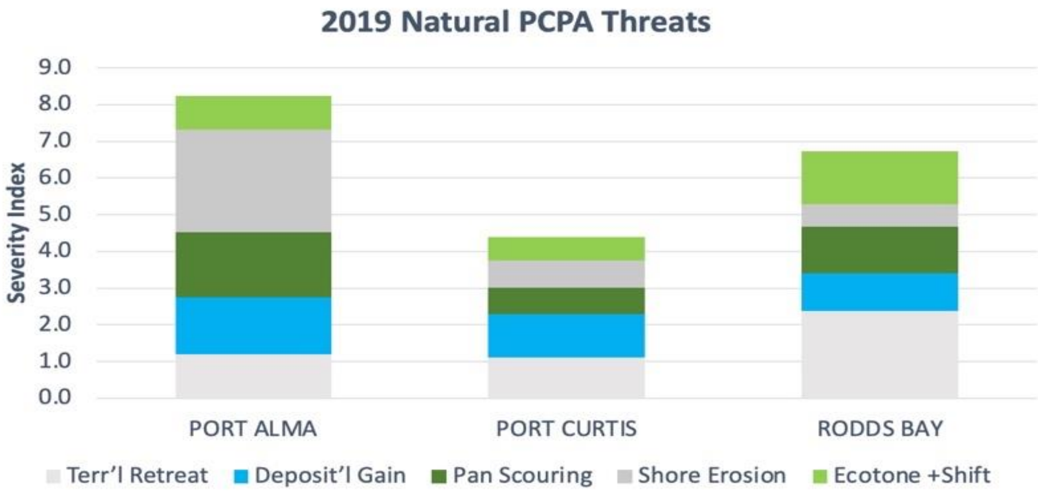


Figure 44. Aggregated scores made in 2019 of severity and extent of the 5 most prevalent climate-natural driver indicators in the three PCPA subregions. See Appendix Tables 6-8.

The spread of these dominant indicators show differing patterns amongst the zones (Fig. 45). Note how 'depositional gain' was widespread, being indicative of the movement of unconsolidated sediments in the system. Trends observed amongst subregions can be further considered for the zones. For example, those indicators associated with rising sea levels, like 'terrestrial retreat' and 'ecotone shift gain', can be seen to increase generally to the south, matching the same trend in rates of sea level rise (see Table 5).

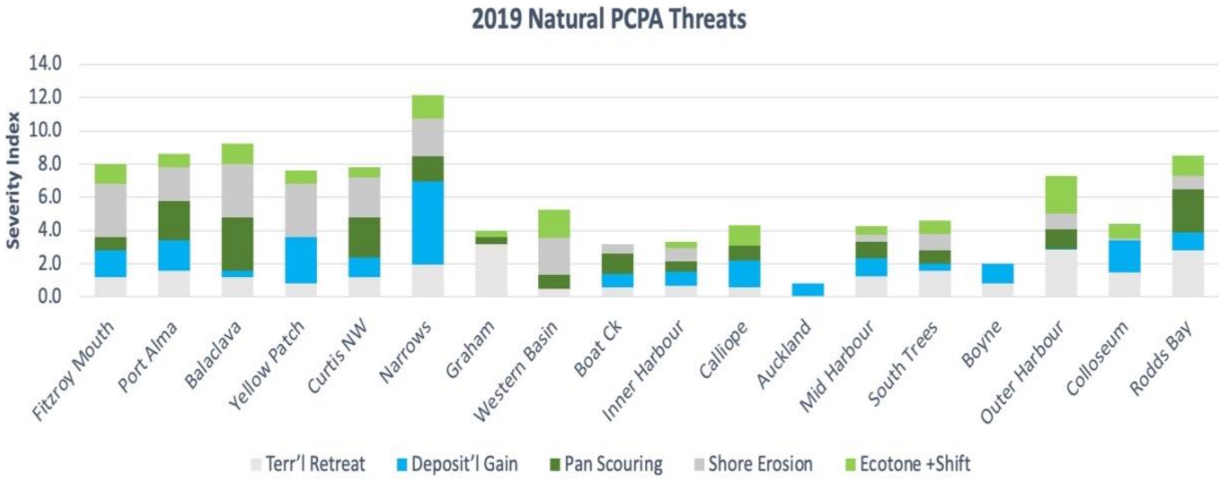


Figure 45. Scores made in 2019 of severity and extent of the 5 most prevalent climate-natural driver indicators in the 18 PCPA zones. See Appendix Tables 6-8.

CHAPTER 6

SPECIFIC INDICATORS OF HUMAN DEVELOPMENT ON MANGROVE TIDAL WETLANDS

‘DIRECT LOSS’
- **ASSOCIATED WITH RECLAMATION, LANDFILL AND CLEARING**

Cause. Direct removal of habitat reduces the extent of tidal wetland vegetation locally.
Indicator. Loss of mangrove and saltmarsh vegetation like tree stumps or loss of area, and activities that are associated with habitat removal and reclamation, such as access roads, cutting, digging equipment (Figs. 46 & 47; Table 11).
Impact. Habitat loss reduces the fitness of tidal wetlands and in consequence the ecosystem benefits are also lost, such as their value to local fisheries or their role in protection of shorelines from erosion.

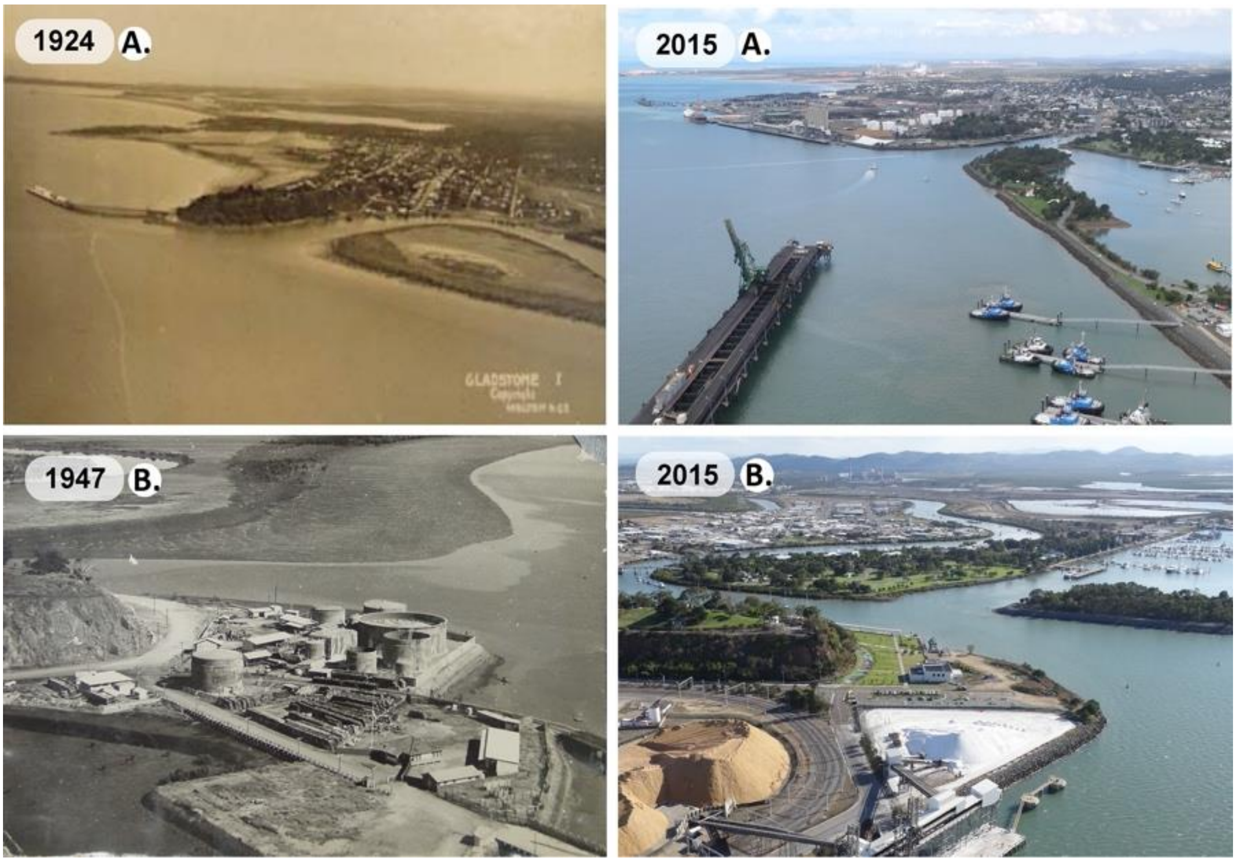


Figure 46. Views of Auckland Hill, Gladstone, from the 2015 aerial survey compared with earlier images (Duke et al. 2003). This is an area of substantive human change with port and shoreline development affecting tidal wetlands along Auckland Creek. Replacement of mangrove and saltmarsh areas by reclamation reduces the natural functioning, resilience and condition of tidal wetlands in Auckland Inlet. (Source: NC Duke).

Table 11. Port Curtis subregion tidal wetland losses between 1941 and 2016 due mostly to reclamation and landfill in Auckland Creek, South Trees Inlet and Boyne River estuaries. While there is uncertainty between mapping studies (see Table 9), longer-term trends are consistent with human expansion and reclamation activities in these three case study areas.

PCPA Area	Acquisition Year	Mangrove (ha)	Saltmarsh (ha)	Tidal Wetland (ha)	WCI %	Source
Auckland Creek/Inlet	1941	1135	561	1696	67	Duke et al., 2003
	1988	821	428	1249	66	Duke et al., 2003
	1999	635	439	1074	59	Duke et al., 2003
	2016	57	171	228	25	This study
	% LOSS 75-yrs	95.0	69.5	86.5		
South Trees Inlet	1941	131	876	1007	13	Duke et al., 2003
	1988	119	603	722	16	Duke et al., 2003
	1999	59	314	373	16	Duke et al., 2003
	2016	52	21	73	71	This study
	% LOSS 75-yrs	60.3	97.6	92.8		
Boyne River Estuary	1941	1445	1316	2761	52	Duke et al., 2003
	1988	1221	799	2020	60	Duke et al., 2003
	1999	845	903	1748	48	Duke et al., 2003
	2016	1003	676	1679	60	This study
	% LOSS 75-yrs	30.6	48.6	39.2		

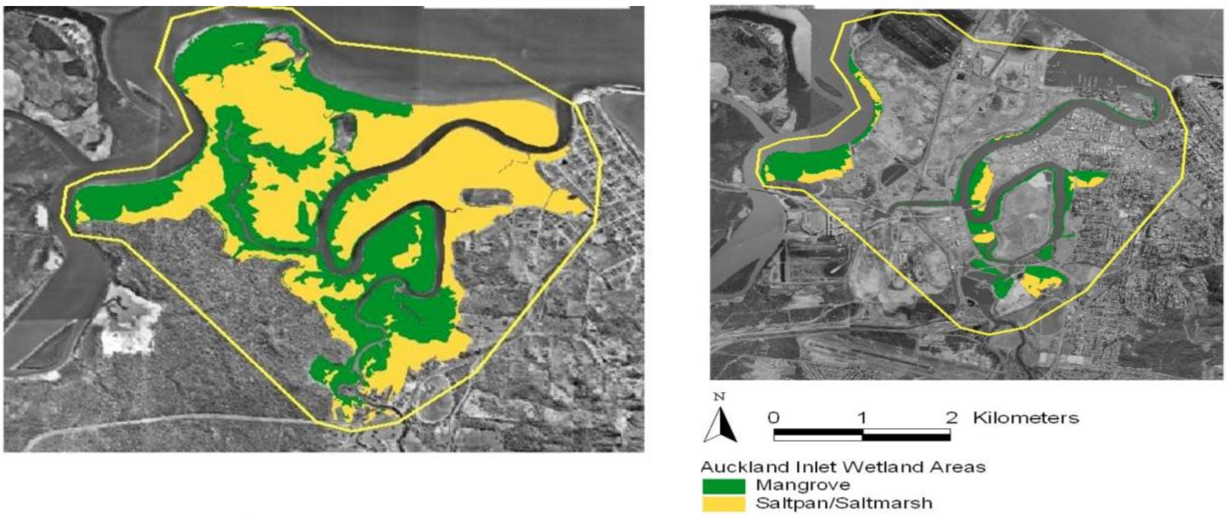


Figure 47. A graphic example of 'Direct Loss'. Tidal wetland areas around Auckland Creek and Inlet have been virtually eliminated by reclamation and infill of tidal lands for port, industrial and urban development between 1946 and 1999 (Duke et al., 2003). As noted in Table 11, this represented a whole of estuarine system loss of around 37% over those 53 years.

Figure 48. Replacement of tidal wetlands in South Trees Inlet indicated by the expansive ponded areas constructed across tidal wetlands. (Source: NC Duke).

***Case study* – 'Built Structures', 'Direct Loss' and 'Encroachment'**

Tidal wetlands of many estuaries and inlet within the Port Curtis subregion have been largely replaced by port, industrial and urban reclamation activities. In Table 11, mapping done in various studies indicate the extent of such losses in Auckland Inlet, South Trees Inlet and Boyne River. The losses in tidal wetlands amount to considerably more than 40% and up to 93% over the last 75 years. While there is uncertainty in comparing these mapping studies, the overall trends appear all headed in one direction with further losses with each study year.

In only one area, the Boyne River estuary (McConchie et al., 1996), did mangrove and saltmarsh areas appear to recover between 1999 and 2016. It is possible that some of this increase may represent recovery from flood damage prior to 1999 and in 2013, as described in Section on 'Flood Damage'.

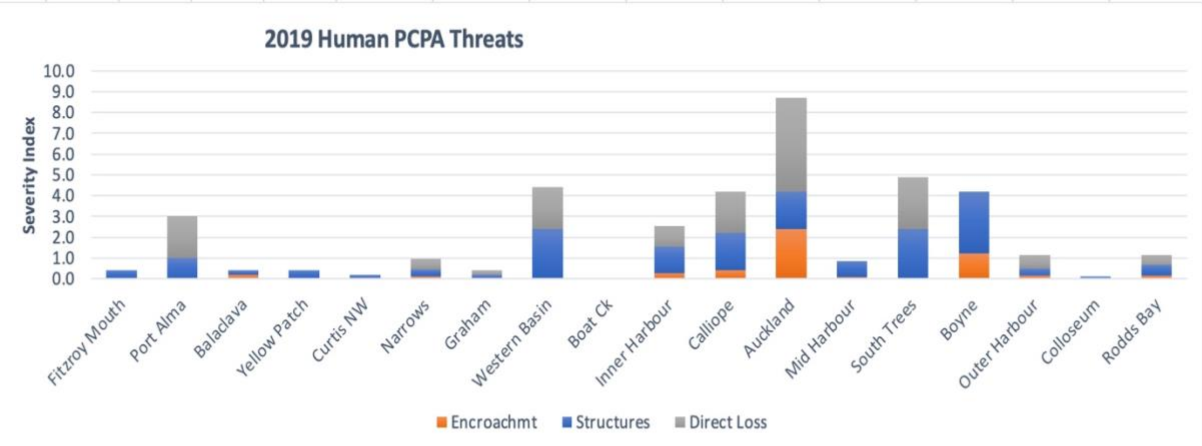


Figure 49. Indicators of 'built structures', 'direct loss' and 'encroachment' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

The various losses ('Structures', 'Direct Loss' and 'Encroachment') of tidal wetland areas are understandably greatest in the Port Curtis subregion (also Figs. 48-49), and in the Port Alma zone area.

'BOAT RAMP DAMAGE'
- **ASSOCIATED WITH REMOVAL FOR ACCESS TO WATER**

Cause. Boat ramp damage occurs when access paths for launching water craft are cut through foreshore mangrove verges.
Indicator. The presence of a boat ramp and the access path created through the shoreline mangrove zone. There will also be an associated road or track to the boat ramp (Fig. 50).
Impact. The damage starts with the loss of mangrove vegetation along the access path of the boat ramp. Furthermore, the damage may be greater where there is additional erosion and deposition from the altered hydrology caused to normal tidal flows.

Figure 50. Boat ramp access at this site in The Narrows appears to have been relocated at various times in the past, causing notable and lasting impacts on the shoreline mangrove zone. Such alterations need to be rationalised with site hardening, and abandoned areas restored. (Source: NC Duke).

Case study – boat ramp damage
The aerial surveys undertaken with this study have acquired observations regarding the location and condition of most if not all boat ramps in the region (see Fig. 50). There were a number of boat ramps that were unknown to the regulatory authority. It would be beneficial to locate and classify each boat ramp for the better management of tidal wetlands.

'POLLUTION DAMAGE'
- **ASSOCIATED WITH A RELEASED CONTAMINANT**

Cause. Leaching and larger spills of concentrated chemicals – natural or unnatural – into tidal wetlands and estuarine waters will have two major effects on mangrove and saltmarsh habitat including the smothering of breathing surfaces, and their toxicity to plants and associated animals.
Indicator. Some substances like petroleum and fuel oil are readily visible in the environment. These can be used to describe the impacted area and the likely threats to others. For these and other less visible substances, the impacted area can be described by linking analysed substrate samples with locations of tree death, stressed canopy foliage, and dead animals (Figs. 51-56).
Impact. Death and dieback of mangrove plants and animals, increased stress on forest canopies and saltmarsh vegetation.

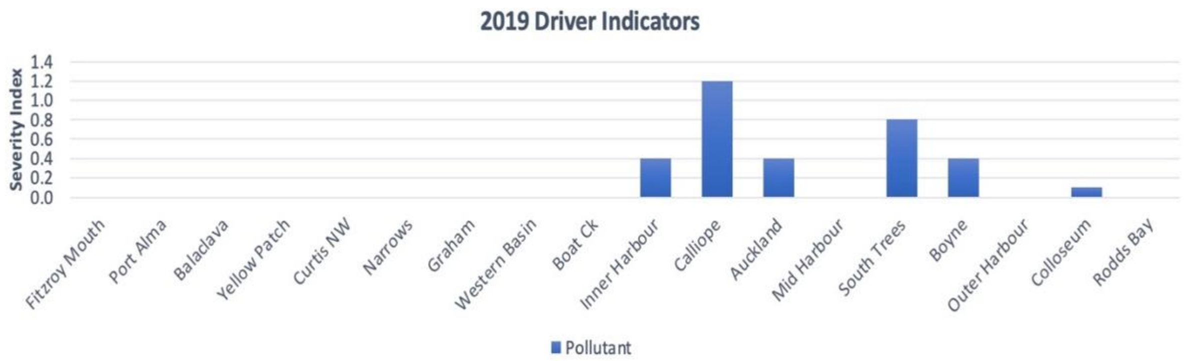


Figure 51. Indicators of 'pollutant presence' in tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

Case study – large oil spill damage
As in other port areas around the world, tidal wetlands of the Port Curtis subregion have been observed having occasional large oil spills (Duke 2016). The types of damage range from short-term impacts from oil blocking respiratory surfaces of trees and fauna, to longer term effects like mutations in mangrove plants (see Figs. 52 & 53).

For instance, in 2006, the vessel 'Global Peace' was ruptured and lost 25 tons of bunker fuel oil (Andersen et al. 2008; Melville et al. 2009; Duke 2016). At least 1.5 hectares of mangroves were oiled around Auckland Inlet and the mouth of the Calliope River (see Fig. 53). The damage caused from this and other large oil spill instances in the region have not been adequately quantified.

Figure 52. The oil lost in 2006 from the rupturing of fuel tanks of 'Global Peace' impacted at least 1.5 hectares of mangroves within the harbour area of Port Curtis (Duke 2016).

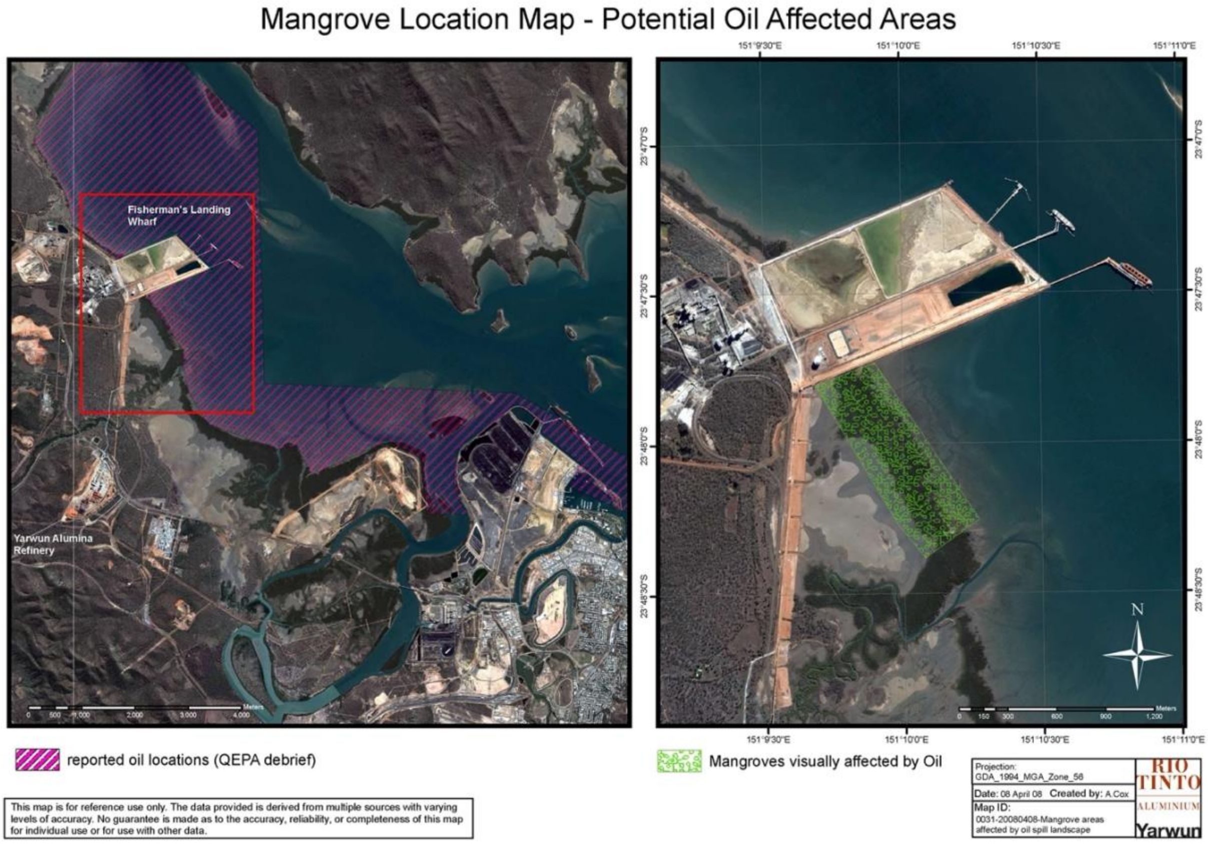


Figure 53. The extent of oiling during the Global Peace spill in 2008 in the Port Curtis subregion. Source: Andersen et al. (2008) & Melville et al. (2009).

It is of interest that the Port Curtis area was also the site of valuable research into the effects of large oil spills on mangrove and saltmarsh ecosystems (Burns et al., 1999; Duke et al., 1999, 2000; Duke 2016). The findings from these innovative studies have been used by the Australian Maritime Safety Authority, the Great Barrier Reef Marine Park Authority, the Australian Petroleum Production and Exploration Association, as well as the Gladstone Ports Corporation. The management strategies involved included first response actions, as well as the longer-term management of dispersants and on water containment to reduce impacts on mangrove ecosystems.

Case study – albino propagules

Tidal wetlands of within the Port Curtis subregion have been observed having relatively large numbers of albino propagules on *Rhizophora stylosa* trees (Fig. 54), the locally dominant, stilt-rooted mangroves. This condition is known to be a lethal mutation found often in areas with high concentrations of petroleum chemicals like polycyclic aromatic hydrocarbons or heavy metals in mangrove sediments (Duke and Watkinson 2002; Bell et al., 2003). A detailed assessment is required to determine the areas affected and their proximity to likely sources of contaminating agents.

Figure 54. Mature propagules of *Rhizophora stylosa* taken directly from normal healthy trees – noting the top five being normal green, while the bottom three are albinos. The albino propagules are observed often in the Port Curtis subregion during the fruiting season, around January to March each year (Source: NC Duke).

Case study – herbicide damage

Tidal wetlands of within the Port Curtis subregion show occasional instances of unexplained dieback of shore edge trees of *Avicennia marina*, the grey mangrove (Fig. 55). Elsewhere such occurrences have been explained by damage from high concentrations of herbicides in runoff waters and drains (Duke et al., 2005). A suspected incident of 'Herbicide Damage' occurred in the Fitzroy River estuary after severe flooding in 2008 (Fig. 56). The herbicides attack the photosynthetic process in plants after penetrating individuals, most likely through their roots. Different species of mangroves have different sensitivities to the herbicides because of their differing abilities to filter harmful chemicals (Bell & Duke 2005). A detailed assessment is required to determine the areas affected and their proximity to possible sources of contaminating chemical agents.

Figure 55. Dead *Avicennia* trees along the waters' edge is an indicator of possible herbicide damage from runoff waters (Source: NC Duke).

Figure 56. Specific dieback observed in the Fitzroy River estuary in 2008 was indicative of herbicides washed downstream in flood runoff waters. Note the dead trees within the mangrove zone were the grey mangrove, *Avicennia marina*, while other species remained green and survived. The harmful agent was species-specific (Source: NC Duke).

Case study – air-borne fine particle damage

Between 1975 and 1982, *Avicennia marina* trees died under mysterious circumstances in tidal wetlands across the Port Curtis subregion (Hutchings & Saenger 1987; Arnold 1996; Joyce 2006). This is somewhat reminiscent of 'Herbicide Damage', but in this case, death of *Avicennia marina* trees occurred where-ever they grew – both along the sea edge, in stands bordering the land and in between (Fig. 57). There were early suggestions that a *Phytophora* pathogen might have been responsible (Hutchings and Saenger, 1987), but this had been dismissed earlier (Pegg and Foresberg, 1981).

To this day, there is a lack evidence and no recorded comparable impacts elsewhere. The suspected cause needs to be better investigated, although the limited evidence available (Saenger 1988; Joyce 2006; Duke personal observations) is consistent with trees dying from poor respiration from leaf stomata blocked by fine air-borne particles. A similar impact was observed by local growers of avocado trees (*Persea americana*) in the same area at the same time. They also observed a shadow effect, where trees behind buildings and larger trees survived while more exposed trees died, or had crown dieback. It was highly unlikely that herbicides would have caused such a widespread impact, and also affected terrestrial farm trees away from flood waters. In any case, the dieback ceased after more efficient filters were installed on the three main chimney stacks of the Gladstone Power Station (Fig. 57). This dieback event and its cause warrant a more detailed and comprehensive investigation.

Figure 57. Extensive dieback of Grey Mangrove *Avicennia marina* throughout the Port Curtis area recorded in 1982 and earlier. The coal-fired Gladstone Power Station marks the location, showing tall dead trees along the Calliope River estuary at the time. Was this an instance of airborne fine particle pollution causing widespread mangrove dieback? (Source: NC Duke).

‘ENHANCED GROWTH POLLUTION’ & ‘NUTRIENT EXCESS’
- ASSOCIATED WITH POINT SOURCE RUNOFF OR DIFFUSE NUTRIENTS

Cause. Excess nutrients or warm water in runoff have direct effects on mangrove and saltmarsh vegetation. Effects range from: enhanced growth with increased canopy heights that destabilises mangrove trees causing them to topple and be uprooted; to fouling caused by enhanced growth of algae that smothers mangrove roots and substrate harming vegetation by blocking their natural breathing and gas exchange.
Indicator. Outflow drainage into tidal wetlands from human activities like sewage treatment facilities and intensive agricultural lands (Fig. 59). Unusually enhanced canopy height and darker green foliage of mangrove forests near human facilities likely to be the source of nutrient or warm water runoff.
Impact. Enhanced growth has at least two likely impacts. One is that these pollutants may cause unsustainable structural development in mangroves, as recorded in Moreton Bay (Lovelock, pers. comm.), leaving mangrove trees weakened with poor root development and vulnerable to uprooting from storm winds and waves. Two is that excessive growth of algae is likely to smoother not only mangrove breathing roots but also mud flats generally.

Case study – enhanced growth from cooling waters
Excessive plant growth can have detrimental impacts on mangrove forests. While expended cooling waters from the Gladstone Power Station do not appear to have impacted marine life in mangroves (Saenger et al., 1982), this study has shown that mangrove tree growth may have been enhanced. Four sites at increasing distance upstream (Fig. 58; Table 12) from the power station outfall showed that canopy growth between 1987 and 2022 increased in sites closest to the outflow source. A more detailed assessment should determine the circumstances surrounding this kind of impact and whether the influential agent was water temperature, nutrients or something else.

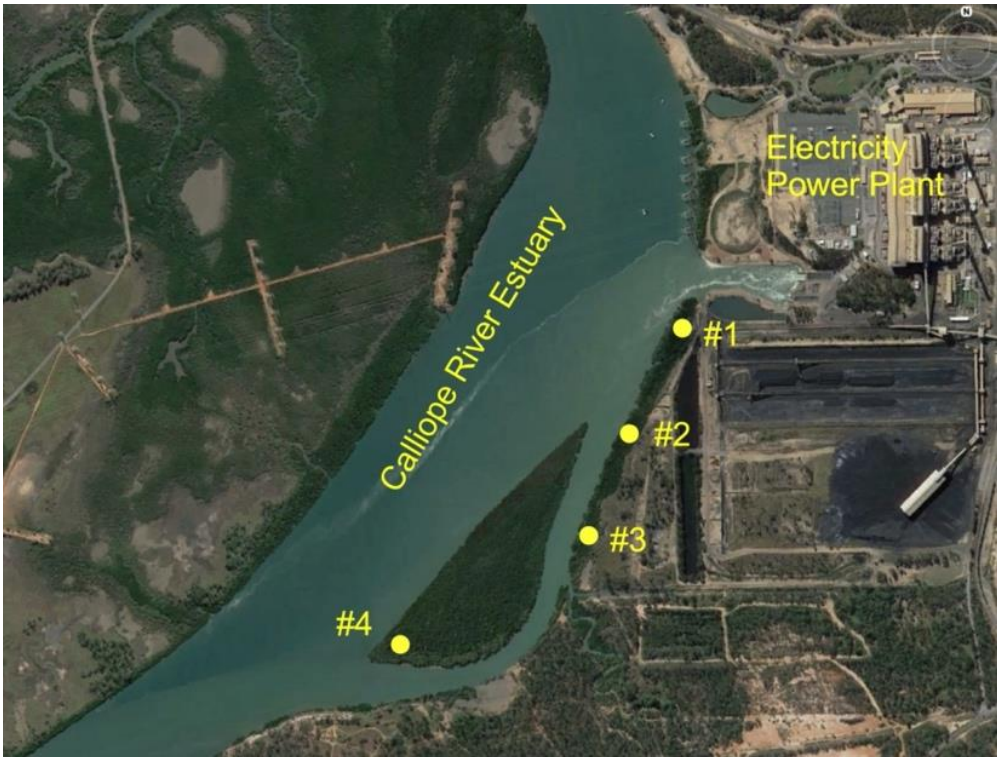


Figure 58. Four sites used for green fraction locations, at various distances from the Gladstone Power Plant cooling water outlet into the Calliope River estuary.

Table 12. Relationship between enhanced mangrove canopy growth and distance upstream from the power plant outflow.

Site #	Approximate Distance from Outflow (m)	% Increased Canopy Condition From 1987 to 2022
1	360	30
2	628	20
3	886	15
4	1481	5

Case study – enhanced algal growth from excess nutrients

Excessive plant growth can have detrimental impacts on mangrove forests and on benthic biota. During this study, aerial surveys identified areas of exposed mud banks covered in bright green algae. This observation warrants further investigation.

Figure 59. At low tide, excess nutrients are believed to be indicated when exposed mud banks are covered in green algae. The evidence at this stage is indicative, but it supports the need for a more detailed study to explain the related enhanced growth observed in this study. (Source: NC Duke).

The presence of surface green algae on exposed mudflats was observed throughout the PCPA region (Fig. 60). No clear patterns were noted, but a detailed study is needed to identify the algae involved and the nutrients present.

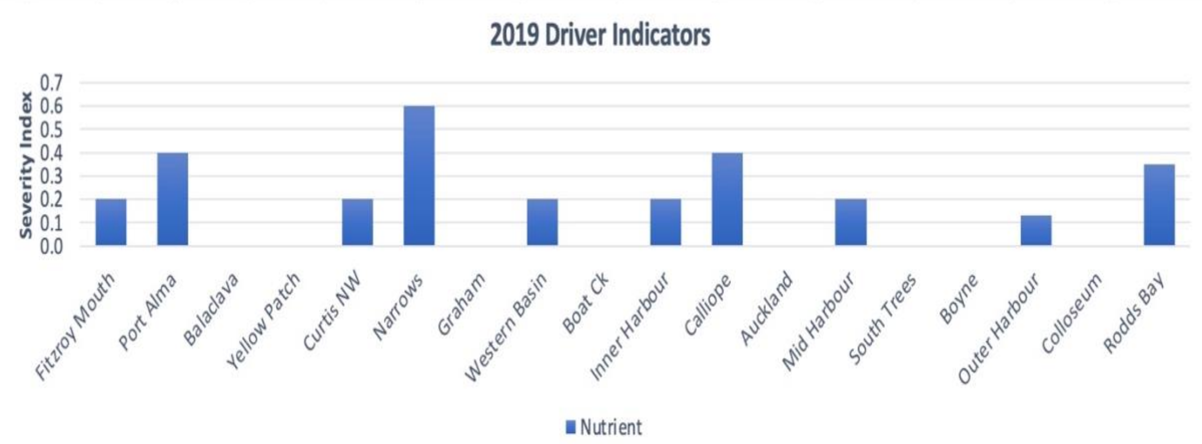


Figure 60. Indicators of 'nutrient excess' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

'HUMAN ALTERED HYDROLOGY'
- **ASSOCIATED WITH ALTERATIONS TO NATURAL TIDAL FLOW**

Cause. When water has not drained from a tidal or other flooded area after surrounding water levels have dropped, this indicates that there had been some alteration to the natural hydrology of the site.
Indicator. The distinguishing feature is unnaturally pooled water amongst tidal wetlands (Fig. 61). The presence of construction works and track damage are indicative of human influences as compared to natural influences, such as storm drift.
Impact. The damage can be dead mangrove trees or canopy dieback.

