Northern Australia Environmental Resources Hub
National Environmental Science Programme

Tropical Water Quality Hub
National Environmental Science Programme

Assessing the Gulf of Carpentaria mangrove dieback 2017–2019

Volume 1: Aerial surveys

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Cover photographs

Front cover: A section of severely impacted shoreline east of the mouth of the Limmen Bight River, NT (photo: Norm Duke).

Back cover: A Carpentaria Land Council Aboriginal Corporation ranger assisting with aerial surveys around Burketown, Qld (photo: Norm Duke).

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Acronyms

ATCOR ....Atmospheric and Terrain Correction

BRDF ....Bi-Directional Reflectance Distribution Function

di-GPS...............Digital images GPS

F–L ....Flinders–Leichhardt

GIS ....Geographical Information Services

GPS ....Global Positional System

JCU ....James Cook University

NASY ....Northern Australia Sustainable Yields

NESP ....National Environmental Science Program

NT ....Northern Territory

Qld ....Queensland

RMSE ....Root Mean Squared Error

SE ....South-East

SOI ....Southern Oscillation Index

SW ....South-West

TC ....Tropical Cyclone

TNRM ....Territory Natural Resource Management

TropWATER .....Centre for Tropical Water and Aquatic Ecosystem Research

USGS ....United States Geological Service

UTM ....Universal Transverse Mercator

WCI ....Wetland Cover Index

Abbreviations

Cape .... Cape York Peninsula

Gulf .... Gulf of Carpentaria

Vol. 2 .... Duke N.C., Mackenzie J., Hutley L., Staben, G., & Bourke A. (2020) Final Report: Assessing the Gulf of Carpentaria mangrove dieback 2017–2019. Volume 2: Field studies. James Cook University, Townsville, 150 pp.

W Cape .... Western Cape

Acknowledgements

We thank and acknowledge the Traditional Owners of the land and sea country in which we conducted these surveys, and we pay our respects to their Elders – past, present and emerging. In doing so, we acknowledge the important role that the traditional custodians of land and sea country continue to play in protecting the cultural, natural and other values of tidal wetlands throughout the Gulf of Carpentaria region (Figure 0.1).

Figure 0.1. "When you kill mangroves, you kill sea turtles". This local artwork by Marranbala Traditional Owners of the Limmen Bight area of the Northern Territory echoes the sentiments of Indigenous peoples across the Gulf region. All marine resources and habitat are intimately connected and they have deep cultural value.

We gratefully acknowledge the rangers in Normanton and Burketown with the Carpentaria Land Council Aboriginal Corporation (Figure 0.2), and in Borroloola with the Mabunji Aboriginal Corporation, plus the budding Marranbala rangers at Limmen fishing camp.

Figure 0.2. These NESP investigations into the 2015–2016 mangrove dieback have involved a large number of local stakeholders and end-users, including the Aboriginal rangers in stations spread across the Gulf region. The research team are grateful for all their interest, comments and assistance in this program.

The Landsat imagery used on this study were supplied by the Northern Territory Government, through a collaborative partnership between the Northern Territory Government's Department of Environment and Natural Resources and Queensland Governments, Department of Science, Information Technology, Innovation and the Arts, Remote Sensing Centre.

The 2019 aerial survey was in large part funded by World Animal Protection[1] and Dr. Denise Hardesty at CSIRO for their interest in stranded marine debris like ghost nets along shorelines surveyed. More that 700 ghost nets were located along with significant numbers of abandoned crab pots and gill nets.

We further acknowledge our great appreciation for the assistance provided by Grant Staben (NT Government) for preparing green fraction plots used with this investigation, plus Rob Coles and Apanie Wood who gave their time freely to the successful conduct of the 2017 and 2019 aerial surveys, respectively. We also thank the manager and pilots with Cloncurry Mustering Company for navigating us safely and efficiently across the Gulf and back on two major aerial surveys and the two field surveys.

This research project involved multiple Hubs of the Australian Government's National Environmental Science Program and we thank the Earth Systems and Climate Change (ESCC) Hub and the Marine Biodiversity Hub for their contributions. The ESCC Hub report, *Climate drivers of the 2015 Gulf of Carpentaria mangrove dieback*, can be found here. Survey data is available at eatlas.org.au.

[1] worldanimalprotection.org.au

Executive summary

1. In late 2015, extensive areas of mangroves across the Gulf of Carpentaria (the Gulf) died under mysterious circumstances. This significant event became public in early 2016 when shocking images by local fishermen and environmental consultants emerged from this remote part of northern Australia. The images showed the impacted area extended along more than 1,000 km of shoreline where at least 7,400 ha of mangroves had died (Figure 0.3) seemingly in a matter of months (Duke et al., 2017). There were many questions about the potential cause but what became clear was the lack of a known responsible factor – like a severe storm or a large chemical spill. The one corresponding event at the time concerned the unusually extreme El Niño weather event with record-breaking high temperatures, a prolonged drought, and an associated sudden temporary drop in sea level. There were no prior records that showed that any of these factors caused such extensive dieback of mangroves before. While there was uncertainty surrounding the cause, the scale of the event was unprecedented in severity and extent.

Figure 0.3. Aerial surveys revealed the full extent of the 2015–2016 mass dieback of mangroves in the Gulf of Carpentaria from Queensland to the Northern Territory. Image shows Transect 1A in the Northern Territory taken in October 2018.

2. Subsequent to this discovery in 2016, the National Environmental Science Program (NESP) funded the James Cook University TropWATER Centre to conduct an urgent 3-year research investigation into this mass dieback. The objective was to elaborate on the circumstances surrounding the event, to map the extent, to conduct aerial surveys to quantify shoreline condition, to carry out field studies to validate remote assessments, to engage with local Aboriginal ranger groups and to raise their capacity for monitoring, and to generally raise awareness of the incident and its cause amongst Gulf community residents and the wider group of stakeholders and end-users in Queensland and the Northern Territory.

3. These investigations completed in late 2019 were led by Dr Norman Duke and Jock Mackenzie from James Cook University (JCU) TropWATER Centre MangroveWatch Hub. The results presented with this final report for the project make up two volumes: Volume 1 – mapping and aerial shoreline surveys of mangrove condition and change along the coastline and major estuary mouths; and Volume 2 – field studies of shoreline condition plus communication efforts achieved and planned.
4. In total, this final report provides a thorough assessment of the 2015–2016 incident – its location, severity and damage, associated influences, links with causal factors, and potential for recovery. Note that a summary of the circumstances surrounding the event and the diversity of findings from each aspect of these investigations is given in Vol. 2: 'The mass dieback of Gulf mangroves in late 2015 – a summary'.
5. This, Volume 1 of the report, documents the major findings of shoreline surveys and mapping studies investigating this 2015–2016 mass dieback of mangroves in the Gulf.
6. Mapping of Gulf shorelines located dieback areas and quantified associated vegetation units, specifically including areas of mangroves, saltpan and saltmarsh, and the 2015–2016 mangrove dieback. These studies found the area of dieback was 7,650 ha – slightly more than previously reported. The proportion of dieback was around 6% of the impacted area. The area impacted extended from Blue Mud Bay in the Northern Territory to just north of the northern Mitchell River mouth in Queensland.
7. Mapping showed dieback areas mostly occurred along Gulf shoreline fringing mangroves rather than along banks bordering estuarine reaches upstream. Specifically, dieback areas consistently occurred at the rear or upper edge of the shoreline mangrove fringe.
8. Historical time series mapping showed the loss and depletion of shoreline mangrove fringing stands as seen in 2015–2016 had occurred earlier between 1978 and 1987. This is the first evidence of an earlier comparable dieback event. Of further note, this earlier dieback had also occurred in sites in both the Northern Territory and Queensland.
9. By using green fraction time series plots of canopy vegetation condition, dieback was shown to have occurred in late 2015, and this period was synchronous across the Gulf. These plots also showed that since 1987 these shorelines had been following an apparent recovery trajectory with stable canopies only established around 2000. This was consistent with the earlier occurrence of dieback prior to 1987 discovered with the mapping studies.
10. Aerial surveys were conducted in consultation with local communities and Indigenous ranger groups, including the Carpentaria Land Council Aboriginal Corporation in Queensland (Figure 0.4) and the Mabunji Aboriginal Corporation in the Northern Territory.
11. The aim of aerial shoreline surveys was to systematically record and investigate the presence of 2015 mangrove dieback, the overall condition of shorelines, processes affecting the mangrove vegetation, and the health of tidal wetlands along Gulf shorelines, as well as in the mouths of major estuarine systems (Figure 0.5). These surveys were repeated in 2017 and in 2019 to gain insight and knowledge of the issues affecting shorelines, and the severity of factors influencing Gulf shorelines.

Figure 0.4. Aboriginal rangers joined our aerial surveys giving advice about their country and learning about our surveys of the 2015–2016 mangrove dieback.

12. A key outcome of the aerial surveys was a baseline database or library of more than 19,534 geotagged oblique images in 2017 and 2019 covering every metre of shoreline plus a series of inland profiles extending to the upper limits of tidal inundation in 37 estuarine outlets. The number of images was roughly equal in number for shorelines and those taken on estuarine mouth surveys. The complete set of imagery is available for further evaluation by specialists who are encouraged to add additional systematic search criteria and to evaluate change in future surveys.
13. Estuary assessments include summaries for estuarine entrances scoring changes to mangroves and tidal wetlands generally. Observed threats and management issues were listed as potentially beneficial management actions. Imagery and other data collected during these surveys provide a baseline from which to assess future change occurring along these Gulf shorelines and estuaries.
14. Compiled observations of current drivers of change and severity of impacts were compiled for 37 major estuarine sites, from east to west including Mission River, Embley River, Watson River, Holroyd River, Christmas Creek, Mitchell River, South Mitchell River, Nassau River, Staatan River, Gilbert River, Accident Inlet, Norman River, Flinders River, Leichhardt River, Albert River, Nicholson River, John's Creek, Syrell Creek, Massacre Inlet, Dugong River, Toongoowahgun River, Elizabeth River, Sandalwood Place River, Calvert River, Robinson River, Wearyan River, McArthur River, Mule Creek, Limmen Bight River, Towns River, Roper River, Miyangkala Creek, Rose River, Muntak River, Walker River, and Koolatong River.
15. The current shoreline and estuarine evaluations identified more than 30 issues in tidal wetland and shoreline habitats. Some were associated with rising sea levels, severe and frequent storms, while others resulted from feral animals plus other seemingly uncontrolled but damaging local land management practices. Issues were divided into direct and indirect human causes, plus others not obviously related to human activities (being for the most part, 'natural' causes). The most notable and dominant issue was shoreline retreat, coupled with landward transgressions of saline water and tidal wetland vegetation.

Figure 0.5. Aerial surveys in 2017 and 2019 filmed shorelines and estuaries around the Gulf from an R-44 helicopter. Observations were made of 37 estuaries, where we scored active indicators of change like the 2015–2016 mangrove dieback and shoreline erosion.

16. A significant outcome with these investigations has been the reporting of previously unrecognised notable impacts on shoreline habitats along the Gulf of Carpentaria shorelines of Queensland and the Northern Territory. These included: a) locally severe damage of mangroves caused by Tropical Cyclone Trevor in early 2019 surrounding the Robinson River mouth (Figure 0.6) and by Tropical Cyclone Owen in late 2018 for the southern part around Limmen Bight (Figure 0.7); and b) severe generalised impacts like terrestrial retreat and shoreline erosion that increased from eastern to south-western estuaries and respective sections of shoreline – consistent with an increasing trend in recorded levels of sea level rise.

17. These incidents were indicative of the state, condition and health of shorelines. These measures shoreline status were used to identify and quantify dominant environmental drivers. A pragmatic classification system developed by Duke and Mackenzie (this report) quantifies ongoing and emerging environmental issues, including human access; impacts by feral pigs; fires; weeds; shoreline and estuarine erosion and deterioration; and landward transgression associated with saline encroachment. These are considered emerging dominant environmental issues in response to changing global climate and rising sea levels.

18. These data provide overall information on the condition and severe changes taking place in critical Gulf shoreline ecosystems. Accordingly, habitat condition was linked to specific drivers of change. This information is necessary for guiding and directing well-informed, local and national management priorities by targeting specific and identifiable issues, their severity, and their most likely causes. The findings of these surveys complement pre-existing, on-going and future resource assessments of shoreline environments and intertidal wetland habitats.

Figure 0.6. During the 2019 aerial survey, we observed extensive and severe canopy damage caused by Category 4 Tropical Cyclone Trevor in February, that year. The impacts were evident in shoreline and mangrove vegetation along 400 km of Gulf coastline from Calvert River to Wearyan River. These impacts on tidal wetlands had been unreported before the NESP surveys. The damage to recovering 2015–2016 dieback areas was significant and emphasised the importance of quantifying accumulative impacts.

19. The aerial surveys are the first comprehensive record of oblique and continuous views of coastal shorelines for this large section of the Gulf of Carpentaria – providing a working database of more than 25,000 high-resolution images. This record is a lasting primary reference for baseline visual characterisations of shorelines for 2017 and 2019.

Figure 0.7. The impact on the Limmen shoreline of Category 3 Tropical Cyclone Owen in December 2018 on 2015–2016 dieback areas. This is more evident when comparing this 'after' image taken in September 2019 with the image taken 'before' in September 2018 (Figure 0.3). Standing dead stems and seedling recruits seen before have a been scoured and dumped inland. Note the piles of wood wrack evident as grey patches centre foreground extending into the distance.

1. Introduction and general observations

This is the final report of National Environmental Science Program (NESP) funded investigations into the 74 km^2 of unusual mass dieback of mangroves that occurred in Australia's Gulf of Carpentaria in late 2015. This incident was the most damaging single event to impact mangrove ecosystems ever recorded. And, its sudden and widespread occurrence was largely unexplained.