Figure 61. Human altered hydrology caused by construction of drainage channels through tidal wetlands. The example from the north end of Curtis Island, identified a road on an earthen bund cutting across a tidal area. Because of inadequate drainage, the upper area has trapped extensive tidal areas, causing excessive ponding with the death of impounded vegetation. Such damage is entirely avoidable and it is easily managed by installing more considered and open drainage under the road. This type of impact should be easily fixed by improving drainage under the road. (Source: NC Duke).

Case study – 'human altered hydrology'
As noted, mangrove and saltmarsh habitats require regular daily exchange with tidal waters. This vulnerability of mangrove ecosystems is observed often throughout the PCPA region in estuaries of the Fitzroy River, Boyne River, Calliope River and Auckland Creek. This feature often occurs in conjunction with reclamation works and the construction of roads and boat ramps. In South Trees Inlet, the constraints on mangrove growth across saltpan flats were tested many decades ago (Fig. 62). While this instance of human altered hydrology was undertaken with the best of intentions, it was not successful and has been far outweighed by the many instances of altered hydrology elsewhere in the region, depicted in Figure 63.

Figure 62. The geometric waterway experimentally created with QDPI approval on a saltpan area in South Trees inlet many decades ago. It demonstrated that more thought is needed to enhance mangrove expansion across the wide, seemingly desolate saltpans of the region. (Source: NC Duke).

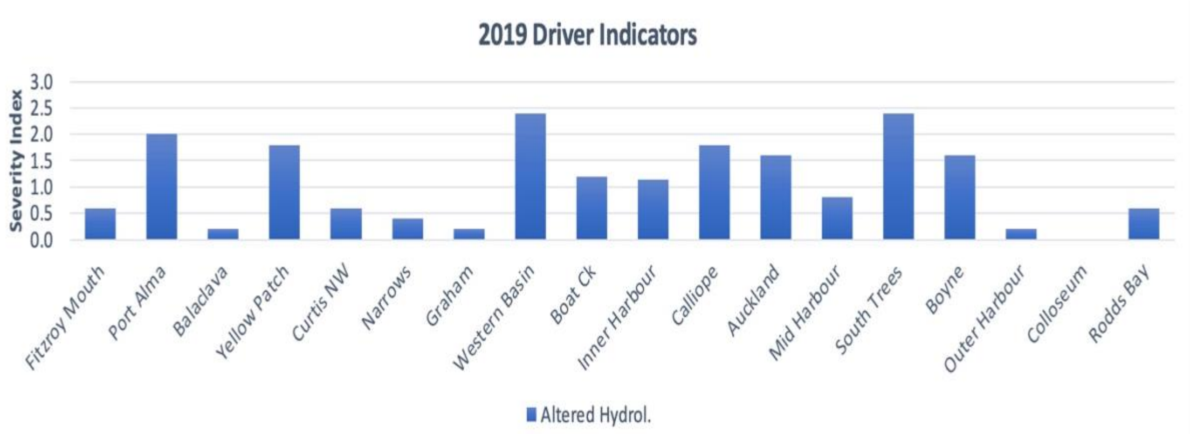


Figure 63. Indicators of 'human altered hydrology' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

'FIRE DAMAGE'

- **ASSOCIATED WITH UNCONTROLLED BUSH FIRES**

Cause. Bush and grassland fires may not burn through mangrove stands, but when they occur in close proximity within the supratidal verges, they can scold and kill trees along the higher intertidal back zone of mangroves.
Indicator. Blackened burnt vegetation in supratidal lands verging mangrove areas, coupled with dead mangrove trees with sometimes intact dead and blistered leaves.
Impact. Extremely severe because mangroves along the back zone of mangroves near highest astronomical tide (HAT) levels are essential points of recruitment for upland migration with sea level rise. With such damage to these critical mangrove stands, the ecosystem will be less resilient and inhibited in its innate and necessary response to rising sea levels. The area of mangroves will be reduced.

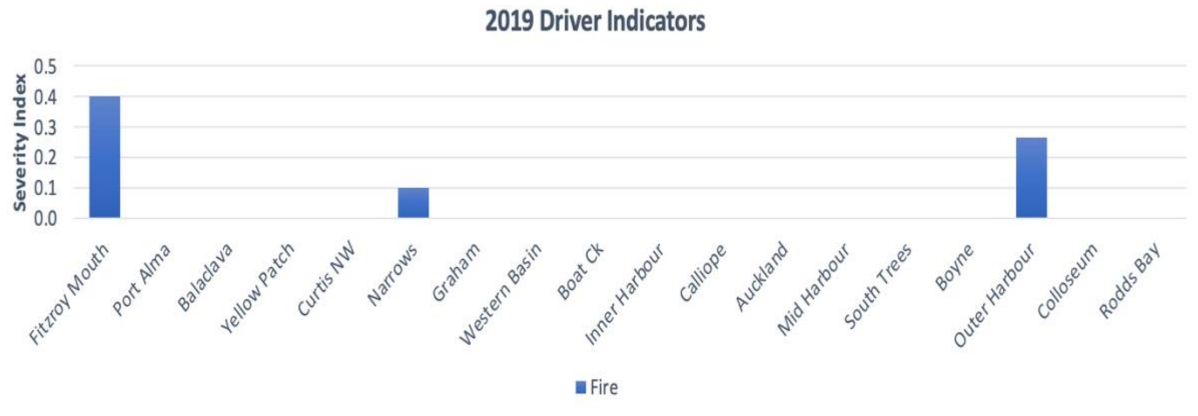


Figure 64. Indicators of 'fire damage' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

Case study – 'fire damage'
'Fire damage' was observed in only three zonal areas in this study – Fitzroy mouth, The Narrows and Outer Harbour (Fig. 64). While it is likely there might be more cases of 'fire damage', it is considered most likely in open bushland and grassland areas of the region, like on Curtis Island.

'VEHICLE DAMAGE'
- **ASSOCIATED WITH VEHICLE USE AND TRACKS**

Cause. When vehicles are used to cross and access tidal wetland areas they disrupt the delicate topography and tidal drainage flows, as well as damaging and killing established plants and seedlings. Native species of mangrove and saltmarsh plants are intolerant to such severe and sustained physical disturbance to the plants and their topographic setting.
Indicator. The presence of vehicle tracks across mudflats, damaged or missing vegetation along tracks and abandoned vehicles (Fig. 65).
Impact. Vehicle damage is associated with mangrove dieback from direct damage and altered hydrologies, as well as a lack of mangrove recruitment at ecotone zones shifting because of other reasons such as increases in long-term rainfall or rising sea levels.

Figure 65. Track damage by vehicles driving across tidal wetlands are widespread and uncontrolled. (Source: NC Duke).

Case study – 'vehicle damage'
Vehicle damage has been observed through much of the study area (Fig. 66). In many instances, vehicle tracks are constrained, but there are multiple cases of clear vandalism shown by track 'dough-nuts' and 'wheelies'. This damage is entirely avoidable. Further, the damage to tidal wetlands is expected to be immense, but it is currently uncontrolled and unstudied. The solution

appears relatively simple - access could be prevented with fencing in the worst affected locations. Detection is also straight forward and readily monitored by aerial surveys, as done with surveys associated with this study.

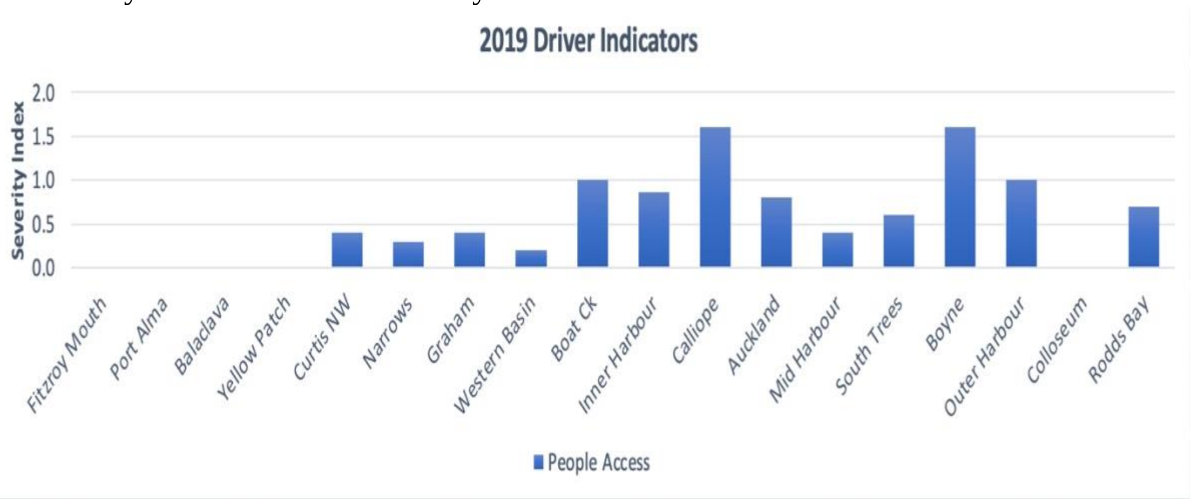


Figure 66. Indicators of 'people access' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

Vehicle access was relatively minor in tidal wetlands of the vast tidal flats around the mouth of the Fitzroy River (Fig. 66) because of their inaccessibility, interrupted by the large and sinuous tidal waterways. Access paths and vehicle tracks were most common in tidal wetlands near major population centres, although this indicator must be taken in consideration also with 'Direct Loss', 'Encroachment' and 'Built Structures'.

'LIVESTOCK DAMAGE'
- **ASSOCIATED WITH CATTLE AND OTHER GRAZING LIVESTOCK**

Cause. Some mangrove species, for example *Avicennia marina,* are sought after by grazing livestock for their nutritious and palatable foliage.
Indicator. Characteristically, angularly damaged leaves, twigs and stems as foliage damage, plus footprints in the muddy sediments, and tracks across saltpans from upland areas (Fig. 67).
Impact. Cattle and other grazers cause significant damage by removing leaves, damaging branches and stems, and by trampling delicate exposed and subsurface roots in the typically soft sediments. The extent of healthy mangroves will be reduced.

Figure 67. Cattle amongst mangroves means not only damage from their tracks altering tidal flows and trampling habitat, but also grazing damages and removes foliage. (Source: NC Duke).

Case study – grazing livestock damage
Livestock damage was most observed in more remote parts of the study area, such as areas bordering grazing properties south around Rodds Harbour, and north bordering The Narrows (Fig. 68). It is a common observation to see multiple track 'highways' across saltpan flats between terrestrial grasslands and mangrove areas (see Fig. 67).

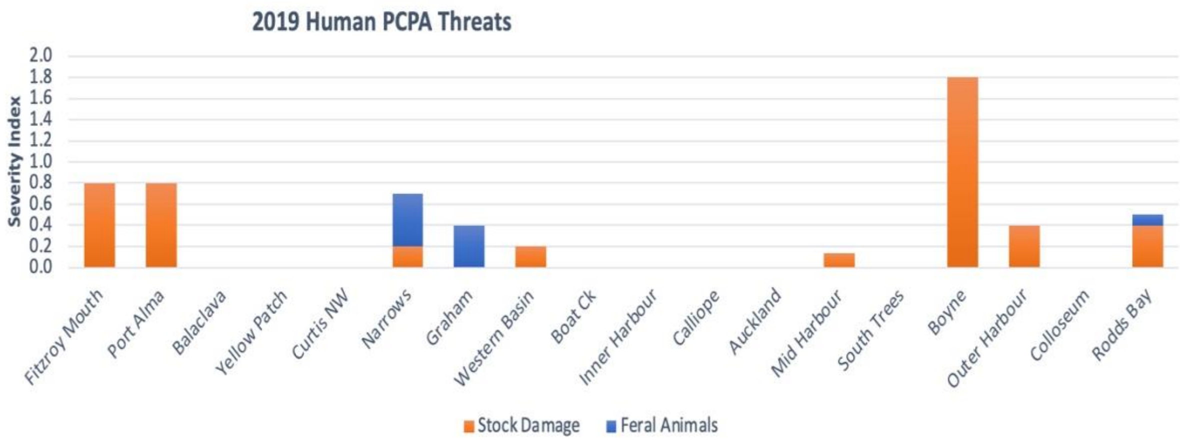


Figure 68. Indicators of 'stock damage' and 'feral animal damage' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

The cattle clearly find food and shelter in mangroves, but their presence is harmful to these places. These impacted mangroves are seriously set back by such pressures causing death and deformities in mangrove plants. A more detailed assessment is required to determine the circumstances surrounding this kind of impact, its longer-term effects, and how it can be mitigated.

As shown in Figure 68, the presence of stock and the damage they cause was observed in rural areas and grazing lands. Stock enter tidal wetlands in the notable absence of fencing. The damage caused is considerable. A small amount of damage was observed from feral horses and cattle on Curtis Island and in Rodds Harbour.

‘CUTTING DAMAGE’
- **ASSOCIATED WITH HUMAN CUTTING & HARVESTING**

Cause. Cutting trees for access or for harvesting timber or foliage.
Indicator. Cut stumps, access paths cut through mangrove stands leading to cleared areas and fallen timber.
Impact. The impact depends on the severity and the extent of damage. Small areas are likely to minimal impacts with recovery after a few years.

Case study – cutting damage
No instances were observed. However, there may be instances of mangrove harvesting, cutting or trimming.

‘PROP SCARS’

- **ASSOCIATED WITH SMALL VESSEL PROP SCARS ON MUD BANKS**

Cause. Prop scars are caused by small vessels with outboard motors speeding across shallow tidal mud flats whilst deploying and retrieving crab pots.
Indicator. At low tide, furrowed prop scars criss-cross exposed mudflats in often broad sweeping tracks with occasional twists and turns, marking the fishermans track (Fig. 69).
Impact. The environmental damage is disturbance to benthic biota, including seagrass beds. However, such rapid vessel movements are likely also to impact fishes, turtles and other megafauna using the shallow tidal drainage channels.

Figure 69. During aerial surveys when mud banks were exposed, there was a common observation of sweeping streaks and grooves across otherwise mostly smooth mudflats. These were considered to be prop scars formed by small vessel movements in shallow waters tending crab pots and fishing nets. The damage was notably greatest in areas closer to boat ramps and population centres. The impacts are not known. (Source: NC Duke).

Case study – ‘prop-scar damage’

Prop-scar damage was observed in greatest frequency in areas near boat ramps. The type of damage varies from furrowing the mud flats and disturbing habitat, to striking and scaring marine life. A more detailed assessment is required to determine the circumstances surrounding this kind of impact and its longer-term effects.

‘ABANDONED CRAB POTS’
- **ASSOCIATED WITH LOST, VANDALISED OR DISCARDED CRAB POTS**

Cause. Crab pots are often left abandoned along shallow mud flat areas for two reasons, the loss of float lines and neglect. In addition, float lines have been known to be cut by rival crabbers.
Indicator. Abandoned, weed covered crab pots often without float lines (Fig. 70).
Impact. Abandoned crab pots are death-traps for marine life. Whilst unattended, they continue to trap crabs and other fauna in a perpetual cycle, as each victim attracts further victims.

Figure 70. Gidarjil rangers after checking on a crab pot near Port Alma. (Source: NC Duke).

Case study – ‘abandoned crab pots’
Abandoned crab pots were a common feature throughout the study area. It was worrying that these pots were observed to be still trapping marine life. There needs to be a program to recover these pots plus other lost and abandoned fishing gear, to minimise their impacts on marine life. In addition, a detailed assessment is required to determine the circumstances surrounding this kind of impact and its longer-term effects.

‘DREDGING AND ALTERED TIDAL EXCHANGE – ASSOCIATED WITH RECLAMATION AND CONSTRUCTION WORKS

Cause. Dredging mobilises sediments within the water column with these sediments likely to settle and deposit amongst nearby mangrove habitat. The amount of sediment and it’s dispersal depends on the precautions implemented by the operator and the local tidal exchange.
Indicator. Dead mangrove trees would be a more extreme indication of sediments having covered and suffocated exposed, air-breathing mangrove roots (Fig. 71). However, a sublethal response by mangrove trees is recognised by the loss of foliage, especially from upper canopy branches of mature trees.
Impact. Loss of mangrove habitat in either their extent or condition would reduce habitat fitness leading to the loss of ecosystem benefits, like their values to local fisheries, their role in the protection of shorelines from sea level rise and storms, and their capacity to sequester atmospheric carbon.

Figure 71. The impacts of ‘root burial’ on mangrove trees depends on the depth of sediment accumulation (e.g., Ellison 1999). This was depicted in this site close to reclamation works at Fisherman’s Landing following construction of an earthen bund wall across an existing mangrove shoreline fringe (to the left). Note the loss of canopy leaves increases in trees closer to the bund wall and the greater depths of sediment burial of roots. (Source: NC Duke).

Case study – ‘Dredging and reclamation activities’

Works associated with the Western Basin Reclamation Area. The Port Curtis Western Basin Dredging and Disposal Project (WBDDP), undertaken by Gladstone Ports Corporation (GPC), included the dredging and spoil disposal of 22 million m^3 of sediments to create a safe shipping channel in Gladstone Western Basin. As part of these works, a portion of the intertidal area adjacent to the mangroves at Fisherman’s Landing was reclaimed through the construction of bund walls, defining the Western Basin Reclamation Area (WBRA) and Fisherman’s Landing

(Fig. 72). The design of the bund was constructed to retain significant mangrove habitat in an area enclosed by rock walls (Fig. 73).

These works and the bunded enclosure of around 6.5 ha of mangroves, were identified as posing a potential environmental risk to mangrove ecosystems in the Port Curtis area. These mangroves were comprised predominantly of dense closed-canopy *Rhizophora stylosa* trees. For the enclosed mangrove stands there was the risk of inadequate tidal exchange. But, for both the enclosed mangroves and others nearby, there was also an overall threat of elevated suspended sediments within the water column. Unnaturally high levels of suspended material are consistent with rapid rates of sediment accumulation on benthic and intertidal mud flats. Where this occurs amongst mangrove trees, it can cause the coating and suffocation of delicate breathing surfaces on exposed mangrove roots (Ellison 1999). When mangrove trees have difficulty breathing, their condition deteriorates dropping leaves and ultimately dying if fine sediment levels continue to accumulate greater than 10 cm.

The Department of Agriculture and Fisheries (DAF) regulator required that the GPC undertake biannual monitoring of these mangroves (as per Marine Plant Disturbance Permits) in order to evaluate any potential impacts on the health of mangroves from the construction works associated with the WBRA.

Figure 72. Locations of three treatment areas used in our assessment of the longer term condition of mangrove areas associated with construction works in the Western Bason Reclamation Area (WBRA), including: the enclosed critical part of the WBRA, the Western Basin reference area (WBEA), and the surrounding Port Curtis reference area (WBSC).

The construction works went to considerable lengths to minimise sediment losses and other possible environmental impacts from altered tidal exchange. These works included trimming reclaimed mangroves at ground level to leave roots intact in-situ (holding sediments intact), followed by clean aggregate bunds and marine mud cover, covered with clean sand and capped with rock and fill above Highest Astronomical Tide (HAT). The construction method was approved by DAF and EHP (Queensland Department of Environment and Heritage Protection).

Several monitoring studies were conducted to evaluate the ongoing condition of mangroves in the vicinity, including those undertaken from 2011 to 2014 by Southern Cross University (SCU; Stokes & Bucher 2012, 2014), and from 2015 to 2016 by Central Queensland University (CQU; Houston et al., 2016). As required by the regulator, such monitoring programs were continued over multiple years to ensure possible impacts from concurrent construction works had minimal or no impacts on nearby mangrove and saltmarsh habitat.

Figure 73. Mangrove area enclosed by the Western Basin Reclamation Area (WBRA) at Fisherman's Landing. (Source: NC Duke).

An evaluation combining the use of green fraction plots. The assessment with the current study evaluated the overall impacts on protected mangrove areas close to construction activities in the WBRA. We considered the prior field monitoring studies undertaken by SCU and CQU (as noted above). However, both had notable deficiencies – primarily concerning the lack of adequate reference sampling sites, resulting in both studies having inconclusive outcomes. Accordingly, our assessment was organised around two component parts consisting of: available observations from field monitoring programs; coupled with an assessment of concurrent remote sensing information. The combination of these components satisfied the requirement for having field observations to validate mangrove condition detected in remote sensing vegetation indices.

To ensure adequate referencing with surrounding mangrove habitat, replicate sites were selected from three treatment categories within the Port Curtis study area (see Fig. 72) including: a) the critical enclosed and bunded area in the immediate vicinity of the Western Basin Reclamation Area (WBRA) (Fig. 73); b) the nearby vulnerable area of the Western Basin Expansion Area (WBEA); and c) a broad comparative reference area representing the surrounding Port Curtis area (WBSC). The full set of sites considered in the current assessment are depicted in Fig. 74, and listed in Appendix Table 11.

Field observations for validation with remote sensing data. Our observations were made using a combination of data sources. For WBRA and WBEA area information, our assessment relied mostly on the annual field observations reported by Stokes & Bucher (2012, 2014) and Houston et al., (2016). For the WBSC area, we referred to plot information collected with the current project (Site #20 in Fig. 74). Specific measures of immediate relevance, and equivalence, included: canopy condition, tree height and stand density.

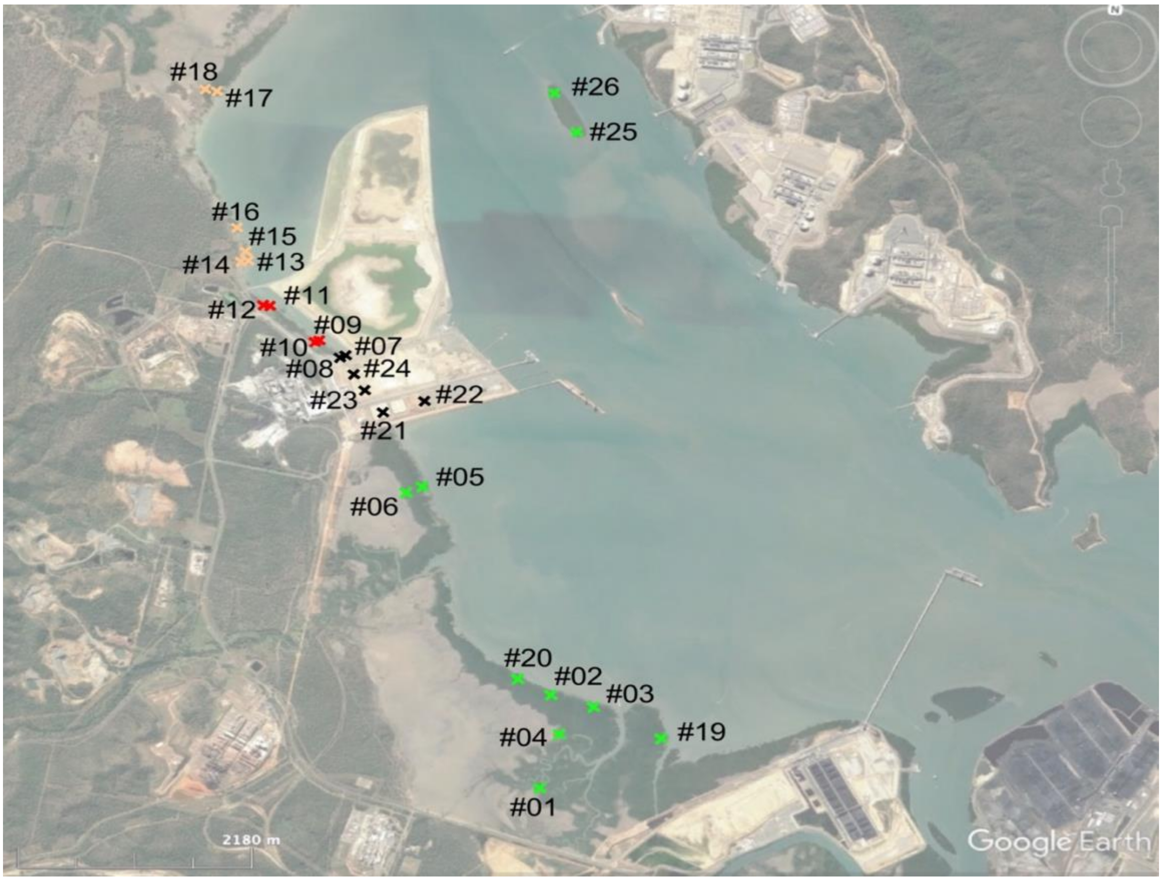


Figure 74. Sites representative of each of the treatment types used in this assessment, including: WBRA (4), WBEA (6), WBSC (10) and RE_CLAM (6). See Appendix Table 11.

Remote sensing green fraction plots. Unlike SCU and CQU monitoring programs, the current project obtained observations from satellite image analyses for remote measures of canopy condition and vegetative condition (as NDVI) of both mangroves and saltmarsh. Accordingly, it is suggested that future monitoring might usefully employ monthly remote measures of canopy condition to evaluate the ongoing impacts of port construction works, more or less indefinitely. Such remote measures can be obtained from multiple treatment sites. This innovative methodology has been termed 'green faction' timeseries plots (see Appendix 8). For example, these green fraction plots were pivotal in the identification of the cause of widespread mass dieback of mangroves in Australia's Gulf of Carpentaria in 2015 (Duke et al., 2019b,c; 2022).

Fisherman's Landing Reclamation Area (FL_RECLAM). Sites of reclamation of mangrove areas were established in this study (for example: Fig. 75) to depict the key dates when mangrove areas were lost. The prior condition of mangroves in these sites could also be determined from the remote sensing analyses.

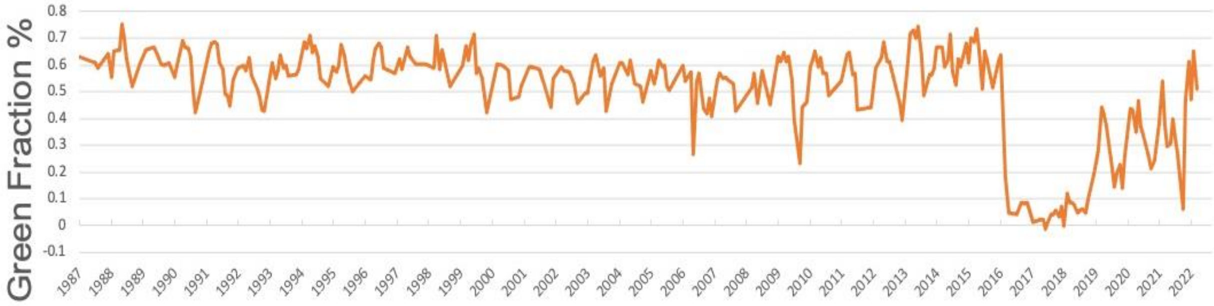


Figure 75. FL_CLAM Site #8 (=#PCPA_91) green fraction monthly timeseries (1987-2022) showing the abrupt loss of mangroves in March 2016 associated with permitted reclamation works at Fisherman's Landing. See Fig. 74, and Appendix Tables 10 & 11.

Western Basin Enclosed Area (WBRA). Sites of the critical assessment area (for example: Fig. 76; Appendix Table 10) consisted of a stand of mangroves approximately 1000 m in length, widths of 30-120 m, and an area of around 6.5 ha. Taller mangrove trees fringe the eastern edge of the mangrove stand, as the 'fringing' or 'seaward' mangroves. The dominant species includes *Rhizophora stylosa* with tree heights ranging up to 7-9 m. The 5-6 years of monitoring in the SCU study (Stokes & Bucher 2012), were based on five transects within the area making regular observations biannually, including: mangrove species, stem diameter, tree height, stem density, mangrove canopy cover and area, extent of insect damage to leaves, seedling abundance and crab burrow densities. In Figure 76, note the overall steady decline and recovery after 2012.

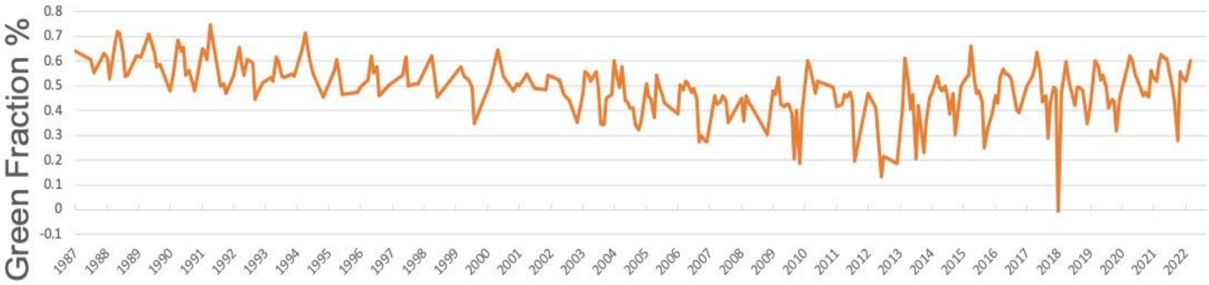


Figure 76. WBRA Site #11 (=#PCPA_93) green fraction monthly timeseries (1987-2022) showing a distinct decline from the early 1990s, with improvements after 2016. See Fig. 74, and Appendix Tables 10 & 11.

Western Basin Reference Area (WBEA). Sites of this intermediate reference area (for example: Fig. 77; Appendix Table 10) were needed in the determination of the extent of influencing factors in the Port Curtis area. Field sites were established in this area by Houston et al. (2016). This CQU study conducted annual monitoring recording observations at both the five SCU sites in the WBRA, plus two additional sites to the north in the WBEA area in 2015 and 2016. Pertinent observations scored included: tree canopy condition, and canopy density. In Figure 77, not similarities with the overall trends shown in Figure 76.

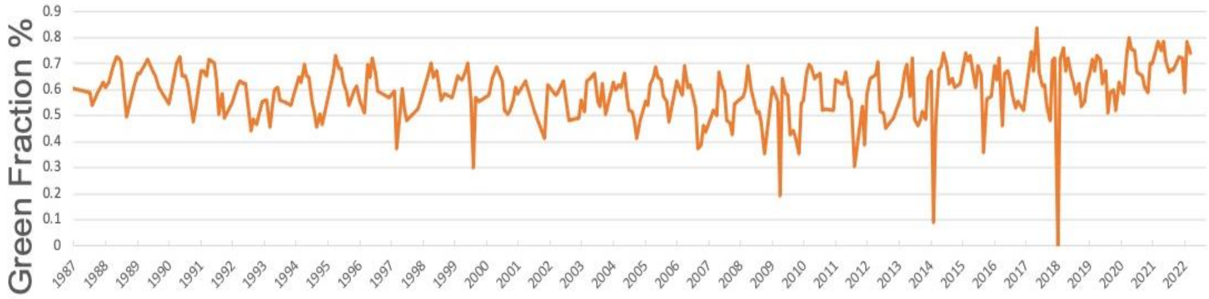


Figure 77. WBEA Site #16 (=#PCPA_98) green fraction monthly timeseries (1987-2022) showing a slight decline from the early 1990s, with improvements after 2016. See Fig. 74, and Appendix Tables 10 & 11.

Port Curtis Reference Area (WBSC). Sites of a wider reference area (for example: Fig. 78; Appendix Table 10) were used to ensure regional influential factors affecting mangrove condition in the WBRA and WBEA were not those associated with construction works. For example, an external factor might be a severe tropical cyclone. In addition, there are also pertinent historical baseline data available from prior mangrove canopy condition (e.g., Duke 2002; Duke & Burns 1999, 2003; Duke et al. 2000, 2003) as well as their on-going monitoring with the GPC ERMP (Duke et al. 2019c; Schultz et al. 2020). In Figure 78, note the more or less level condition of the mangrove canopy from 1987 to 2022.

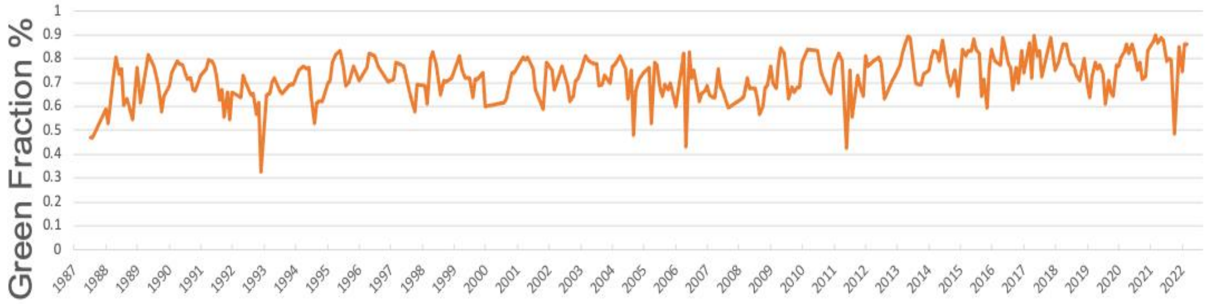


Figure 78. WBSC Site #20 (=#PCPA_102) green fraction monthly timeseries (1987-2022) showing only seasonal change for the duration. See Fig. 74, and Appendix Tables 10 & 11.

Results of the WBRA mangrove monitoring. There were a number of key conclusions from our assessment of changes to the Western Basin Reclamation Area and the impacts on protected mangrove areas nearby. Our overall findings are briefly summarised in Fig. 79.

Firstly, there were no serious or abrupt declines observed in protected mangrove areas for duration of major reclamation activities depicted as abrupt events such as those in 1998, 2001, 2003, 2016 and 2018 (black boxes in Fig. 79; Appendix Table 10). In each case, abrupt losses in mangroves were recorded in sites 7, 8, 21, 22, 23 and 24 (see Fig. 74).
Secondly, while the Port Curtis reference area (WBSC) maintained relatively constant canopy conditions, around 0.6 canopy density (Fig. 79), there was a noticeable decline in mangrove condition in both WBRA and WBEA treatment areas. The decline appears likely roughly equivalent in WBRA and WBEA sites. This implied that water turbidity and sediment accumulation may have been the dominant influencing factors. Unfortunately, there were no observations to confirm this possibility since no sampling was undertaken in WBEA sites until 2015 (Houston et al., 2016).
Thirdly, mangrove canopy declines in WBRA and WBEA sites however notably recovered after 2017, with treatment levels comparable in 2021 as they were prior to 1998.