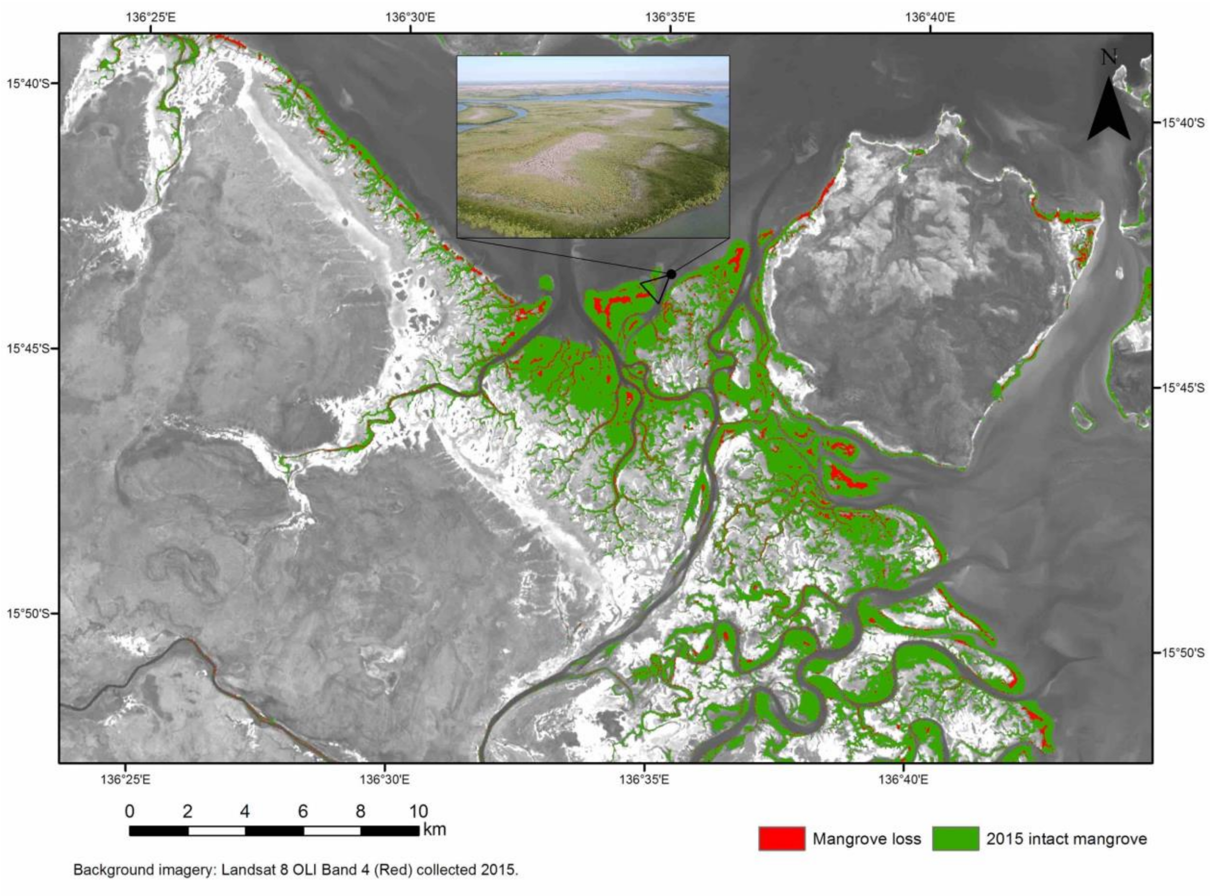

Figure 1.1. Mangrove dieback was notable (in red) amongst surviving mangroves to show the common occurrence of greatest impact along seaward shorelines rather than in estuaries. This image shows the coast around the mouth of the McArthur River and Centre Island just south of Mule Creek in the Northern Territory. The inset image taken in June 2016 shows a section of mangrove shoreline where dieback was in adjoining mangrove zones of Avicennia marina *and* Rhizophora stylosa *where the former bordered the inner saltpan–saltmarsh zone. Such distributional patterns uniquely distinguished this instance of mangrove dieback in 2015–2016.*

The situation in late 2016 (Figure 1.1) was summarised by Duke et al. (2017):

> During the summer of 2015–16, mangroves in the sparsely populated Gulf of Carpentaria (the Gulf) area of northern Australia suffered a particularly severe occurrence of dieback. News of the incident was, at first, slow to emerge from this remote, largely unmonitored region. A small number of reports and images from concerned community members along the Gulf coast were followed up by *ad hoc* scientific surveys during 2016 to better define the affected area. The total area affected extended from Roper River in the Northern Territory to Karumba in Queensland, a distance of more than 1,000 km of shoreline.

This mysterious occurrence of mass dieback of mangroves was concurrent with destructive, high water temperatures that bleached lengthy sections of Australia's Great Barrier Reef (Hughes et al., 2017), and its reported culprit – the 2015–2016 El Niño weather event. This association prompted understandable questions about links also between the nearby mangrove dieback and extreme weather conditions at the time (Harris et al., 2017). Could these weather conditions also be responsible for mangrove dieback? Whatever the answer, such a situation had never arisen before with mangroves dying in such dramatic circumstances. This was unprecedented. Accordingly, the likely cause was considered seemingly unusual and rarely realised, with earlier instances possibly going undetected.

Figure 1.2. Mangroves are acknowledged habitat for all sorts of marine life. When the habitat is damaged by severe dieback, these animals are displaced and usually die.

1.1 Climate and natural drivers of change

Given the important ecological (Figure 1.2) and economic services provided by these coastal marine ecosystems, there was an urgent need to better understand the drivers of this serious environmental impact; its sudden and profound ecosystem perturbations, the likelihood of its reoccurrence, and the processes disrupted within these vulnerable coastal marine ecosystems. Serious concerns had been raised regards the implications of such an event for management strategies and policy direction in the face of such sudden depreciation of crucial natural resource at both local and regional scales. These concerns were compounded further by questions as to whether the event might re-occur, and whether there might have been prior occurrences.

For these reasons, the dieback event re-enforced a desire amongst local stakeholders and end-users to find ways to minimise future damaging impacts on the social, cultural and economic well-being of communities living in this remote Gulf region. Local people are reliant in many ways on the ecosystem services provided by such natural marine coastal habitats like commercial and recreational fishing industries, carbon sequestration, and shoreline stability. Most notably, these views were now underpinned by the novel realisation that mangroves and tidal wetland ecosystems appeared now to be uncharacteristically vulnerable and sensitive to extreme weather events and climate change.

These NESP funded investigations set out to settle such questions by carefully taking a close look at the evidence from a range of sources including historical archives of weather conditions, sea levels, tidal variation, the Southern Oscillation Index (SOI), satellite imagery, and other published accounts. These records could then be compared with other evidence gathered from the scene using aerial surveys and field studies. Getting to impacted sites was integral to these enquiries as these were the actual places where dieback had occurred – and, where dead and damaged vegetation remained. This was done to answer whether there were any indications or evidence left behind at these scenes of dieback impact.

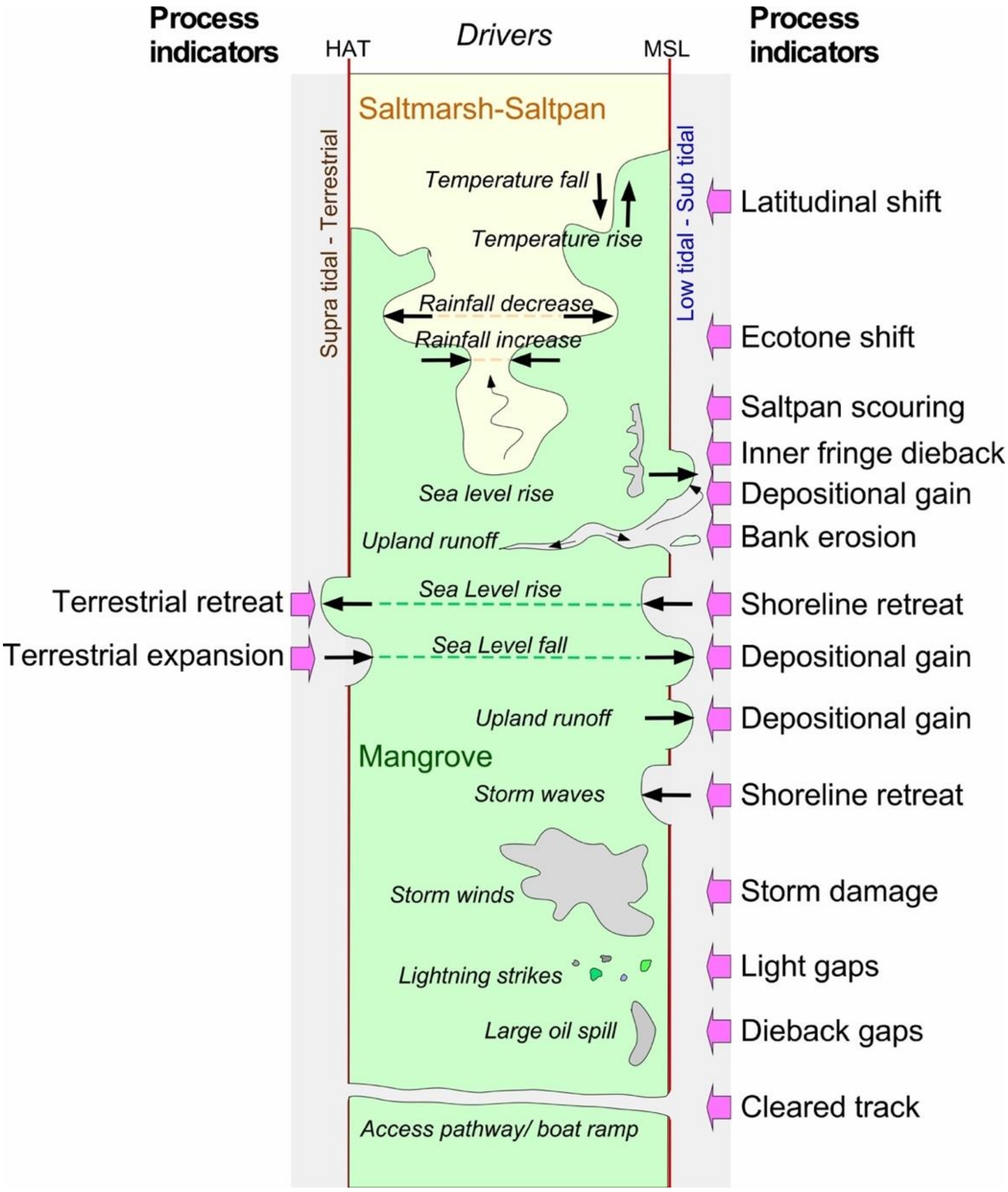

Figure 1.3. An illustrative schematic of tidal wetland habitat (shaded green and pale yellow) and degraded habitat (grey shading) showing process-response indicators associated with respective drivers (pink arrows) acting at specific ecotone locations across the tidal profile between land (left) and sea (right).

Shoreline aerial surveys and field studies were undertaken along most of the remote coastline of Australia's Gulf of Carpentaria from 2017 to 2019. As noted, the objective with these studies was to investigate the mass dieback of mangroves along with the most likely cause. These studies also set out to evaluate how damaged mangrove forests were coping 3–5 years afterwards. Accordingly, we set out to review records and evidence from remote and on-ground sources to gain a pragmatic and informative outcome.

In this, Volume 1, we examine key factors influencing tidal wetlands along with the responses of the ecosystem as observed in mapping and from two major aerial surveys in 2017 and 2019. Our aim was to link observed processes of change (the indicators) to key drivers responsible where possible. To do this, we specifically drew on recent monitoring surveys of environmental condition and processes observed along more than 15,000 km of shorelines across northern Australia, including shoreline surveys of eastern northwestern Australia (Duke et al., 2010), the Torres Strait Islands (Duke et al., 2015), and Cape York Peninsula (Duke & Mackenzie, 2017). The 2015 event notably affected a vast region of coastal tidal wetlands and warranted specific and targeted attention. The current status has been evaluated in this treatment, but first, we briefly review the factors that form and shape the tidal wetland habitat, including mangroves. The responses observed to the various factors (Figure 1.3) has helped to identify the responsible drivers and quantify their influences.

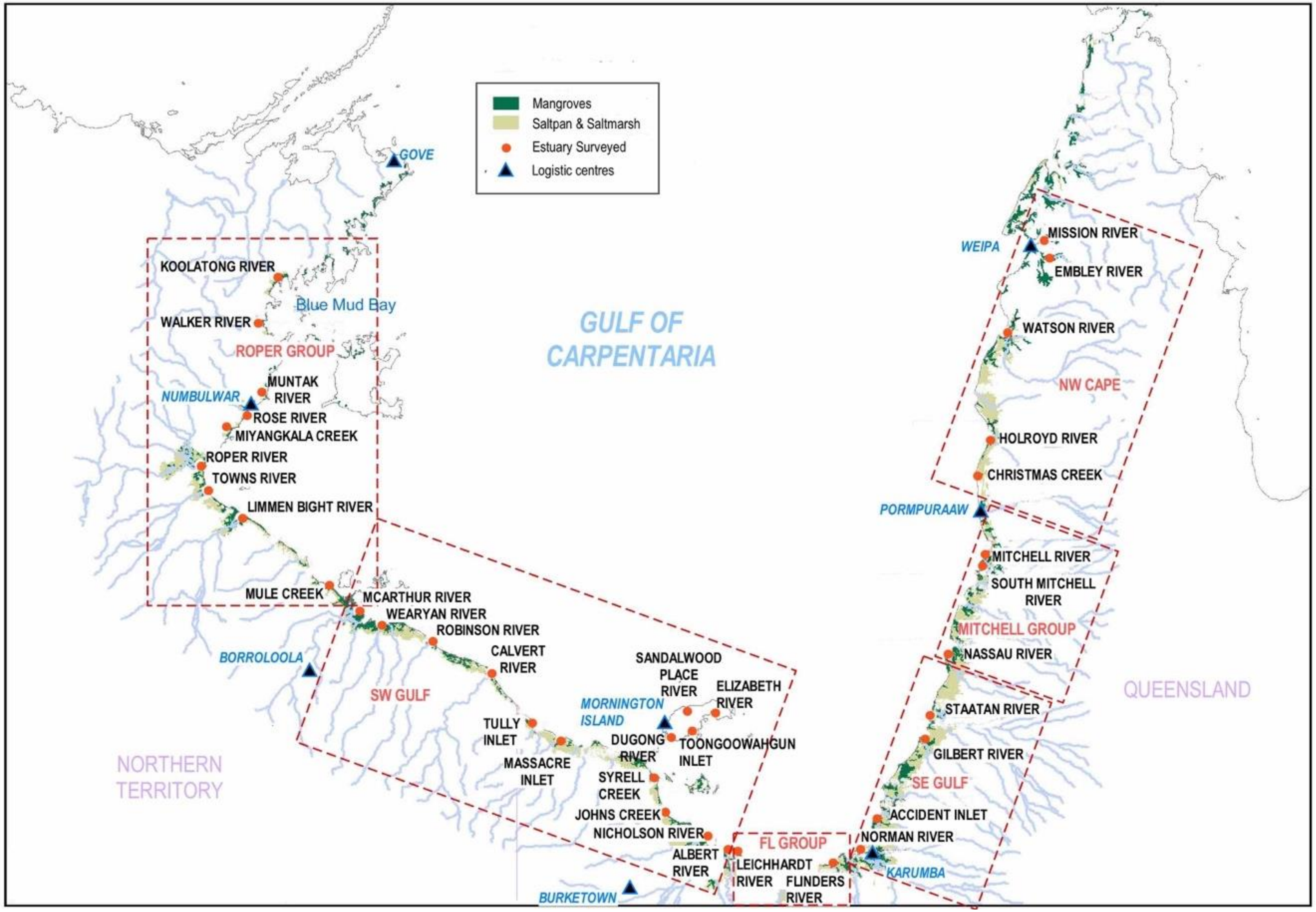

Figure 1.4. Map of surveyed shorelines and estuary mouths from Mission River in Weipa, Queensland, to Koolatong River in Blue Mud Bay, Northern Territory. Dashed rectangles show estuaries and shorelines according to the CSIRO NASY project (CSIRO, 2009a, 2020b, 2020c).

The tidal wetland habitats are comprised of at least three broad vegetation types (Duke et al., 2019a) including mangroves (trees and shrubs), tidal saltmarsh (succulents and sedges), and saltpans (microphytobenthos). This broadly defined habitat type is collectively influenced by a series of environmental drivers where each can be linked to recognisable processes and changes within mangrove tidal wetlands (like dieback) in response to changes in particular environmental factors (like decreased soil moisture and high salinities). Based on this encompassing framework, we have identified a number of drivers operating at different spatial and temporal scales and linked each to an observed indicator (Figure 1.3). These indicators are further described and explained in a number of earlier publications (Duke, 2014; Duke & Mackenzie, 2018; Duke et al., 2019a). By systematically scoring observations of these indicators, it was possible to rapidly both identify and quantify the drivers at play across a broad landscape. For example, dieback or expansion of mangroves alongside saltmarsh and pans has been significantly correlated with longer-term rainfall (Duke et al., 2019a).

As noted, these observations were gathered during two major aerial surveys in 2017 and 2019 recording imagery and observations from the entire length of shoreline, around 2,000 km of shoreline from Weipa to Blue Mud Bay along the southern shorelines of the Gulf of Carpentaria, and included estuary mouth surveys of 37 river mouths and inlets (Figure 1.4).

1.2 Summary of planned outcomes

1. A thorough assessment of the 2015 incident of mass mangrove dieback – its location, severity and damage, associated influences, links with causal factors and potential for recovery,
2. Consultation with local communities and Indigenous ranger groups,
3. Extensive archived database of imagery and data documenting the 2017 and 2019 condition of the entire shoreline of the southern shorelines of the Gulf of Carpentaria,
4. All imagery and data will be made available for public use,
5. Conclusions and preliminary analyses, plus an additional database of observations made during both aerial surveys,
6. Maps of the shorelines surveyed, including specific parameters, regards the 2015–2016 dieback plus the influences of other factors like storm damage, and areas of excessive feral animal presence,
7. Summaries of data for the 37 estuaries quantifying condition indicators for tidal wetland, with comment on the key observed threats and management issues and scores ranking each threat (Figure 1.3) in support of beneficial intervention, and
8. Imagery and other data collected during these surveys provide a baseline from which to assess the future change that occurs along these surveyed shorelines and estuaries.

2. Research methods for aerial surveys

2.1 Study area

The Gulf of Carpentaria study area was divided into six catchment areas according to the drainage basin regions defined in the CSIRO Northern Australia Sustainable Yields (NASY) Project (CSIRO, 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i). These regions include Western Cape, Mitchell, South-East (SE) Gulf, Flinders–Leichhardt (F–L), South-West (SW) Gulf and Roper (Table 2.1, Figure 1.4 and Figure 2.1).

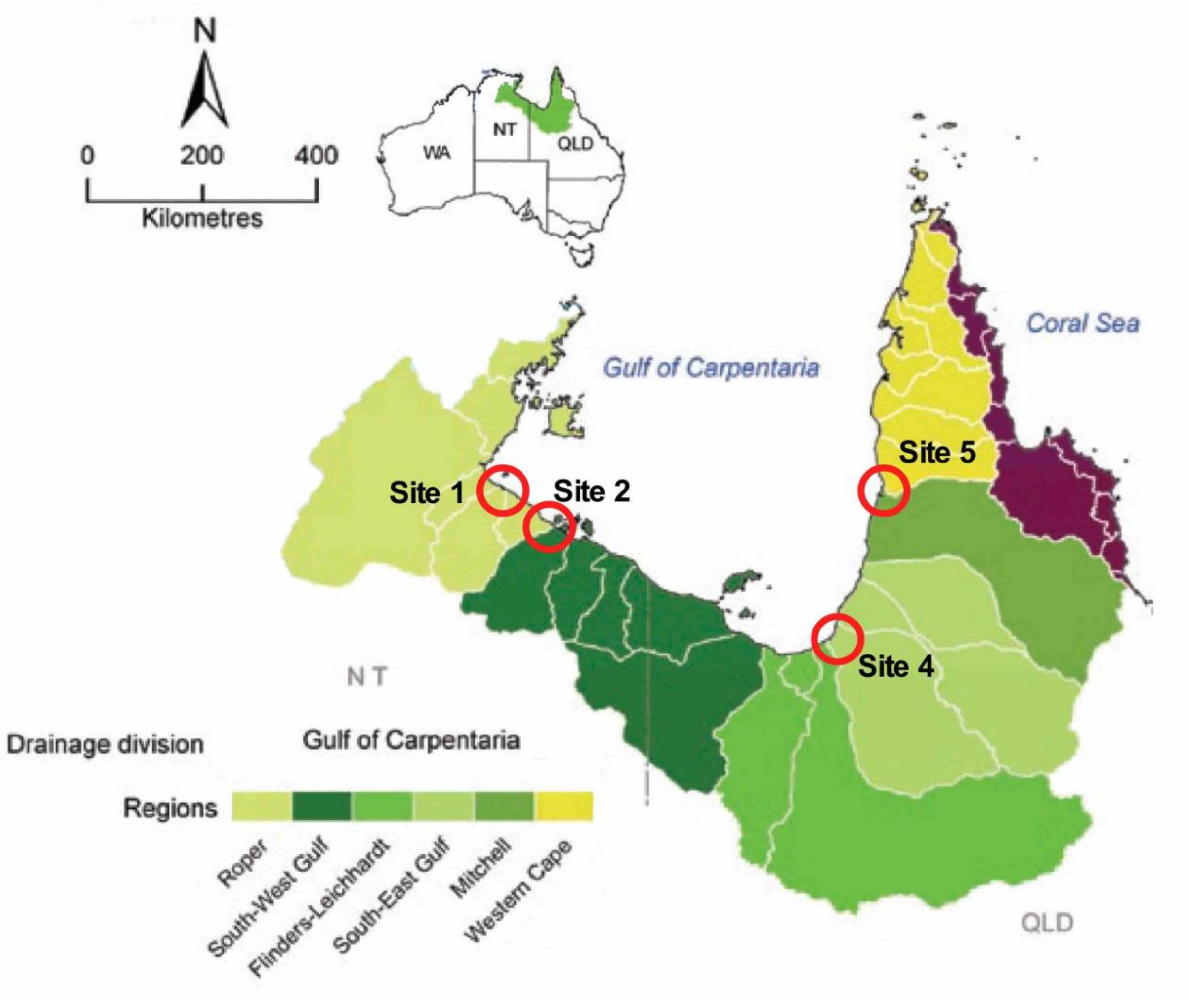

Figure 2.1. Map of catchment sub-basin shorelines for estuarine tidal wetland areas surveyed in the Gulf of Carpentaria (source: CSIRO, 2009a). The four sites (red circles) were those used for green fraction plots, and they were also those used for the field studies in Vol. 2.

The survey work undertaken was to systematically film and evaluate the 2015–2016 mangrove dieback event as well as the condition of shorelines and the health of tidal wetlands, including mangroves, along the entire southern shoreline of the Gulf of Carpentaria from Weipa in Queensland to Blue Mud Bay in the Northern Territory – a distance of around 2,000 km.

2.2 Aerial surveys

The method used in aerial surveys was an adapted version of the boat-based shoreline video assessment method (Mackenzie at al., 2016) used extensively in other significant sections of the northern Australian coastline (Duke & Mackenzie, 2018a, 2018b; Duke et al., 2010, 2015; Mackenzie & Duke, 2017). For the current aerial surveys, we used high-resolution time-interval photography to improve overall image quality and to ensure there was sufficient overlap between images for continuous coverage of surveyed shorelines. These overlapping images captured the complete coastline used in the current evaluations of shoreline and estuarine habitat condition. The image archive also provided a permanent reference resource.

Figure 2.2. Six categories used in the assessment of mangrove presence and dieback severity quantified in these investigations by the proportional loss of the rear or upper back part of the shoreline mangrove fringe (Vol. 2: Figure 2.2). Shorelines without mangroves at the sea edge were classified as non-mangrove shoreline. Images taken during the 2017 aerial survey.

Aerial surveys were conducted in two series during 2017 and 2019. Those in 2017 were completed over 11 days from 1–11 December and included the shoreline survey plus surveys of 37 estuary mouths (Table 2.1). The shoreline distance surveyed in 2017 was 2,633 km with a total flying distance of 4,646 km over 173 hours. A follow-up survey in 2019 was completed over nine days from 12–21 September and included the shoreline survey plus surveys of 31 estuary mouths. The slightly reduced scope of the latter survey took account of lessons learnt from the earlier survey and budget limitations. Both surveys were conducted during lower tidal levels where this was logistically feasible to do so – to gain the greatest visibility of the shoreline intertidal vegetation – positioned between the mean sea level and highest tide levels.

Table 2.1. Location coordinates of 37 estuary sites surveyed in the Gulf of Carpentaria study area in 2017. Estuaries are grouped in drainage areas (Figure 1.1 and Figure 2.1) described in the CSIRO Northern Australia Sustainable Project (CSIRO, 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i). Thirty-one site locations were re-surveyed in 2019. Coordinates mark the location of each estuary mouth. Mangrove species records from Duke (2006, 2016; Wells 1983, 1985, 1995) are considered minimal.

CSIRO catchment	Site #	2017 survey locations	Repeated in 2019	Latitude S	Longitude E	Mangrove species #
NW Cape	1	Mission River	X	-12.6201	141.8372	23
	2	Embley River	X	-12.6676	141.8297	25
	3	Watson River	X	-13.3465	141.6612	
	4	Holroyd River	X	-14.1633	141.5945	
	5	Christmas Creek	X	-14.5448	141.5412	
Mitchell	6	Mitchell River	X	-15.2004	141.591	
	7	South Mitchell River	X	-15.3578	141.5404	
	8	Nassau River	X	-15.9074	141.3952	
SE Gulf	9	Staatan River	X	-16.401	141.296	
	10	Gilbert River	X	-16.5575	141.2695	
	11	Accident Inlet	X	-17.1834	140.9389	
	12	Norman River	X	-17.464	140.8194	
F–L	13	Flinders River	X	-17.5977	140.595	7
	14	Leichhardt River	X	-17.5787	139.7944	
SW Gulf	15	Albert River	X	-17.5744	139.7559	12
	16	Nicholson River	X	-17.507	139.6051	
	17	Johns Creek	X	-17.3956	139.4513	
	18	Syrell Creek	X	-17.0043	139.0924	
	19	Massacre Inlet	X	-16.738	138.3355	
	20	Tully Inlet	X	-16.6776	138.158	
	21	Dugong River		-16.7083	139.2071	8
	22	Toongoowahgun River		-16.6405	139.3841	
	23	Elizabeth River		-16.4854	139.5576	
	24	Sandalwood Place		-16.4582	139.3582	
	25	Calvert River	X	-16.266	137.7442	8
	26	Robinson River	X	-16.0311	137.2683	8
	27	Wearyan River	X	-15.9139	136.8585	9
	28	McArthur River	X	-15.7105	136.6117	11
Roper Gulf	29	Mule Creek	X	-15.6394	136.425	
	30	Limmen Bight River	X	-15.1153	135.7212	12
	31	Towns River	X	-14.9142	135.4307	8
	32	Roper River	X	-14.7513	135.3968	13
	33	Miyangkala Creek	X	-14.4398	135.6077	
	34	Rose River	X	-14.2885	135.7344	13
	35	Muntak River	X	-14.1638	135.8817	11
	36	Walker River		-13.5905	135.8369	16
	37	Koolatong River		-13.2543	135.9474	14
Total		**37**	**31**			

Surveys were undertaken in conjunction with shoreline mapping using satellite imagery combined with field investigations for on-ground validation (Vol. 2) with data on habitat type, composition, and condition, the severity of 2015–2016 mangrove dieback (Figure 2.2), as well as observations of change and relevant processes (additional comparable case studies include: Mackenzie & Duke, 2016; Duke et al., 2017).

Project goals were accompanied by a high-level assessment of observed tidal wetland, mangrove and shoreline condition and value indicators along with the surveyed shoreline and 37 target estuarine tidal wetland areas. Summary listings for shoreline indicators for estuary assessments and tidal wetland condition can be found in Appendix 3 and Appendix 4. Assessments included advice on the causes of impact to inform relevant agencies of priority high-risk areas that may require a management response to address the key threats identified.

Aerial surveys were made using an R-44 helicopter flying at around 150 metres altitude (Figure 2.3). The aircraft windows and doors were removed to aid easier and best quality image capture. The entire shoreline from Mission River at Weipa (Queensland) to Koolatong River in Blue Mud Bay (Northern Territory) was surveyed (Figure 1.4). Shoreline and target estuaries were assessed in their order of occurrence travelling in a westerly direction. The direction of travel was used to allow filming from the left side of the aircraft allowing two observers clear line of sight. One observer collected the continuous shoreline imagery while the other collected specific images of shoreline processes and features. The surveys took nine and 11 days of flying time each survey, although 3–4 days were also required for the transport of the aircraft, crew, and equipment. The flying crew consisted of the pilot plus two or three survey team participants.

Figure 2.3. Aerial surveys were conducted using R-44 helicopters.

As noted, filming was done to acquire continuous imagery of the shoreline. These were geo-tagged high-resolution digital images of shorelines, taken obliquely at low elevations ~150 metres altitude. All imagery was geo-reference tagged for later use in GIS analyses, database storage, image display, reporting and archiving.

Shoreline filming acquired a considerable number of images – for instance in 2017, around 60,000 photographs in total were taken over the 9–11 days of surveys. These photographs were comprised of three categories of images – survey, scenic and general. Survey photos made up ~60% and consisted of high-resolution images using a Nikon D800E camera with AF-S Nikkor 50 mm 1:1.4 G-series lens and di-GPS. These images were taken to give overlapping continuous coverage of shorelines centred up from the mean sea level contour – as the seaward edge of mangroves. Scenic photos made up ~33% and consisted of high-resolution images using a Nikon D850 camera with AF-S Nikkor 28–300 mm 1:3.5–5.6 G-series and di-GPS. A similar number and types of images were acquired in 2019.

Where necessary, and where possible, on-ground field checks were made to validate aerial observations. Due to budget constraints, these visits mostly generated qualitative information on tidal wetland vegetation condition and other variables. But, they did allow further specific collections of imagery along with observations made during each survey.