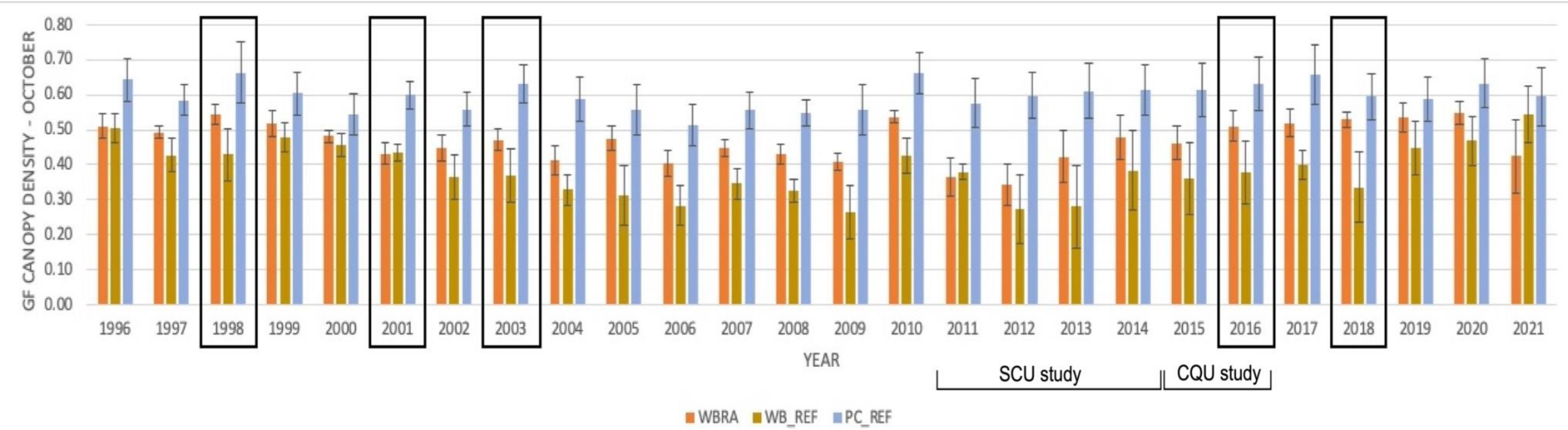


Figure 79. Mean canopy condition (green fraction NDVI, 1996-2021) each October for the three treatment site groupings of WBRA (4), WBEA (3, =WB_REF) and WBSC (6, =PC_REF). Treatment locations are displayed in Figs. 72 & 74. Error bars signify Standard Errors. Where these overlap between treatments, there were no apparent differences between them.

Overall, losses sustained by WBRA and WBEA sites while experiencing declines greater than 33% of 1996 levels (see 2012 for lowest levels), these levels of impact were not apparently critical for these trees. And, over a period of almost 25 years, these moderately impacted forests have been able to recover their prior canopy status. Furthermore, there had not been an appreciable loss of mangrove area, remaining at around 6.5 ha of mangroves in the enclosed WBRA area.

Accordingly, mitigation measures implemented by GPC to minimise harm and losses to mangrove areas from dredging works in this case appear to have been successful.

Figure 80. Measuring a reference forest plot of *Rhizophora stylosa* trees (Site #20 in Fig. 122) in Port Curtis with the Gidarjil ranger field team in 2019. (Source: NC Duke).

However, there is one caveat that must be mentioned in this context. Based on the broad understanding of mangrove fitness and durability, the serious loss of mangrove condition from reference conditions (Fig. 80) displayed during the dredging period, is reason for concern. If there had been a serious pollution incident, or a severe weather event, at the time of their reduced resilience, this would probably have resulted in more severe damage to the weakened trees.

CHAPTER 7

NATURAL AND CLIMATIC FACTORS INFLUENCING MANGROVE TIDAL WETLANDS

'SHORELINE EROSION'
- **ASSOCIATED WITH RISING SEA LEVELS & STORMS**

Cause. Storm conditions coupled with progressively rising sea levels cause incremental and progressive loss of shoreline mangrove habitat.
Indicator. Loss of foreshore and shoreline mangrove vegetation is marked by fallen and eroded dead trees and exposed stumps, eroded peat mat and uprooted mobilised stem wood. Some trees also have a lack of seedlings and have slower regrowth recovery, as well as with the close proximity of depositional sediment banks and berm ridges showing mobilised sediments (see Fig. 81).
Impact. The loss of shoreline mangrove vegetation not only represents the loss of habitat and ecosystem benefits, but it also identifies locations currently experiencing unsustainable impacts. Once shoreline trees have been killed or damaged, these eroded shorelines become vulnerable to further disruptive events as inner stand trees are notably less exposure-adapted. Mangrove tree structural types differ in growth form depending on their position along the tidal profile, and where in an estuary they become established. Once mature, these trees are less able to change and adapt further.

Figure 81. Shoreline erosion and retreat of tidal wetlands occurs when sea edge trees are lost. (Source: NC Duke).

For instance, trees positioned at the seafront develop sturdy support structures and a sprawling habit with complex tangled exposed roots, epitomised by *Rhizophora* species (see Figs. 80 & 81). When such mangrove species grow in the middle of a forest they develop significantly fewer prop roots and support structures, and instead produce much greater stem height. When such inner trees become exposed by shoreline erosion, they offer little or no inhibition to retreating shorelines. Such damaged shoreline defence trees can only be re-established from future recruits getting established and growing up in exposed conditions. This process takes more than two decades, if at all. The more or less fixed rate of plant development is expected to have some limit where it is overwhelmed (Duke 2001) once a certain high threshold of damaging impacts, like the rate of sea level rise, is exceeded. Accordingly, the re-establishment of damaged shorelines becomes more vulnerable with accumulative impacting events, such as storms, floods and human pressures.

Case study – 'shoreline erosion'
A notable and specific location of shoreline retreat was associated with the mangrove 'islands' in the mouth of the Fitzroy River (Duke et al., 2003). While these mangroves colonising mudbanks had increased rapidly over the last half century, they had also lost parts of their shorelines to erosion (see Fig. 78). This kind of change is probably also linked with pulse events of unusually high sea level or flooding (see 'drowning dieback & 'fringe collapse' as well as 'flood damage'), or with pressure events with rising sea levels. In any case, the timing and rate of shoreline retreat is likely to be indicative of this specific driver of change. There are likely to be more factors influencing such changes, so a detailed assessment of 'shoreline erosion' would usefully quantify rates of shoreline retreat, and the benefits of mangrove vegetation in buffering this retreat.

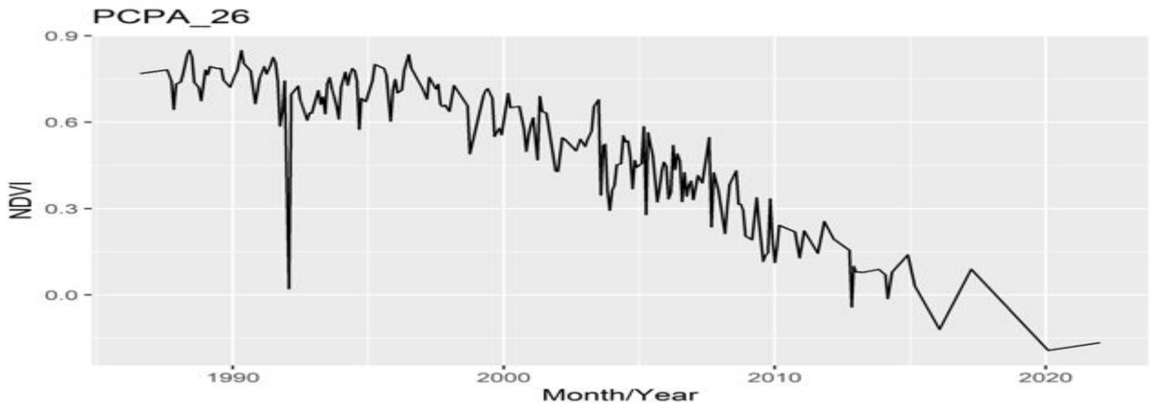


Figure 82. 'Shoreline erosion' is exemplified in this green fraction plot taken at a seaward edge location of one of the mangrove 'islands' in the Fitzroy River mouth. Note, the once dense mangrove canopy in 1987 started to deteriorate after 1996 and lost all vegetation by 2013. The combination of unusually high sea levels and flooding rains in the early 1990s are consistent with the timing of this erosion.

The overall occurrence and severity of 'shoreline erosion' was notably greatest in the northern areas of the PCPA region. This was observed in both aerial surveys (Fig. 83). A likely factor influencing this overall pattern of impact across the region may have been the severe cyclonic conditions caused by tropical cyclone *Marcia* in early 2015 (Fig. 27). During that storm category 1 and 2 cyclonic winds battered northern parts of the PCPA region, the PA subregion.

Figure 83. Indicators of 'shoreline erosion' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

The same overall trend had been observed also during boat S-VAM surveys with the Gidarjil rangers in 2017 (Fig. 84).

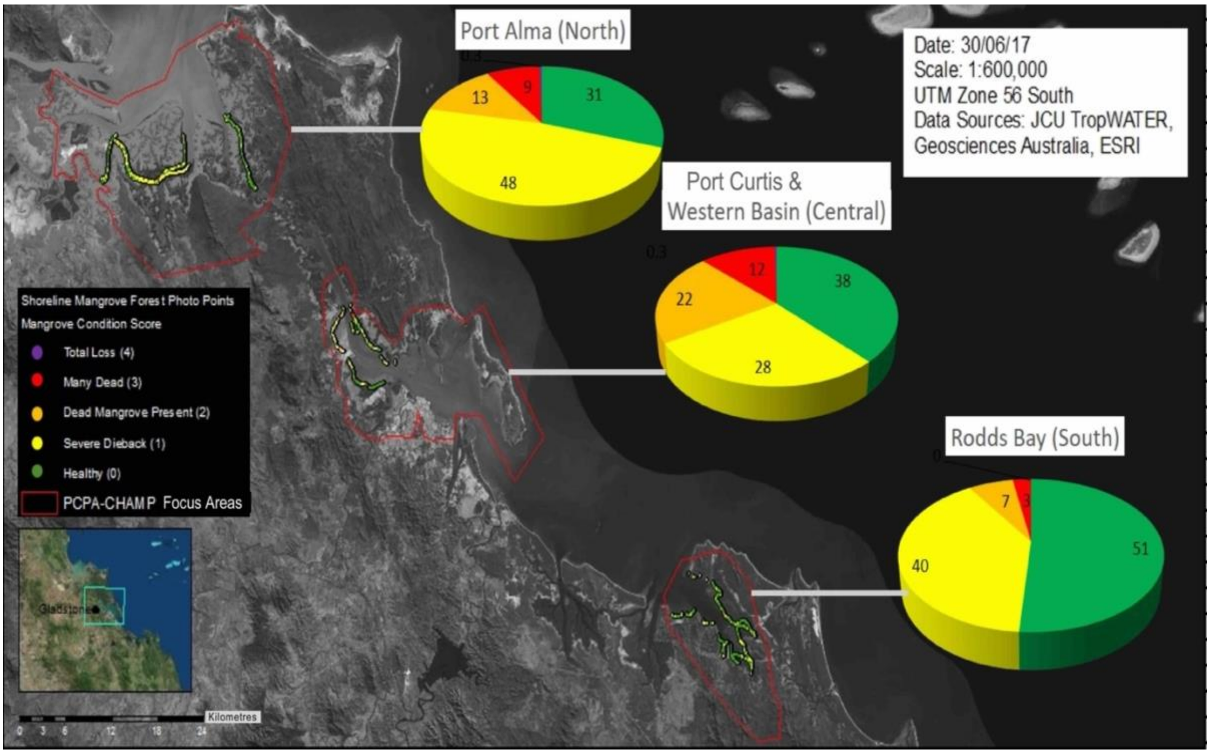


Figure 84. Summary pie diagrams of 'shoreline erosion' levels recorded in 2017 boat surveys in Port Alma, Port Curtis and Rodds Harbour subregions using the shoreline video assessment method (S-VAM) undertaken with Gidarjil rangers (Duke et al., 2018). (Source: J. Mackenzie).

'BANK EROSION'
- ASSOCIATED WITH FLOODS AND RISING SEA LEVELS

Cause. The banks of estuarine channels are regularly inundated by seawater and drained with each tidal cycle. Depending on tide levels, higher flow rates during flooding can cause severe erosion. Tidal flow rates are amplified further as sea level rise adds greater volumes of water into estuarine catchments. These processes cause significant bank erosion, restructuring of channel margins and mobilisation of sediments. The alternate condition in part, is described as depositional gain.
Indicator. Eroded banks are steep slopes, showing bare and crumbling earth faces, slumped bank sections with intact vegetation, along with general remnants of collapsed and undermined vegetation like fallen trees, uprooted and inundated plants as seen in the major PCPA estuaries (Fig. 85).
Impact. Lost mangrove habitat represents a loss of ecosystem benefits. Also significant is the loss of bank stability much as mentioned with Shoreline Erosion. Such estuarine banks are highly vulnerable.

Figure 85. Bank erosion occurs when estuarine banks become undermined by waves and currents. (Source: NC Duke).

During the 2019 aerial survey, 'bank erosion' was observed throughout the PCPA region (Fig. 86). Impact levels were greatest in the Port Alma subregion with lesser levels in southern subregions (also see Table 10).

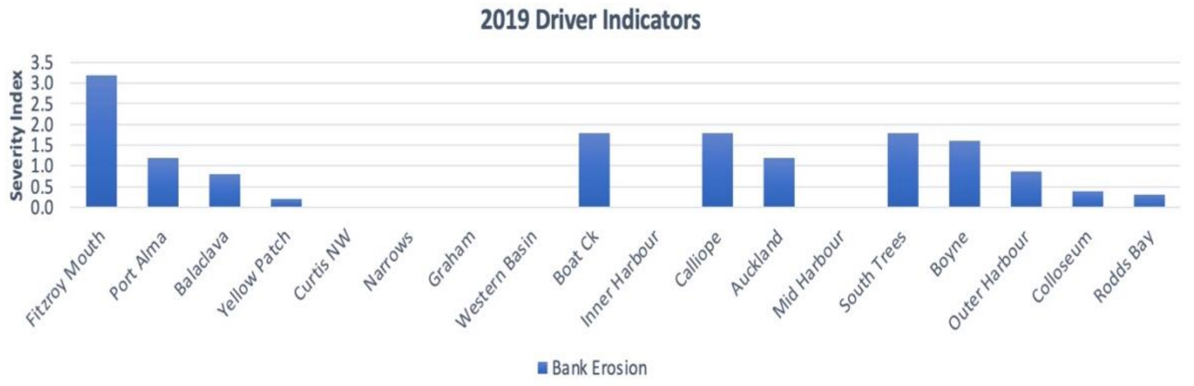


Figure 86. Indicators of 'bank erosion' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

This was a trend common with 'shoreline erosion' and 'depositional gain'. By its character, 'bank erosion' was also understandably greatest in larger catchment and riverine estuary dominated zones including the Boyne, South Trees, Calliope, Boat and Fitzroy estuaries. Accordingly, these impacts are also indicative of flooding and storm events, and the combination was extreme in northern areas with severe tropical cyclone *Marcia* in 2015 (Fig. 27).

'TERRESTRIAL RETREAT' & 'UPLAND MIGRATION' - ASSOCIATED WITH RISING SEA LEVELS

Cause. When sea levels rise progressively over time, there is continual pressure on high intertidal shorelines behind tidal wetland habitat and bordering the verge of supratidal vegetation. This upward pressure is caused by saltwater encroachment, and higher tidal inundation levels during seasonal and daily highwater tidal peaks.
Indicator. There are two notable effects that represent these types of changes: 1) erosion along the upper intertidal edge as a shallow eroded ledge, and as scouring of small runoff tributaries; and 2) death of established supratidal vegetation, like dead *Melaleuca*, *Casuarina* and *Eucalyptus* trees (Fig. 87). These effects are combined with mangrove encroachment which may be scored separately, but dead mature terrestrial trees are more visible than newly established mangrove seedlings, as seen in upper tidal shorelines. Sometimes these affects are combined with Terrestrial Retreat Erosion which has been scored separately.
Impact. This impact mostly concerns the loss of supratidal vegetation, and the possible expansion of mangrove areas. However, the ongoing erosion and death of terrestrial vegetation however makes it difficult for the re-establishment of bank stability along this major ecotone. These areas are highly vulnerable to added pressures on seedling establishment such as the damage caused by rising sea levels or feral pigs.

Figure 87. Terrestrial retreat, coupled with saline intrusion, is marked by dieback of supratidal terrestrial vegetation, possible encroachment by seedling mangroves, and erosion along highest seawater margins. This impact comes as a direct consequence of progressively rising sea levels. Such an occurrence is considered a valuable indicator and because it depends on elevation, the breadth of impacted sites might be greatest in areas of flatter terrain. (Source: NC Duke).

Case study – 'terrestrial retreat' and 'upland migration'

Observations of terrestrial retreat at the upland ecotone were not detected using green fraction plots – chiefly because of the image pixel sizes involved, regarding the steep slope and rapid transition in vegetation at the highest tide levels. However, for site locations at the back of the shoreline mangrove zone, comparable changes appear more easily detected (Fig. 88), but these may also be driven upland with rising longer-term rainfall. The challenge is to discriminate between these drivers. Both are gradual and steady trends, but while sea level rise should correspond with encroaching mangroves in the back zone, only rising rainfall levels would match upland expanding mangroves.

There were numerous observed instances of 'terrestrial retreat' and 'upland migration' (= mangrove encroachment landward) recorded in aerial surveys in the PCPA region. As noted, these trends were consistent with rising sea levels.

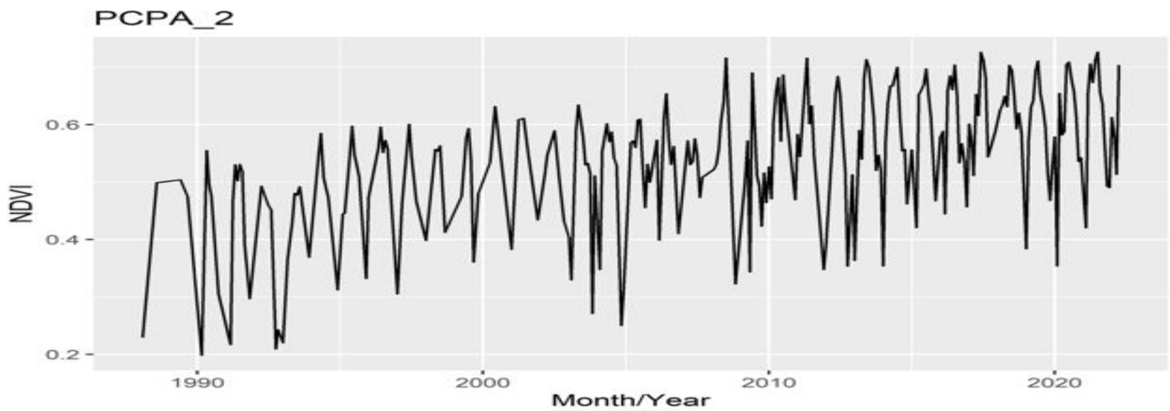


Figure 88. 'Upland migration' is shown in this green fraction plot at the rear edge of the shoreline mangrove zone. There were steadily increasing levels of canopy density, as the mangrove area became more established. These changes were consistent with the likely driver being either rising sea levels or increasing rainfall. However, since there had been a decline in the longer-term rainfall for the region (Fig. 19), it seems likely that this trend relates to rising sea levels as the responsible driver (Fig. 20).

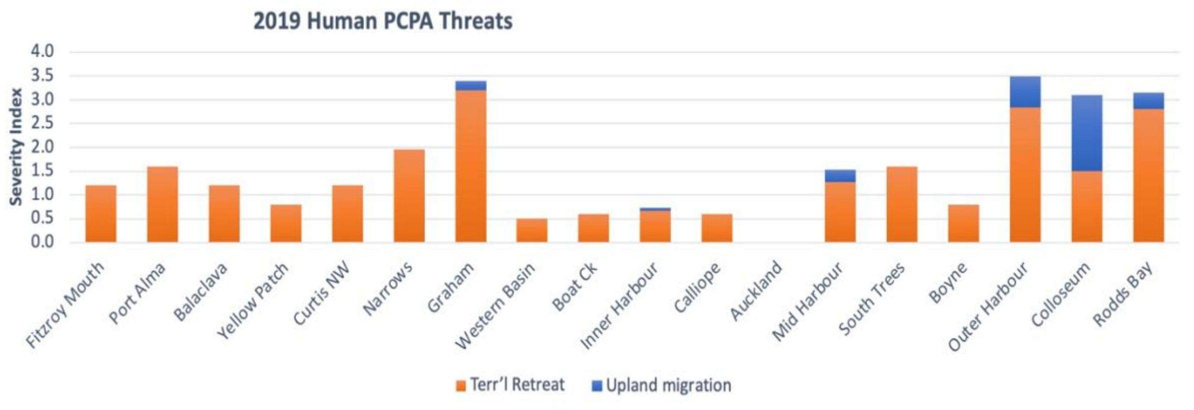


Figure 89. Indicators of 'terrestrial retreat' and 'upland migration' of tidal wetlands in the 18 PCPA zones observed during 2019 aerial survey.

Observations made during the 2019 aerial survey (Fig. 89) showed there was an overall trend towards higher impacts of 'terrestrial retreat' and 'upland migration' in southern areas. This was consistent with higher rates of sea level rise also in southern subregions (Table 5).

‘PAN SCOURING’
- **ASSOCIATED WITH RISING SEA LEVELS**

Cause. When unusual and progressively higher levels of tidal waters flood across tidal saltpans, sediments can be sheet-eroded, scoured and transported into tidal channels. An associated driver with this one might be Terrestrial Retreat Erosion. This impact is driven by rising sea levels and amplified in effect on wide gentle sloping profiles.
Indicator. Scoured saltpan surfaces marked with drainage lines coupled with a lack of saltmarsh vegetation across the saltpan surface, as see in the PCPA area (Fig. 90).
Impact. The loss of saltmarsh habitat is significant. There is also a further supply of fine sediments finding their way into the estuary and probably further contributing to depositional gain. In extreme instances, saltmarsh vegetation including natural layers of microphytobenthos have been unable to re-establish so the whole inundated area is actively scoured leaving bare sediments and pools of residual tidal waters.

Figure 90. ‘Pan scouring’ was observed throughout the PCPA region (see Fig. 91). (Source: NC Duke).

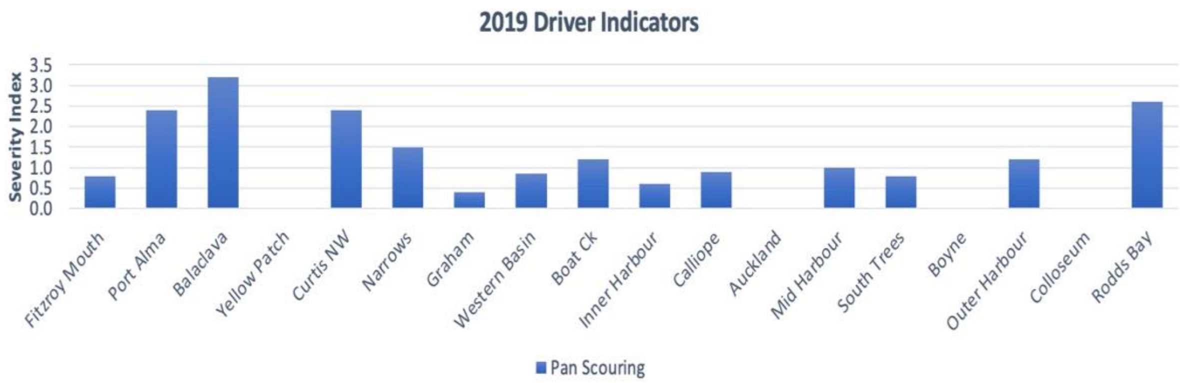


Figure 91. Indicators of ‘pan scouring’ of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

Observations made during the 2019 aerial survey (Fig. 91) showed there was ‘pan scouring’ distributed across all subregions (Table 10). There was no recognisable correlation with environmental variables although the impact is most likely associated with rising sea levels.

‘DEPOSITIONAL GAIN’
- **ASSOCIATED WITH SEDIMENTS FROM FLOOD RUNOFF**

Cause. Depositional gain is particularly evident along estuarine channels where seedlings colonise accreting banks. When sediments are flushed downstream from catchment areas disturbed by flooding erosion, they are usually deposited towards the river mouth and along lower estuarine channel margins. The depositional materials often emerge as large mudbanks and form mangrove ‘islands’ when colonised naturally by mangrove vegetation. Mangroves appear to colonise these banks after mud banks exceed mean sea level elevations – the mangrove ‘sweet spot’ zone.
Indicator. Newly recruited mangrove seedling and sapling stands growing on shallow muddy banks generally towards the lower estuarine reaches towards the mouth of riverine estuaries (Fig. 92). Various key mangrove genera are involved including mostly *Avicennia*, *Rhizophora*, *Aegialitis*, *Aegiceras* and *Sonneratia*. In general, depositional gain is indicative of the combination of sediment transport processes including catchment runoff and the reworking of deltaic sediments, as seen at the mouth of the Fitzroy River, Port Alma subregion.
Impact. With the increase in mangrove plants, there is a gain for mangrove habitat. However, these new habitats will take many decades to achieve the roles provided by mature stands. As such, this process is probably offset by bank erosion upstream, which is generally seen as the active alternate condition to depositional gain along typical estuarine meanders. It occurs mainly because of increased flooding across areas of largely unconsolidated sediments, coupled with rising sea levels.

Figure 92. Depositional gain occurs when mangrove seedlings and saplings occupy accreting mudbanks exceeding elevations above mean sea level. This view of the Fitzroy River mouth shows a terrestrial island amongst many mangrove ‘islands’ marking sediment deposition locations following periodic flood events. (Source: NC Duke).

Case study – 'depositional gain'

Mangrove 'islands' in the mouth of the Fitzroy River represent much exaggerated instances of depositional gain. Sediments washed downstream have deposited in the slower flowing waters of the wide mouth area. Mangroves naturally colonise depositing mud banks after the elevation of the mud banks exceeds mean sea level. This has resulted in the overall expansion of mangrove 'islands' from ~260 ha to 340 ha (Fig. 93), an increase of ~30.8% during the 60 years up to 2000, as estimated in this study. Presumably the rate of mangrove 'island' expansion (as depositional gain) has been driven by the supply of sediments from upstream.

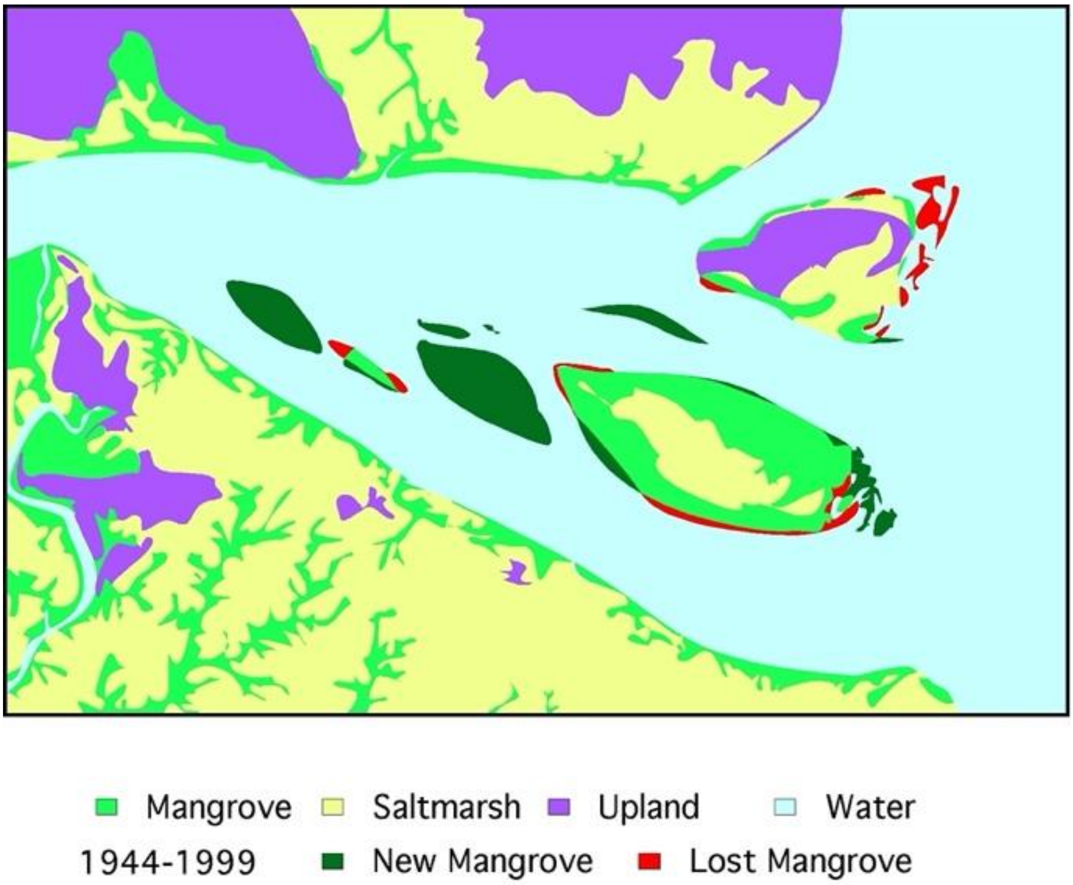


Figure 93. Expanding mangrove areas with mangrove 'islands' at the mouth of the Fitzroy River between 1944 and 1999 (Duke et al., 2003).

There are important questions about why the supply of sediments had risen sharply since the 1940s, while there had been no appreciable 'island' expansion between 1895 and 1941. It seems that eroded sediments in catchment runoff were responsible. In Figure 94, we investigated the appearance of shoreline mangrove vegetation on one of the Fitzroy mangrove 'islands' using a green fraction timeseries plot from 1987-2022. This plot showed the timing of colonisation and establishment of these mangroves was around 2003. As noted, in Figure 19, this was coincident with a year of maximal rainfall and flooding, probably bringing sediments in runoff eroded from catchment areas upstream.

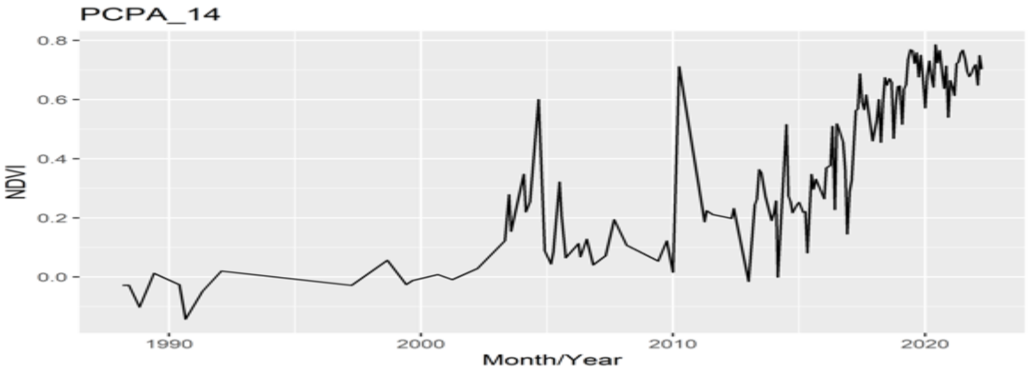


Figure 94. Depositional gain was depicted in the establishment and growing mangrove vegetation at the waters' edge of a mangrove 'island' stand in the mouth of the Fitzroy River (see Fig. 93). Note the bare mud bank up to 2003, which became established with mangroves that grew to attain canopy closure by 2020.

These observations have profound implications for catchment management, and accordingly underpin the need for a more detailed study of 'depositional gain' in this region, and especially regards the mangrove 'islands' at the mouth of the Fitzroy River.

More generally, 'depositional gain' occurs across the entire PCPA region, but as with 'shoreline erosion', there were greater impacts in northern zones (Fig. 95). This association is perhaps not surprising since erosion would also be indicative of more sediments being mobilised and probably contributing to mudbank expansion, and 'depositional gain' as mangroves colonise these mudbanks. The associated drivers influencing this indicator would be flooding and storm events, typified by tropical cyclone *Marcia* in 2015 (Fig. 27).

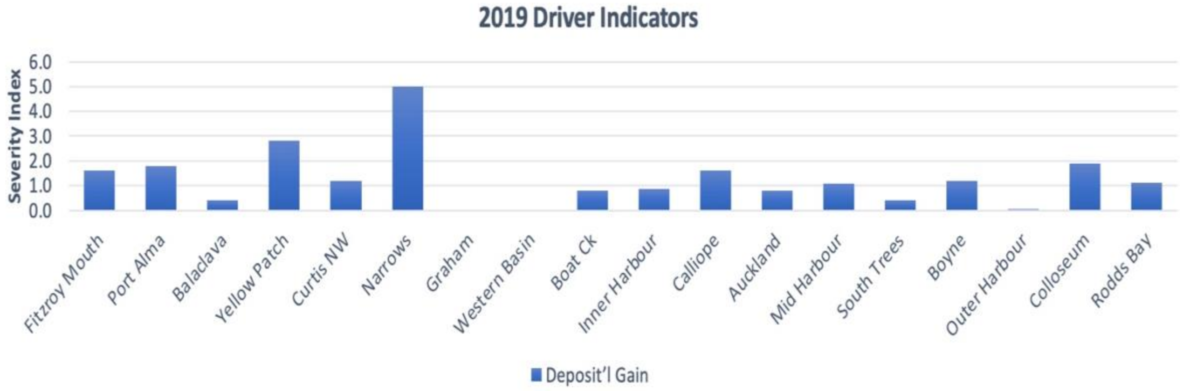


Figure 95. Indicators of 'depositional gain' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

'STORM DAMAGE'

- **MANGROVE DIEBACK, EROSION FROM STRONG WINDS & WAVES**

Cause. Storm conditions bring heavy seas, strong winds and rapid scouring that often cause significant and extensive damage to tidal wetland and mangrove habitat. A key agent causing such destructive weather conditions is a severe tropical cyclone. Tracks recorded over the last 40 years (Fig. 25; Table 6) show their distribution and regular occurrence in the region.
Indicator. Loss of saltmarsh vegetation and loss of mangroves as defoliated uprooted broken trees as well as the loss of trees (Fig. 96). For mangroves, both the re-established younger plants and the degraded dead trees are indicative of when the damage occurred.
Impact. Habitat damage and losses reduce the fitness of tidal wetlands. As a consequence, the ecosystem services are also lost. It is important to quantify such indirect consequences. One key example the likely effects on local fisheries, or any loss of shoreline protection with erosion. It occurs mainly because of severe storms coupled with a shoreline weakened by rising sea levels.