2.3 Mapping studies

To determine the extent of mangrove loss between 2015 and 2016, a quantitative binary change detection approach (Kovacs et al., 2001) was conducted on recent Landsat 8 Level 1 products (Table 2.2). Specifically, a near anniversary date comparison was conducted between these years. Of the 12 Landsat products, eight scenes used, ten acquired in April and, due to cloud cover, one each was acquired from late March and early May. The affected area occurred across two Universal Transverse Mercator (UTM) zones. Therefore, the imagery covering Queensland was left projected in UTM Zone 54, whereas the Northern Territory imagery was left projected to UTM Zone 53. Each image was first radiometrically corrected to surface reflectance using PCI Geomatica's (PCI Geomatics, Richmond Hill, ON, Canada) atmospheric and terrain correction (ATCOR) module. The surface reflectance images were then mosaicked for each year and UTM zone, resulting in four separate mosaic images.

Data, imagery and observations collected were compiled and analysed. Particular attention was given to describing and quantifying severely impacted areas, as well as ensuring the dominant drivers, or likely drivers, of change for each study site (explained later, see Table 2.3 – Table 2.5). For example, where shorelines were affected by severe storm conditions, a number of key features were quantified including the extent of damage, its severity, the timing, the mangrove species affected, and any recovery. Where appropriate, recommendations were made about the need for follow-up investigations or mitigation.

2.4 Green fraction plots

Green fraction plots showing changes in green fractional cover were determined for eight locations from the four study sites representing 2015–2016 impacted areas in the Gulf of Carpentaria (Figure 2.1). The location coordinates of these field transect sites (Vol. 2) are listed in Table 2.2. The plots displayed in the results section show time series of vegetation indices taken for each single point location coordinate using data from Landsat satellites freely available via the USGS web site[2].

Estimates of green fractional cover were obtained from the Landsat satellite sensors – spanning three decades (1987–2020) – to produce time series plots of the percentage of vegetation cover for dieback areas on each transect. 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

[2] https://glovis.usgs.gov/app?fullscreen=0

period of May 1987 and May 2020. A number of pre-processing steps were applied to the Landsat imagery, which includes 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).

Table 2.2. Specific locations of field study sites of mangrove dieback that occurred in 2015–2016 (Figure 1.4) in Queensland (Qld) and the Northern Territory (NT) also used for green fraction plots. Within the eight transects, those marked with an asterisk lost 90%–100% of the seaward fringe, while the others had substantial surviving canopy trees along the sea edge (~60%–90% loss from the back edge ecotone).

State	Transect #	Site and transect locations	Latitude S	Longitude E
NT	1A*	Limmen – Roper region	-15.146215°	135.788778°
	1B		-15.171145°	135.836993°
	2B*	Mule – Roper region	-15.650919°	136.441971°
	2A		-15.647369°	136.434148°
Qld	4A*	Karumba – SE Gulf	-17.422561°	140.853576°
	4B		-17.340024°	140.896250°
	5A*	Mitchell north – W Cape	-15.027324°	141.665424°
	5D		-14.996484°	141.660752°

The green fractional cover estimates were obtained from a linear spectral unmixing model developed by 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). 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 the annual mangrove extent across the Australian continent (Lymburner et al., 2019).

The time series plots were produced from homogenous patches of mangrove forests adjacent to the field sites. For each of these plots, 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 the production of the time series plot. To assist in the interpretation of the time series, a fitted line was produced using a rolling window, calculating the mean value from three data points.

2.5 Shoreline survey assessments

2.5.1 Estuary mouths

Observations and data were recorded during two surveys of the shorelines of 31–37 major estuary mouths along shorelines of the Gulf of Carpentaria in 2017 and 2019 (Table 2.1, Figure 1.4). These records represent the major estuaries and their tidal wetlands of this region impacted by mass dieback of mangroves in 2015–2016. The primary aim of this assessment was to evaluate the full extent of the dieback and the major associated changes taking place amongst these estuaries. The recognisable responses and impacts observed will where possible be linked to the most likely drivers of change in this remote region of northern Australia.

Figure 2.4. Data were scored after filming each of 37 estuary mouths.

Criteria scored for each estuary mouth (Table 2.3 and Table 2.4) were described as:

1. Driver type: list the drivers of change observed,
2. Indicator: the indicator observed,
3. Habitat: listing of the tidal wetland habitats affected,
4. Extent: estimate the proportion of the tidal wetland affected,
5. Severity: estimate severity of impact – time to natural recovery and effect on ecosystem function/structure,

6. Time frame: when did the impact occur, and
7. Observations: notes and other comments.

Using these criteria, the state, condition, and health of shorelines were classified and quantified. The evaluation scheme developed by Duke and Mackenzie involves indicators and drivers of change (Duke, 2014). The information gathered provides an enhanced capacity to monitor the current condition, drivers, and likely future changes along shorelines. These strategies were used to evaluate habitat condition associated with particular drivers, as well as providing an evaluation of local and national management priorities. These images and data usefully complement the pre-existing mapping of the coastal environment and intertidal wetland habitats using remote sensing.

Table 2.3. Estuarine survey assessment criteria and classification of driver descriptors and observed impacts particularly for indicators of human impacts (pink shaded) and climate-natural impacts (green shaded).

Variable	Variable descriptor	Assessment scoring criteria	Assessment metric
Human impacts	The types of human impacts present	*Direct and indirect human impacts present* Reclamation – landfill, modification Lethal damage (cutting) – cleared Altered hydrology – ponding, altered flows Encroachment – proximity of agriculture Access (vehicles) – present, tracks Stock (cattle) impacts – grazing, tracks Feral (pigs) damage – diggings, tracks Pollutants present – oil spill, herbicides Nutrients – as effluent effects, algae, growth Fire scorch – blackened ground, dead trees Weeds – introduced, smothering Buffer deficient, agricultural encroachment Sub-lethal damage (trimming) canopy cutting Waste litter – ghost gear, vessels	*Direct human impact type* – Identification of human impacts present.
Climate–natural impact descriptors	The types of relatively natural impacts present	*Climate–natural impacts present* Storm damage – broken stems, canopy loss Shoreline erosion – seaward edge Root burial – dead trees, sand deposits Inner fringe collapse – holes in fringing forest Bank erosion – estuarine channels Saltpan scouring – floods, absence of salt Ecotone shift negative – dieback on zone Ecotone shift positive – seedlings on zone Depositional gain – seedlings in front Terrestrial retreat – erosion + dieback	*Climate–natural impact type* – Identification of natural and climate-related impacts present.

Variable	Variable descriptor	Assessment scoring criteria	Assessment metric
		Light gaps – canopy holes, lightning strikes Altered hydrology – ponding, altered flows 2015 mangrove dieback – temporary sea level drop Upstream shift – estuarine encroachment Fruit bat roost site – upper canopy loss Herbivory – loss of canopy, insect Fire damage – verge effects, natural	
Mangrove habitat descriptors	The type of mangrove habitat present	*Mangroves habitat type present* Mangroves at channel edge Mangrove forest Mangroves back fringe All mangrove Samphire Salt couch All saltmarsh Pan plus saltmarsh Buffer zone All	*Mangrove habitat score* – Quantity & types of mangrove habitat along shorelines.

Table 2.4. Estuarine survey image point assessment criteria and classification for tidal wetland habitat and environmental condition descriptors.

Variable	Variable descriptor	Assessment scoring criteria	Assessment metric
Shoreline human modification	The presence of human-related shoreline physical modification (e.g. walls, boat ramps, pontoons), and the resulting level of habitat modification.	*Shoreline modification* 1. Natural – No obvious human modification 2. Modified – human-related habitat modification but some habitat integrity maintained. 3. Highly modified – human-related shoreline habitat modification resulting in the complete alteration of habitat structure or loss of habitat integrity.	*Shoreline naturalness* – the proportion of shoreline classified as natural. *Shoreline modification* – the proportion of shoreline modified.
Extent of impact on tidal wetland area	The extent of tidal wetlands impacted determined by the proportional area showing impact	*Impact extent* 1. 1–10% 2. 10–30% – around 25% 3. 30%–60% – around 50% 4. 60%–90% – around 75% 5. >90%	*Extent score* – extent of impact in the tidal wetland area.
Severity of impact on tidal wetland area	The severity of tidal wetlands impacted as determined by the degradation state observed.	*Impact severity* 1. None – present but no observable effect 2. Minor – recovery within less than one year 3. Moderate – recovery over 1–2 years 4. Major – recovery over 2–10 years 5. Severe – recovery unlikely – collapse/replace	*Severity score* – severity of impact in the tidal wetland area.
Time frame of impact on tidal wetland area	The timing of the impact on tidal wetlands as determined by the recovery potential observed.	*Impact time frame* 1. No observable effect, but potentially so 2. Current – now 3. Recent – less than 2 years ago 4. Old – 2–10 years ago 5. Very old – >10 years	*Time frame score* – time of occurrence of impact affecting tidal wetland area.

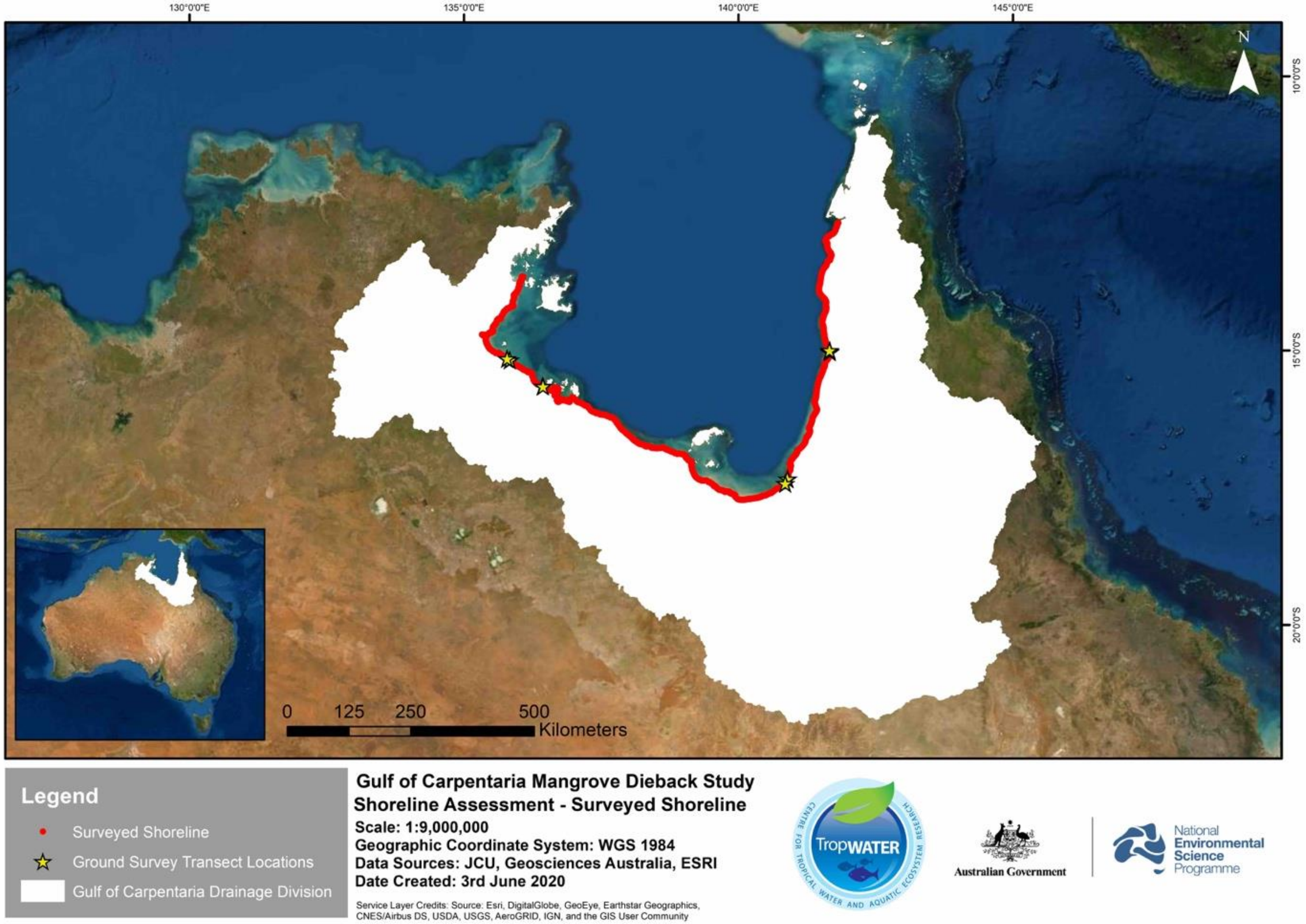

Figure 2.5. Aerial surveys were undertaken in 2017 and 2019 (red track) to evaluate the presence of mangroves and the extent of dieback along the same shoreline around the Gulf of Carpentaria. During these surveys, up to 37 estuary mouths were also assessed for key indicators of change and responsible drivers. The locations of field transect sites are also shown (stars).

2.5.2 Shorelines of the coastal mangrove sea edge

Based on the survey imagery of shorelines acquired during these surveys, this assessment covers the entire length of the coastline study area (1,953 km of Gulf shoreline; Figure 2.5). Features were classified at regular intervals for the presence of 2015–2016 mangrove dieback, mangroves, and the status of shoreline condition, processes influencing mangrove vegetation (Duke, 2014; Duke et al., 2010; Mackenzie et al., 2016). As such, particular focus was made of the factors influencing the mass dieback of mangroves in 2015–2016.

Evaluation of the condition of tidal wetlands, particularly mangroves, was made from oblique aerial imagery collected during these surveys and aligned with recent satellite imagery. The observations and scores made may, therefore, be verified from the archive of photographic images. The shoreline assessment used a similar strategy as used for assessment of the major estuaries and tidal wetlands. Both assessment methods were applied in prior aerial surveys of coastlines across northern Australia, including north-western Australia (Duke et al., 2010), north-eastern Queensland (Duke & Mackenzie, 2018a), Princess Charlotte Bay (Duke & Mackenzie, 2017), Port Curtis (Duke & Mackenzie, 2018b; Schultz et al., 2020), and the northern Torres Strait Islands (Duke et al., 2015). However, there were differences with the current surveys because the current assessments primarily focused on the extent and severity of the 2015–2016 dieback and its recovery along coastal shorelines. However, as shown in earlier surveys, the images collected can also be used to evaluate a much broader range of factors driving change (Duke, 2014). While these other factors are not fully assessed with this report, an example of additional key information (Figure 2.5) shows how these image resources hold exceptional and extensive records of the condition of this vast section of the Australian coastline.

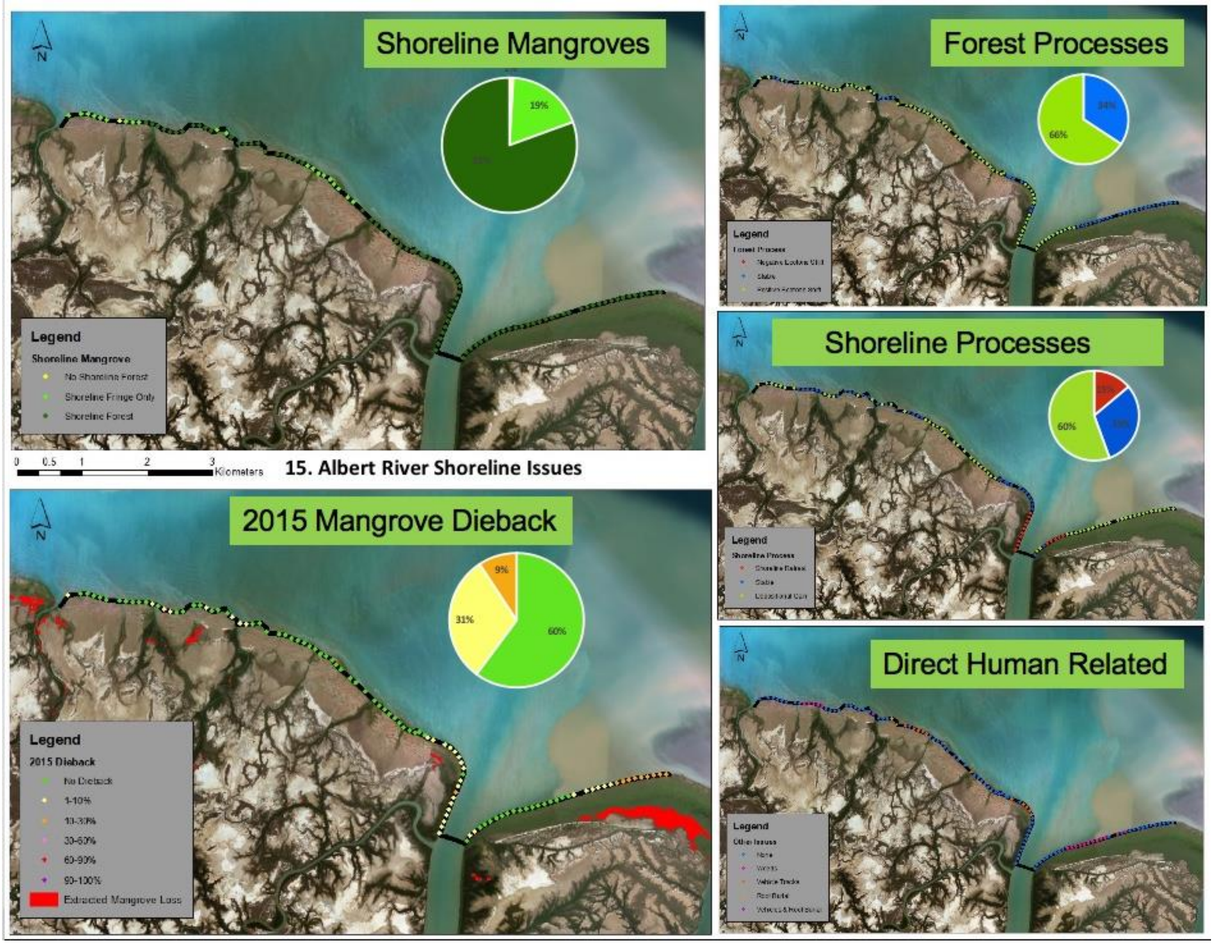

Figure 2.6. An example of the key features of shoreline change observed and recorded in the Albert River mouth and shoreline.

For assessments made with this study, scores of a common selection of characters were made from specific images selected at 100 metres intervals along the entire shoreline. The total number of images used in this assessment was 9,841 covering 984 km of shoreline. A spreadsheet metadata record lists each image, its geotagged location coordinates and the data scored for this report.

The shoreline assessment criteria for the evaluation of the 2015–2016 dieback is shown in Table 2.5. As noted, the criteria were modified from the broader assessment methods referred to above. These assessments chiefly used the 2017 aerial survey as the baseline for the dieback event. Further assessments will document the changes visible in the 2019 imagery. The assessment process developed for these continuing investigations is listed in Table 2.6.

Table 2.5. Shoreline survey image point 2015 dieback assessment criteria and classification.

Variable	Variable descriptor	Assessment scoring criteria	Assessment metric
Mangrove presence	The presence of mangroves along the shoreline	0. Mangroves not visible along the shoreline 1. Mangroves visible along the shoreline	*% cover* – Percentage cover of mangroves as a proportion of total shoreline.
Mangrove habitat and shoreline descriptors	The type of mangrove habitat present	*Mangroves habitat type present* 1. Sparse and scattered mangrove 2. Mangroves behind the shoreline 3. Patchy occurrence 4. Fringing narrow edge 5. Forested edge Represents mangroves with direct tidal interface with shoreline. Only these classifications were used for detailed assessment.	*Mangrove habitat score* – Quantity & types of mangrove habitat along shorelines.
Shoreline mangrove 2015 dieback severity	The condition of mangroves determined by status of live and dead mangrove trees and the presence of young plants.	*Shoreline mangrove condition* 1. No 2015 dieback present 2. <30% 2015 dieback 3. 30%–60% 2015 dieback 4. 60%–90% 2015 dieback 5. >90% 2015 dieback (For reference images, see Figure 2.2)	*2015 dieback severity* – Percentage of shoreline mangrove within each 2015 dieback severity class

Table 2.6. Shoreline survey image point 2017–2019 mangrove forest recovery assessment.

Variable	Variable descriptor	Assessment scoring criteria	Assessment metric
Condition improvement indicators			
Resprouting (RS)	Evidence of trees with past dieback having notable regrowth. Observed as a proportion of forest showing dieback in 2015	0. No resprouting 1. <30% resprouting 2. 30%–60% resprouting 3. 60%–90% resprouting 4. >90% resprouting	
Growth (G)	Proportion of seedlings, saplings and trees observed in 2015 showing increased height	0. No growth 1. <30% with growth 2. 30%–60% with growth 3. 60%–90% with growth 4. >90% with growth	**Improvement score =** $\frac{(2*RS + G + NSF + NSS)}{2}$
New seedlings within forest (NSF)	The presence of new seedlings within dieback or bare areas. Recorded as a proportion of total forest area.	0. No seedlings 1. <30% seedlings 2. 30%–60% seedlings 3. 60%–90% seedlings 4. >90% seedlings	
New seedlings along shoreline (NSS)	The presence of new seedlings at the shoreward margin of the forest. Recorded as a percentage increase of the total forest area.	0. No seedlings 1. <30% seedlings 2. 30%–60% seedlings 3. 60%–90% seedlings 4. >90% seedlings	

Variable	Variable descriptor	Assessment scoring criteria	Assessment metric
Condition deterioration indicators			
New dead trees (DT)	Proportion of trees alive in 2015 observed as dead in 2019	0. No new dead 1. <30% new dead 2. 30%–60% new dead 3. 60%–90% new dead 4. >90% new dead	
New dieback (DB)	Proportion of trees experiencing loss of canopy cover between 2015 & 2019	0. No dieback 1. <30% dieback 2. 30%–60% dieback 3. 60%–90% dieback 4. >90% dieback	
New fallen trees (FT)	New shoreline trees fallen. Recorded as a proportion of the total forest area.	0. No fallen trees 1. <30% fallen trees 2. 30%–60% fallen trees 3. 60%–90% fallen trees 4. >90% fallen trees	
Shoreline retreat – forest loss (SR)	Loss of mangroves at the shoreline margin. Recorded as a proportion of the total forest area	0. No shoreline loss 1. <30% shoreline loss 2. 30%–60% shoreline loss 3. 60%–90% shoreline loss 4. >90% shoreline loss	**Deterioration score** = (2*DT + DB + NF + SR + 0.5*SLF + 0.5*SLS) 2
Seedling loss within forest (SLF)	Proportional loss of seedlings and under-canopy present in 2015	0. No seedling loss within forest 1. <30% seedling loss within forest 2. 30%–60% seedling loss within forest 3. 60%–90% seedling loss within forest 4. >90% seedling loss within forest	
Seedlings loss from shoreline (SLS)	Proportional loss of shoreline seedlings present in 2015	0. No seedling loss on shoreline 1. <30% seedling loss on shoreline 2. 30%–60% seedling loss on shoreline 3. 60%–90% seedling loss on shoreline 4. >90% R seedling loss on shoreline	
Overall recovery score	The difference between Improvement and Deterioration scores, noting that there can be both improvement and deterioration indicators present concurrently.	**Recovery score** = **Improvement score + Deterioration score**	
2019 condition score	The relative shoreline mangrove forest condition score factored for 2015 dieback severity	**2019 Condition score** = **(1–2015 Dieback score) + Recovery score**	

2.6 Drivers, causes, indicators and impacts

In the following section, a selection of recognised major drivers of change are described (Duke, 2014) – as used with the *Estuary mouths* assessments. These are grouped as Human derived and Climate-Natural influences affecting tidal wetlands and shorelines throughout the impacted area of the Gulf. The 2015–2016 dieback is treated as an additional indicator.

2.6.1 Human-related influences

Altered hydrology (Figure 2.7)

Cause. Water runoff contained or blocked from natural tidal drainage especially when downstream water levels have dropped, marked by notable alteration to the natural hydrology of the site.

Indicator. The distinguishing feature is unnaturally pooled water amongst tidal wetlands. The presence of likely construction works, and track damage can be indicative of Human influences as compared to Natural influences like storm drift.

Impact. The damage can be dead mangrove trees or canopy dieback as well as the dieback of flooded vegetation upstream.

Figure 2.7. Altered hydrology causes the blocking of natural flushing of tidal mangrove channels.

Feral animal damage – wild pigs (Figure 2.8)

Cause. Wild pigs wallow and dig amongst tidal wetland vegetation to damage established plants and kill seedlings. Native species of mangrove and saltmarsh plants are intolerant to severe and sustained physical disturbance of this kind.

Indicator. The presence of feral pigs, their tracks across mudflats, uprooted vegetation, digging excavations, and wallow pools.

Impact. Pig damage is associated with a lack of mangrove recruitment at ecotone zones shifting because of other reasons like increases in long term rainfall, or rising sea levels.

Figure 2.8. Severe damage caused by feral pigs roaming freely across tidal and freshwater wetlands. The presence of wallows shows the extent of severely damaged habitat as well as disruptions to natural water flows.

Stock damage – cattle (Figure 2.9)

Cause. Cattle walking and browsing amongst tidal wetland vegetation can damage and kill established plants and kill seedlings. Native species of mangrove and saltmarsh plants are intolerant to such severe and sustained physical disturbance.

Indicator. The presence of cattle, their tracks across mudflats, browsed vegetation stubble, under-canopy pruning and footprint pools.

Impact. Cattle damage is associated with mangrove dieback as well as a lack of mangrove recruitment at ecotone zones shifting because of other reasons like increases in long term rainfall, or rising sea levels.

Figure 2.9. Trampling damage caused by cattle roaming amongst tidal wetlands.

Access damage – vehicles (Figure 2.10)

Cause. Vehicles used to cross and access tidal wetland areas can 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.

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 like increases in long term rainfall, or rising sea levels.

Figure 2.10. Track damage caused by vehicles driving across tidal wetlands.

Mangrove clearing and removal (Figure 2.11)

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, like access roads, cutting, and digging equipment.

Impact. Habitat loss reduces the fitness of tidal wetlands, and, as a consequence, the ecosystem benefits are also lost, like their value to local fisheries or their role in the protection of shorelines from erosion.

Figure 2.11. Replacement marginal mangrove areas and encroachment reduces the function and condition of tidal wetlands

Nutrient point source

Cause. Excess nutrients in runoff waters 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. Unusually enhanced canopy height and darker green foliage of mangrove forests near human facilities likely to be the source of nutrient runoff.

Impact. Enhanced height growth causes destabilisation of trees, making them highly vulnerable to storm winds, large waves and strong currents. Trees also die from the smothering by excessive algal growth covering their air-breathing roots.

Chemical leachate and oil spills

Cause. Leaching and larger spills of concentrated chemicals – both 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 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.

Impact. Death and dieback of mangrove plants and animals, and increased stress on forest canopies and saltmarsh vegetation.

Weed smothering (Figure 2.12)

Cause. A number of plants, often considered associates of mangroves, occasionally occupy tidal wetland habitat and mangroves. When these plants are introduced to a new region, they can become exotic invasive weeds in local tidal wetland settings.

Indicator. The presence of exotic associate plants amongst native tidal wetland habitat and mangroves. Note that weed species can only be detected from aerial surveys where larger infestations occur. Isolated occurrences of invasive weed species are difficult to detect from rapid aerial surveys and require targeted weed survey methods.

Impact. The introduced plants often spread rapidly and replace native species to change the native habitat characteristics. They can also aid the introduction of other exotic pests and diseases.

Figure 2.12. Invasive weeds like Rubber Vine spread along the upper margins of tidal wetlands to smother mangrove habitat and increase fire damage risk.

2.6.2 Drivers influenced by climate and other natural influences

Storm damage and stem breakage dieback (Figure 2.13)

Cause. Storm conditions bringing heavy seas, strong winds and rapid currents often cause significant and extensive damage to the tidal wetland and mangrove habitat. A key agent causing such destructive weather conditions are tropical cyclones.

Indicator. Loss of saltmarsh vegetation and loss of mangroves as defoliated uprooted broken trees as well as the loss of area. The influence of cyclones was quantified in terms of their frequency in proximity to respective shoreline sectors (Figure 2.14). Data was sourced from the Australian Bureau of Meteorology website.

Impact. Habitat loss reduces the fitness of tidal wetlands and, as a consequence, the ecosystem benefits are also lost, like their value to local fisheries or their role in the protection of shorelines from erosion.

Figure 2.13. Strong cyclones cause severe damage to mangrove forests. Damaged shorelines may recover but only after several decades provided seedlings can rapidly re-establish amongst the dead, damaged and uprooted trees.