Figure 96. Strong cyclones can cause severe damage to mangrove forests. Damaged shorelines may recover but only after several decades provided seedlings are rapidly re-established amongst the dead and damaged trees. (Source: NC Duke).

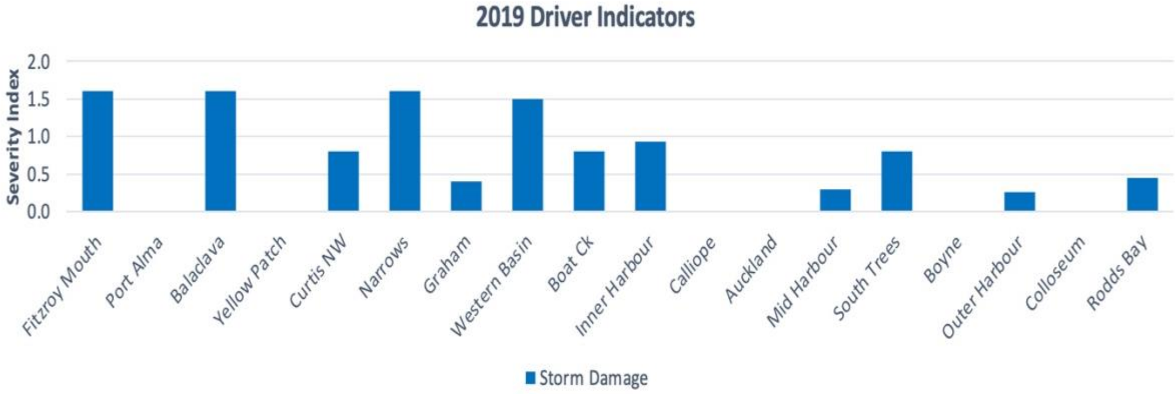


Figure 97. Indicators of 'storm damage' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

While 'storm damage' would include mostly the physical damage caused by strong winds and large waves (Fig. 96), there are also other distinctive types of storm damage. Those observed in the PCPA region included: wave effects causing 'root burial' (page 109) and 'natural altered hydrology' (page 102); hail causing 'hail damage' (page 97); excessive river flows causing 'flood damage' (page 99); and, lightning strikes causing 'light gaps' (page 103). As noted, specific local examples are described in the following sections.

‘HAIL DAMAGE’
- ASSOCIATED WITH SEVERE HAIL STORMS

Cause. Severe hail storms.
Indicator. A patch of mangrove forest with distinctly shredded leaves, and bare branches with bark stripped away (Fig. 98). Tree stems lacerated and scored with cuts along one side – marking the direction of the storm. Often notable instances of surviving small trees in the ‘shadow’ of larger trees.
Impact. Damaged mangrove trees have a mixed response depending on the severity of damage and the species (Houston 1999). Some species, like *Avicennia marina*, are more resilient to such physical damage and these can recovery. However, species of *Rhizophora* and *Ceriops* are especially vulnerable where loss of leaves result in rapid death. Where trees die recovery can take 15-20 years as it depends on recruitment and growth of replacement vegetation (Duke 2001).

Figure 98. Severe damage by a hail storm in the Anabranch of the Calliope River in 1994 (Houston 1999). (Source: NC Duke).

Case study – ‘hail damage’
In October 1994, a severe hail storm struck mangrove areas along the Calliope Anabranch near the mouth of the Calliope River (Arnold 1996; Houston 1999). Between 211-291 ha of mangrove and saltmarsh tidal wetlands were impacted (Houston 1999; Duke et al., 2003) representing around 20-27% of tidal wetlands in the Calliope River estuary, and 2.5-3.4% of tidal wetlands in the Port Curtis subregion. At least one third of the impacted area was severely affected with more than 75% loss of canopy foliage (Houston 1999; see Figs. 99 & 100).

Our study showed there had been recovery in some impacted locations. For example, a site with a severe 30% drop in canopy condition in 1994, displayed in a 1987-2020 green fraction timeseries plot (Fig. 100), showed canopy recovery from that damage took around 3-4 years. However, in neighbouring sites, it was evident that recovery was dependent on the severity of the impact. Based on a study of recovery in the Gulf in Carpentaria (Duke et al., 2022), recovery from the large severely damaged area would take at least 15-20 years. The necessary data is available for an assessment of the full extent of recovery. Such a study is needed to better answer questions about the longer-term impacts of this and other severe storm events.

Figure 99. Severe hail damage was observed across a large area of tidal wetlands along the Calliope Anabranch near the mouth of the Calliope River in 1994 (Houston 1999). Note the grey hue across the normally green mangrove vegetation. (Source: NC Duke).

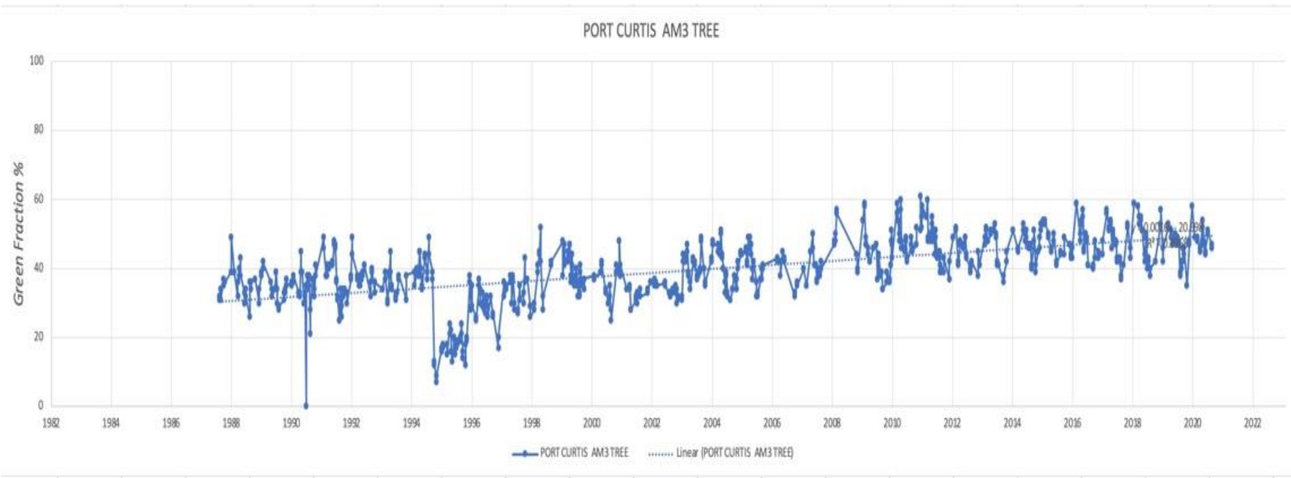


Figure 100. This green fraction timeseries plot shows the abrupt damage by a severe hail storm in 1994 (Houston 1999) to mangrove canopies at one site along the Calliope Anabranch estuary.

'FLOOD DAMAGE'
- ASSOCIATED WITH EXCESSIVE STORM RUNOFF & FLOWS

Cause. When flooding catchment runoff waters add to the downstream flow of estuarine waters, this causes significant damage to tidal wetlands and estuarine banks. Notable debris are also transported downstream ending up in downstream mangroves where water flow rates were slower. The eroding effects are comparable to the bank erosion effects of Upstream Migration. Also associated with flooding events is Depositional Gain, having the same effect with additional sediment deposits downstream.
Indicator. Flood debris caught up in shoreline vegetation coupled with damaged trees leaning in the downstream flow direction, eroded banks and overwash areas with deposited sediments and scoured channels (Fig. 101).
Impact. The dominant impacts from flooding include damaged mangroves, bank erosion and scouring.

Figure 101. 'Flood damage' was observed affecting mangrove trees following severe flooding in the Boyne River estuary in 2013. (Source: NC Duke).

Case study – 'flood damage'
In 2013, a severe flooding associated with tropical cyclone *Oswald* impacted mangrove areas along the Boyne River estuary (Table 6). The excessive river flows resulted in extensive damage to mangrove vegetation with uprooted, water-swept and drowned trees and shrubs. There was also significant erosion of mangrove embankments (Fig. 102). Our field surveys with Gidarjil rangers in 2014 recorded extensive damage along 19 km of the Boyne estuary, and that damage was the most severe in upstream reaches (Duke et al., 2019b).

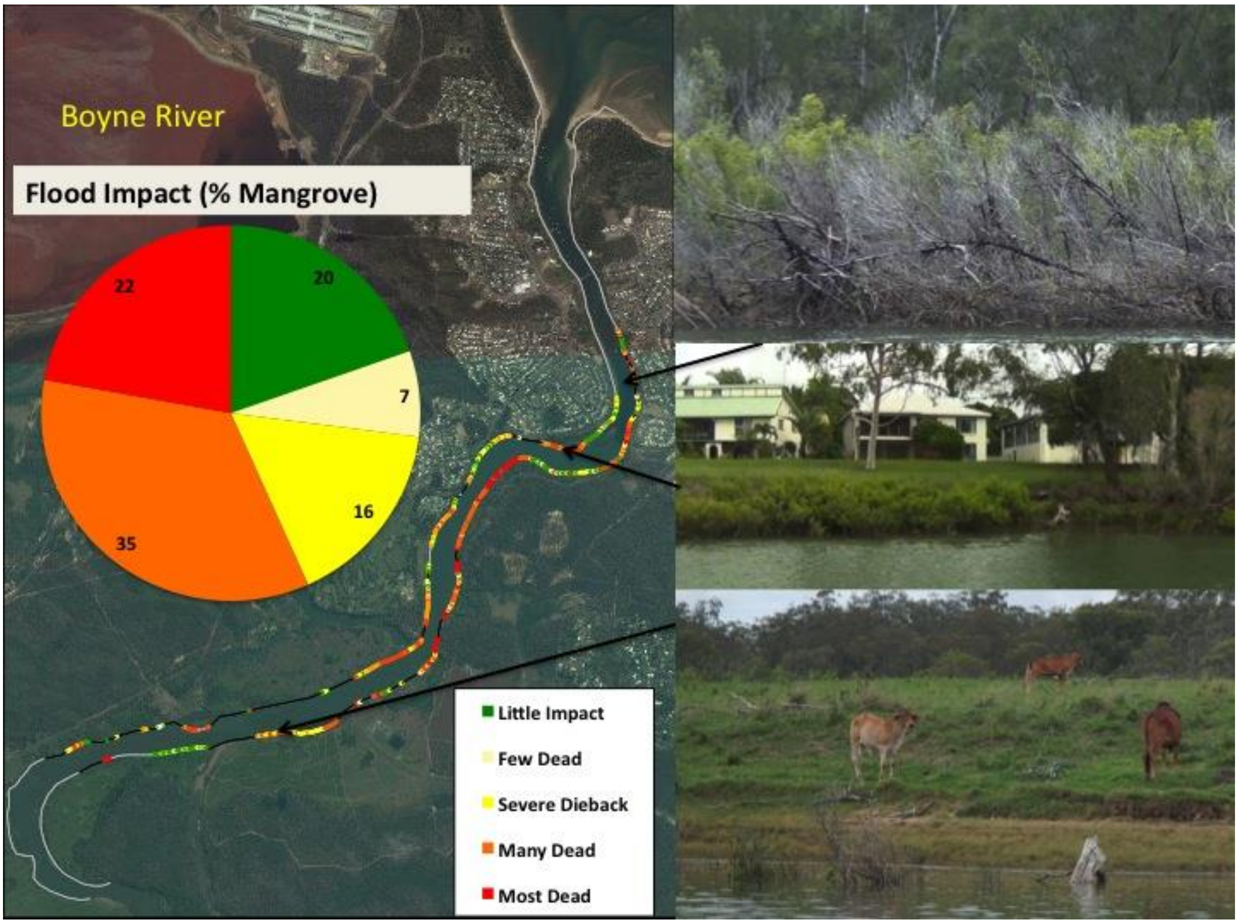


Figure 102. The severity and extent of 2013 flood damage recorded in S-VAM surveys of 2014 in the Boyne River estuary. Image acquisitions for these data were made by Gidarjil indigenous rangers (Duke at al., 2019b). (Source: J. Mackenzie).

Our further assessment with this report using green fraction timeseries plots indicated that ‘flood damage’ was abrupt in 2013, with the canopy loss at site number ‘PCPA_49’ (midway along the estuary) around 20% (Fig. 103). Levels of canopy loss were similarly abrupt at other sites, but decreased in sites further towards the mouth with losses of 5-13%, while upstream losses were greater around 40%. Overall, there was a notable trend with mangrove losses increasing with distance upstream from the mouth.

And, as was noted with ‘hail damage’, this was consistent with mangrove recovery taking a predictable amount time (also see Duke et al., 2022), being more rapid (2-5 years) in downstream mangrove areas whilst the areas upstream would take much longer (>9 years).

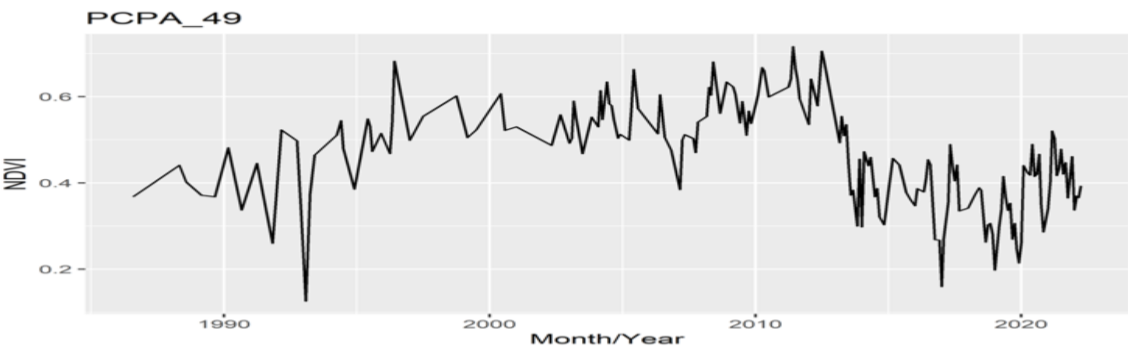


Figure 103. Mangrove damage caused by severe flooding in the Boyne River estuary associated with Tropical Cyclone *Oswald* in January 2013.

It was further evident in the green fraction plot (Fig. 103) that the particular site appears to have been on a recovery trajectory after likely earlier severe damage prior to 1987. A possible impacting event may have been severe Tropical Cyclone *Emily* which struck the local area in April 1972. These observations strongly support the need to conduct a more detailed study of flood impacts on estuarine mangrove and saltmarsh vegetation along riverine estuaries prone to flooding in the PCPA region (Fig. 104).

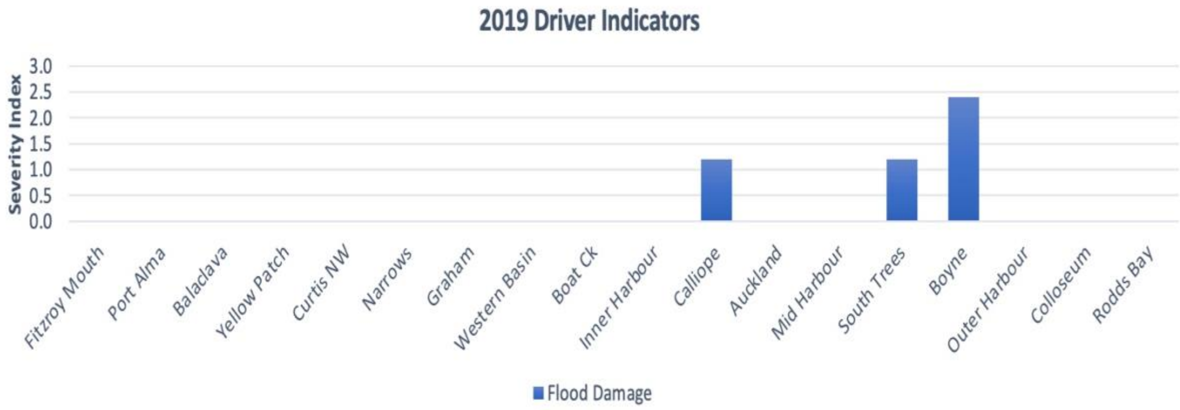


Figure 104. Indicators of 'flood damage' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

The extent of 'flood damage' impacts were notably associated with rainfall and flooding of larger catchment estuaries, such as the Calliope, South Trees and Boyne. Further such impacts were also observed in the upper reaches of the Fitzroy estuary in 2008 (Fig. 56).

‘NATURAL ALTERED HYDROLOGY’
- **IMPOUNDMENT WITH STORMS BLOCKING TIDAL EXCHANGE**

Cause. When water has not drained from a tidal or other flooded area after surrounding water levels have dropped, this is indicative of notable alteration to the natural hydrology of the site. This driver is associated with Human Altered Hydrology, as described above as a different process. This driver is also associated with Shoreline Erosion also described as a separate process.
Indicator. The distinguishing feature is pooled water amongst tidal wetland habitat that is deemed to have resulted from natural causes. The absence of construction works and track damage in the area helps isolate the potential natural influences, like drainage cut-off (Fig. 105).
Impact. The damage is often dead mangrove trees or canopy dieback.

Figure 105. Movement of beach sand blocks tidal exchange with the sea. (Source: NC Duke).

Case study – ‘natural altered hydrology’
Multiple localised instances of natural altered hydrology were observed to have impacted mangroves across the PCPA region (Fig. 106). The instances have not been quantified but they are considered indicative of rising sea levels, and the consequential re-adjustments to the hydrological conditions.

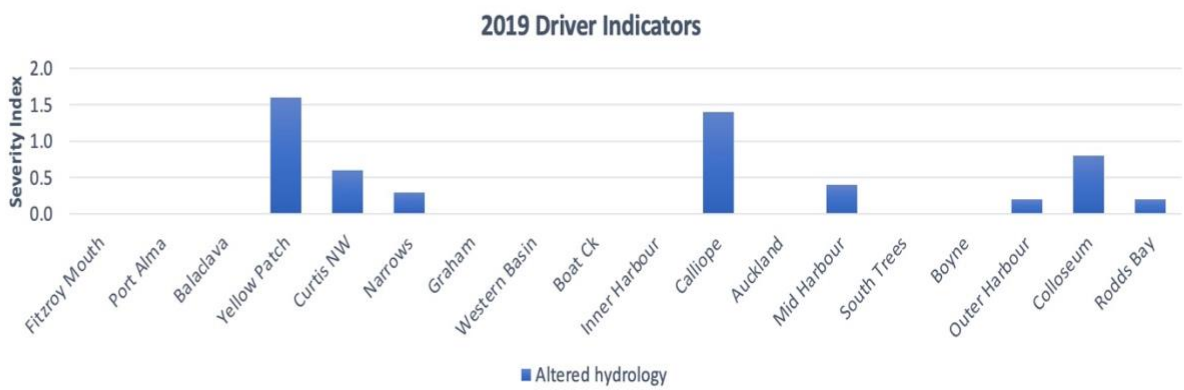


Figure 106. Indicators of ‘natural altered hydrology’ of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

‘LIGHT GAPS’

- **ASSOCIATED WITH LIGHTNING STRIKES DURING STORMS**

Cause. Severe storm weather with lightning strikes causes notable and distinctive damage to mangrove forests in the form of discrete, circular light gaps (Fig. 14). These gaps are typically 50-100 m^2 in area. The impacts are unlike other storm damage where trees die standing and unbroken. As gaps mature, the dead trees deteriorate, seedlings establish and grow, and eventually after about 2-3 decades the gap fills (Amir & Duke 2019). This process may explain how mangrove forests naturally regenerate and sustain their existence in such a wide selection of locations.

Indicator. These small circular light gaps are observed in mangrove forest canopies worldwide. It is important to recognise that gaps will be at a particular stage towards recovery and closure depending on when they were created (Fig. 107). Only for 1-8 year old gaps will the original trees be recognisable as the ones that started the process. While the number of gaps is considered an indicator of storm frequency, the net effect appears to influence stand age of mangrove forests which curiously lack old senescent stands (Duke 2001).

Impact. Light gaps are considered fundamental to forest replacement and turnover. It is notable that the frequency of gap creation is probably dependent on storm severity. As such, increases in any particular area will have a profound effect on forest turnover rates. At higher levels, these forests are predicted to be unable to sustain the natural processes involved in their replacement (Duke 2001). At that point, mangrove forests would enter a state of ecosystem collapse as the stand becomes fragmented and dysfunctional. It occurs because gap creation is coupled with the increased severity of damaging factors like storms.

Figure 107. Light gaps are caused by lightning strikes killing a small patch of mangrove trees in amongst otherwise undamaged surrounding mangrove forests. The impact and its recovery are distinct and unlike that in terrestrial forests. The number of gaps is an indicator of the frequency of storms. The one depicted in the image is hard to spot being small and full of dead limbs and branches. (Source: NC Duke).

Case study – ‘light gaps’

The frequency of ‘light gaps’ was relatively low (Duke 2001) but they were widespread across the region (Fig. 108).

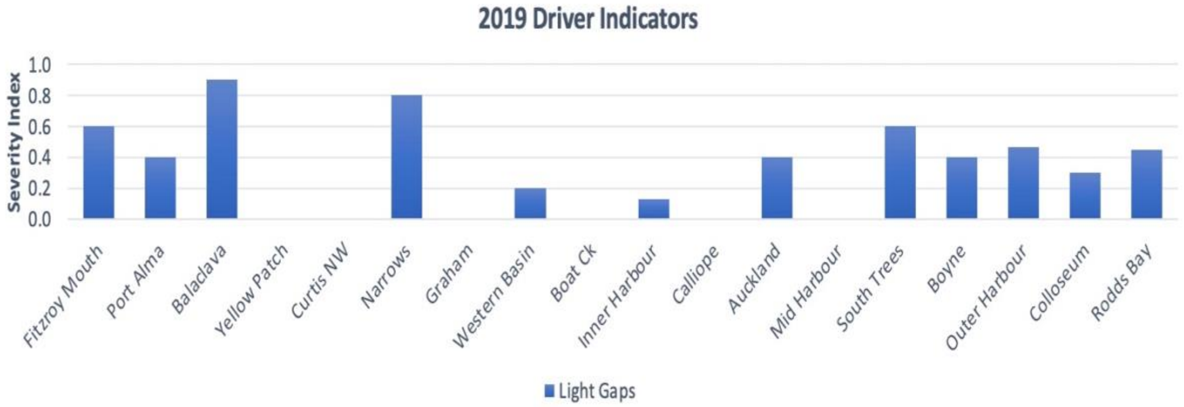


Figure 108. Indicators of 'light gaps' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

There are two reasons why that was probably the case – one, that largely short thicket-like mangrove stands may not show light gaps clearly as in taller forested stands; and two, the lightning storms that create these gaps may be less frequent. While a detailed study is needed to unravel such questions, the amount of damage caused in the PCPA region is arguably minor (Fig. 108). One instance was characterised in a green fraction timeseries plot (Fig. 109) showed an abrupt but minor impact in 2016. Recovery was rapid, occurring within one-two years.

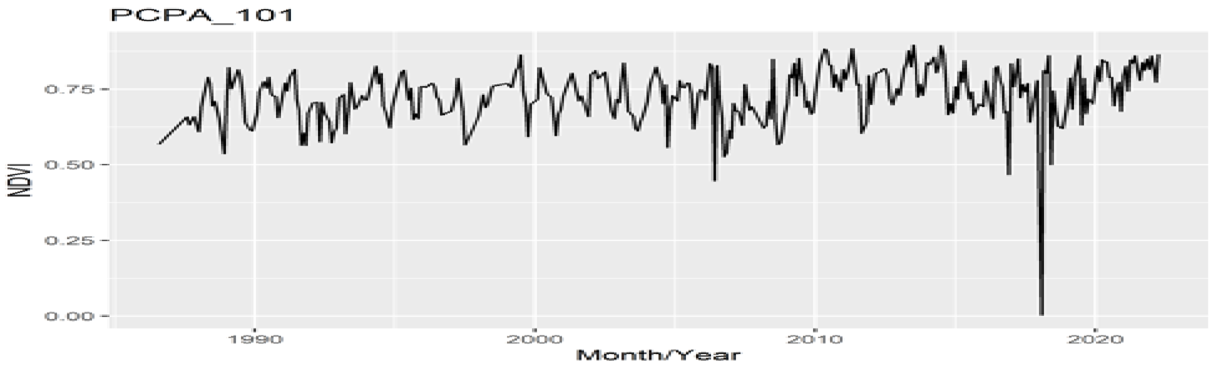


Figure 109. A light gap created in 2016 in *Rhizophora* mangroves in the Port Curtis area, showed minor damage with rapid recovery.

'ECOTONE SHIFT LOSS'
- **ASSOCIATED WITH DECLINING LONG-TERM RAINFALL**

Cause. When longer term rainfall levels decrease in an area, there is significant pressure on mangrove survival along critical saltmarsh-mangrove ecotones of affected tidal wetlands. Mangrove plants grow within tidal wetlands where moisture conditions from rainfall and tides are suitable. So when conditions change, the plants respond. The re-sorting of species across tidal elevation profiles slightly modifies their distinctive zonation – a notable feature of tidal wetland areas. These zones are dynamic and dependent on longer term moisture conditions.
Indicator. Lines and linear patches of dead and stressed mangrove vegetation along upper saltmarsh transition zones within tidal wetlands (Fig. 110).
Impact. With the loss of mangrove plants, there is a loss of mangrove habitat. However, there is a direct and natural transition to an equivalent area of tidal saltmarsh and saltpan vegetation.

Figure 110. 'Ecotone shift loss' around saltpan margins is attributed to a longer-term decrease in rainfall affecting catchment areas influencing tidal wetlands. (Source: NC Duke).

Case study – ecotone shift loss
The occurrence of mangrove areas impacted by ecotone shift loss were observed commonly during aerial surveys throughout the PCPA region (Fig. 111). As noted, the indicator was fringing stands of dead mangrove areas bordering saltpan areas. Their presence was indicative of declines in regional rainfall. A useful additional observation was that such changes were incremental and progressive in the longer-term, rather than abrupt or sudden in effect.

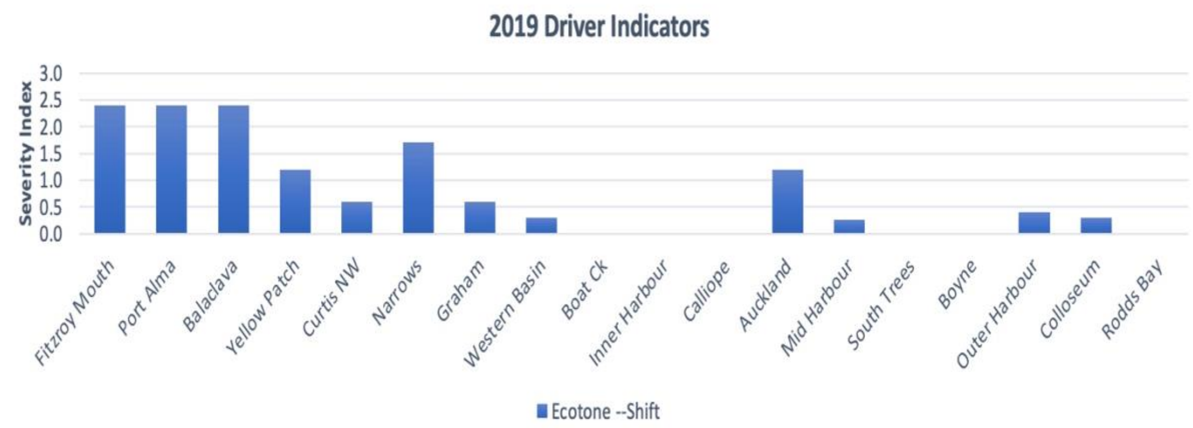


Figure 111. Indicators of 'ecotone shift loss' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

'ECOTONE SHIFT GAIN'

- **ASSOCIATED WITH INCREASING LONG-TERM RAINFALL AND RISING SEA LEVELS**

Cause. When longer term rainfall levels or rising sea levels increase in an area, there is significant pressure for mangrove encroachment along critical saltmarsh-mangrove ecotones of affected tidal wetlands. Mangrove plants grow within tidal wetlands where moisture conditions from rainfall and tides are suitable. So when conditions change, the plants respond. The re-sorting of species across tidal elevation profiles slightly modifies their distinctive zonation – a notable feature of tidal wetland areas. These zones are dynamic and dependent on longer-term moisture conditions.
Indicator. Expanded mangrove vegetation as seedlings and recruitment along upper saltmarsh transition zones within tidal wetlands (Fig. 112).
Impact. With the increase in mangrove plants, there is a gain of mangrove habitat. However, there is a direct and natural transition away from an equivalent area of tidal saltmarsh and saltpan vegetation.

Figure 112. 'Ecotone shift gain' indicated by flushing new growth of expanding mangroves across once bare saltpan. (Source: NC Duke).

Case study – 'ecotone shift gain'
Mangrove areas impacted by ecotone shift gain were common in the PCPA region. Given the trend to higher rainfall levels from Port Alma to Rodds Harbour (Fig. 113), it seems highly likely these 'ecotone shift gain' changes were driven by the alternate driver of rising sea levels. Each driver would cause a similar response with enhanced mangrove growth along the upper ecotone of the shoreline mangrove zone.

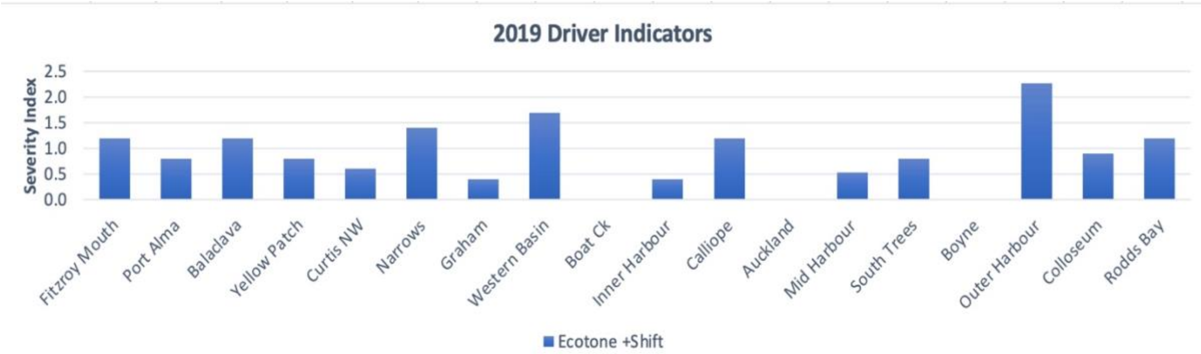


Figure 113. Indicators of 'ecotone shift gain' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

‘ROOT BURIAL’
- **ASSOCIATED WITH SHIFTING SEDIMENTS AND BURIAL BY STORMS**

Cause. When sediments are mobilised and adrift amongst mangrove vegetation, it results in the burial of their roots. As mangrove trees are sensitive to rapid changes to things that affect their breathing surfaces, an increase level of 10 cm or more with a storm event will result in the dieback and death of affected trees. This is largely the same for all mangrove species. This driver is commonly associated with Shoreline Erosion described as a separate process.
Indicator. Loss of mangrove vegetation as mostly standing dead trees with stem bases emergent from an active sandy berm (Fig. 114).
Impact. Habitat loss reduces the fitness of tidal wetlands and in consequence the ecosystem benefits are also lost, such as their value to local fisheries or their role in the protection of shorelines from erosion.

Figure 114. ‘Root burial’, linked to ‘drowning dieback’ with high sea levels, is caused by a natural shift in sand and sediments that bury exposed breathing roots and suffocate mangrove trees. This was observed at the site of severe mangrove dieback at the southern mouth of South Trees Inlet. (Source: NC Duke).

For the PCPA region, ‘root burial’ closely matched ‘depositional gain’ (page 93) regards to the trend from higher level impacts in the north, and lower values in the south (Fig. 116). However, as an indicator, ‘root burial’ involved tree death from suffocation, while depositional gain involved seedling recruitment, establishment and growth.

Case study – ‘root burial’
As noted, mangrove dieback from root burial is driven by the relocation of eroded sediments that build up around the trees, burying their exposed breathing roots. When sediments suddenly build up by around 10 cm above prior levels following storm waves and currents, the trees can be impacted and often die. This has occurred in multiple locations, but it was especially apparent in a large patch of mangroves that died along shorelines of the southern mouth of South Trees Inlet (see Fig. 114). As seen in Figure 115, the impact takes place over several years, presumably as sediment levels accumulate.

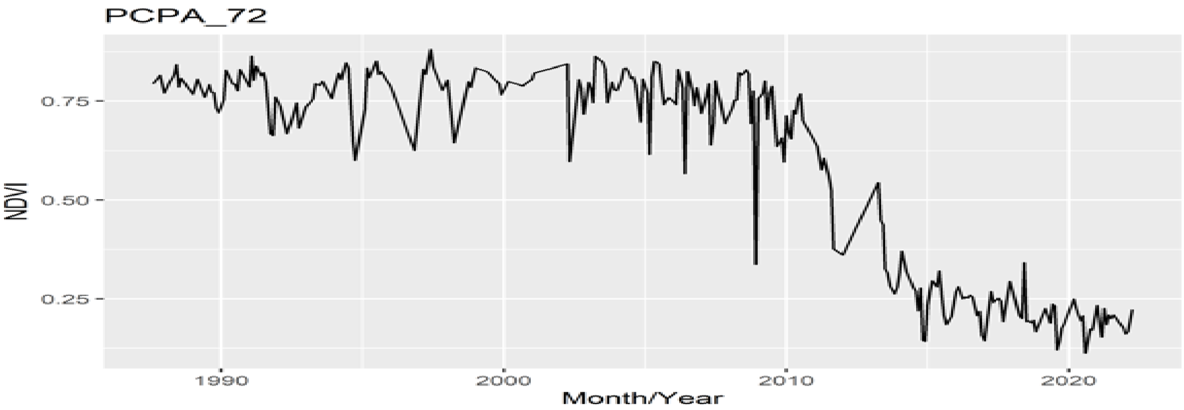


Figure 115. The timing of the mangrove response to root burial is displayed in this green fraction plot taken from a location within impacted mangroves at the site of South Trees Inlet dieback.