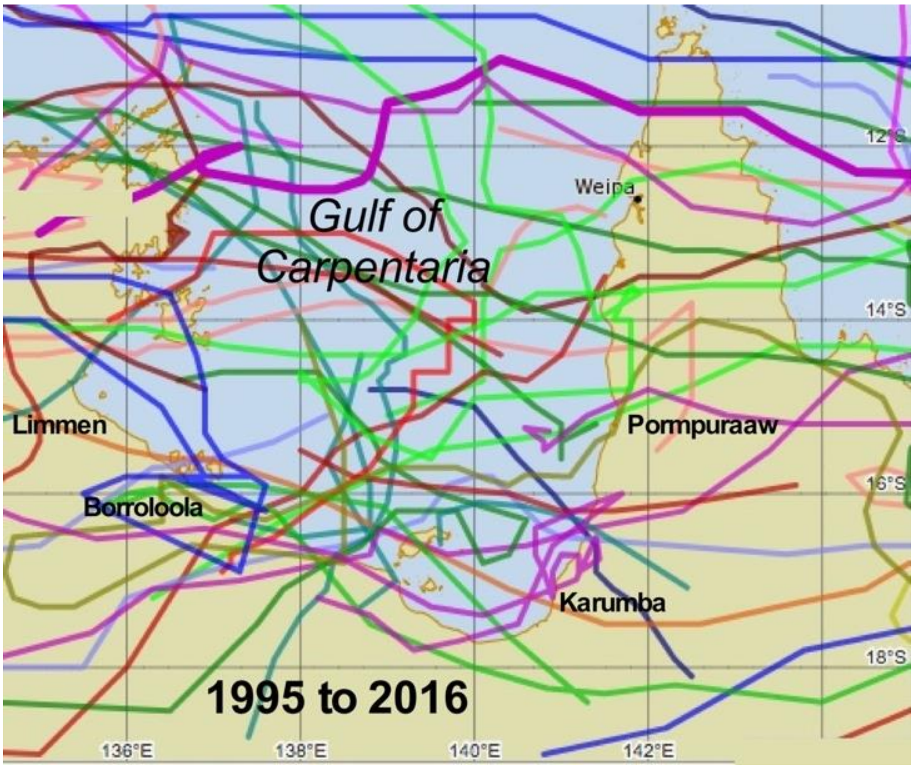

Figure 2.14. Cyclones are a common feature in the Gulf of Carpentaria. This figure shows tracks of cyclones in the region during the 20 years up to 2016 (BOM website, accessed 2019), with around one cyclone every two years. Although cyclones have a regional influence, the damage caused by these events is mostly localised. This was exemplified further where some shorelines suffered notably less than other sections. Note shorelines of intense cyclone activity around Borroloola in particular.

Shoreline erosion and seafront retreat erosion (Figure 2.15)

Cause. Storm conditions, coupled with progressively rising sea levels, cause the systematic and incremental loss of shoreline mangrove habitat.

Indicator. Loss of foreshore and shoreline mangrove vegetation is marked by fallen and eroded dead trees and uprooted stumps. Instances often also have a lack of seedlings and recovery regrowth, along with the close proximity of mobile sediment banks and berm ridges.

Impact. Loss of shoreline mangrove vegetation not only represents the loss of habitat and ecosystem benefits, but it also identifies locations currently experiencing unsustainable rates of change. Such eroded shorelines are highly vulnerable to further imminent disruptive events because they lack the normal protection of exposure-adapted, frontal trees. These trees, often of the same species, have different growth forms depending on where they grow along the tidal profile. And, once matured, the trees are unable to change and adapt. Exposed frontal trees develop sturdy support structures like the tangle of prop roots of *Rhizophora* species. When the same species grows in the middle of a forest, it has significantly fewer prop roots and support structures. In these circumstances, the inner trees redirect their growth and structure into gaining maximal crown height to better compete and survive. When exposed by shoreline erosion, these inner trees offer no benefit to shoreline protection. The only way shoreline mangroves can be re-established is by new recruits growing in the exposed conditions. This may not be possible during a period of rapidly rising sea levels. Such shorelines are highly vulnerable.

Figure 2.15. Shoreline erosion and retreat of tidal wetlands occur when sea edge trees are lost. Unlike specially adapted sprawling sea edge trees, lanky inner stand trees are unable to resist strong winds and waves that regularly buffet exposed shorelines. Seedling re-establishment is notably too slow and unable to keep up with the frequency of disturbance in some locations.

Terrestrial retreat erosion (Figure 2.16)

Cause. Sea level rise progressively occurs 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, notably dead *Casuarina* and *Eucalyptus* trees. These effects are combined with Mangrove Encroachment which has been scored separately.

Impact. This impact mostly concerns the loss of supratidal vegetation and the possible expansion of mangrove areas. The ongoing erosion and death of terrestrial vegetation, however, make it difficult for the re-establishment of bank stability along this major ecotone. These areas are highly vulnerable to added pressures on seedling establishment.

Figure 2.16. 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 low relief terrain.

Ecotone shift loss (Figure 2.17)

Cause. Longer-term decreases in rainfall levels put 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.

Impact. With the loss of mangrove plants, there is a loss of mangrove habitat. But, there is a direct and natural transition to an equivalent area of tidal saltmarsh and saltpan vegetation.

Figure 2.17. Ecotone shift negative around saltpan margins is attributed to a longer-term decrease in rainfall affecting catchment areas influencing the tidal wetlands.

Ecotone shift gain

Cause. Where longer-term rainfall levels increase in an area, there is significant pressure for mangrove encroachment along critical saltmarsh-mangrove ecotones of affected tidal wetlands (Duke et al., 2019a). 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.

Impact. With the increase in mangrove plants, there is a gain of mangrove habitat. But, there is a direct and natural transition away from an equivalent area of tidal saltmarsh and saltpan vegetation.

Root burial (Figure 2.18)

Cause. Sediments become mobilised and adrift amongst mangrove vegetation, sometimes causing the burial of their breathing roots. As mangrove trees are sensitive to rapid changes to the burial of breathing surfaces, a sudden 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.

Impact. Habitat loss reduces the fitness of tidal wetlands and, as a consequence, the ecosystem benefits are also lost, like their value to local fisheries or their role in the protection of shorelines from erosion.

Figure 2.18. Root burial, linked to shoreline erosion, storm damage and mangrove dieback, is caused by a natural shift in sand and sediments that bury roots and suffocate mangrove plants.

Natural altered hydrology and impoundment (Figure 2.19)

Cause. Where water has been unable to drain from a tidal or other flooded areas after surrounding water levels have dropped, this shows there has been a notable alteration to the natural hydrology of the site. This driver is comparable to human altered hydrology, as described above, but in this case, it is a natural process. This driver is also associated with shoreline erosion, while root burial is 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 storm drift and channel cut-off.

Impact. The damage is often dead mangrove trees or canopy dieback.

Figure 2.19. Natural altered hydrology caused by the re-deposition of sediments blocking tidal flushing of mangrove-fringed channels.

Depositional gain (Figure 2.20)

Cause. Sediments flushed downstream from catchment areas and distributed by flooding erosion are often deposited towards the river mouth, shorelines and along lower estuarine channel edges. The depositional materials often emerge as mudbanks and form mangrove islands when colonised naturally by mangrove vegetation. Mangroves appear to colonise these emerging banks after they have exceeded mean sea level elevations – the mangrove 'sweet spot' zone. Depositional gain is particularly evident along estuarine channels as seedling-colonised accreting banks with most meanders upstream.

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. Various key mangrove genera are involved, including mostly: *Avicennia, Aegialitis,* and *Rhizophora*. In general, the depositional gain is indicative of the combination of sediment transport processes including catchment runoff and the reworking of deltaic sediments.

Impact. With the increase in mangrove plants, there is a gain for mangrove habitat. But, these new habitats will take many decades to achieve the roles provided by mature stands. As such, this process is likely offset by bank erosion upstream which is generally seen as the active counter condition to depositional gain along typical estuarine meanders.

Figure 2.20. Depositional gain occurs when mangrove seedlings and saplings occupy accreting mudbanks exceeding elevations above mean sea level. Because sediment deposition can be associated with periodic flood events, the expanding vegetation canopy is often stepped and incremental.

Bank erosion upstream (Figure 2.21)

Cause. The banks of estuarine channels are regularly inundated by seawater and drained with the regular tidal cycle. Depending on tide levels, higher flow rates can cause severe erosion. Tidal flow rates are amplified further during periodic flood runoff events. These processes cause significant bank erosion, restructuring of channel margins, and mobilisation of sediments. The counter condition in part is described as depositional gain.

Indicator. Eroded banks are steep slopes, showing bare and crumbling earth faces, slumped bank pieces with intact vegetation, along with general remnants of collapsed and undermined vegetation like fallen trees, uprooted and inundated plants.

Impact. Lost mangrove habitat represents a loss of ecosystem benefits. Also significant is the loss of bank stability, much as mentioned in the *Shoreline erosion and seafront retreat erosion* (Figure 2.15) section. Such estuarine banks are highly vulnerable.

Figure 2.21. Bank erosion occurs in a similar way to shoreline erosion, although bank erosion is arguably more normal where it occurs in counter-response to depositional gain. Accordingly, the two processes are responsible for the slow but natural shift of riverine channels as they meander and migrate across the lower estuarine flood plain. However, when there is an imbalance in these processes, and bank erosion exceeds depositional gain, this would indicate additional influences, as might be expected with rising sea levels and an increase in the volume of water in the estuary.

Pan scouring and erosion (Figure 2.22)

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.

Indicator. Scoured saltpan surfaces marked with drainage lines coupled with a lack of saltmarsh vegetation across the saltpan.

Impact. The loss of saltmarsh habitat is significant. There is also a further supply of fine sediments finding its way into the estuary and likely further contributing to depositional gain.

Figure 2.22. Surface sheet erosion is another consequence of additional water in an estuary. As with terrestrial retreat, saline intrusion, and mangrove encroachment, this impact is also associated with rising sea levels. In this case, greater water volumes inundating upper saltpan areas results in sheet erosion and scouring of surface sediments with regular tidal flooding and drainage. In extreme instances, saltmarsh vegetation, including natural layers of microphytobenthos, have been unable to establish, so the whole inundated area is scoured leaving bare sediments and pools of residual waters.

Mangrove encroachment

Cause. Sea levels rising progressively over time put continual pressure on higher-level 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. These effects are combined with terrestrial retreat erosion which has been scored separately.

Indicator. The most notable feature is the upland encroachment and establishment of mangrove plants, recognising further that this is coupled most likely with the dieback of established terrestrial trees.

Impact. The impact mostly concerns the increase in mangrove vegetation, coupled with the loss of established supratidal plants. The ongoing erosion and death of terrestrial vegetation, however, make it difficult for the re-establishment of bank stability along this major ecotone. These areas are highly vulnerable to added pressures on seedling establishment like their damage caused by feral pigs.

Flood damage (Figure 2.23)

Cause. Flooding of catchment runoff waters adds to the downstream flow of estuarine waters to cause 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.

Impact. The dominant impacts from flooding include damaged mangroves, bank erosion, and scouring.

Figure 2.23. Flood damage is indicated by bank erosion, uprooted trees, scouring of saltmarsh, and tree remains in estuarine tributaries.

Light gaps (Figure 2.24)

Cause. Severe storm weather often includes atmospheric electrical activity cause lightning strikes that result in notable and distinctive damage to mangrove forests in the form of small circular light gaps. These gaps are each roughly around 50–100 sqm in area, as found in taller, uniform height mangrove forests consisting of locally dominant species. The impacts are unlike other storm impacts where trees die standing and unbroken. And, as gaps mature, the dead trees deteriorate, seedlings are established and grow, and eventually the gap fills after about 2–3 decades. It is thought this process helps explain how mangrove forests naturally regenerate and sustain their existence in such a wide selection of locations.

Indicator. The small circular light gaps are distinct in the forest canopy – although it is important to recognise that each will be at a particular stage towards recovery and canopy closure depending on when it was created. Only for 1–8 year old gaps will the original trees be recognisable as the ones that died to create the gap.

Impact. Light gaps are considered a natural part of forest replacement and turnover. It is notable that the frequency of gap creation is likely dependent on storm severity. As such, where this might increase in any particular area, then it will have a profound influence on forest turnover rates. At some higher level, however, these forests are predicted to be unable to sustain the natural processes involved in their replacement. At some point, mangrove forests would enter a state of ecosystem collapse with fragmented stands.

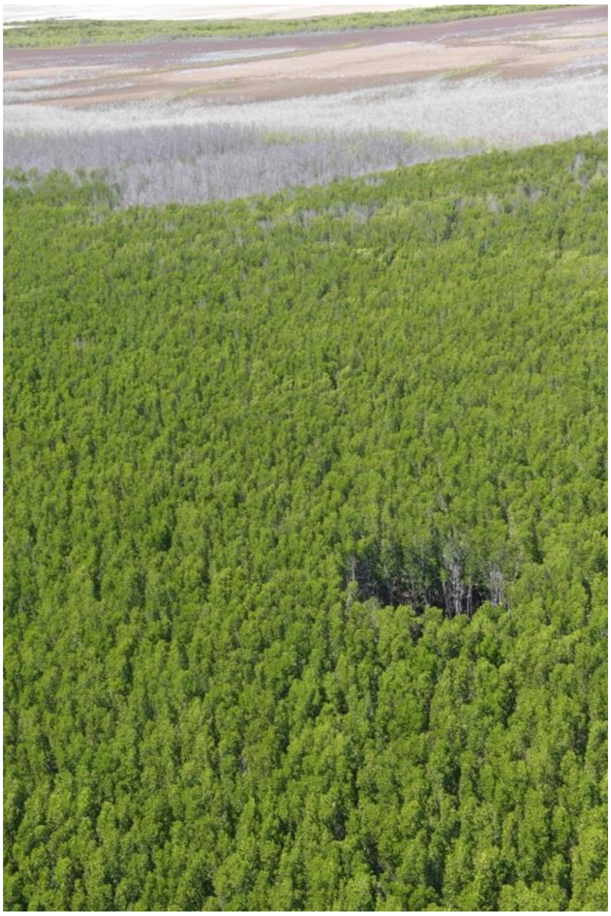

Figure 2.24. Light gaps are caused by lightning strikes killing a small patch of mangrove trees in amongst otherwise undamaged surrounding mangrove forests. The impact and its recovery are distinct and unlike that in terrestrial forests. The number of gaps is an indicator of the frequency of storms.

2015–2016 Mangrove dieback (Figure 2.25)

Cause. A temporary drop in sea level concurrent with extremely high temperatures and prolonged drought. These conditions occur during severe El Niño events. In 2015–2016, sea levels in the Gulf of Carpentaria dropped by 20 cm to cause extensive dieback from upper zonal margins bordering wide saltmarsh-saltpan areas.

Indicator. The zone of dieback extending along the 'back' edge of the seaward mangrove fringe. Occasionally the entire fringe dies. Also, where there are distinct zones of *Avicennia* and *Rhizophora,* the dieback edge occurs at the upper margins of each zone separately.

Impact. This kind of dieback is uncommon; however, the effect is in some ways similar to that of ecotone shift loss (negative). The latter is driven by longer-term decreases in rainfall while the 2015 mangrove dieback is also due to severe moisture deficit with reduced tidal flushing levels. The latter may be temporary, but the impact is long-lasting and severely damages affected shoreline environments. These damaged areas are highly vulnerable to severe storms like tropical cyclones.

Figure 2.25. The 2015–2016 mass dieback of mangroves mostly was distinguished by dead trees at the upper tidal elevation edge of species zones, like this less common instance at the mouth of the Leichhardt River in September 2019 involving concurrent dieback in adjoining zones of Rhizophora stylosa *(centre left) and rear fringe* Avicennia marina *(to the right). Such a broad zone of* R. stylosa *was absent along most shorelines around the Gulf.*

3. Results of mapping and aerial surveys

3.1 Mapping of dieback impacted areas

Mapping accomplished several primary tasks including the location of areas of the 2015–2016 dieback in the Gulf of Carpentaria; quantification and measurement of the size of mangroves and dieback areas; the approximate synchronous timing of the incident; and the characteristics that distinguish this dieback event (Figure 3.1). Impacted areas, as noted earlier (Figure 1.4), extended from Blue Mud Bay in the Northern Territory (western side of the Gulf) to just north of the Mitchell River estuary in Queensland (eastern side of the Gulf).

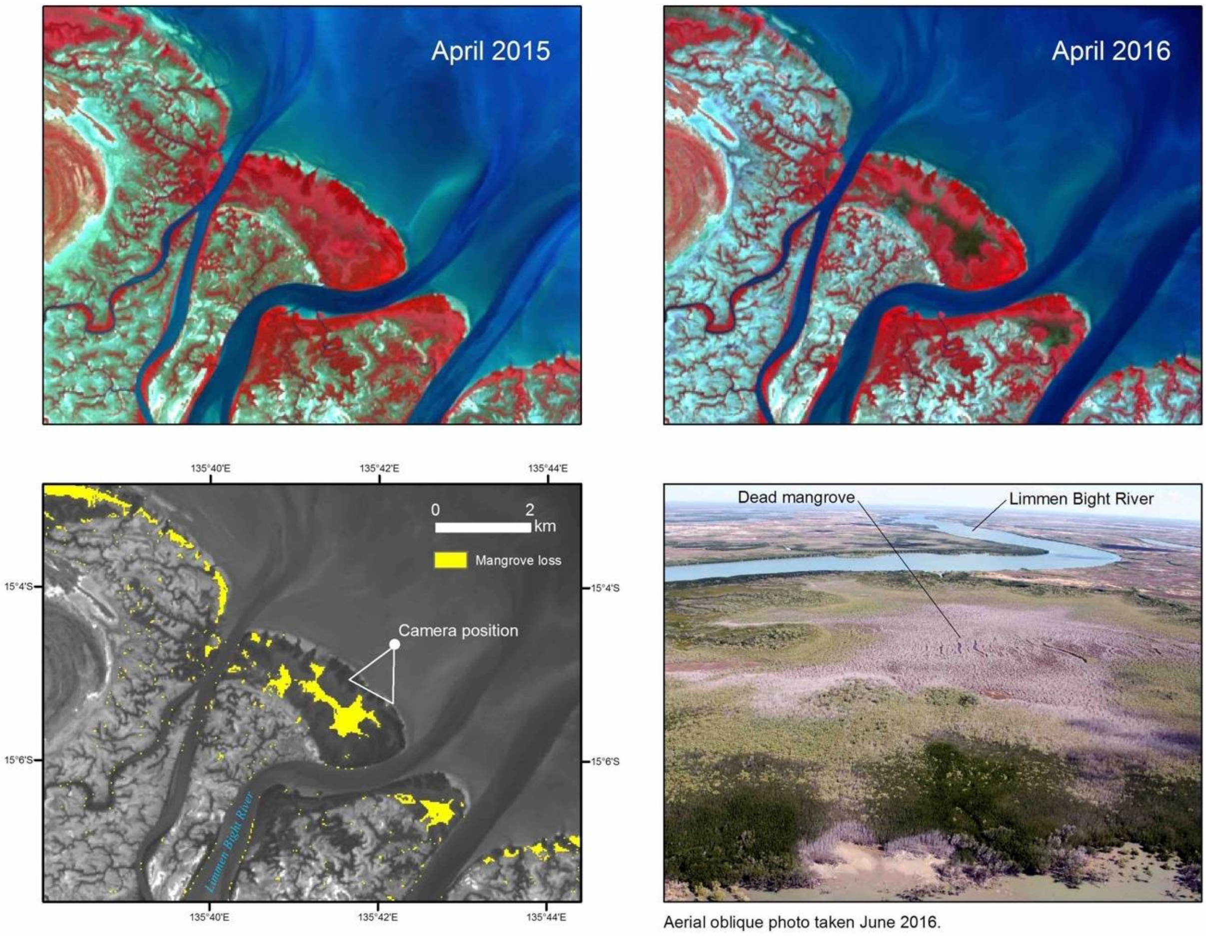

Figure 3.1. Interpretations from satellite imagery compared to an image taken during a preliminary aerial survey in June 2016 (lower right). These images show the occurrence and nature of the 2015–2016 mangrove dieback event. The top two images show mangrove areas in false red colour before and after the event. The lower left image shows areas of dieback and the position of the camera taking the aerial survey image.

Polygons described the size and shape of mangrove and saltpan–saltmarsh vegetation units throughout the study area. The locations and sizes of each vegetation unit were mapped from change detection of satellite imagery acquired between April 2015 and April 2016 (see *Region and site summary data* section). A notable feature was the major occurrence of dieback amongst mangroves in fringing stands bordering the seaward margin. By contrast, mangroves bordering estuarine systems were relatively unaffected by the mass dieback event (Figure 1.1 and Figure 3.2).

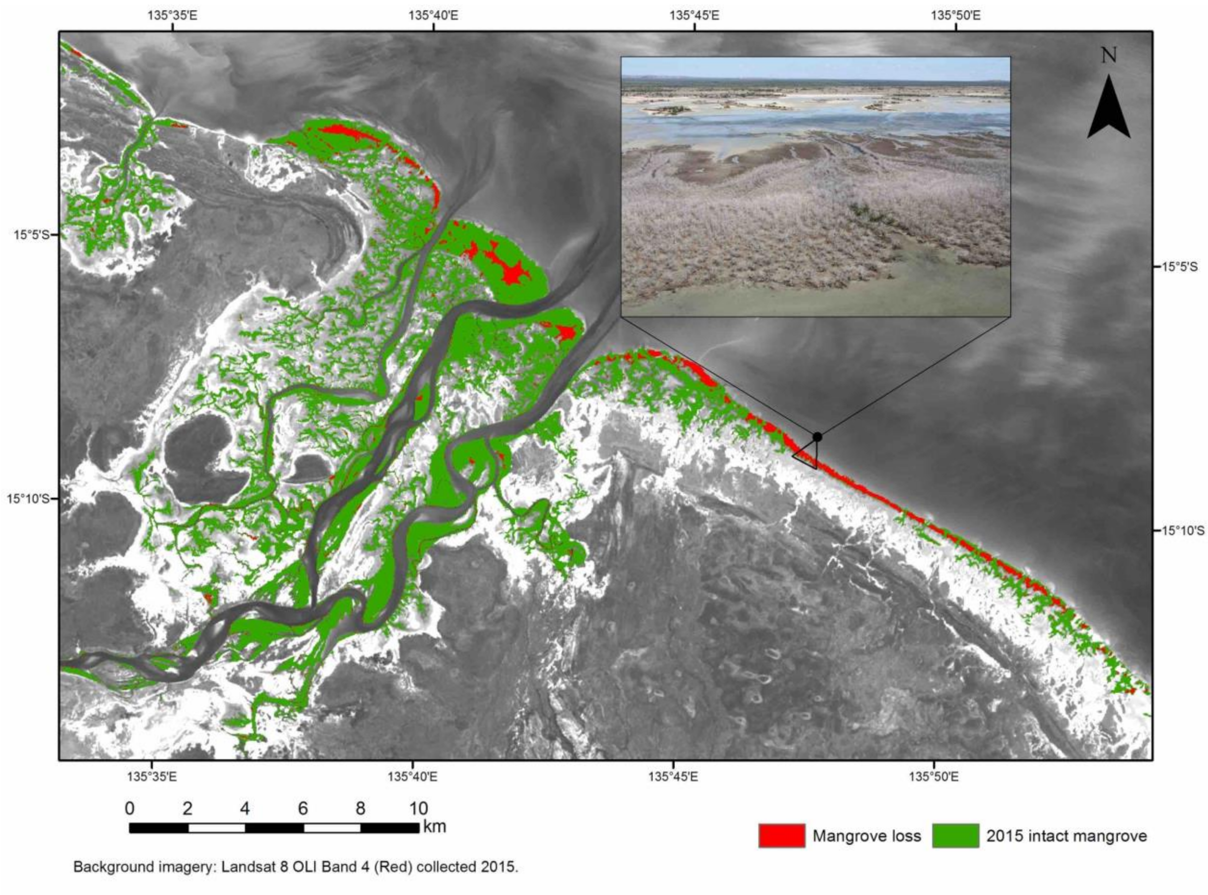

Figure 3.2. The mapping assessment used change detection between 2015 and 2016 imagery to show the timing and locations of mangrove loss. This view shows the distribution and nature of the 2015–2016 mangrove dieback event in the area around the mouth of the Limmen Bight River, in the south-west region of the Gulf of Carpentaria. The inset image taken in June 2016 shows a section of mangrove shoreline where all of the shoreline mangrove fringes had been lost.

A summary of mapped vegetation units is given in Table 3.1. Note that the dieback area of 76.5 km^2 measured during this study was slightly larger than that recorded early (Duke et al., 2017). The mapped area was extended with this investigation because an additional significant dieback area was located to the north of Karumba in Queensland along shorelines just north of the North Mitchell River estuary mouth (just south of Pormpuraaw). The larger area (plus 2.5 km^2) included all confirmed areas of 2015–2016 mangrove dieback discovered and validated with these investigations. In total, our estimates show that the percentage of mangroves lost in the 2015–2016 dieback event was 6.04% of impacted areas across the Gulf region. This compares with the total area of mangroves in the impacted portion of the

Gulf being 1,225.03 km^2, representing around 59.4% of the total area of mangroves in the entire Gulf.

There has been one comparable mapping study undertaken for the eastern side of the Gulf, although this study reported an inexplicably larger comparable area. Queensland Government mapping of dieback areas (Queensland Government, 2020a) reported there were 27.7 km^2 of dieback in that state. This was 28.3% greater than the 21.6 km^2 measured for Queensland in the JCU investigations. There is no satisfactory explanation for this difference, but might it be possible Queensland Government mapping included dieback areas other than 2015–2016 mangrove dieback? Such areas were identified and excluded in the JCU studies. These other dieback types recorded during the JCU surveys included damage from cyclones, low rainfall, flooding, impoundment, root burial, shoreline retreat, bank erosion, fires, and lightning strikes.

Table 3.1. Summary of mapped vegetation units based on the assessment of tidal wetlands in the Gulf of Carpentaria (mapped area from Blue Mud Bay to just north of the Mitchell River; Figure 3.3), including intact mangroves, mangroves impacted by the 2015–2016 dieback, and saltpan–saltmarsh. Regions are mostly those used with the CSIRO NASY project (CSIRO, 2009a, 2009b, 2009c).

Areas	W Cape*	Mitchell	SE Gulf	F–L	SW Gulf	Roper	Total
Tidal wetland (km^2)	41.4	308.8	1829.9	1369.2	2559.3	1238.2	7347
Mangroves (km^2)	15.8	85.8	211.3	172.9	482.2	374.8	1343
Saltpan–saltmarsh (km^2)	25.7	223.0	1618.6	1196.5	2077.1	863.4	6004
% Wetland Cover Index	38.1	27.8	11.5	12.6	18.8	30.3	23.2
Dieback mangroves (km^2)	1.6	7.1	4.0	4.0	40.3	19.6	76.5
% dieback	10.0	8.2	1.9	2.3	8.4	5.2	6.0

Note: * data from only a small southern part of the region.

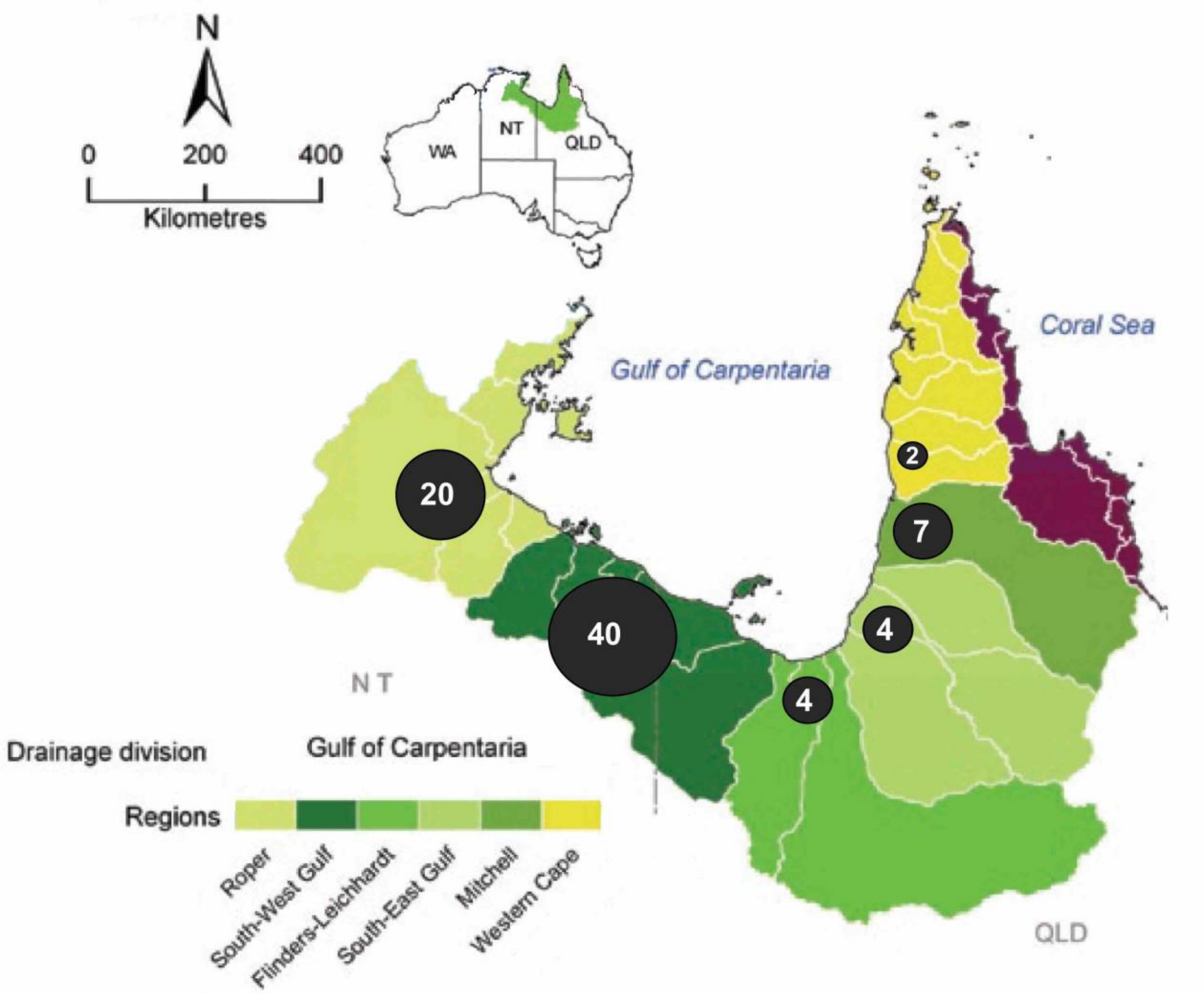

Figure 3.3. Areas of mangrove dieback loss (black circles, values in km²) determined from the mapping of tidal wetland habit in 2015 and 2016. Six regional areas as the major Gulf drainage divisions (CSIRO, 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i).