The relationship with levels of sediment accumulation is depicted in Figure 116, where greater depths of sediment burial have greater impacts on mangrove trees. While the particular site shown in the figure was caused by human altered hydrology, it does show a progression of impact from severe on the left nearer the newly constructed earthen bund to less severe further away.

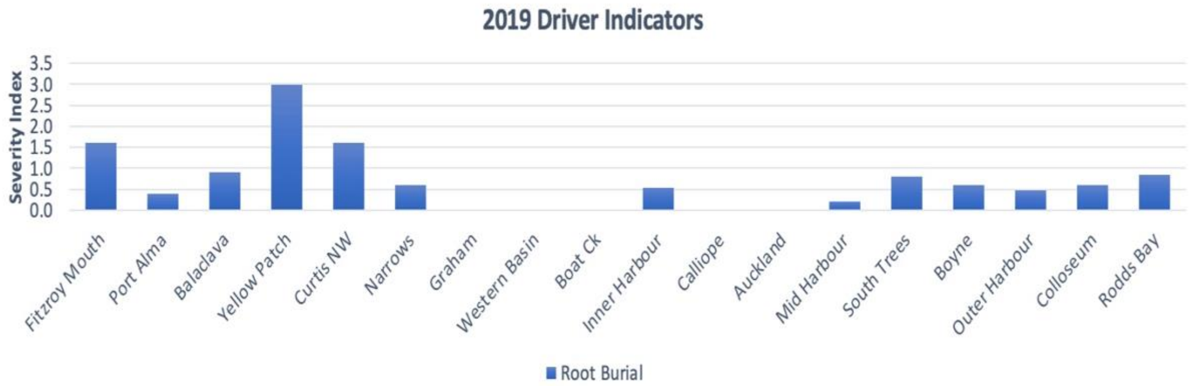


Figure 116. Indicators of 'root burial' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

'Root burial' was observed chiefly in Port Alma and Rodds Harbour subregions (Fig. 117). The occurrence of this indicator in the Port Curtis subregion, may been masked by the 'direct loss' and hardening of areas of unconsolidated sediments. As discussed with 'depositional gain', this indicator was also driven by the presence of unconsolidated sediments – as the result of shoreline and bank erosion, and the transport of sediments eroded downstream in catchment runoff.

Figure 117. Sediment accumulation causes a 'root burial' response in mangrove trees as sediments shift amongst mangrove trees. This was depicted in this site at South Trees Inlet following a period of high sea levels in the region. (Image sources: NCD). Also see the section on 'Drowning Dieback' (page 113). (Source: NC Duke).

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'DROWNING DIEBACK' OR 'FRINGE COLLAPSE'
- ASSOCIATED WITH EXTREME HIGH SEA LEVEL EVENTS

Cause. Mangroves trees die from 'drowning dieback' during periods of unusually high MSL resulting from very strong La Niña conditions (Duke et al., 2022). Trees die from excessive inundation when sea levels fail to retreat for more than 50% of the time. This kind of dieback is also probably associated with rising sea levels, especially where such impacts occur during periods of periodically high sea levels.
Indicator. Patches of dieback, dead trees, regrowth and forest gaps close to the seaward edge of mangroves of the shoreline mangrove zone (Fig. 118). This differs from 'storm damage' which tends to be associated with 'shoreline erosion' plus broken branches and uprooted trees. Trees killed by 'drowning dieback' noticeably die standing without physical damage.
Impact. Damage to the seaward edge of mangroves reduces their resilience to the pressures of rising sea levels. Such damage can often be associated with erosion of exposed trees along the seaward edge. Shorelines in such a damaged state are further vulnerable to large waves and gale-force winds from occasional severe tropical cyclones and severe flood events.

Figure 118. 'Drowning dieback', also called 'Fringe Collapse', is characterised by patches of dead trees or gaps close to and along the seaward edge of the shoreline mangrove zone (also see Fig. 104). Note, the impact zone borders the seaward ecotone (Source: NC Duke).

Case study – 'drowning dieback' (= 'fringe collapse')
During 2011, 'drowning dieback' impacted ~3.1 ha of seaward fringing mangroves at the southern mouth of South Trees Inlet (Fig. 119). Damage appears to have occurred when sea levels exceeded 150 units on the SLSI during pronounced La Niña conditions (Fig. 120). Such impacts observed elsewhere in northern Australia have been linked with occasional, prolonged high sea levels (Duke et al., 2022).

Figure 119. Sudden severe mangrove dieback near the southern mouth of South Trees Inlet (Source: NC Duke).

It would be beneficial for the full extent of damage to be determined. Such a study is needed to better answer questions about the longer-term impacts of this unusual type of event. This impact indicator, also known as 'Fringe Collapse', occurred amongst mangroves at the seaward edge, where it may also suffer from 'Root Burial'. Furthermore, this impact is associated with rising sea levels, so it may be a compounded influence. The more severe impacts occurred relatively suddenly, with the forested stands dying within a few months of the very high sea level peak (see Figs. 120-121).

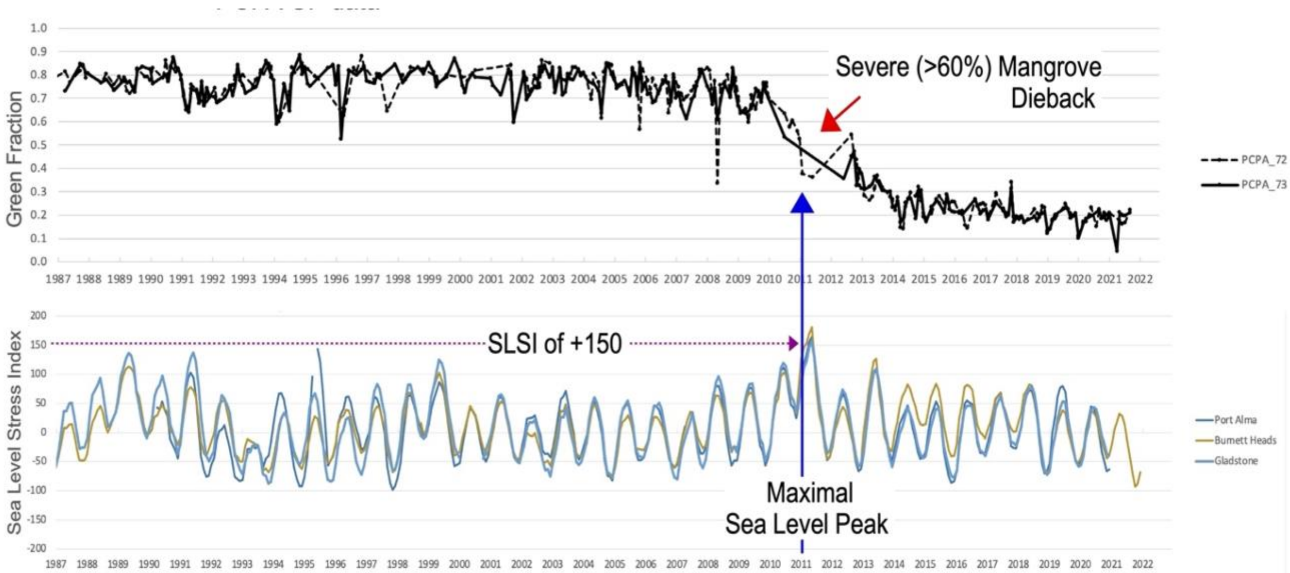

Figure 120. An instance of drowning dieback (Duke et al., 2022) in the PCPA region. Unusually high sea levels (>150 SLSI) occurred in 2011 corresponded with the extensive mangrove dieback observed at the southern mouth of South Trees Inlet (Fig. 121).

Also shown in Figure 120 was the lack of recovery over the following decade. This lack of recovery may be a distinctive feature of this kind of dieback since it is associated with rising sea levels.

Figure 121. 'Drowning dieback' observed at the southern mouth of South Trees Inlet after early 2011. (Source: modified from Google Earth).

'Drowning dieback', also known as 'fringe collapse', was observed widely throughout the PCPA region during the 2019 aerial survey (Fig. 122). Its occurrence was roughly similar in each of the subregions. Because of the relationship with high sea levels, displayed in Figure 120, a detailed assessment would be expected to confirm the more or less synchronous timing of occurrences.

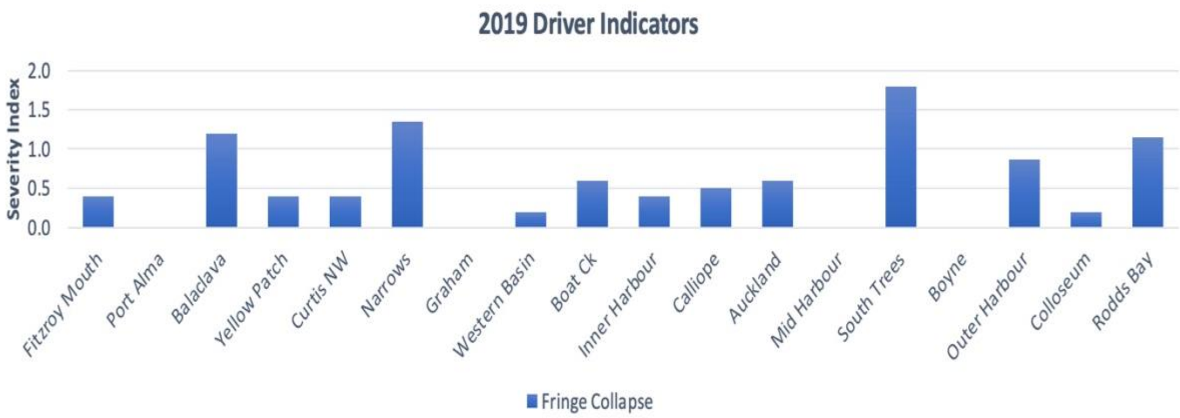

Figure 122. Indicators of 'fringe collapse' (= 'drowning dieback') of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

‘DESICCATION DIEBACK’
- ASSOCIATED WITH EXTREME LOW SEA LEVEL EVENTS (TAIMASA)

Cause. Mangroves trees die from ‘desiccation dieback’ during periods of unusually low mean sea level resulting from very strong El Niño conditions. The low sea levels responsible have been estimated to be less than -40 cm over six months during the dry season. Trees die from severe moisture deficit in the absence of seawater inundation or moisture from any other source, such as rainfall.
Indicator. Broad, abrupt and widespread dieback of mangroves at and below the upland ecotone of the shoreline mangrove zone (Fig. 123). This differs from rainfall influenced ‘ecotone shift’ which is relatively moderate and progressive in response to longer-term trends in climate (Duke et al., 2019a). Trees killed by both these kinds of dieback noticeably die standing without any physical damage.
Impact. Damage to the shoreline zone can be particularly severe where most, if not all, of the shoreline zone trees are killed. Impacted shorelines become highly vulnerable to shoreline erosion from other factors including severe cyclones and the progressive pressure of rising sea levels. Where more than 20% of the shoreline zone mangroves remain, the longer-term impacts are significantly reduced with recovery notably more likely.

Figure 123. ‘Desiccation dieback’, similar to ‘ecotone shift negative’ (Duke et al., 2019a) in Australia’s Gulf of Carpentaria, varied in severity from extreme (A), to moderate (B), to minor (C). This was quantified, as indicated, by the proportional loss of the shoreline mangrove zone down from the upper ecotone edge (see Duke et al., 2022).

Case study – ‘desiccation dieback’
There were no instances of ‘desiccation dieback’ observed in the PCPA region. This contrasts with the catastrophic instances recorded in northern tropical Australia (Duke et al., 2022). As noted, this type of dieback, also known as Taimasa, was associated with extreme low sea levels impacting mangroves at the upper ecotone of the shoreline mangrove zone. Damage in the PCPA region would only have been expected to occur if the SLSI was less than -300, usually during severe El Niño conditions. As noted in Figure 120, the SLSI never dropped below -100 between 1987 and 2022.

'BAT DAMAGE'
- **ASSOCIATED WITH ROOSTING FRUIT BAT COLONIES**

Cause. When fruit bats are 'moved on' from their preferred coastal forest roost sites, they occasionally end up in mangrove forests. It seems that mangrove trees are not the first choice of roost site for any of the various species. The mangrove sites do however offer respite to these significant and highly beneficial wildlife.
Indicator. The presence of a colony of fruit bats is recognised both visually and by their distinctive smell and noise. Bats roost in upper canopy branches during the day, and by night they venture far afield to feed (Fig. 124). The size of bat colonies varies but often cover up to around one hectare of forest canopy.
Impact. The damage to mangrove forest canopies caused by fruit bats is notable, but it predominantly causes defoliation. Recovery of damaged canopies is rapid once the fruit bats have decamped the site.

Figure 124. Fruit bats, or flying foxes, roosting in mangrove trees along Auckland Creek. (Source: NC Duke).

Case study – 'bat damage'
Roosting flying foxes cause relatively minor damage to mangrove stands in the PCPA region. Colonies have been observed during this study in mangroves along Auckland Creek and on a mangrove 'island' near the mouth of the Calliope River. Damage appears relatively minimal (no more than 20% canopy loss) with rapid recovery (around 5-10 years) after the colony had relocated (see Fig. 125). Note that the distinctive impacts were not abrupt, as with 'light gaps' or 'root burial' (Fig. 117). As flying foxes relocated before damage to mangroves became greater, it seems likely that mangroves would gain the benefit of extra nutrients from bat droppings. A detailed investigation would be useful and informative to fully evaluate such longer-term relationships and the likely mutual benefits.

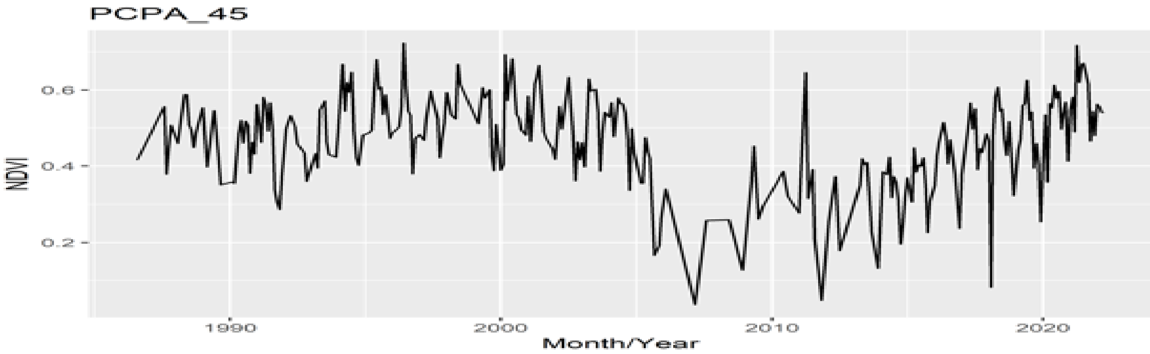

Figure 125. As shown in this Auckland Creek site, mangroves impacted by flying foxes show relatively moderate damage with rapid recovery.

'Bat damage' was observed in three discrete areas in 2019, including Auckland Creek, Calliope River and Inner Harbour zones (Fig. 126). However, the fruit bats had abandoned the Auckland Creek site, and it had been left to recover.

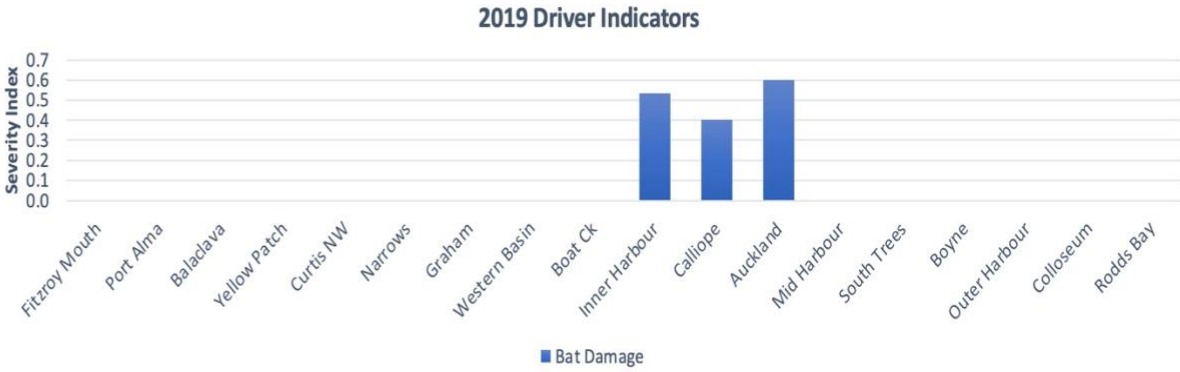

Figure 126. Indicators of 'bat damage' of tidal wetlands in the 18 PCPA zones observed during the 2019 aerial survey.

'INSECT DAMAGE'

- **ASSOCIATED WITH HERBIVORY BY INSECTS**

Cause. Herbivorous insect larvae (caterpillars) occasionally eat excessive amounts of mangrove leaves.
Indicator. Multiple indicators include: partially eaten leaves with distinctive remnants, like midvein to petiole leaf portions (Fig. 127); a dust of insect frass scattered across the mangrove forest floor sediments; small egg-like cocoons attached under leaves; and caterpillars on leaves eating or moving about.
Impact. The damage caused is likely to be substantial in depleting forest productivity, depending on the severity and extent of infestation. In a case in Port Curtis mangroves, one type of caterpillar was observed moving in long conga lines from one tree to another, and thus minimising their impact on any individual tree (Duke 2002).

Figure 127. Insects have caused severe loss of mangrove canopy leaves of *Rhizophora* forests in the Port Curtis region (Duke 2002). (Source: NC Duke).

Case study – insect damage

Severe loss of mangrove leaves was observed in the area around Fishermans Landing of Port Curtis in 1996-1998 (Duke 2002). The moth larva, *Doratifera stenosa* (Lepidoptera: Limacodidae), was observed feeding voraciously in great numbers on leaves of *Rhizophora stylosa* in mature mangroves. During a two-year study (1996-1998), larvae consumed around 30-40% of canopy leaves each year, and it was of interest that affected mangroves appeared able to sustain this high level of herbivory. No tree deaths or dieback were observed. Sustained survival was likely because after the gregarious larvae had moulted they immediately formed single-file processions along branches and down stems to neighbouring unaffected trees. This action is probbably responsible for saving host trees while the herbivore continued to heavily crop these mangrove forests. Further studies are needed to better demonstrate the role and importance of foliar herbivory to forest productivity and forest turnover in mangrove ecosystems.

'DECIDUOUS MANGROVE'
- **ASSOCIATED WITH NORMAL SEASONALLY LOW SEA LEVELS**

Cause. Seasonal influences drive the phenology of mangrove plants. Recent evidence now suggests that a key factor driving seasonal changes is the annual oscillation in mean sea level coupled with climatic variables (Duke et al., 2022). One mangrove species, the Cedar Cannonball Mangrove *Xylocarpus moluccensis*, is uniquely deciduous. It loses its leaves naturally each year around July and August.
Indicator. Leaves that are mostly green throughout the year (Fig. 128), around July-August become orange and red (Figs. 129 & 130) before being dropped entirely shortly afterwards. The limbs remain bare for a week or so before bright green new leaves appear and refresh the mangrove canopy.
Impact. This is a natural and normal transition. This indicator of change shows that all is well with these mangroves.

Figure 128. Deciduous trees of Cedar Mangrove displaying orange-coloured canopies amongst neighbouring evergreen mangrove species. (Source: NC Duke).

Case study – 'deciduous mangrove'
A significant and attractive feature of mangroves in the Port Curtis region is the annual flush of orange-red colouration of falling leaves (Fig. 128) by the uniquely deciduous mangrove, *Xylocarpus moluccensis* (Duke 2006). For a short time after the leaves fall, the branches remain stark and completely bare, before they flush with new growth in the months afterwards. This is a completely natural event, but curious observers have mistakenly raised concerns about likely dieback and damage.

Our observations of the 'red leaf' deciduous condition made from NearMap imagery between July 2011 and May 2019 (Table 13) identify the timing as an annual event in August. Note that in every August image available, the foliage was red in all 4 sites. Further, from late May to July, the scores were mixed. October, November, December, April and early May all had no red deciduous foliage.

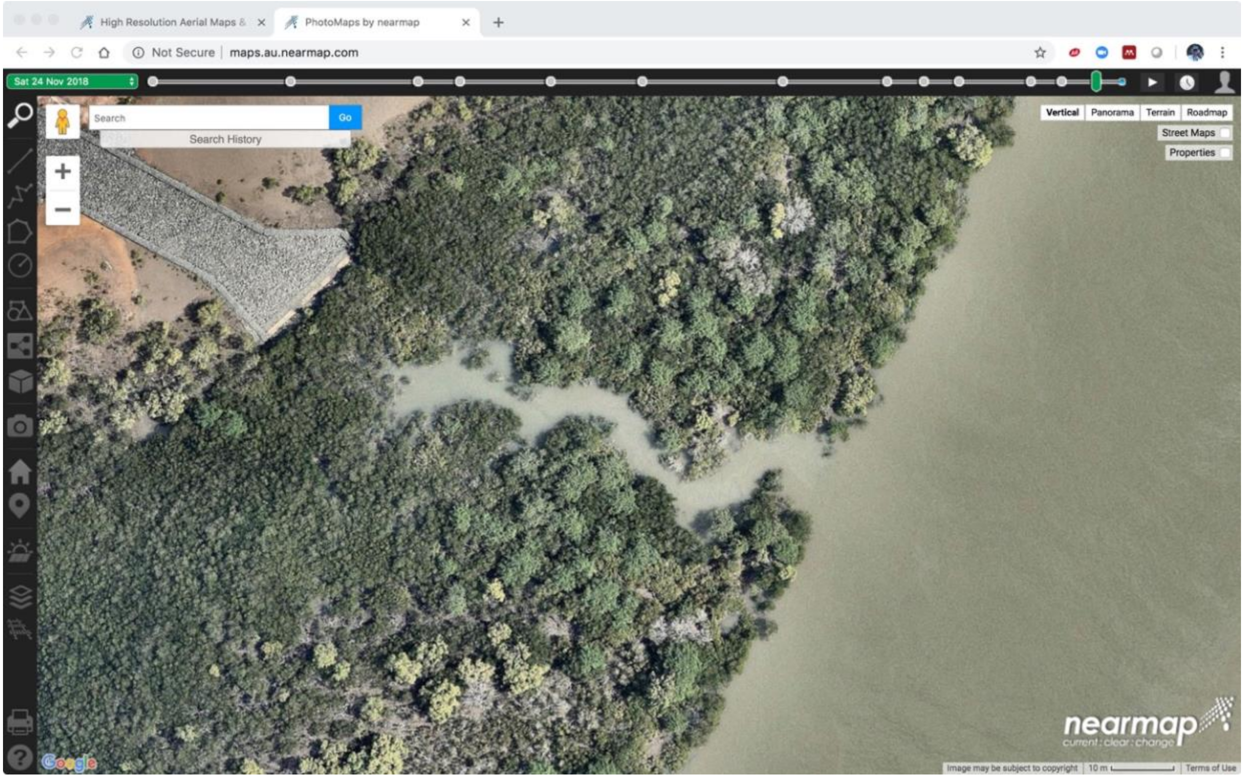

Figure 129. 'Fresh Green' phenological stage of *Xylocarpus moluccensis* with refreshed green canopies around November each year. Image location and date: Anabranch bridge site, 24 November 2018. (Source: NearMap).

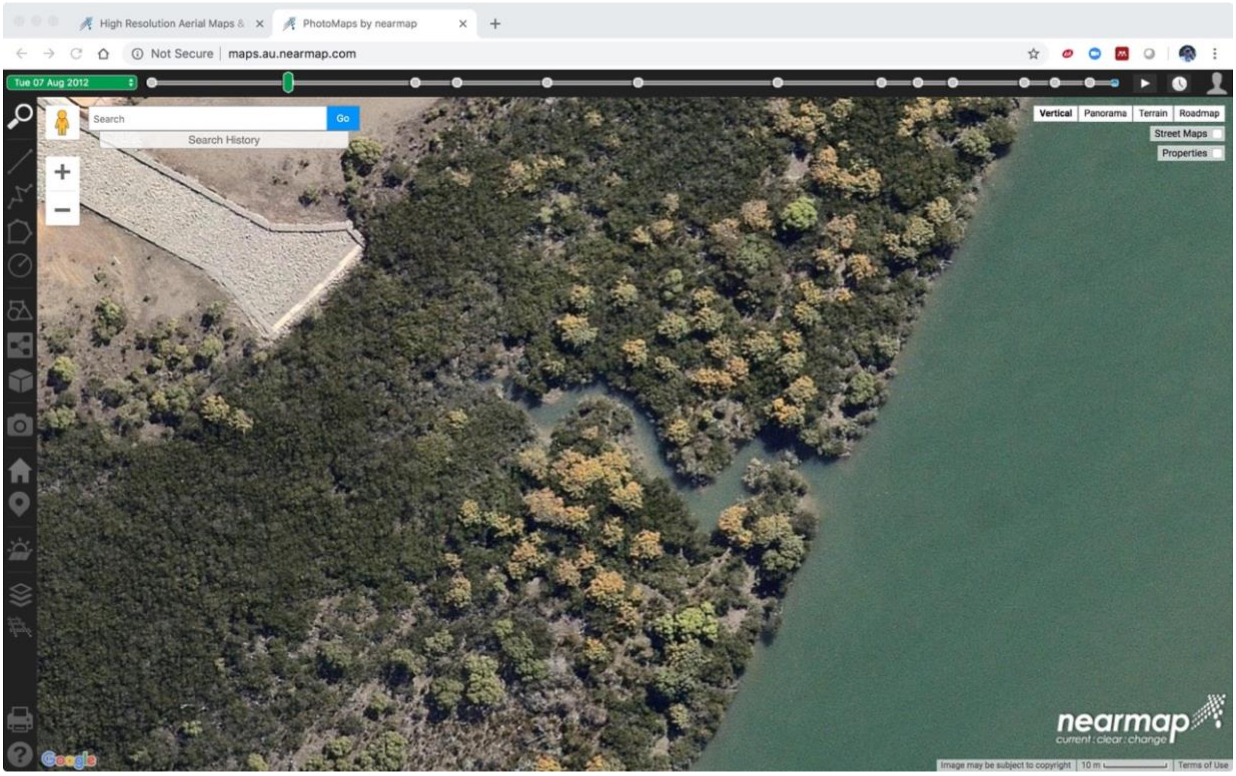

Figure 130. 'Red' phenological stage of *Xylocarpus moluccensis* with red-yellow canopies and dropping leaves, around early August each year. Image location and date: Anabranch bridge site, 7 August 2012. (Source: NearMap).

Table 13. Status of *Xylocarpus moluccensis* deciduous condition seen in various NearMap satellite image dates of 4 sites in the PCPA region, including Calliope Anabranch, Calliope River bridge, The Narrows and South Trees Inlet. Note canopy foliage deciduous condition: ‘>’ = yellow-orange-reddish leaves; and ‘X’ = bright red leaves.

#	Date	Calliope Anabranch	Calliope Bridge	The Narrows	South Trees	FREQ. SCORES %
1	5 May 2019			No data		0
2	24 Nov 2018			No data		0
3	16 Aug 2018	>	>	No data	>	100
4	20 May 2018	>	>	No data		67
5	26 Oct 2017			No data		0
6	20 July 2017	>		No data	>	67
7	4 April 2017			No data		0
8	10 Jun 2016	>	>	No data		67
9	7 May 2015			No data		0
10	20 Aug 2014	>	>	No data	>	100
11	3 Dec 2013			No data		0
12	7 Aug 2013	>	>	No data	>	100
13	7 Aug 2012	X	X	X	X	100
14	11 July 2011	>	>	>	No data	100

The cedar mangrove species is unlike all other mangroves in the region. The others are mostly evergreen with leaf loss and replacement occurring progressively over 6-18 months in most cases. There is also a seasonal rhythm amongst evergreen mangroves, as shown in the annual oscillations in green fraction plots (Fig. 100) where the annual highs and lows in canopy density match the highs and lows in mean sea level depicted in the SLSI (Fig. 22; Duke et al., 2022). While these recent discoveries provide a tangible link with the responsible environmental driver, further studies are required to fully confirm sea level influences on the seasonal phenology of *Xylocarpus moluccensis* trees.

CHAPTER 7

A STRATEGY FOR FUTURE MONITORING OF TIDAL WETLANDS

Our assessment of the key drivers of change, documented in Chapters 4-7, offer valuable insights and a practical method for both understanding and managing the environmental changes observed in tidal wetlands. What is apparent, is that there have been many instances of change having taken place in the PCPA region, especially seen in mangrove ecosystem as they respond to pressures from human development, climate change, and changes in sea level. Our findings demonstrate how each type of change can, and must be identified, explained and quantified. And, where environmental managers are so informed by these changes, they will be in a better position to respond and mitigate effectively. By knowing the extent of each type of impact, the responsible driver, and how remedial intervention is best delivered is considered the optimal way to deliver effective and sustained outcomes at local and regional scales.

In this way, our findings about specific drivers of change, provide a basis and a baseline for the development of a strategy for on-going evaluation and monitoring of mangrove habitat condition. Furthermore, the monitoring method most needed to achieve the level of assessment required, was that derived from satellite imagery as the long-term timeseries plots of NDVI values of canopy reflectance (a measure of canopy condition) for specific coordinate locations. The key tool behind this methodology is referred to as 'green fraction' plots of monthly measures of canopy condition from 1987 onwards (see Appendix 9).

The method has been particularly useful for this assessment because of the typically closed-canopy of mangrove forests. Accordingly, we have been able to make notable and crucial observations of otherwise unexplained changes having impacted mangrove ecosystems in the PCPA region. Specific instances include: 1) the mysterious dieback of several hectares of mangroves at the mouth of South Trees Inlet (see page 112); and 2) the severe flood damage and loss of mangroves along estuarine water courses of rivers such as the Boyne River (see page 99). While these events were grouped under the climate-natural drivers of change, this remote sensing tool also enabled the tracking of direct human-related changes. The types of changes in each case further included quantification of both the impact and its recovery. In Figure 47, historical maps show the massive loss of mangrove areas to reclamation. As noted, the green fraction plots further enabled the evaluation and monitoring of sublethal damage on nearby protected mangrove areas. We presented a pragmatic and cogent example by providing our overall assessment of reclamation works associated with the Western Basin Reclamation Area between 1996 and 2022 (see Chapter 6, page 76). We propose that the methodology applied in this assessment offers an effective methodology and basis for future monitoring of threatened mangrove tidal wetland areas.

A proposal for future monitoring with an Alert to Action program

A key message from our findings concerns the choice of methodology used in ongoing monitoring projects. Our results highlight the great interpretative and reporting benefits gained from green fraction timeseries plots. The method offers several unique advantages over prior assessment methods, especially compared to field studies alone. The green fraction method has the following benefits:

1. ***Cost effective & greater ease of access.*** While requiring field validation, the full selection of treatment sites do not rely solely on field sampling costs and logistics;
2. ***Long-term view & monthly sampling.*** Monitoring linked to remote sensing sites will have a longer-term perspective (1987 onwards) with at least monthly records, allowing for past and current condition comparisons;
3. ***Broader distribution of treatment site locations.*** With remote sensing, the full selection of monitoring treatment sites is far less limited; and
4. ***A more responsive & amenable methodology for an effective 'Alert to Action' monitoring program.*** Using readily available satellite information, treatment sites can be constantly monitored, and provide more rapid early warning of changes taking place and their severity.

Overall, the severity and extent of any changes taking place can readily inform managers using a specific decision tool by which managers can rapidly determine the level and type of mitigation response required for any particular environmental changes taking place. The basis for the decision tool would be a carefully considered risk response matrix, linking observed environmental changes with appropriate management responses. The aim being, if at all possible, to minimise any preventable damaging activity. Our plan for a proposed 'Alert to Action' monitoring project is detailed further in Appendix 9. The program consists of a field assessment component that principally provides effective monthly validation with concurrent field monitoring.

Such an 'Alert to Action' monitoring strategy for future mangrove monitoring programs can be readily adapted to comply with relevant project scopes of work, along with clear outcomes including: a well-considered monitoring program of 10 or more years to ensure there are no direct impacts affecting marine plants adjacent to a development area; and an 'Alert to Action' capability designed to meet and exceed the requirements of the local environmental regulator such as the Queensland Department of Agriculture and Fisheries. In this way, the effective outcomes maybe expanded upon to form a monitoring program with monthly updates on the condition and health of mangrove and saltmarsh habitat in the vicinity of any construction or shoreline modification works.

COLLABORATION AND PARTNERSHIP WITH GIDARJIL RANGERS

An outstanding and significant outcome from this ERMP project has been our partnership with the indigenous land and sea rangers of the Gidarjil Development Corporation. Being based in this region, the rangers have demonstrated overwhelming dedication to tidal wetland country, in assisting with our surveys, and being always observant and interested in the monitoring and survey works being undertaken.

A particular milestone of some note, had been the ability of the rangers to conduct independent monitoring works after embracing the training and perfecting the use of appropriate survey equipment. We believe the proven expert capability of the Gidarjil rangers (Figs. 131-134) demonstrates their readiness to:
a) assist in well-considered responses to future unexpected events and accidents that impact upon local tidal wetlands;
b) assist in investigations of past events and matters like a proposed survey of albino propagules and their association with petroleum hydrocarbons; and
c) assist in an 'Alert-to Action' monitoring with on-going development works (see Appendix 9).

Figure 131. Gidarjil rangers conducting S-VAM surveying of flood damage in the Burnett River estuary, also part of the local TUMRA (Duke et al, 2019b). (Source: NC Duke).

Figure 132. Gidarjil rangers assisted with the aerial surveys of the PCPA region. (Source: NC Duke).

Figure 133. Gidarjil rangers conducting field surveys of mangrove areas. (Source: NC Duke).

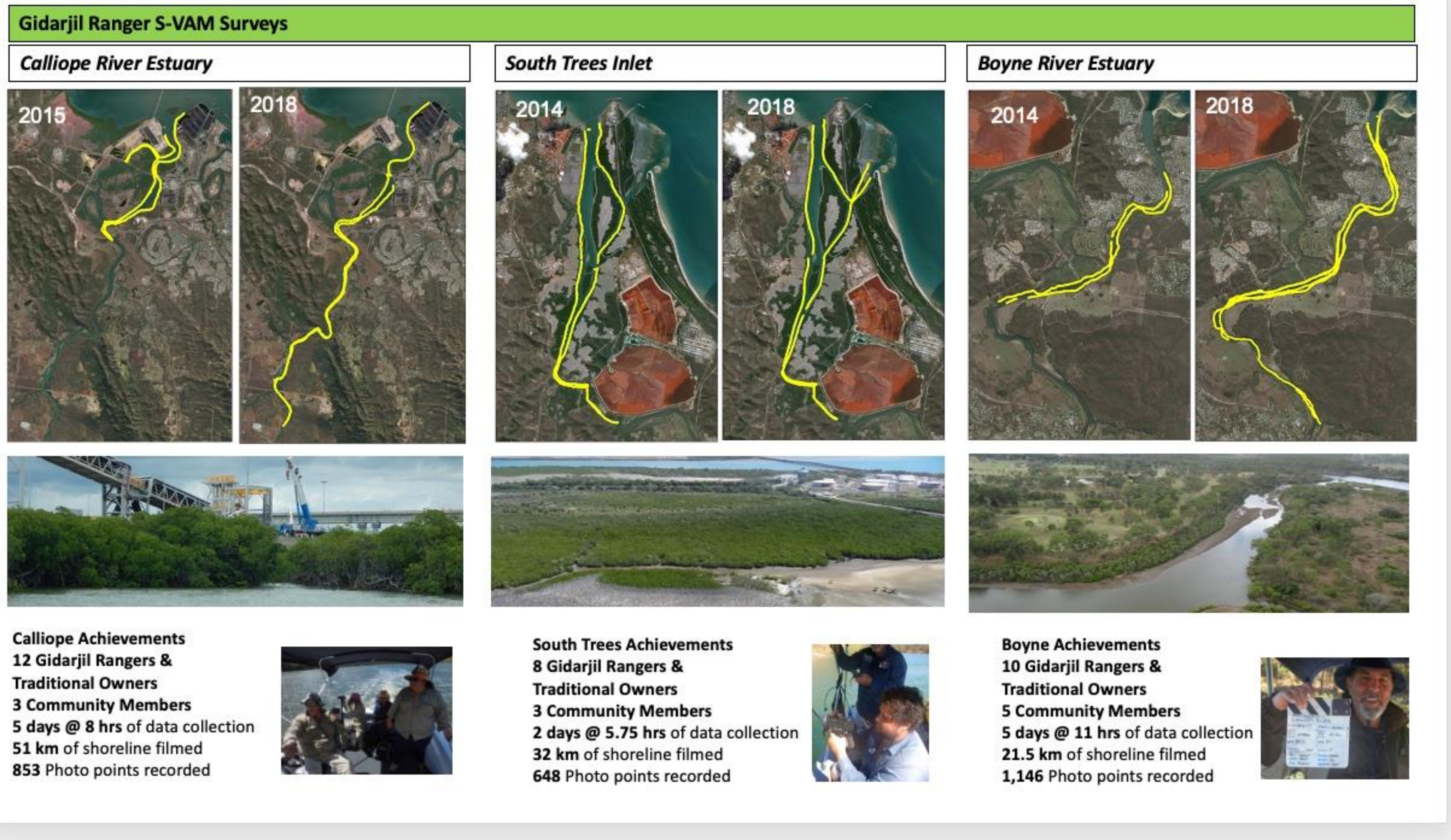

Figure 134. Three examples of S-VAM surveys undertaken by the Gidarjil rangers. In all, 36 S-VAM surveys were undertaken during 2014 to 2021 as listed in Appendix Table 10. (Source: NC Duke & J. Mackenzie).

OVERALL SYNTHESIS

The importance of the studies reported here is shown, in part, by the number of primary research publications that accompany this and the 6 prior reports. The project team have taken full advantage of the rare opportunity provided by this program to both develop and enhance the available knowledge base of mangrove ecosystems of the PCPA region, including their functioning, and in the development of better methods for assessment and monitoring of tidal wetlands at landscape scales.

An example is the newly-developed method of ‘green fraction’ timeseries plots that usefully quantify the monthly condition of mangrove canopies from 1987 to the present day (Appendix 8). This method has been used throughout this report – uniquely addressing key matters of interest that would otherwise have remained unexplained. For instance, this methodology enabled the profound identification of a previously unrecognised threat to mangroves in the PCPA region known as ‘fringe collapse’. From concurrent studies in the Gulf of Carpentaria (Duke et al., 2022), we learnt that this type of mangrove dieback in the PCPA region was the dramatic consequence of unusually extreme high oscillations in mean sea level in 2011 (Chapter 7, page 112). Accordingly, we were able to explain the mysterious mangrove dieback of 3 ha of mangroves at the southern mouth of South Trees Inlet.

There are three critical components of the newly-developed assessment methodology for tidal wetlands of the PCPA region:
1) ***Identification of change indicators***. The overall assessment of tidal wetland condition was based on 28 or more indicators of both human-related, and climate-natural drivers of change;
2) ***Shoreline survey image archive***. Baseline ground truth with a database of observations and imagery including: geo-referenced, high-resolution images covering every metre of shoreline surveyed – for example taking 3-4 days using a small helicopter to fly all the major shorelines of the region; and
3) ***Methodology for scoring habitat condition***. Condition scores determined for each indicator observed during the shoreline surveys define the extent and severity of each, allowing the ranking of their respective influences and impacts.

Such an assessment and monitoring program might usefully be repeated every 2-3 years at relatively minimal cost. The great benefit would be the on-going evaluation of mangrove and saltmarsh condition across the PCPA region, updates on the changes taking place (getting worse or better), and the location of these changes. The program has embedded flexibility where it allows for new issues, as may occur on occasion. For instance, since there is now an established baseline from our current assessment, it would be useful also to monitor soon after any future development works, or following an unexpected impacting event such as a severe tropical cyclone, extreme flooding, or a large oil spill.

In all cases, this assessment provides a broad and encompassing baseline evaluation of tidal wetlands throughout the PCPA region. The report not only lists immediate, direct and indirect impacts of human development, but it also includes the various climate and sea level influences impacting tidal wetlands. In fact, as observed, the ‘climate-natural’ influences have greater diversity and extent than the more localised direct human impacts. Although the former had on occasion been outweighed by earlier catastrophic losses in some reclaimed areas.

In general now, however, knowledge of each responsible driver and their resulting influences are considered fundamental to determining the most effective direction and implementation of a responsible and sustainable environmental management strategy. For instance, the impacts of changing climate associated with rising temperatures, rising sea levels, and the wider oscillations in mean sea level all rely on national efforts towards the mitigation of global climate change. Therefore, the role of local environmental managers is firstly to discriminate between respective changes and their drivers, before disseminating the information.

Meanwhile local management efforts might be beneficially directed towards increasing and maintaining the resilience of locally threatened tidal wetland areas. Such measures might include fencing to reduce vehicle access and grazing livestock, or applying procedures to reduce pollution. In all cases, there are benefits from better targeted mitigation works in combination with a concurrent and frequent 'Alert-to-Action' monitoring program. Such well-considered management actions are considered essential to the longer-term sustainability of mangrove and tidal wetland ecosystems of the PCPA region.

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Duke, N.C., J.M. Kovacs, A.D. Griffiths, L. Preece, D.J.E. Hill, P.v. Oosterzee, J. Mackenzie, H. S. Morning and D. Burrows. **2017a**. Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event. **Marine and Freshwater Research** 68(10): 1816-1829. http://dx.doi.org/10.1071/MF16322

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Duke N.C., J. Mackenzie, J. Kovacs, R. Cormier, F. Eilert, I. Atkinson and S. van der Valk. **2018.** '2017-2018 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 18/52, James Cook University, Townsville, 34 pp.

Duke, N.C., C. Field, J.R. Mackenzie, J.-O. Meynecke and A.L. Wood. **2019a**. Rainfall and its possible hysteresis effect on the proportional cover of tropical tidal wetland mangroves and saltmarsh-saltpans. **Marine and Freshwater Research** 70(8): 1047-1055. DOI: 10.1071/MF18321.

Duke, N.C., J. Mackenzie, R. Fennessy, R. Cormier and J. Kovacs. **2019b**. 'Final Report: Southern GBR Coastal Habitat Archive and Monitoring Program (S-GBR CHAMP)'. Final Report for the National Science Environmental Programme Tropical Water Quality Hub. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER). Two Volumes: Report #19/11. James Cook University, Townsville, 74 & 162pp.

Duke N.C., J. Mackenzie, J. Kovacs, R. Cormier, F. Eilert, I. Atkinson and S. van der Valk. **2019c**. '2018-2019 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Report 19/28, James Cook University, Townsville, 66 pp.

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Duke, N.C., J.R. Mackenzie, A. Canning, L. Hutley, A. Bourke, J. Kovacs, R. Cormier, G. Staben, L. Lymburner and E. Ai. **2022**. ENSO-driven extreme oscillations in mean sea level destabilise critical shoreline mangroves – an emerging threat with greenhouse warming. **PLOS Climate** 1(8), 23pp. https://doi.org/10.1371/journal.pclm.0000037

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Mackenzie, J.R., N.C. Duke and A.L. Wood. **2016**. The Shoreline Video Assessment Method (S-VAM): using dynamic hyperlapse image acquisition to evaluate shoreline mangrove forest structure, values, degradation and threats. **Marine Pollution Bulletin** 109(2): 751-763. DOI: 10.1016/j.marpolbul.2016.05.069

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APPENDICES

APPENDIX 1

PUBLICATIONS RELATED TO THE PCPA CHAMP PROJECT WITH NOTES

Abhik, S., P. Hope, H.H. Hendon, L.B. Hutley, S. Johnson, W. Drosdowsky, J.R. Brown and N.C. Duke. ***2021****. Influence of the 2015-16 El Niño on the record-breaking mangrove dieback along northern Australia coast.* ***Scientific Reports*** *11(20411): 12 pp. https://doi.org/10.1038/s41598-021-99313-w*

NOTE: Publication reporting on the relationship between ENSO atmospheric fluctuations and mangrove dieback, a feature of close relevance to the Port Curtis Port Alma region..

Amir, A. A., and N. C. Duke ***2019****. Distinct characteristics of canopy gaps in the subtropical mangroves of Moreton Bay, Australia.* ***Estuarine Coast Shelf Science*** *222: 66-80. DOI: 10.1016/j.ecss.2019.04.007.*

NOTE: Publication reporting on the role and functioning of forest light gaps in mangrove forests, a feature in common with mangroves in the Port Curtis Port Alma region.

Bergstrom, D.M., B.C. Wienecke, J. van der Hoff, L. Hughes, D.L. Lindemayer, T.D. Ainsworth, C.M. Baker, L. Bland, D.M. J. S. Bowman, S.T. Brooks, J.G. Canadell, A. Constable, K.A. Dafforn, M.H. Depledge, C.R. Dickson, N.C. Duke, K.J. Helmstedt, C.R. Johnson, M.A. McGeoch, J. Melbourne-Thomas, R. Morgain, E.N. Nicholson, S.M. Prober, B. Raymond, E.G. Ritchie, S.A. Robinson, K.X. Ruthrof, S.A. Setterfield, C.M. Sgro, J.S. Stark, T. Travers, R. Trebilco, D.F.L. Ward, G.M. Wardle, K.J. Williams, P.J. Zylstra and J.D. Shaw. ***2021****. Ecosystem collapse from the tropics to the Antarctic: an assessment and response framework.* ***Global Change Biology*** *27: 1692-1703. https://doi.org/10.1111/gcb.15539*

NOTE: Publication recognising the recent common occurrences of catastrophic impacts on terrestrial and coastal marine ecosystems.

Duke, N.C. ***2020****. Mangrove harbingers of coastal degradation seen in their responses to global climate change coupled with ever-increasing human pressures.* ***Human Ecology Journal of the Commonwealth Human Ecology Council*** *– Mangrove Special Issue 30: 19-23.*

NOTE: Publication acknowledging the importance of mangrove ecosystems as powerful indicators of environmental change - an essential feature of the proposed plan for the future monitoring of mangrove ecosystems in the Port Curtis Port Alma region.

Duke, N.C., and A.W.D. Larkum ***2019****. Mangroves and seagrasses. Chapter 18 in 'The Great Barrier Reef: Biology, Environment and Management.' 2nd Edition. P.A. Hutchings, M.J. Kingsford and O. Hoegh-Guldberg. Collingwood, VIC, CSIRO Publishing: 219-228. ISBN: 9781486308194*

NOTE: Publication recognising the importance of mangrove ecosystem services to the Great Barrier Reef biome.

*Duke, N.C., and J. Mackenzie. **2015**. 2015 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP). Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication. Townsville, Queensland, TropWATER Centre, James Cook University**:** 50 pages.*

NOTE: the 2015 technical report documenting progress with the PCPA CHAMP projects – and recognising the dedicated monitoring activities of Gidarjil Traditional Owner Rangers in the Port Curtis Port Alma region.

*Duke N.C., and J. Mackenzie. **2020**. '2019-2020 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Report 20/29, James Cook University, Townsville, 7 pp.*

NOTE: the 2019-2020 technical report documenting progress with the PCPA CHAMP projects – and recognising the dedicated monitoring activities of Gidarjil Traditional Owner Rangers in the Port Curtis Port Alma region.

*Duke, N.C., and J.R. Mackenzie. **2020**. Indigenous Ranger field guide to the Shoreline Video Assessment Method. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER publication #20/26), James Cook University, Townsville. 37 pp.*

NOTE: The instruction manual for the Shoreline Video Assessment Method used in the training of Traditional Owner rangers for their monitoring of coastal shorelines.

*Duke N.C., J. Mackenzie, J. Kovacs, D. Hill, F. Eilert, I. Atkinson and S. van der Valk. **2016**. '2015---2016 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 16/52, James Cook University, Townsville, 59 pp.*

NOTE: the 2015-2016 technical report documenting progress with the PCPA CHAMP projects – and recognising the dedicated monitoring activities of Gidarjil Traditional Owner Rangers in the Port Curtis Port Alma region.

*Duke, N.C., J. Mackenzie, J. Kovacs, D. Hill, D. Carder, F. Eilert, I. Atkinson, M. Wyatt and S. van der Valk. **2017**. 2016-2017 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP). Townsville, James Cook University TropWATER Centre**:** 43 pages. TropWATER Report# 17/56.*

NOTE: the 2016-2017 technical report documenting progress with the PCPA CHAMP projects – and recognising the dedicated monitoring activities of Gidarjil Traditional Owner Rangers in the Port Curtis Port Alma region.

*Duke N.C., J. Mackenzie, J. Kovacs, R. Cormier, F. Eilert, I. Atkinson and S. van der Valk. **2018.** '2017-2018 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and*

Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 18/52, James Cook University, Townsville, 34 pp.

NOTE: the 2017-2018 technical report documenting progress with the PCPA CHAMP projects – and recognising the dedicated monitoring activities of Gidarjil Traditional Owner Rangers in the Port Curtis Port Alma region.

*Duke N.C., J. Mackenzie, J. Kovacs, R. Cormier, F. Eilert, I. Atkinson and S. van der Valk. **2019a**. '2018-2019 Annual Report: Port Curtis and Port Alma Coastal Habitat Archive and Monitoring Program (PCPA CHAMP)'. Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Report 19/28, James Cook University, Townsville, 66 pp.*

NOTE: the 2018-2019 technical report documenting progress with the PCPA CHAMP projects – and recognising the dedicated monitoring activities of Gidarjil Traditional Owner Rangers in the Port Curtis Port Alma region.

*Duke, N.C., J. Mackenzie, R. Fennessy, R. Cormier and J. Kovacs. **2019b**. 'Final Report: Southern GBR Coastal Habitat Archive and Monitoring Program (S-GBR CHAMP)'. Final Report for the National Science Environmental Programme Tropical Water Quality Hub. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER). Two Volumes: Report #19/11. James Cook University, Townsville, 74 & 162pp.*

NOTE: Final report acknowledging the dedicated monitoring activities of Gidarjil Traditional Owner Rangers in the southern GBR region, including the Port Curtis Port Alma region.

*Duke N.C., J. Mackenzie, J. Kovacs, G. Staben, R. Coles, A. Wood and Y. Castle. **2020**. 'NESP Report 2020' Final Report: Assessing the Gulf of Carpentaria mangrove dieback 2017-2019. Volume 1: Aerial Surveys. Report to the NESP, Commonwealth of Australia. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 20/20, James Cook University, Townsville, 181 pp.*

NOTE: Final report acknowledging the dedicated monitoring activities of Carpentaria Land Council Aboriginal Corporation Traditional Owner Rangers in the southern Gulf of Carpentaria region, using survey methods developed in the Port Curtis Port Alma region.

*Duke N.C., J. Mackenzie, L. Hutley, G. Staben and A. Bourke. **2020**. 'NESP Report 2020' Final Report: Assessing the Gulf of Carpentaria mangrove dieback 2017-2019. Volume 2: Field Studies. Report to the NESP, Commonwealth of Australia. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication 20/21, James Cook University, Townsville, 133 pp.*

NOTE: Final report acknowledging the dedicated monitoring activities of Carpentaria Land Council Aboriginal Corporation Traditional Owner Rangers in the southern Gulf of Carpentaria region, using survey methods developed in the Port Curtis Port Alma region.

*Duke, N.C., L.B. Hutley, J.R. Mackenzie and D. Burrows. **2021**. Processes and factors driving change in mangrove forests – an evaluation based on the mass dieback event in Australia's*

Gulf of Carpentaria. In: 'Ecosystem Collapse - and Climate Change', editors: Josep G. Canadell and Robert B. Jackson, Springer, Ecol. Studies 241: 221-264. *https://link.springer.com/chapter/10.1007/978-3-030-71330-0_9*

NOTE: Publication documenting further use of the survey methodologies developed and used in the Port Curtis Port Alma region.

Duke, N.C., J.R. Mackenzie, A. Canning, L. Hutley, A. Bourke, J. Kovacs, R. Cormier, G. Staben, L. Lymburner and E. Ai. ***2022****. ENSO-driven extreme oscillations in mean sea level destabilise critical shoreline mangroves – an emerging threat with greenhouse warming.* ***PLOS Climate*** *1(8), 23pp. https://doi.org/10.1371/journal.pclm.0000037*

NOTE: Publication reporting on the discovery of the ENSO-driven influences on the oscillations in sea level and their occasional impacts on mangroves in the Port Curtis Port Alma region.

Gauthey, A., D. Backes, J. Balland, I. Alam, D.T. Maher, L.A. Cernusak, N.C. Duke, B.E. Medlyn, D. T. Tissue and B. Choat. ***2022****. Natural water-availability gradient accentuates the risk of hydraulic failure in Avicennia marina during physiological drought.* ***Frontiers Plant Science*** *13: 822136. https://doi.org/10.3389/fpls.2022.822136*

NOTE: Publication reporting on the influences of moisture deficits on mangrove ecosystems, including those brought on by extreme low oscillations in sea level.

Hardesty, B.D., L. Roman, N.C. Duke, J.R. Mackenzie and C. Wilcox. ***2021****. Abandoned, lost and derelict fishing gear 'ghost nets' are increasing through time.* ***Marine Pollution Bulletin*** *173 (112959): 10pp. https://doi.org/10.1016/j.marpolbul.2021.112959*

NOTE: Publication reporting on the shoreline survey methodology that included assessments of marine debris and drift nets along tidal shorelines, as also undertaken in the Port Curtis Port Alma region.

Harris, R.M., L.J. Beaumont, T. Vance, C. Tozer, T.A. Remenyi, S.E. Perkins-Kirkpatrick, P.J. Mitchell, A.B. Nicotra, S. McGregor, N.R. Andrew, M. Letnic, M.R. Kearney, T. Wernberg, L B. Hutley, L.E. Chambers, M. Fletcher, M.R. Keatley, C.A. Woodward, G. Williamson, N.C. Duke and D.M. Bowman ***2018****. Linking climate change, extreme events and biological impacts.* ***Nature Climate Change*** *8(7): 579-587. DOI: 10.1038/s41558-018-0187-9. Author Correction: Nature Climate Change 8(9): 1; DOI: 10.1038/s41558-018-0237-3.*

NOTE: Publication reporting on the differences between, and the ecological implications of, pressure and pulse impacts on mangroves generally, and in the Port Curtis Port Alma region.

Salmo, S., I.R. Tibbetts and N.C. Duke. ***2019****. Recolonization of mollusc assemblages in mangrove plantations damaged by Typhoon Chan-hom in the Philippines.* ***Estuarine Coastal and Shelf Science*** *228 (:106365).*

NOTE: Publication reporting on the recovery of mangrove molluscs after catastrophic damage from a severe tropical cyclone, with relevance to flood damaged mangroves observed in the Port Curtis Port Alma region.

Schultz, M., M. Hansler, M. Logan, A. Carter, K.M. Chartrand, J. Wells, M.A. Rasheed, P. Costello, A.A. Thompson, J. Davidson, N.C. Duke, J.R. Mackenzie, N. Flint, A. Irving, A.

Anastasi, E.L. Jackson, S. Sawynok, B. Sawynok, A. Dunlop, P. Sawynok, J.D. Valck and M. Star. ***2020****. Gladstone Harbour Report Card 2019 - Technical Report. F. B. Association. Rockhampton, Gladstone Healthy Harbour Program (GHHP). 228 pp.*

NOTE: the 2020 technical report documenting ecosystem health condition scores for mangrove ecosystems of the Port Curtis region. Surveys were conducted in unison with PCPA CHAMP project activities.

Younes, N., T.D. Northfield, K.E. Joyce, S.W. Maier, N.C. Duke and L. Lymburner ***2020****. A novel approach to modelling mangrove phenology from satellite images: a case study from Northern Australia.* ***Remote Sensing 12****: 26 pages. https://www.mdpi.com/2072-4292/12/24/4008*

NOTE: Publication reporting on the remote sensing characterisation and assessment of vegetative phenologies of the common mangrove, Rhizophora stylosa, monitored during 1996-1998 in the Port Curtis Port Alma region, around Fisherman's Landing.

APPENDIX 2

PRESENTATIONS RELEVANT TO THE PCPA CHAMP PROJECT

1) **Community Workshop and Project Launch on 28 March 2015.**

Leo Zussino Building, Central Queensland University, Gladstone.
Attending, included: Peter Corones, GAGAL Chair; Deb Henry, Wildlife Preservation Society Queensland; Kerry Blackman, Gidarjil Development Corporation; Norm Duke JCU; John Kovacs NU; Ruth Crosson Society for Growing Australian Plants, Gladstone; plus Arthur Dahl, Peter Brockhurst and Richard Johnson with Gidarjil Development Corporation.

2) **Presentation by NC Duke at the 2016 Australian Mangrove and Saltmarsh Network (AMSN) Conference, *Darwin, 3 May 2016.***
   Presentation title. Indigenous ranger management of Southern GBR estuarine mangrove wetlands.

3) **Presentation by NC Duke at the** 3rd International Symposium on the Conservation and Management of Wetlands, Sabah, Malaysia. September 2018.
   Presentation title. We are losing mangrove tidal wetlands - so what is being done about it?

4) **Presentation by NC Duke at the** Torres Strait Environmental Management Committee (EMC27), Thursday Island. March 5th 2019
   Presentation title. Mangrove dieback – does it matter?

5) **Presentation by NC Duke at the** Queensland Indigenous Ranger Workshop, Cairns. 2019 March 25-28th
   Presentation title. Mangrove monitoring – why & how to do it!
   Presenters. Phillip George, Brenton Yanner & Norman C. Duke

6) **Presentation by NC Duke at a** Community meeting, Mackay. 2019 April 26th
   Presentation title. Mangroves. Why they are important!

7) **Presentation by NC Duke at the** MMM5 : Mangrove Macrobenthos & Management Conference, Singapore. 2019 July 1-5th
   Presentation title. Coastal and estuarine mangrove ecosystems are feeling the pinch – what do we know about the threats, the processes affected, and the prognosis for not coping?

APPENDIX 3

MANGROVE AND SALTMARSH SPECIES (Appendix Tables 1 & 2)

Appendix Table 1. The 16 mangrove plant species in the PCPA region (Source: NC Duke)

Mangrove species	Common name
Acanthus ilicifolius L.	Holly leaf mangrove
Acrostichum speciosum Willd.	Mangrove fern
Aegialitis annulata R. Br.	Club mangrove
Aegiceras corniculatum (L.) Blanco	River mangrove
Avicennia marina (Forsk.) Vierh.	Grey mangrove
Bruguiera dungarra N.C. Duke & H. Kudo	Dungarra orange mangrove (Duke & Kudo 2018)
Bruguiera exaristata Ding Hou	Rib-fruited orange mangrove
Bruguiera gymnorhiza (L.) Savigny ex Lam. & Poiret	Large-leafed orange mangrove
Ceriops australis (C.T. White) Ballment, Smith & Stoddart	Smooth yellow mangrove
Excoecaria agallocha L.	Milky mangrove
Lumnitzera racemosa Willd.	Black mangrove
Osbornia octodonta F. Muell.	Myrtle mangrove
Pemphis acidula J.R. Forst. & G. Forst.	Reef barrier mangrove
Rhizophora stylosa Griff.	Stilt-root mangrove
Xylocarpus granatum J. Konig	Cannonball mangrove
Xylocarpus moluccensis (Lam.) M. Roemer	Cedar mangrove

Appendix Table 2. The 18 Tidal saltmarsh plant species of the PCPA region (Source: J. Mackenzie)

Saltmarsh species	Common name
Atriplex semibaccata	Creeping saltbush
Dysphania littoralis	Wormseed
Einadia hastata	Hastate saltbush
Enchylaena tomentosa	Ruby saltbush
Fimbristylis ferruginea	Marine rusty sedge
Fimbristylis polytrichoides	Marine sedge
Halosarcia halocnemoides	
Halosarcia indica	Glasswort samphire
Halosarcia pergranulata	
Limonium australe	
Salsola kali	Prickly saltwort
Samolus repens	
Sarcocornia quinqueflora	Beed Weed Samphire
Schoenoplectus littoralis	
Sesuvium portulacastrum	False Portulacca
Sporobolus virginicus	Marine Couch
Suaeda arbusculoides	Jelly Bean Plant
Suaeda australis	Sea Blite Samphire

APPENDIX 4

SOURCES OF ENVIRONMENTAL DATA

Monthly mean air temperature data
Australian Bureau of Meteorology (BoM) web site
(http://www.bom.gov.au/climate/data/index.shtml?bookmark=136)

Port Alma subregion (PA)
Rockhampton (39083), Yeppoon (33294)
Date range: 1939-2021, 1993-2021

Port Curtis subregion (PC)
Gladstone Radar (39123), Gladstone Airport (39326)
Date range: 1957-2021, 1993-2022

Rodds Harbour subregion (Rodds)
Bustard (39018), 1770 (39314)
Date range: 1913-1986, 1986-2021

Monthly rainfall data
Australian Bureau of Meteorology (BoM) web site
(http://www.bom.gov.au/climate/data/index.shtml?bookmark=136)

Port Alma subregion (PA)
Glenlands (39043), Bajool (39002), Pacific Salt (39078), Broadmeadows (39242)
Date range: 1928-2022, 1912-2021, 1899-2009, 1956-2022

Port Curtis subregion (PC)
Mount Larcom (39068), Gladstone Radar (39123), Gladstone Airport (39326), Curtis South (39241)
Date range: 1912-2022, 1957-2022, 1994-2022, 1973-2021

Rodds Harbour subregion (Rodds)

Turkey Station (39261), Bustard (39018), Springs (39255), Ferndale (39252)
Date range: 1973-2021, 1888-2021, 1961-2021, 1973-2021

Monthly Southern Oscillation Index (SOI) data
Australian Bureau of Meteorology (BoM) web site (http://www.bom.gov.au/climate/enso/soi/)

Date range: 1876-2022

Monthly sea level data
Permanent Service for Mean Sea Level (PSMSL) web site (https://www.psmsl.org/data/)

Port Alma subregion (PA)

Port Alma (2072)
Date range: 1986-2020

Port Curtis subregion (PC)
Gladstone (825)
Date range: 1978-2020

Rodds Harbour subregion (Rodds)
Burnett Heads (1154)
Date range: 1966-2021

APPENDIX 5

SPOT IMAGE PROCESSING METHODS

Data Acquisition: To cover the entire study area for the baseline image and map, three separate scenes of SPOT imagery were collected between August 7 and September 23 of 2016. Once collected, these data were radiometrically and geometrically corrected. Since several swaths of imagery were needed to cover the entire PCPA study area, the many surface reflectance images may also be mosaicked. For each scene, this included four bands of multi-spectral imagery at a 6m spatial resolution and one panchromatic band at 1.5m spatial resolution.

Image Pre-Processing

Pan-sharpening and orthorectification of pan-sharpened products

For each scene an additional set of pan-sharpened bands were created using a Toutin model. This resulted in four bands of multi-spectral imagery at a 1.5m spatial resolution. These data were then ortho-rectified using Ground Control Points (GCPs) collected manually from the geo-referenced Queensland 5m LIDAR digital surface model and using the SRTM 30m DEM for terrain correction. The ortho-rectified products were corrected to a sub-pixel root mean square error accuracy.

Multi-spectral surface reflectance and orthorectification

For each scene, the original 6m multi-spectral images were atmospherically corrected using Geomatica’s ATCOR module without cloud and water masking or haze removal. This resulted in multi-spectral bands with surface reflectance values. These new data were then ortho-rectified (Toutin’s model) using GCPs automatically collected from the corrected pan-sharpened products (1.2.1). The SRTM 30m DEM was again used for terrain correction.

Mask creation for subsequent image classification procedures

The target area vector polygons provided were first converted into target area bitmap binary masks. Using the ortho-rectified surface reflectance bands (1.2.2) the NDWI was calculated for each of the three scenes. Values above approximately 0.0 are considered water and values below approximately 0.0 considered land. For this investigation, it was determined that a threshold value of -0.2 or greater represented areas of water. Consequently, the NDWI was employed to create a surface water binary bitmap mask. A final classification mask was created using the surface water binary bitmap masks, the target area bitmap binary masks and a HAT area binary mask. Specifically, the HAT area binary mask areas within the target area mask were selected and then edited by removing those areas identified as surface water based on the surface water binary bitmap mask.

Image Classification: Using the classification masks an iterative unsupervised classification procedure was applied for all three target areas. Specifically, all four pan-sharpened bands were classified only under the classification mask areas using a K-means classification algorithm. Ancillary data were then used to assist in post-classification manually editing of the output maps.

The NDVI will be produced from each surface reflectance mosaic. NDVI is calculated using the following formula: NDVI = $\frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})}$. The NDVI images can then be used to monitor changes in the health of the vegetation by comparing them with future NDVI images collected of the same locations. Finally, using more recent ancillary data (e.g., our project field surveys), an updated per pixel classification procedure will be applied to the newly acquired imagery in order to map the most recent areas of mangrove and saltpan/saltmarsh land cover.

Queensland Wetlands Mapping: Mangrove areas are defined by the mapped polygons (DSITI 2015) where mangroves (RE 12.1.3) are the dominant vegetation type. Dataset is titled as Queensland wetland data version 4 - wetland areas. The dataset provides mapping of water bodies and wetland regional ecosystems at 1:100,000 scale across Queensland.

The positional accuracy of wetland data mapped at a scale of 1:100 000 is +/-75m is described as: the minimum polygon size depicted is 5 ha or 75m wide for linear features, except for areas along the east coast which are mapped at the 1:50 000 scale with a positional accuracy of +/-50m, with a minimum polygon size of 1 ha or 35m wide for linear features. Wetlands smaller than 1 ha are not delineated on the wetland data. Note that consideration of the effects of mapped scale is necessary when interpreting data at a larger scale (eg: 1:25,000).

A close look at satellite image data

Mangrove vegetation maps – SPOT 2016: While mangrove vegetation dominates shoreline areas across PCPA study area, there are notable differences from north, to central and southern sections (see Appendix Table 3). Also note, saltpan/saltmarsh areas are more dominant in the north with a trend to greater mangrove dominance in the south. The key correlate with these differences is annual rainfall, being much lower in the north than towards the south.

Appendix Table 3. Tidal wetland areas in the Port Curtis Port Alma region for each of the three subregions showing for 2016 (also see Table 8). WCI = Wetlands Cover Index (% mangrove). Asterisk (*) indicates the subregion under greatest anthropogenic influence. Tree heights and carbon (C) stock determined in a biomass assessment with this study (also Appendix 6).

PCPA Subregion	PCPA #	Zone Name	Mangrove (ha)	Saltmarsh (ha)	Tidal Wetland (ha)	WCI %	Tree Hgt. (m)	C Stock (Mt)
Port Alma	1	Fitzroy mouth	708	1331	2038	34.7		
	2	Port Alma	8362	18156	26518	31.5		
	3	Balaclava	1382	3073	4455	31.0		
	4	Yellow Patch Curtis Island	1743	2249	3992	43.7		
	5	Northwest Curtis Island	892	1849	2741	32.6		
		PA Subregion	13087	26658	39745	32.9	3.2	9.0
Port Curtis*	6	Narrows West	1896	1270	3166	59.9		
	7	Narrows East	1460	976	2436	59.9		
	8	Graham Creek	804	298	1102	73.0		

	9	Western Basin West	286	554	840	34.0		
	10	Western Basin East	106	93	198	53.4		
	11	Boat Creek	41	92	133	30.6		
	12	Inner Harbour - Enfield Creek	419	468	888	47.2		
	13	Inner Harbour - Barney Point	5	32	37	13.3		
	14	Calliope Estuary	398	112	510	78.1		
	15	Auckland Inlet	9	1	10	89.9		
	16	Mid Harbour - Curtis Island	24	179	203	11.7		
	17	Mid Harbour - Facing Island	28	271	299	9.4		
	18	South Trees Inlet	587	797	1384	42.4		
	19	Boyne Estuary	5	14	18	25.2		
		PC Subregion	6068	5156	11224	54.1	3.8	5.4
Rodds Harbour	20	Outer Harbour - Wild Cattle Ck	2161	1135	3295	65.6		
	21	Outer Harbour - Split End	71	65	136	51.3		
	22	Colloseum Inlet - Main	342	168	509	67.1		
	23	Colloseum Inlet - Hummock Hill Is.	31	4	34	88.9		
	24	Colloseum Inlet - Wild Cattle	22	52	74	30.0		
	25	Rodds Harbour East	1171	469	1641	71.4		
	26	Rodds Harbour - West	389	254	643	60.5		
	27	Rodds Harbour - Pancake Creek	1221	804	2024	60.3		
	28	Rodds Harbour - Hummock Hill Island	50	128	178	28.1		
		Rodds Subregion	5454	3078	8532	63.9	5.4	6.5
PCPA Total			**24541**	**34828**	**63048**	**41.4**	**4.0**	**20.9**

APPENDIX 6

CALCULATING MANGROVE CARBON STOCK LEVELS

We applied the equation of best fit ($r2 = 0.4775$; $n = 117$) as derived from studies of mangrove biomass in the South West Pacific Islands of Fiji, Samoa, Solomon Islands, Tonga and Vanuatu (Duke et al. 2013) as:

*Total Carbon (AGB+BGB) = 21.721*L-Hgt – 4.1833*

- where total carbon is dry weight in $tC.ha^{-1}$, and canopy height is in metres of both above and below ground sources.

Note: *AGB* = above ground biomass; *BGB* = below ground biomass.

The data on carbon stocks show a range for the subregion areas of the PCPA CHAMP study area (Fig. 16) and specifically for each of the subregion areas (Table 8), including each zone area (Appendix Table 3). Carbon stocks range from 59-140 $tC.ha^{-1}$. These values are at the low end of amounts measured in the Pacific island sites at around 200 $tC.ha^{-1}$. However, this is consistent with sites of similarly lower rainfall climatic zones.

APPENDIX 7

TIDAL WETLANDS CONDITION ASSESSMENT

Boat-based S-VAM surveys

S-VAM shoreline monitoring (Mackenzie et al., 2016) of the PCPA study area was undertaken by the Gidarjil rangers on 36 occasions from 2014 to 2021 (Appendix Table 4). These surveys used various small vessels carrying up to 5 people on each occasion. The main aim was to gather imagery as part of a baseline archive, and a record of factors affecting shoreline mangroves plus their condition. These surveys have been described in prior annual reports (Duke et al., 2015-2019).

Aerial S-VAM surveys

Aerial surveys were conducted over two days during April 2019. The survey used a Robinson 44 helicopter (Appendix Fig. 1) In all missions, the timing of flights was chosen to maximise favourable light conditions in conjunction with the moreorless mid-day occurrence of low tides. The goal was to photograph and observe exposed tidal wetlands and their vegetation at their greatest exposure and clarity.

Appendix Figure 1. TropWATER aerial survey team with Gidarjil rangers filmed the tidal wetland shorelines from Fitzroy River to Rodds Harbour in 2 days.

The aerial survey crew consisted of Dr Duke and Jock Mackenzie on all flights, plus a third survey member rotated amongst Gidarjil rangers. The survey crew operated 5 cameras in total along with a portable GPS device to record the flight track, and a voice recorder set to record the cockpit conversation. All cameras and other electronic devices were synchronised for common time reference, and with their internal GPS recording.

The cameras and hand-held GPS device used included:

- Large format Nikon D800E with Nikkor 50mm 1:1.4G lens & GPS, 2 sec. time lapse
- HD Sony video HDR-PJ430 with GPS
- Sony Cyber-shot DSC-HX50V with GPS
- Sony Cyber-shot DSC-HX5 with GPS
- Garmin GPSmap 62s loaded with local satellite imagery

Appendix Table 4. Dates (year, day/month) of the 36 S-VAM surveys conducted by rangers of the Gidarjil Development Corporation from 2014 to 2021 in prominent locations and sub-regions of the PCPA area. Key survey achievements of three of these surveys (in bold) are shown in Figure 132. Note: PA = Port Alma; PC = Port Curtis; and Rodds = Rodds Harbour.

Sub-region	Location	2014	2015	2016	2017	2018	2019	2020	2021
PA	Port Alma		1-3/9				2-3/5		
PC	The Narrows		26/5		13/7	6/3			
PC	Targinie Ck					15/3			
PC	Grahams Ck				14/7	15/3 - 29/8			6/1
PC	Port Curtis		2/9						
PC	Calliope River		**25/5**		13/6	**5-6/3**	18/4-10/5		7/1
PC	Auckland Ck					29/8		3-15/9	
PC	South Trees	**18/2**				**17/3**	30/4	16/9	
PC	Boyne River	**19/2**		10/6		**30/8**		18/8-15/9	
Rodds	Rodds Harbour		31/8						12/5,18-19/10

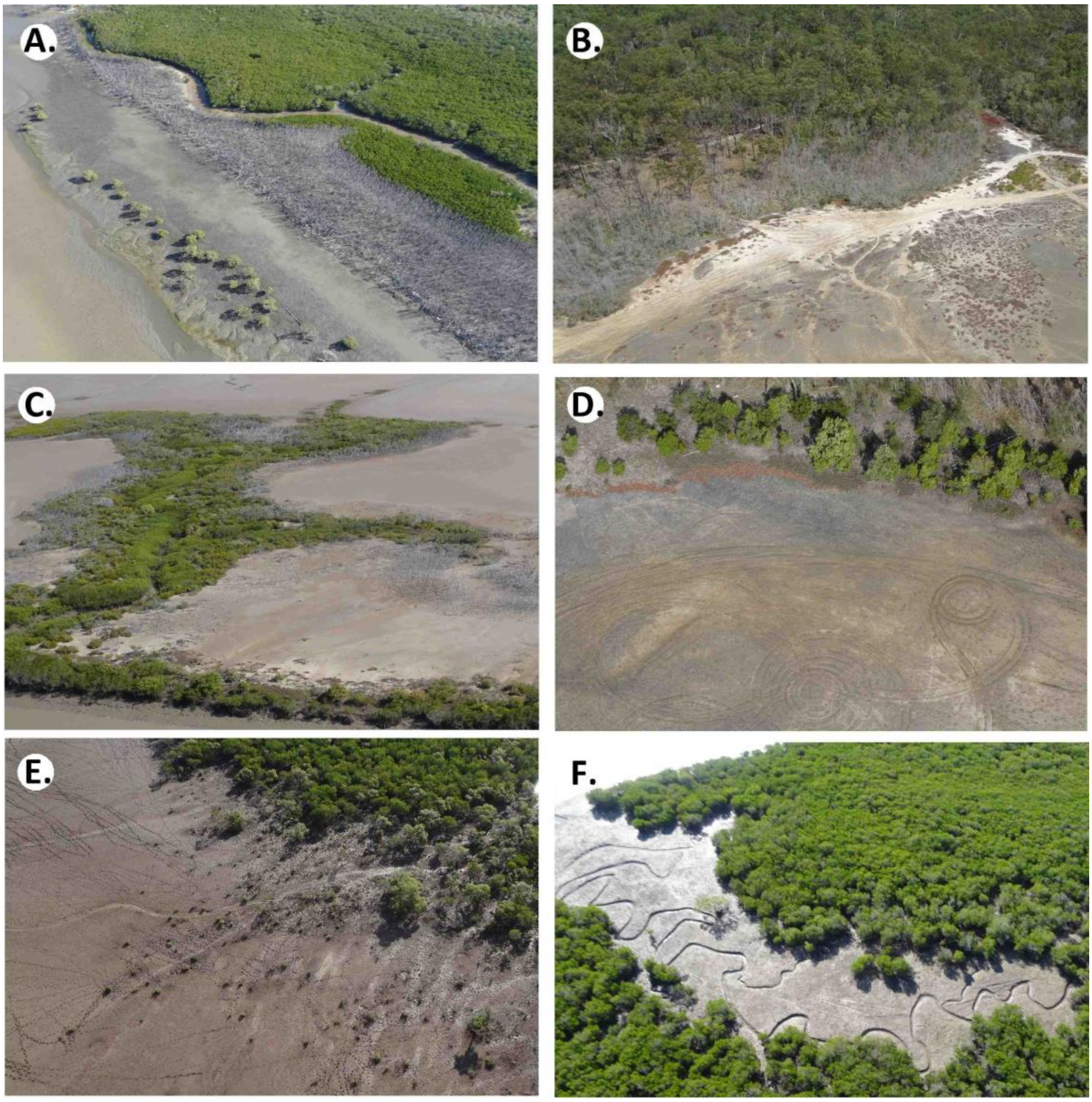
Observations and environmental indicators observed

Aerial surveys were undertaken to identify and quantify the key environmental changes taking place. The indicators used range from human-related drivers like altered hydrology, cattle damage, vehicle access and reclamation, to the more indirect climate or natural drivers, like drought effects, floods and erosion. One additional feature was the presence of the seasonally deciduous mangrove, *Xylocarpus mollucensis*, the Cedar Mangrove, because its reddening and entire leaf shedding has at times been mistakenly interpreted as mangrove dieback.

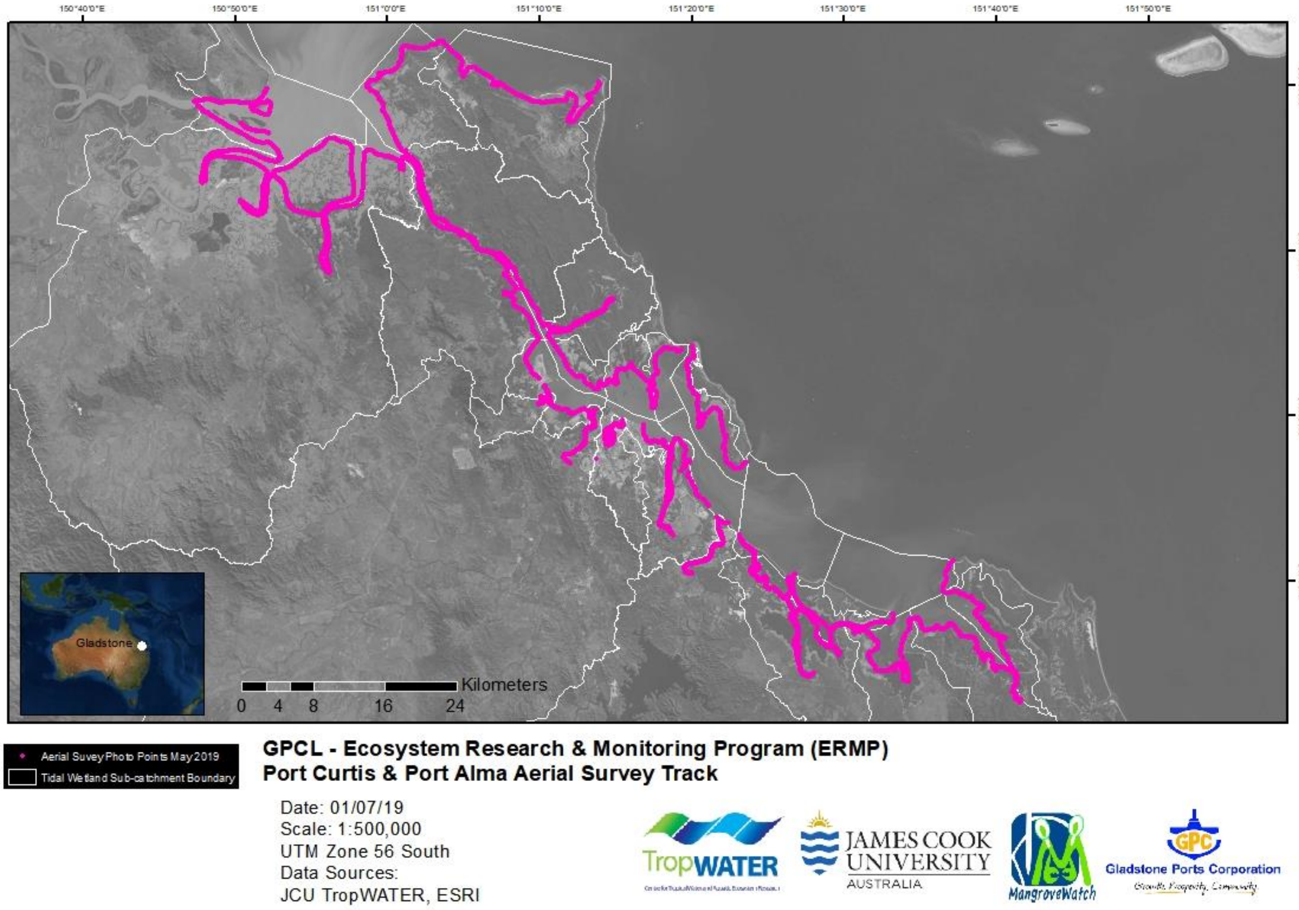
Appendix Table 5. Features and issues affecting tidal wetlands across the PCPA study area during both aerial and boat-based surveys.

Issues & Features	Aerial S-VAM	Boat-based S-VAM
Direct damage – reclamation, landfill	+	+
Direct damage – surface sand extraction	+	
Direct damage – boat ramps	+	+
Direct damage – vehicle tracks	+	
Direct damage – cattle tracks	+	+
Direct damage - flood damage	+	+
Direct damage - boat prop scars	+	
Altered hydrology - impoundment	+	
Green mudbanks - eutrophication	+	+
Species specific effect – harmful agricultural chemicals	+	+
Upland shift/retreat – sea level rise	+	+
Eroding banks – dynamic hydrologies	+	+
Depositional gain – runoff sediments	+	+
Burial dieback – shifting sediments	+	+
Light gaps – lightning strike damage	+	+
Ecotone shift loss - drought effect	+	+
Deciduous trees – natural seasonal defoliation	+	+

During the aerial survey, we observed at least 28 features and issues (Appendix Tables 5 & 6). These are defined further in Appendix Tables 7 & 8. Six of the more notable issues are shown in Appendix Fig. 2. These include inner fringe collapse, upland retreat, drought effects, vehicle tracks, cattle trampling and prop wash scars. The track of the aerial survey is shown in Appendix Fig. 3. Additional features, including boat-based observations are shown Appendix Fig. 5.



Appendix Figure 2. Six indicators and features observed during the aerial surveys of the study area, including: A. inner fringe collapse of foreshore mangroves; B. upland retreat from saline incursion; C. drought affected ecotone shift; D. direct damage from vehicle access; E. direct damage from cattle grazing; and F. propeller wash damage.



Appendix Figure 3. Map showing the shorelines filmed in June 2019, throughout the PCPA study area – from Port Alma to Port Curtis and Rodds Harbour.

Mangrove condition indicator scoring methodology

Classification of observed indicators of drivers active or influencing tidal wetland habitat are described in Tables 6 & 7. Scores of observed extent and severity were made during the aerial surveys (Appendix Table 6). These observations were made for each of the sub areas across the PCPA study area – see Figure 39 and Table 9.

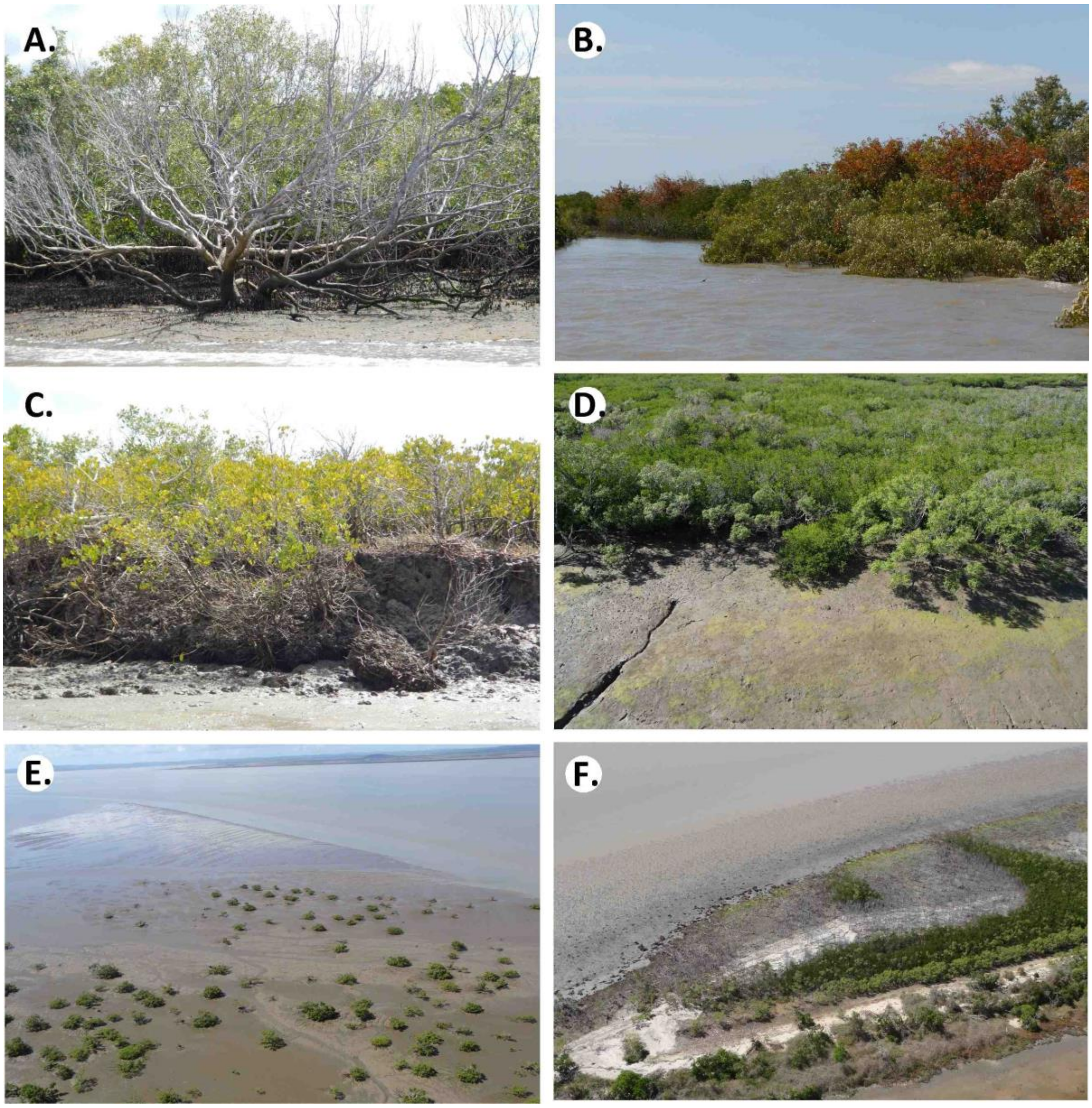
Tidal wetland habitat categories used in this study included: the mangrove shoreline fringe; mangrove forests; the mangrove back edge; all mangroves; samphire areas; salt couch areas; all saltmarsh areas; salt pans and the major ecotone interfaces with both marine and estuarine waters, as well as the supratidal upland terrestrial and freshwater areas. Examples of observed features are shown in Appendix Figure 5.

'Extent' was scored as the estimated proportion of the tidal wetland affected. This was scored from five categories as follows: 0-10%; 10-30 (~25)%; 30-60 (~50)%; 60-90 (~75)%; and greater than 90%.

'Severity' was scored as the severity of impact affecting natural recovery time, and overall prospect of recovery of ecosystem structure and function. This was scored from five categories as follows: None – maybe present – no observable effect; Minor – recovery within 6 months – no substantive ecological effect; Moderate – recovery between 6 months and two years – some ecological effect; Major – recovery from two to ten years – significant ecological effect; and, Severe – recovery unlikely – permanently damaged and reduced ecosystem services.

The field score sheet used is shown in Appendix Figure 6. Based on prior experience, these extent and severity scores for each indicator and site were combined for this assessment using the following equation:
Condition Score = Extent X (Severity/5)

Data scored in the 2019 aerial survey of the PCPA area are presented in Appendix Tables 7-9.



Appendix Figure 5. Example indicators and features observed during the 2019 aerial and boat-based surveys within the study area, including: A. species specific dieback of *Avicennia marina*; B. seasonally red deciduous *Xylocarpus moluccensis*; C. eroding bank with *Ceriops australis*; D. green algal cover on the mud flats fronting mixed mangroves; E. depositional gain mangrove expansion of *Avicennia marina*; and F. root burial and drowning dieback of *Rhizophora stylosa* associated with shifting sediments and extreme high sea levels.

Coll.: **Tidal Wetland Threat Assessment** **WP:**

ZONE: **Time:**

Location: **Date:**

Driver Type	Indicator	Habitat	Extent	Severity	Time Frame	Restor'n Potential	GT-Site	Observations
Human related Structures	rockwalls, wharf, ramps, roads	any zone						
Human related Direct Loss	clearing, dead trees, landfill	any zone						
Human related Altered Hydrol.	bunds, drains, impounded areas	mostly upper zones						
Human related Ag. Encroachmt	no buffer, cut-off tributaries	upper edge zone						
Human related People Access	vehicles, tracks, foot pathways	mostly saltpans						
Human related Stock Damage	cattle, horses, goats, tracks	mostly saltpan-upper						
Human related Feral Animals	pigs, tracks, wallows, diggings	mostly saltpan-upper						
Human related Pollutant	oil spill, scum, dump site, dieback	any zone						
Human related Nutrient	enhanced growth, expansion	any zone						
Human related Fire	fire damage, dieback	upper edge zone						
Human related Weeds	smothering, weeds, dieback	mostly edge zone						
Climate/Natural – Storm Damage	broken trees, forest damage	mangrove zones						
Climate/Natural – Shore Erosion	fallen trees, steep bank, dieback	seaward zone						
Climate/Natural – Root Burial	fallen trees, steep bank, dieback	mostly seaward zone						
Climate/Natural – Fringe Collapse	irregular dieback, canopy gaps	sea-edge mangroves						
Climate/Natural – Bank Erosion	fallen trees, steep channel bank	channel edges						
Climate/Natural – Pan Scouring	sheet erosion, missing saltmarsh	saltpan zone						
Climate/Natural – Ecotone --Shift	dead trees, fringe loss, retreating	saltpan-mangrove						
Climate/Natural – Ecotone +Shift	young trees, fringe gain, encroaching	saltpan-mangrove						
Climate/Natural – Deposit'l Gain	young trees, bank & edge expansion	water edge						
Climate/Natural – Terr'l Retreat	back edge dieback, scouring erosion	upper zone						
Climate/Natural – Light Gaps	circular canopy holes/dieback	mangrove zones						

Appendix Figure 6. Field data sheet for tidal wetlands threat assessment in aerial surveys.

Appendix Table 6. For human-related and climate-natural drivers, 28 indicator mean scores made during 2019 aerial surveys of the PCPA region. *indicators not scored for each subregion.

Driver Grouping	#	Indicator
Human-related	1	Structures
	2	Direct Loss
	3	Human Altered Hydrology
	4	No Buffer
	5	People Access
	6	Stock Damage
	7	Feral Animals
	8	Pollutant
	9	Nutrient
	10	Fire
	11	Weeds
Climate-Natural	1	Storm Damage
	2	Shore Erosion
	3	Bank Erosion
	4	Root Burial
	5	Fringe Collapse
	6	Pan Scouring
	7	Ecotone Shift Loss
	8	Ecotone Shift Gain
	9	Depositional Gain
	10	Terrestrial Retreat
	11	Upland migration
	12	Light Gaps
	13	Natural Altered Hydrology
	14	Bat Damage
	15	Flood Damage
	16*	Hail Damage
	17*	Deciduous Mangroves

Appendix Table 7. Indicator scores of severity and extent of 11 human related features observed in the 28 PCPA zones during aerial surveys in 2019. The features are listed in Appendix Table 6.

PCPA#	GHHP#	Zone Area	1	2	3	4	5	6	7	8	9	10	11
1		Fitzroy mouth	0.4	0	0.6	0	0	0.8	0	0	0.2	0.4	0.2
2		Port Alma	1	2	2	0	0	0.8	0	0	0.4	0	0
3		Balaclava	0.2	0	0.2	0.2	0	0	0	0	0	0	0
4		Yellow Patch Curtis Island	0.4	0	1.8	0	0	0	0	0	0	0	0.2
5		Northwest Curtis Island	0.2	0	0.6	0	0.4	0	0	0	0.2	0	0.2
6	1a	The Narrows West	0.5	1	0.4	0.2	0.6	0.4	0.2	0	0.8	0	0.4
7	1b	The Narrows East	0.2	0	0.4	0	0	0	0.8	0	0.4	0.2	0.4
8	2	Graham Creek	0.2	0.2	0.2	0	0.4	0	0.4	0	0	0	0
9	3a	Western Basin West	1.6	2	1.6	0	0.4	0.4	0	0	0.4	0	0
10	3b	Western Basin East	3.2	2	3.2	0	0	0	0	0	0	0	0
11	4	Boat Creek	0	0	1.2	0	1	0	0	0	0	0	0
12	5a	Inner Harbour - Enfield Creek	0.8	0	0	0.2	1	0	0	0	0	0	0
13	5b	Inner Harbour - Barney Point	1.8	3	3	0.6	1.2	0	0	1.2	0.2	0	0.2
	5C + 8C	Quoin	1.2	0	0.4	0	0.4	0	0	0	0.4	0	0.8
14	6	Calliope Estuary	1.8	2	1.8	0.4	1.6	0	0	1.2	0.4	0	0
15	7	Auckland Inlet	1.8	4.5	1.6	2.4	0.8	0	0	0.4	0	0	0
16	8a	Mid Harbour - Curtis Island	0.6	0	0.4	0.2	0.4	0.4	0	0	0.2	0	0.4
17	8b	Mid Harbour - Facing Island	0.6	0	1.6	0	0.4	0	0	0	0		0
18	9	South Trees Inlet	2.4	2.5	2.4	0	0.6	0	0	0.8	0	0	0
19	10	Boyne Estuary	3	0	1.6	1.2	1.6	1.8	0	0.4	0	0	0.4
20	11a	Outer Harbour - Wild Cattle	0	1	0	0.2	2.4	1.2	0	0	0.4	0.8	0
21	11b	Outer Harbour - Split End	1	0	0.6	0	0	0	0	0	0	0	0
	11C	Outer Harbour - GHHP 11C	0	1	0	0.2	0.6	0	0	0	0	0	0
22	12a	Colloseum Inlet - Main	0.2	0	0	0	0	0	0	0.2	0	0	0
23	12b	Colloseum Inlet - Hummock Hill Island	0	0	0	0	0	0	0	0	0	0	0
25	13a	Rodds Harbour East	0	0	0	0	0	0	0.4	0	0.8	0	0
26	13b	Rodds Harbour - West	0.4	1	1.2	0.2	1.6	1.2	0	0	0.2	0	0.4
27	13c	Rodds Harbour - Pancake Creek	0.6	1	0.6	0.2	0.8	0.4	0	0	0.4	0	0
28	13d	Rodds Harbour - Hummock Hill Island	1	0	0.6	0.2	0.4	0	0	0	0	0	0

Appendix Table 8. Indicator scores of severity and extent of 16 climate-natural related features observed in the 28 PCPA zones during aerial surveys in 2019. The features are listed in Appendix Table 6.

PCPA #	GHHP #	Zone Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1		Fitzroy mouth	1.6	3.2	1.6	0.4	3.2	0.8	2.4	1.2	1.6	1.2	0.6	0	0	0	0
2		Port Alma	0	2	0.4	0	1.2	2.4	2.4	0.8	1.8	1.6	0.4	0	0	0	0
3		Balaclava	1.6	3.2	0.9	1.2	0.8	3.2	2.4	1.2	0.4	1.2	0.9	0	0	0	0
4		Yellow Patch Curtis Island	0	3.2	3	0.4	0.2	0	1.2	0.8	2.8	0.8	0	0	1.6	0	0
5		Northwest Curtis Island	0.8	2.4	1.6	0.4	0	2.4	0.6	0.6	1.2	1.2	0	0	0.6	0	0
6	1a	The Narrows West	1.6	3.2	0.6	2.1	0	1.8	1	1.2	8.8	2.1	1	0	0	0	0
7	1b	The Narrows East	1.6	1.4	0.6	0.6	0	1.2	2.4	1.6	1.2	1.8	0.6	0	0.6	0	0
8	2	Graham Creek	0.4	0	0	0	0	0.4	0.6	0.4	0	3.2	0	0	0	0	0
9	3a	Western Basin West	1.8	3.2	0	0.4	0	1.2	0	1.8	0	0.8	0.4	0	0	0	0
10	3b	Western Basin East	1.2	1.2	0	0	0	0.5	0.6	1.6	0	0.2	0	0	0	0	0
11	4	Boat Creek	0.8	0.6	0	0.6	1.8	1.2	0	0	0.8	0.6	0	0	0	0	0
12	5a	Inner Harbour - Enfield Creek	1.2	0.8	0	1.2	0	1.8	0	1.2	0.6	1.8	0.4	0	0	0	0
13	5b	Inner Harbour - Barney Point	1.6	1.6	1.6	0	0	0	0	0	1.6	0	0	0	0	1.6	0
	5C + 8C	Quoin	0	0	0	0	0	0	0	0	0.4	0.2	0	0	0	0	0
14	6	Calliope Estuary	0	0	0	0.5	1.8	0.9	0	1.2	1.6	0.6	0	0	1.4	0.4	1.2
15	7	Auckland Inlet	0	0	0	0.6	1.2	0	1.2	0	0.8	0	0.4	0	0	0.6	0
16	8a	Mid Harbour - Curtis Island	0	0.6	0	0	0	1.8	0	0.4	2.4	1.2	0	0	0	0	0
17	8b	Mid Harbour - Facing Island	0.9	0.6	0.6	0	0	1.2	0.8	1.2	0.4	2.4	0	1	1.2	0	0
18	9	South Trees Inlet	0.8	1	0.8	1.8	1.8	0.8	0	0.8	0.4	1.6	0.6	0	0	0	1.2
19	10	Boyne Estuary	0	0	0.6	0	1.6	0	0	0	1.2	0.8	0.4	0	0	0	2.4
20	11a	Outer Harbour - Wild Cattle	0	1.2	0.6	0.8	0.8	1.8	0.6	2.4	0.2	4	0.4	0	0.6	0	0
21	11b	Outer Harbour - Split End	0	0.8	0	1.8	0	1.8	0	1.2	0	2.1	0.6	1	0	0	0
	11C	Outer Harbour - GHHP 11C	0.8	0.8	0.8	0	1.8	0	0.6	3.2	0	2.4	0.4	1	0	0	0
22	12a	Colloseum Inlet - Main	0	0	0.8	0.4	0.8	0	0.6	1.8	3.2	1.2	0.6	0	0	0	0
23	12b	Colloseum Inlet - Hummock Hill Island	0	0.2	0.4	0	0	0	0	0	0.6	1.8	0	3	1.6	0	0
25	13a	Rodds Harbour East	0	1.2	0.8	2.4	0	3.2	0	1.8	0	2.4	0.6	0	0	0	0
26	13b	Rodds Harbour - West	1	0.6	1.6	0.6	1.2	3.2	0	0.4	1.8	3.2	0.6	0	0.8	0	0
27	13c	Rodds Harbour - Pancake Creek	0.8	0.6	0.6	0.8	0	2.8	0	1.8	0.2	3.2	0.6	0	0	0	0
28	13d	Rodds Harbour - Hummock Hill Island	0	0.8	0.4	0.8	0	1.2	0	0.8	2.4	2.4	0	1	0	0	0

Appendix Table 9. Aerial shoreline surveys through the PCPA study area during April 2019. Factors related to Human (pink shaded) and Natural (green shaded) drivers are displayed for the three top ranking indicators, based on extent and severity scored from field observations made for each sub area. Refer to Tables 7 & 8, for an explanation of the indicator codes used; and to Table 9 for site locations.

Site #	PCPA Site Code	GHHP SubZone#	Condition Score Nat:Hum	Human	Human	Human	Natural	Natural	Natural
				1	2	3	1	2	3
1	FRM	-	0.1	Stock	Altered	Struct's	ErosionS	ErosionB	Ecoton-
2	POA	-	0.5	DirectL	Altered	Struct's	PanScour	Ecoton-	ErosionS
3	BIS	-	0.0	Struct's	Altered	NoBuffer	ErosionS	PanScour	Ecoton-
4	CYP	-	0.2	Altered	Struct's	Weeds	ErosionS	RootB	DepGain
5	CNW	-	0.1	Altered	Access	Struct's	ErosionS	PanScour	RootB
6	NWM	1a	0.2	DirectL	Nutri's	Access	ErosionS	TerrRetr	FringeC
7	NEC	1b	0.2	Ferals	Altered	Polluts	Ecoton-	TerrRetr	StormD
8	GCC	2	0.3	Access	Ferals	Struct's	TerrRetr	Ecoton-	StormD
9	WBM	3a	0.7	DirectL	Struct's	Altered	ErosionS	StormD	Ecoton+
10	WBC	3b	1.6	Struct's	Altered	DirectL	Ecoton+	StormD	ErosionS
11	BCK	4	0.3	Altered	Access		ErosionB	PanScour	StormD
12	IHE	5a	0.2	Access	Struct's	NoBuffer	PanScour	TerrRetr	StormD
13	IHB	5b	1.4	DirectL	Altered	Struct's	ErosionS	StormD	Bats
14	CAR	6	1.0	DirectL	Struct's	Altered	ErosionB	DepGain	NAlterd
15	ACK	7	2.4	DirectL	NoBuffr	Struct's	ErosionB	Ecoton-	DepGain
16	MHC	8a	0.4	Struct's	Altered	Access	DepGain	PanScour	TerrRetr
17	MHF	8b	0.3	Altered	Struct's	Access	TerrRetr	PanScour	Ecoton+
18	STI	9	0.8	DirectL	Struct's	Altered	ErosionB	FringeC	TerrRetr
19	BOR	10	1.4	Struct's	Stock	Access	FloodD	ErosionB	DepGain
20	CCK	11a	0.4	Access	Stock	DirectL	TerrRetr	Ecoton+	PanScour
21	CHH	11b	0.2	Struct's	Altered		TerrRetr	FringeC	PanScour
22	CWC	11c	0.2	DirectL	Access	NoBuffer	Ecoton+	TerrRetr	ErosionB
23	OHW	12a	0.0	Struct's	Polluts		DepGain	Ecoton+	TerrRetr
24	OHS	12b	0.0				UplandM	TerrRetr	NAlterd
25	RBE	13a	0.1	Nutri's	Ferals		PanScour	TerrRetr	FringeC
26	RBW	13b	0.4	Access	Stock	Altered	TerrRetr	PanScour	DepGain
27	RBP	13c	0.4	DirectL	Access	Struct's	TerrRetr	PanScour	Ecoton+
28	RBH	13d	0.2	Struct's	Altered	Access	TerrRetr	DepGain	PanScour
				1	2	3	1	2	3
	ALL			Altered	Struct's	DirectL	TerrRetr	PanScour	ErosionS

APPENDIX 8

MANGROVE CANOPY CONDITION AND 'GREEN FRACTION' PLOTS

'Green fraction' plots were used in this investigation since they conveniently displayed fluctuations in mangrove condition at selected site locations. Timeseries plots showed changes in mangrove canopy cover (linked to density and condition) between 1987 and 2022 for a number of study locations across the PCPA study area (Fig. 10). These findings were used to evaluate variations in canopy dynamics across the region. Location coordinates of these sites are listed in Appendix Table 10. For each site, differences in dieback severity were conveniently classified according to the amounts of canopy loss; where lethal losses were maximal ~50-70% with recovery taking around 10-15 years, and sub-lethal was <50% with recovery taking <10 years (Duke et al., 2021b,c).

Specific canopy data were derived from Landsat satellite imagery freely available from the USGS web site (https://glovis.usgs.gov/app?fullscreen=0). Measures of green fractional cover were obtained from Landsat satellite sensors spanning three decades, to produce time series plots of percent vegetation cover for dieback areas at each site. The time series plots were produced from all available Landsat imagery for path/row's 102/71, 99/72 and 98/70, between the time period May 1987 and May 2020. A number of pre-processing steps were applied to these images, which included atmospheric correction using 6S radiative transfer code and a bi-directional reflectance distribution function (BRDF) model was applied to take into account topographic illumination effects, producing surface reflectance values at nadir and a solar zenith angle of 45° (Flood et al., 2013; Flood, 2014). Water, cloud and cloud shadow were also masked from each Landsat image (Goodwin et al., 2013; Danaher & Collett, 2006).

Green fractional cover estimates were obtained from a linear spectral un-mixing model (Scarth et al., 2010) which provides estimates of the proportion of green, non-green and bare cover for each Landsat pixel. The model was developed using field data collected across Australia (Scarth et al., 2015; Gill et al., 2017). Others (cs. Guerschman et al., 2015) assessed the accuracy of the fractional cover model and reported a Root Mean Squared Error (RMSE) of 11.2% and r of 0.87 for the green fractional cover estimate. Comparisons between estimates of mangrove green foliage cover obtained from UAS imagery (Unmanned Aerial Systems) and Landsat green fractional cover reported similar RMSE of 11.6 % (Staben et al., 2019; Datt & Staben, 2020). The Landsat green fraction of the fractional cover product has also been used to map annual mangrove extent across the Australian continent (Lymburner et al., 2019).

The resulting green faction timeseries plots were produced from homogenous patches of mangrove forests near to both field and reference sites. For each plot, zonal statistics representing an area of 3x3 Landsat pixels were extracted from each image and the mean green fractional cover value was calculated. When less than three pixels were available for a given image date (due to masking of cloud, cloud shadow and water) the mean green fractional cover value was not calculated and those dates were not used in production of the timeseries plot. To assist in the interpretation of each timeseries a fitted line was produced using a rolling window, calculating the mean value from three data points.

Appendix Table 10. Location coordinates for green fraction timeseries plots.

Sub Reg#	Zone #	GF SITE #	Location	Shoreline Zone	Latit. S	Longit. E	Indicator	GAIN/ LOSS
2	9	89	Western Basin	front	-23.789169	151.159233	TAI/IFC	-50
2	9	90	Western Basin	back	-23.78933	151.158671	TAI/IFC*	-15
2	9	91	Western Basin	front	-23.788089	151.157345	TAI/IFC	10
2	9	92	Western Basin	back	-23.788175	151.156982	TAI/IFC	5
2	9	93	Western Basin	front	-23.784855	151.152475	TAI/IFC	-10
2	9	94	Western Basin	back	-23.784838	151.15185	TAI/IFC	10
2	9	97	Western Basin	mid zone	-23.77942	151.149541	TAI/IFC	-10
2	9	98	Western Basin	mid zone	-23.777213	151.148417	TAI/IFC	5
1	1	8	Fitzroy River	mid zone	-23.516791	150.826025	DeG*	50
1	1	9	Fitzroy River	mid zone	-23.518163	150.813758	DeG	80
1	1	10	Fitzroy River	front edge	-23.525632	150.840437	DeG	20
1	1	11	Fitzroy River	front edge	-23.525762	150.840114	DeG	45
1	1	12	Fitzroy River	front edge	-23.525892	150.839811	DeG*	60
1	1	13	Fitzroy River	front edge	-23.525829	150.839554	DeG	60
1	1	14	Fitzroy River	front edge	-23.525957	150.839211	DeG*	70
1	1	15	Fitzroy River	front edge	-23.525933	150.838897	DeG	70
1	1	16	Fitzroy River	front edge	-23.517216	150.812819	DeG	35
1	1	17	Fitzroy River	front edge	-23.517414	150.813074	DeG	26
1	1	18	Fitzroy River	front edge	-23.517607	150.81331	DeG	25
1	1	19	Fitzroy River	front edge	-23.517771	150.81351	DeG	30
1	1	20	Fitzroy River	front edge	-23.51792	150.813793	DeG	50
1	1	21	Fitzroy River	front edge	-23.518098	150.814011	DeG	50
1	1	22	Fitzroy River	front edge	-23.518282	150.814256	DeG	65
1	1	23	Fitzroy River	front edge	-23.518555	150.814484	DeG	55
3	25	105	Rodds Harbour	front edge	-24.11849	151.560935	DeG	23
3	25	106	Rodds Harbour	second back	-24.118551	151.56103	DeG	25
1	3	4	Balaclava Is	inner zone	-23.576405	150.953286	ES-L	0
1	3	5	Balaclava Is	inner zone	-23.579182	150.943158	ES-L	10
1	3	6	Balaclava Is	inner zone	-23.584793	150.946785	ES-L	15
1	1	38	Fitzroy River	inner zone	-23.520255	150.82647	IFC	-10
1	1	39	Fitzroy River	inner zone	-23.521432	150.827705	IFC	-10
1	1	40	Fitzroy River	inner zone	-23.520009	150.826573	IFC	-7
1	1	41	Fitzroy River	inner zone	-23.520749	150.829804	IFC	-5
2	19	46	Boyne River	estuary edge	-23.949276	151.357785	FLOOD	10
2	19	47	Boyne River	estuary edge	-23.948746	151.357659	FLOOD	10
2	19	48	Boyne River	estuary edge	-23.949546	151.357888	FLOOD	0
2	19	49	Boyne River	estuary edge	-23.951395	151.358566	FLOOD*	0
2	19	50	Boyne River	estuary edge	-23.957589	151.358765	FLOOD*	20
2	19	51	Boyne River	estuary edge	-23.957975	151.356809	FLOOD	0
2	19	52	Boyne River	estuary edge	-23.971303	151.344463	FLOOD	20
2	15	44	Auckland Creek	estuary edge	-23.847658	151.23095	FOX	20
2	15	45	Auckland Creek	estuary edge	-23.846907	151.231081	FOX*	5
2	14	61	Calliope River	Lower stand	-23.831128	151.217429	FOX	5
2	14	62	Calliope River	Lower stand	-23.8321	151.218128	FOX	15
2	14	63	Calliope River	Lower stand	-23.832663	151.218778	FOX	10
2	14	43B	Anabranch	channel edge	-23.838503	151.197853	HAIL*	0
2	14	49B	Anabranch	channel edge	-23.839073	151.197393	HAIL	15
1	14	7	Calliope River	edge	-23.834032	151.20463	HAIL	5
2	14	64	Calliope River	inner zone	-23.83518	151.207178	HAIL	0
2	14	65	Calliope River	inner zone	-23.834139	151.205469	HAIL	0
1	3	3	Balaclava Is	lower fringe	-23.574991	150.956712	IFC	0
2	12	67	Endfield	lower fringe	-23.820992	151.181524	IFC*	10
2	9	69	Fishermans	lower fringe	-23.761405	151.260428	IFC	12
2	18	77	South Trees In	estuary edge	-23.92769	151.295495	IFC	5
2	18	78	South Trees In	estuary edge	-23.92999	151.294526	IFC	10
2	18	81	South Trees In	estuary edge	-23.899787	151.308113	IFC	25
2	9	85	Western Basin	back zone	-23.821366	151.185501	IFC	-10
2	9	87	Western Basin	back zone	-23.801197	151.168093	IFC	-5
2	9	95	Western Basin	front	-23.780238	151.150005	IFC	0
2	9	99	Western Basin	front	-23.76411	151.145521	IFC	3
3	28	104	Rodds Harbour	lower fringe	-24.071817	151.560405	IFC	9
2	18	83	South Trees In	mid zone	-23.858723	151.315228	LiG*	0
2	18	84	South Trees In	mid zone	-23.86246	151.316298	LiG	3
2	9	101	Western Basin	front	-23.824569	151.192084	LiG	9
2	12	37	Endfield	lower fringe	-23.820992	151.181524	TAI/IFC	0
1	3	1	Balaclava Is	LOW	-23.6027	150.95659	TAI/IFC	5
1	1	42	Fitzroy River	LOW	-23.53385	150.85995	TAI/IFC	0
1	6	43	Narrows	LOW	-23.57352	151.02782	TAI/IFC	0

2	14	53	Calliope River	LOW	-23.81758	151.22198	TAI/IFC	20
2	18	70	South Trees	LOW	-23.86554	151.31787	TAI/IFC	5
2	18	71	South Trees	LOW	-23.87675	151.31796	TAI/IFC	5
2	9	102	Western Basin	LOW	-23.81932	151.1783	TAI/IFC	10
3	28	107	Rodds Harbour	LOW	-24.06855	151.53606	TAI/IFC	
3	28	108	Rodds Harbour	LOW	-24.06855	151.53606	TAI/IFC	
3	28	109	Rodds island	LOW	-24.0789	151.55974	TAI/IFC	10
2	14	54	Calliope River	Lower stand	-23.853299	151.21318	POLN	30
2	14	55	Calliope River	Lower stand	-23.855553	151.211909	POLN	20
2	14	56	Calliope River	Lower stand	-23.857672	151.210923	POLN	15
2	14	57	Calliope River	Lower stand	-23.859591	151.206613	POLN	5
1	1	24	Fitzroy River	front edge	-23.534317	150.857378	ES-L	-50
1	1	25	Fitzroy River	front edge	-23.534126	150.85741	ES-L	-70
1	1	26	Fitzroy River	front edge	-23.533951	150.857444	ES-L*	-70
1	1	27	Fitzroy River	front edge	-23.533287	150.857456	SReTr	0
1	1	28	Fitzroy River	front edge	-23.533606	150.857512	SReTr	-30
1	1	29	Fitzroy River	front edge	-23.533394	150.857543	SReTr	5
1	1	30	Fitzroy River	front edge	-23.526323	150.833839	SReTr	-25
1	1	31	Fitzroy River	front edge	-23.526263	150.833866	SReTr	-25
1	1	32	Fitzroy River	front edge	-23.526203	150.833907	SReTr	-70
1	1	33	Fitzroy River	front edge	-23.526137	150.833948	SReTr	-70
1	1	34	Fitzroy River	front edge	-23.526058	150.833982	SReTr	-70
1	1	35	Fitzroy River	front edge	-23.525998	150.834009	SReTr	-70
1	1	36	Fitzroy River	front edge	-23.525905	150.83405	SReTr	-20
1	1	37	Fitzroy River	front edge	-23.525823	150.834219	SReTr	0
2	18	72	South Trees In	sea edge	-23.860514	151.318371	SReTr	-60
2	18	73	South Trees In	sea edge	-23.861483	151.318381	SReTr	-60
2	18	74	South Trees In	sea edge	-23.86306	151.318659	SReTr	-50
2	18	75	South Trees In	sea edge	-23.864238	151.318607	SReTr	-45
2	18	76	South Trees In	sea edge	-23.865773	152.318375	SReTr	
1	3	2	Balaclava Is	upper fringe	-23.574783	150.95524	TAI	25
2	12	66	Endfield	upper fringe	-23.830333	151.181456	TAI	25
2	9	68	Fishermans	upper fringe	-23.763115	151.256853	TAI	10
2	18	79	South Trees In	back zone	-23.904776	151.306273	TAI	10
2	18	80	South Trees In	back zone	-23.902058	151.30788	TAI	10
2	18	82	South Trees In	back zone	-23.897655	151.30898	TAI*	10
2	9	86	Western Basin	sea edge	-23.824758	151.183214	TAI	10
2	9	88	Western Basin	sea edge	-23.801919	151.166418	TAI*	8
2	9	96	Western Basin	back	-23.780577	151.149559	TAI	0
2	9	100	Western Basin	back	-23.763769	151.14423	TAI	15
3	27	103	Rodds Harbour	upper fringe	-24.069928	151.56138	TAI	15
2	14	58	Calliope River	mid edge	-23.836043	151.202322	TAI/IFC	0
2	14	59	Calliope River	mid edge	-23.838301	151.197623	TAI/IFC	5
2	14	60	Calliope River	mid edge	-23.83764	151.199863	TAI/IFC	10
1	3	33B	Balaclava Is	upper fringe	-23.574783	150.95524	TAI/IFC	20
1	3	34B	Balaclava Is	lower fringe	-23.574991	150.956712	TAI/IFC	-10
2	9	35B	Fishermans Ldg	upper fringe	-23.763115	151.256853	TAI/IFC	5
2	12	36B	Endfield	upper fringe	-23.830333	151.181456	TAI/IFC	15
2	9	38B	Fishermans	lower fringe	-23.761405	151.260428	TAI/IFC	10
3	27	39B	Rodds Harbour	upper fringe	-24.069928	151.56138	TAI/IFC	0
3	27	40B	Rodds Harbour	lower fringe	-24.071817	151.560405	TAI/IFC	0
1	3	41B	Port Alma	channel edge	-23.587448	150.860936	TAI/IFC	-10
1	6	42B	Narrows	channel edge	-23.59859	151.043067	TAI/IFC	-5
2	14	44B	Calliope	channel edge	-23.84463	151.211745	TAI/IFC	5
2	18	45B	South Trees	channel edge	-23.920493	151.298435	TAI/IFC	0
2	18	46B	South Trees Brg	channel edge	-23.938709	151.291063	TAI/IFC	0
1	3	47B	Port Alma	channel edge	-23.588285	150.860183	TAI/IFC	20
1	6	48B	Narrows	channel edge	-23.599379	151.041663	TAI/IFC	0
2	14	50B	Calliope	channel edge	-23.844112	151.211859	TAI/IFC	0
2	18	51B	South Trees	channel edge	-23.920846	151.29809	TAI/IFC	0
2	18	52B	South Trees Brg	channel edge	-23.938673	151.290681	TAI/IFC	10

Appendix Table 11. Codes, classifications, locations and descriptive information for Western Basin treatment sites (WB_PC) in the evaluation of dredging and construction activities in Port Curtis between 1987 and 2022. Site locations are displayed in Figure 122. 'FL_CLAM' sites are those showing abrupt mangrove losses with reclamation at Fisherman's Landing.

# CODE	Treatment	PC_WB Site	GF Ref#	Latitude	Longitude	Profile	Abrupt LOSS	Comment on Observed Change
1	FL_RECLAM	7	#1_89	-23.789169	151.159233	front	2016	5% decline 1987-2016/3 75-70, abrupt to 0-5%
1	FL_RECLAM	8	#1_90	-23.78933	151.158671	back	2016	5% decline 1987-2016/3 65-60, abrupt to 0-5%
1	FL_RECLAM	21	#2-01	-23.794438	151.163678	sea edge	2001	5% decline 1987-1998, 70-65, 25% decline 2001, abrupt to 0-5%
1	FL_RECLAM	22	#2-02	-23.79322	151.167216	island	2003	0% rise 1987-1998 50, 10% decline to 2003, abrupt 0-5%
1	FL_RECLAM	23	#2-03	-23.792195	151.162146	sea edge	2018	0% rise 1987-1998, 70, abrupt to 20%, 2018 abrupt 0%
1	FL_RECLAM	24	#2-04	-23.791149	151.16063	sea edge	1998	0% rise 1987-1998, 70, abrupt to 0-15%
2	WBRA	9	#1_91	-23.788089	151.157345	front		10% rise 1987-2022, 60-70
2	WBRA	10	#1_92	-23.788175	151.156982	back		5% rise 1987-2022, 50-55
2	WBRA	11	#1_93	-23.784855	151.152475	front		10% decline 1987-2022, 60-50
2	WBRA	12	#1_94	-23.784838	151.15185	back		10% rise 1987-2022, 50-60
3	WB_REF	13	#1_95	-23.780238	151.150005	front		0% rise 1987-2022, 50%
3	WB_REF	14	#1_96	-23.780577	151.149559	back		0% rise 1987-2022, 60%
3	WB_REF	15	#1_97	-23.77942	151.149541	mid zone		5% decline 1987-2022, 50-45
3	WB_REF	16	#1_98	-23.777213	151.148417	mid zone		10% rise 1987-2022, 60-70
3	WB_REF	17	#1_99	-23.76411	151.145521	front		10% rise 1987-2022, 65-75
3	WB_REF	18	#1_100	-23.763769	151.14423	back		15% rise 1987-2022, 55-70
4	PC_REF	1	#0_36	-23.830333	151.181456	upper fringe		10% rise 1987-2022, 55-65
4	PC_REF	2	#0_37	-23.820992	151.181524	lower fringe		0% rise 1987-2022, 80
4	PC_REF	3	#1_85	-23.821366	151.185501	back zone		10% decline 1987-2022, 50-40
4	PC_REF	4	#1_86	-23.824758	151.183214	sea edge		10% rise 1987-2022, 50-60
4	PC_REF	5	#1_87	-23.801197	151.168093	back zone		0% rise 1987-2022, 60%
4	PC_REF	6	#1_88	-23.801919	151.166418	sea edge		10% rise 1987-2022, 60-70
4	PC_REF	19	#1_101	-23.824569	151.192084	sea edge		10% rise 1987-2022, 70-80

4	PC_REF	20	#1_102	-23.81932	151.1783	sea edge	PLOT: 10% rise 1987-2022, 70-80
4	PC_REF	25	#2-18	-23.765142	151.17799	sea edge	0% rise1987-2022, 70%
4	PC_REF	26	#2-20	-23.76197	151.17625	sea edge	10% rise 1987-2022, 70-80

Appendix Table 12. Green fraction October data for Western Basin treatment sites in Port Curtis between 1996 and 2021. Site locations are displayed in Figure 122, and listed in Appendix Table 11.

	WBSC	(PC_REF)					WBEA	(WB_REF)		WBRA			
YEAR	**2**	**3**	**5**	**19**	**20**	**6**	**16**	**13**	**15**	**9**	**10**	**11**	**12**
	#0_37	#85	#87	#101	#102	#2-20	#98	#95	#97	#91	#92	#93	#94
1996	0.8	0.409	0.516	0.671	0.736	0.731	0.582	0.481	0.45	0.606	0.447	0.484	0.505
1997	0.72	0.422	0.507	0.614	0.58	0.66	0.503	0.437	0.344	0.533	0.47	0.507	0.461
1998	0.975	0.388	0.475	0.764	0.702	0.68	0.576	0.331	0.382	0.594	0.477	0.515	0.586
1999	0.665	0.318	0.572	0.699	0.713	0.657	0.557	0.418	0.454	0.608	0.512	0.429	0.517
2000	0.41	0.384	0.437	0.667	0.687	0.668	0.518	0.451	0.406	0.499	0.425	0.508	0.491
2001	0.59	0.44	0.559	0.694	0.631	0.682	0.464	0.391	0.449	0.477	0.383	0.488	0.378
2002	0.625	0.368	0.461	0.653	0.644	0.595	0.485	0.266	0.343	0.555	0.428	0.397	0.413
2003	0.775	0.457	0.49	0.659	0.728	0.678	0.508	0.359	0.24	0.558	0.417	0.448	0.456
2004	0.75	0.365	0.435	0.686	0.665	0.631	0.412	0.267	0.306	0.512	0.377	0.322	0.446
2005	0.615	0.272	0.413	0.736	0.671	0.633	0.476	0.201	0.26	0.57	0.474	0.407	0.452
2006	0.645	0.256	0.427	0.539	0.623	0.589	0.39	0.258	0.201	0.477	0.414	0.3	0.431
2007	0.61	0.339	0.45	0.657	0.613	0.662	0.426	0.274	0.339	0.516	0.439	0.402	0.441
2008	0.56	0.408	0.474	0.607	0.598	0.65	0.353	0.257	0.366	0.5	0.427	0.362	0.437
2009	0.71	0.316	0.343	0.668	0.659	0.647	0.41	0.145	0.24	0.456	0.344	0.401	0.426
2010	0.825	0.429	0.556	0.77	0.692	0.708	0.521	0.345	0.41	0.58	0.504	0.508	0.555
2011	0.72	0.278	0.472	0.641	0.729	0.616	0.42	0.355	0.362	0.423	0.224	0.471	0.339
2012	0.705	0.291	0.549	0.726	0.682	0.636	0.471	0.162	0.186	0.429	0.3	0.201	0.442
2013	0.81	0.277	0.519	0.73	0.69	0.638	0.514	0.13	0.199	0.562	0.392	0.233	0.508
2014	0.8	0.324	0.478	0.701	0.708	0.677	0.606	0.233	0.314	0.607	0.493	0.306	0.507

2015	0.77	0.243	0.582	0.7	0.715	0.673	0.565	0.242	0.273	0.532	0.459	0.326	0.535
2016	0.8	0.293	0.541	0.677	0.762	0.713	0.555	0.263	0.313	0.599	0.507	0.393	0.544
2017	0.875	0.312	0.519	0.71	0.805	0.717	0.481	0.369	0.348	0.622	0.51	0.43	0.515
2018	0.78	0.353	0.438	0.621	0.706	0.668	0.536	0.217	0.251	0.578	0.507	0.48	0.554
2019	0.735	0.345	0.433	0.71	0.657	0.645	0.596	0.407	0.34	0.641	0.52	0.436	0.541
2020	0.76	0.368	0.461	0.773	0.711	0.725	0.609	0.417	0.377	0.631	0.539	0.473	0.548
2021	0.77	0.371	0.51	0.849	0.484	0.764	0.703	0.481	0.45	0.663	0.215	0.278	0.541

APPENDIX 9

'ALERT-TO-ACTION' MONITORING OF THREATENED MANGROVES

A Proposal for an Informative Monitoring Program
NC Duke, 22 August 2022

The project offers a scientifically-validated framework for compliance and dissemination of expert technical advice for key stakeholders in industry, government, universities and with indigenous rangers and community volunteers. The outcome will provide the proponent with a robust and sensitive program FOR monitoring the health of mangrove ecosystems in the vicinity of development works or other potentially threatening activities.

The project is organized as two component parts consisting of: 1) a monitoring and inspection phase; and 2) an alert-to-action response phase. The combination of these components follows the technical requirement where field surveys will be used to validate canopy condition measured using appropriate remote-sensing vegetation indices. The outcome will be a monitoring program with monthly updates on the condition and health of mangrove and saltmarsh habitat in the vicinity of development works being undertaken. Based on these canopy measures, the project team in consultation with stakeholders will develop and seek to apply a risk assessment matrix for management responses ranging from targeted investigations regarding the cause of any impact, mitigation measures as needed, and any requirements for works to be interrupted, as necessary. As stipulated by the regulator, the monitoring program may be continued for 5 or more years post construction to ensure development works cause no longer-term harm or influence on the potentially threatened mangrove habitat.

Monitoring would be conducted at a minimum of three representative mangrove areas for each treatment grouping, including: a) sites in the immediate vicinity of development works; and, b) sites in a reference area nearby but remote from the threatened area.

Project Components

COMPONENT 1 – TASK A

Criteria: ***Monitoring and Inspection Program***. A program to evaluate tidal wetlands (mangroves and saltmarsh plants) to detection and quantify change, such as net losses and gains in key habitat criteria (canopy density, % cover and biodiversity) – continuing for 5 years post development works.

Detailed Plan

This component essentially comprises field work divided into two parts to span the period of 5-plus years, since the program is required to operate until at least 5 years post construction works. This project component is required for field validation of specific monthly changes and fluctuations in mangrove and saltmarsh vegetation at scales matching empirical proxies measured from satellite imagery.

1. ***Mangrove long-term plots***. The monitoring program will compare the condition of mangroves in at least two treatment areas as the potentially impacted area for comparison with the non-impacted reference area. Three representative 20 m X 10 m long term plots will be established in

each area and measured in Year 1, and remeasured in year 5. These data are required for description of forest structure (species, tree density, basal area) and biomass (kg woody material per hectare) for the respective areas over the longer-term. As these locations represent otherwise common shoreline environments, the data are required to quantify underlying differences between the three areas. Each plot will be measured under this plan just twice during the 5 plus year program.

2. ***Mangrove litterfall and shoot observations***. Further to establishment above of three treatment areas (vulnerable and comparative), 6 x 1 m^2 litterfall traps and 6 shoot observation stations (30 tagged canopy leafy shoots) will be established in each. For litter traps, content will be collected each month for 12 months minimum in the first year, and again for the 5^{th} year post construction. This is considered sufficient for validation of the local monthly relationship with remote-sensing measures of canopy condition. Each collection is required to be sorted, dried and weighed each month of collection. Sorting involves separation of leaves, stipules, reproductive parts, wood and debris. Further field canopy condition measures include below canopy light meter readings. These data are required for quantification of variability in canopy condition through annual seasonal cycles, and for validation of changes in density for comparison with satellite sensing data. With each 12-month record of canopy condition, data will be used to derive allometric equations to define satellite vegetation indices for use as proxies of the field measures of canopy condition. Accordingly, specific correlative relationships enable satellite measures of canopy condition to be used for the monitoring of mangrove canopy health based on definable thresholds as action triggers. These are defined in the Project Component 2.

COMPONENT 2 – TASK B

Criteria: ***Alert to Action Program***. Development and application of three critical work sections for the protection of tidal wetland (mangrove) areas threatened by development works, based on a species-specific risk matrix, appropriate trigger criteria, and linked to Alert to Action procedures – with 6-monthly reporting.

Detailed Plan

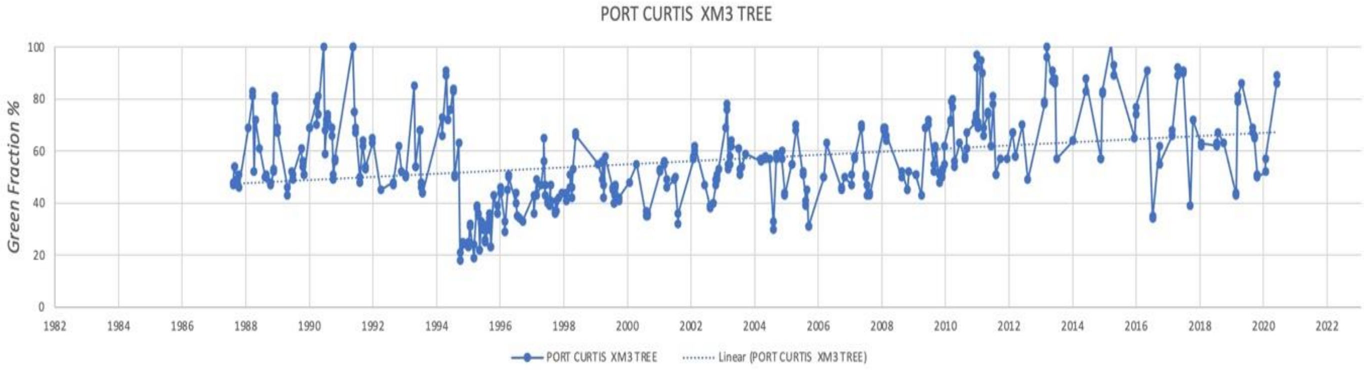
This project component utilises satellite image data for remote measures of canopy and vegetation condition of mangroves. The plan is to compile these measures on a monthly basis during development works and afterwards for at least 5 years. The remote measures will be taken for each sampling site established in Project Component 1. This applies in particular to litterfall and shoot observation plots where comparative measures of canopy condition are to be taken. Remote sensing of canopy condition at specific point locations has been developed and proven highly beneficial and accurate for monitoring canopy condition. This innovative procedure, based on 'green faction' timeseries plots was applied during assessment of widespread mass dieback of mangroves in the Gulf of Carpentaria (Duke et al., 2022).

For the proposed program, data for each monthly period will be compiled and averaged for each monthly interval during the 5-plus year monitoring program. Application of remote sensing data will be classified and developed according to the three criteria with this component, including a species-specific risk matrix, appropriate trigger criteria, and their linking with suggested Alert to Action procedures.

- ***Risk matrix***. Mangrove canopy condition varies notably on a monthly basis (Appendix Fig. 7). This defines a range of normal canopy variability between roughly 80-100% - but specifically defined for each site. By contrast, catastrophic canopy decline, as inflicted by severe storm defoliation, would be down to 0-10%. A further characteristic will also be used for any progressive decline over a number of months. This would be especially notable where the decline was only detected in specific plots and not others. This allows the risk matrix to equate directly to canopy condition as a percentage of maximal values. In this way, lower values represent greater damage while higher values indicate least harm, or normal seasonal variation. These conditions can only be defined fully after the sites have been selected and monitoring started.

- ***Trigger criteria***. As set out above, the relevant criteria applicable for this monitoring program are proposed for the three monitored Work Areas, as follows (% of maximal): a) 0-10 as **catastrophic**; b) 10-30 as **severe**; c) 30-60 as **threatening**; d) 60-80 as **notable**; e) 80-100 as **normal**. See Appendix Table 13 for an example draft of a risk matrix table. The impact criteria and this risk matrix will be reviewed further once initial 3 months and 12 months of sensor measures have been generated and compared with actual field measures. However, it is expected the hierarchy of severity ratings will remain.

- ***Alert to action procedures***. Also set out in Appendix Table 13 are possible alerts and proposed responses for investigations into the causes of any impacts, mitigation intervention, and development works. These responses will be initiated when specified trigger criteria are met, or exceeded. The trigger criteria outlined above have been tentatively linked to various response actions depending on the monthly measures calculated and which site locations have been impacted, being critical, vulnerable or comparative. While there will be on-going re-evaluation of green fraction satellite data and field measured canopy condition, there will also require response options to be discussed and agreed upon by the stakeholders. In any case, it is suggested these responses will be ranked according to the range of damage severity classifications (especially for critical and vulnerable sites) as, for example: a) **catastrophic** – cease construction works, conduct detailed assessment of the cause of damage and apply mitigation actions to reduce further harm; b) **severe** – cease construction work, conduct detailed assessment of the cause of damage and its mitigation; c) **threatening** – moderate level alert with reduction in potentially harmful work activities; d) **notable** – initial alert with a watching brief on potentially harmful work practices; e) **normal** – business as usual. Alteration to development works will depend on whether the impact was deemed to be derived from the development works, or from an external source such as a severe cyclone, or flooding. These considerations would be addressed in the selection of monitoring sites, both within and near the work area. Furthermore, the program team will develop a decision tree schematic to clearly depict and define how amended management practices will mitigate the issues at hand, and be most effective.



Appendix Figure 7. Monthly Green Fraction timeseries data from satellite imagery shows changes in mangrove canopy condition at a site in the mouth of the Calliope River, Port Curtis (-23.839073, 151.197393). This site had notable dieback around 1994/1995, when it was struck by a severe hail storm in October 1994 (Houston 1999). These monthly measures of canopy condition show the impact and proportional loss (down to 10-20%, from 60-70%) at the time, notably followed by recovery over the next 4-5 years. Data like these will be used to monitor the condition each month of threatened mangroves.

Appendix Table 13. An example of a Risk Matrix for Likely Impacts on Mangrove Areas based on Duke et al. (2020a,b).

IMPACT CRITERIA	Sensor Sites Condition									
	Canopy Condition %	Sites #'s	Work Area Code	Work Area Description	Work Area Risk Category	Habitat IMPACT Description	Monitoring Work	INVESTIGATIVE RESPONSE	WORK RESPONSE	MITIGATION RESPONSE
Catastrophic	0-10	13-18	WBRA	Surrounding Area	Comparative	Extreme habitat loss/damage	Continue Monitoring	Identify Cause	Continue Work	Apply Mitigation
	0-10	7-12	WBEA	Broader Work Area	Vulnerable	Extreme habitat loss/damage	Continue Monitoring	Identify Cause	Stop Work	Apply Mitigation
	0-10	1-6	WBSC	Bunded Work Area	Critical	Extreme habitat loss/damage	Continue Monitoring	Identify Cause	Stop Work	Apply Mitigation
Severe	10-30	13-18	WBRA	Surrounding Area	Comparative	Moderate habitat loss/damage	Continue Monitoring	Identify Cause	Continue Work	Apply Mitigation
	10-30	7-12	WBEA	Broader Work Area	Vulnerable	Moderate habitat loss/damage	Continue Monitoring	Identify Cause	Stop Work	Apply Mitigation
	10-30	1-6	WBSC	Bunded Work Area	Critical	Moderate habitat loss/damage	Continue Monitoring	Identify Cause	Stop Work	Apply Mitigation
Threatening	30-60	13-18	WBRA	Surrounding Area	Comparative	Anticipated habitat loss/damage	Continue Monitoring	Identify Cause	Continue Work	Apply Mitigation
	30-60	7-12	WBEA	Broader Work Area	Vulnerable	Anticipated habitat loss/damage	Continue Monitoring	Identify Cause	Reduce Work	Apply Mitigation
	30-60	1-6	WBSC	Bunded Work Area	Critical	Anticipated habitat loss/damage	Continue Monitoring	Identify Cause	Reduce Work	Apply Mitigation
Notable	60-80	13-18	WBRA	Surrounding Area	Comparative	Likely habitat damage	Continue Monitoring	Identify Cause	Continue Work	Continue Maintenance
	60-80	7-12	WBEA	Broader Work Area	Vulnerable	Likely habitat damage	Continue Monitoring	Identify Cause	Continue Work	Continue Maintenance
	60-80	1-6	WBSC	Bunded Work Area	Critical	Likely habitat damage	Continue Monitoring	Identify Cause	Continue Work	Continue Maintenance
Normal	80-100	13-18	WBRA	Surrounding Area	Comparative	Normal seasonal variations in canopy condition	Continue Monitoring	None	Continue Work	Continue Maintenance
	80-100	7-12	WBEA	Broader Work Area	Vulnerable	Normal seasonal variations in canopy condition	Continue Monitoring	None	Continue Work	Continue Maintenance
	80-100	1-6	WBSC	Bunded Work Area	Critical	Normal seasonal variations in canopy condition	Continue Monitoring	None	Continue Work	Continue Maintenance

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