The Wetland Cover Index (WCI) showed that tidal wetlands had around 23.2% mangrove area with the remainder dominated by expansive saltpan–saltmarsh flats. The WCI is indicative of the influences of rainfall on mangrove dominance of tidal wetlands where these habitat components exist in a state of dynamic co-existence (Duke et al., 2019a). The WCI is the percentage of mangrove area to the total area of tidal wetlands including mangroves and saltpan–saltmarsh vegetation. Given the significant positive relationship with rainfall, this extent of mangroves was predictable for any given longer-term rainfall condition. For this reason, the index levels for each of the six regions matched the corresponding rainfall records (see *Region and site summary data* section), while rainfall levels had not dropped in a way that would explain the 2015–2016 dieback.

The Gulf drainage division (Figure 3.3) with the most mangrove dieback was the SW Gulf region with a significant second in the Roper region, followed by much lower amounts in the other four regions. In summary, the total area of mangroves affected was 7,650 ha (76.5 km²) from a total mangrove area within the impact study area of 134,270 ha (1,342.7 km²). This showed that around 6% of mangroves were severely impacted across this large southern section of the Gulf.

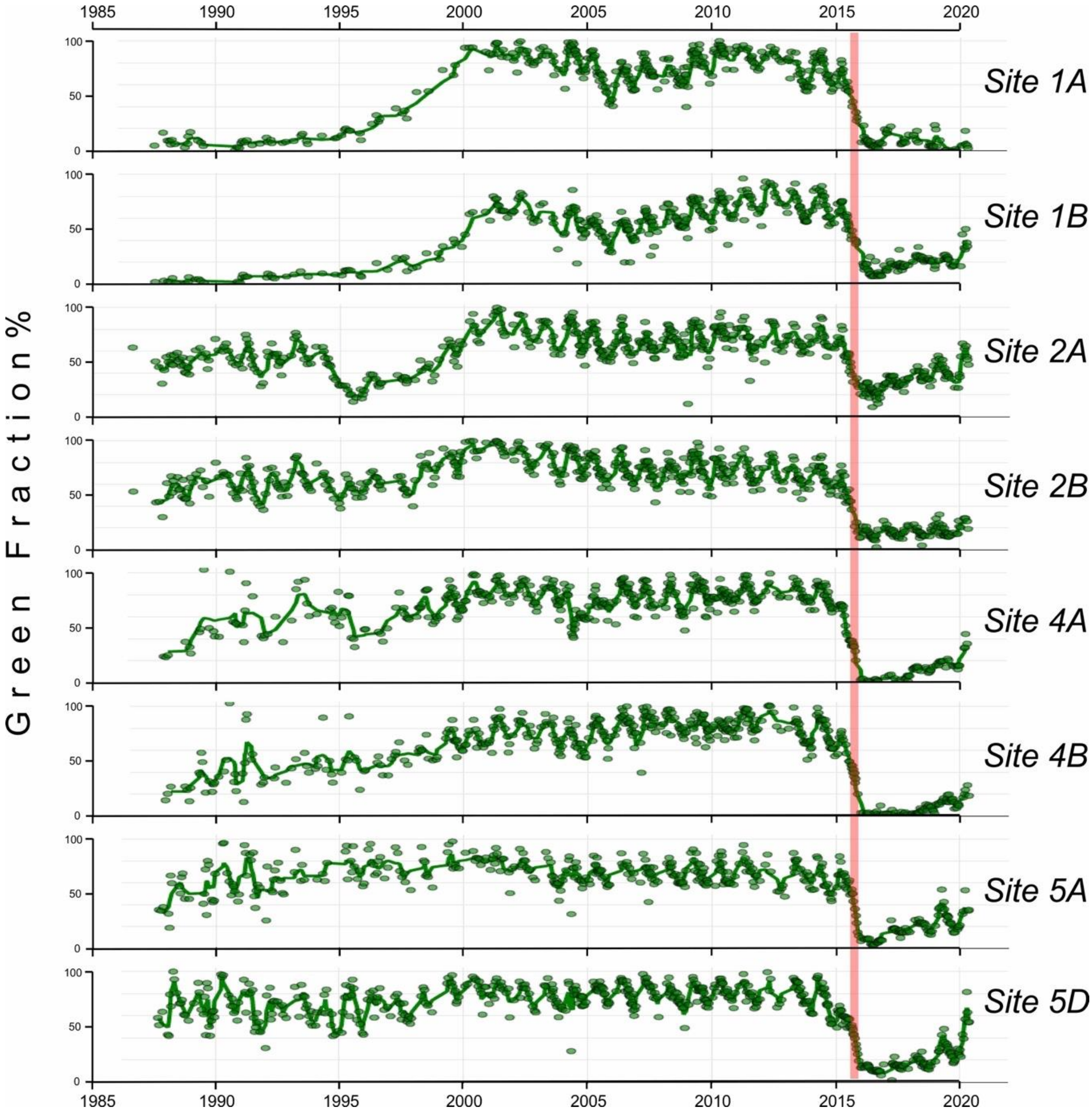

Figure 3.4. Time series plots of green fractional cover estimates from Landsat for the eight transect locations at the four field sites (Figure 2.1) in the Northern Territory (sites 1 and 2) and Queensland (sites 4 and 5) during 1987 to 2020. The red line indicates the synchronous timing of the late 2015 mass dieback event. The widespread impact was coincident with the widespread, dramatic and sudden temporary drop in sea level registered in local port tide gauge records.

3.2 Timing and synchronicity of 2015–2016 mangrove dieback

The key feature of the 2015–2016 dieback of mangroves in the Gulf of Carpentaria was its distinct and synchronous occurrence along more than 2,000 km of coastline. This was evident in canopy vegetation density expressed as a fractional green cover derived from Landsat data for each of eight sites at four locations spread across the Gulf (Figure 3.4). The distinguishing event occurred in each location in late 2015 (red line). Furthermore, note the change in levels of canopy density (the green fraction) in each of the eight time series from 1987 to 2020. Levels start off low in 1987 and generally rise until 2000 at which date they mostly achieved maximum levels. These features were comparable in all locations where there was an apparent recovery trajectory. There were two deductions to be made from these observations. First, these data indicate that severely depleted shoreline fringe mangroves had recovered naturally, taking around 20 years to achieve closed canopy cover. Second, the generally comparable extreme low levels in 1987 suggest there may have been an earlier widespread and synchronous damaging event, prior to 1987. This indicates there may have been an earlier event like that in 2015–2016. It was not possible to extend these time series back further. The green fractional cover data used in the production of these time series plots were not available for earlier periods.

3.3 Landsat imagery with further indications of an earlier dieback event

Landsat satellite imagery from 1972 to 2020 provided a time series of the condition of mangroves bordering Gulf shorelines throughout this time period. While the quality of imagery prior to 1987 was relatively poor, there was, however, good evidence of an earlier occurrence of severe mangrove dieback (Figure 3.5). As such, the dieback event would have occurred after 1978 and before 1989 based on imagery currently available. Fringing mangroves were present and appeared well-established along the Limmen shoreline in both 1972 and 1978 imagery. Imagery afterwards from 1989 to 2015 showed the steady recovery of the shoreline mangroves before their dramatic loss in 2016.

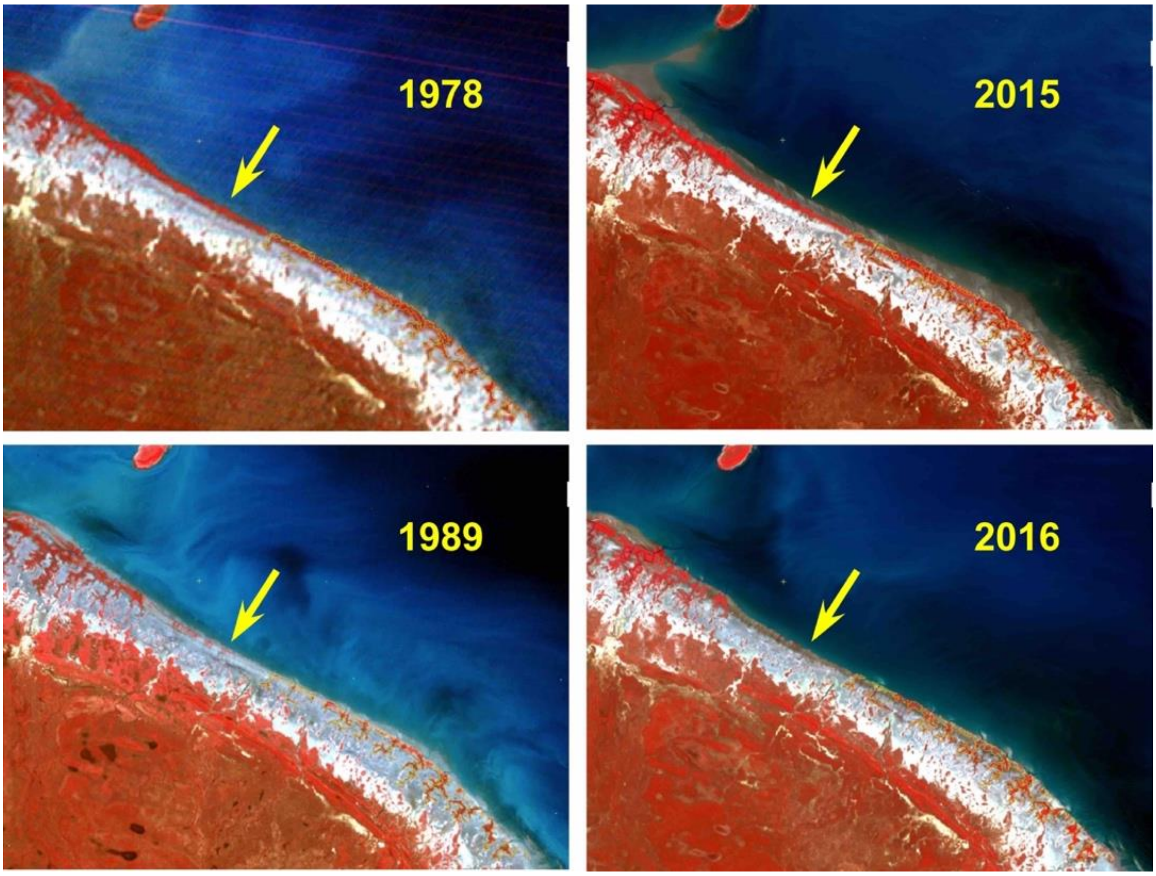

Figure 3.5. Selected time series comparisons show losses of shoreline mangroves (in false red colour) as seen in Landsat imagery. These compare the known 2015–2016 incident (right) with those likely much earlier between 1978 and 1989 (left). These views show the same severely impacted shoreline just east of the Limmen Bight River mouth (Figure 5.102). While no accounts of comparable mangrove losses were reported for the earlier event, these images and other evidence make this a serious possibility. As seen at sites 1A and 1B in Figure 3.4, the foreshore fringing stand followed a recovery trajectory.

Moreover, this earlier occurrence of severe mangrove dieback also appeared to be equally widespread across the Gulf region. Comparable losses along shoreline mangroves near the mouths of the Mitchell and Norman Rivers in Queensland had also occurred in 1989. These findings provide compelling evidence for a possible earlier incident of comparable mass dieback of mangroves in the Gulf region.

3.4 Evaluations of shoreline condition in estuary mouths

The map (Figure 3.6) shows the locations of 37 estuary sites grouped for convenience into the six regional areas. A primary observation for our investigations concerned the distribution of the 2015–2016 mangrove dieback along shorelines of the Gulf of Carpentaria. This was comparable between surveys in 2017 and 2019. In each case, 2015 mangrove dieback was notable in the same five regions, and appreciably less in Western Cape (W Cape) estuaries. Overall levels of severity of 2015 dieback were equivalent between surveys and highest in the Flinders–Leichhardt (F–L) and Roper regions.

With these surveys, 24 indicators listed in Table 2.3 were observed and scored for each estuary mouth. These indicators were divided into two broad categories of impacts: human-induced as both direct and indirect (11 indicators); and, those not obviously human affected as climate-natural impacts (13 indicators). All impacts were considered for each site.

Indicators of mangrove and shoreline condition were grouped for the relative influences of human and climate-natural drivers. A notable trend of increasing climate-natural factors (green bars) was observed for regions in the east and extending to the west in 2017 and 2019 (Figure 3.8). Human influences (red bars) were less severe, but there was a tendency for their decreased influence over the same ordering of regions to the west. Human influences were generally greatest in Western Cape and the SE Gulf regions, a feature largely consistent with port and urban facilities of Weipa around Mission and Embley Rivers, and Karumba at the mouth of the Norman River. High levels in the Mitchell region during September 2019 reflect the relatively high level of recreational and monitoring activities compared to those in December 2017.

The five most severely rated indicators overall were: human impacts (Figure 3.9) – weeds (particularly rubber vine), vehicle tracks, feral pigs, stock animals and fire scorch; and climate-natural impacts (Figure 3.10) – saltpan scouring, bank erosion, terrestrial retreat, ecotone shift negative and 2015–2016 mangrove dieback.

There was reasonable consistency between sampling periods amongst the indicators, although there were differences. On the whole, the dominant human impacts in the Western Cape were feral pig damage, and fires, Mitchell, SE Gulf and Flinders–Leichhardt had dense weed, particularly rubber vine, infestations encroaching on mangrove verges, while in the SW Gulf and Roper it was more about access tracks (Figure 3.9), feral animal (pigs and water buffalo) damage and grazing stock impacts. Of note, there was noticeably more fire damage in eastern regions and on the western side of the peninsula.

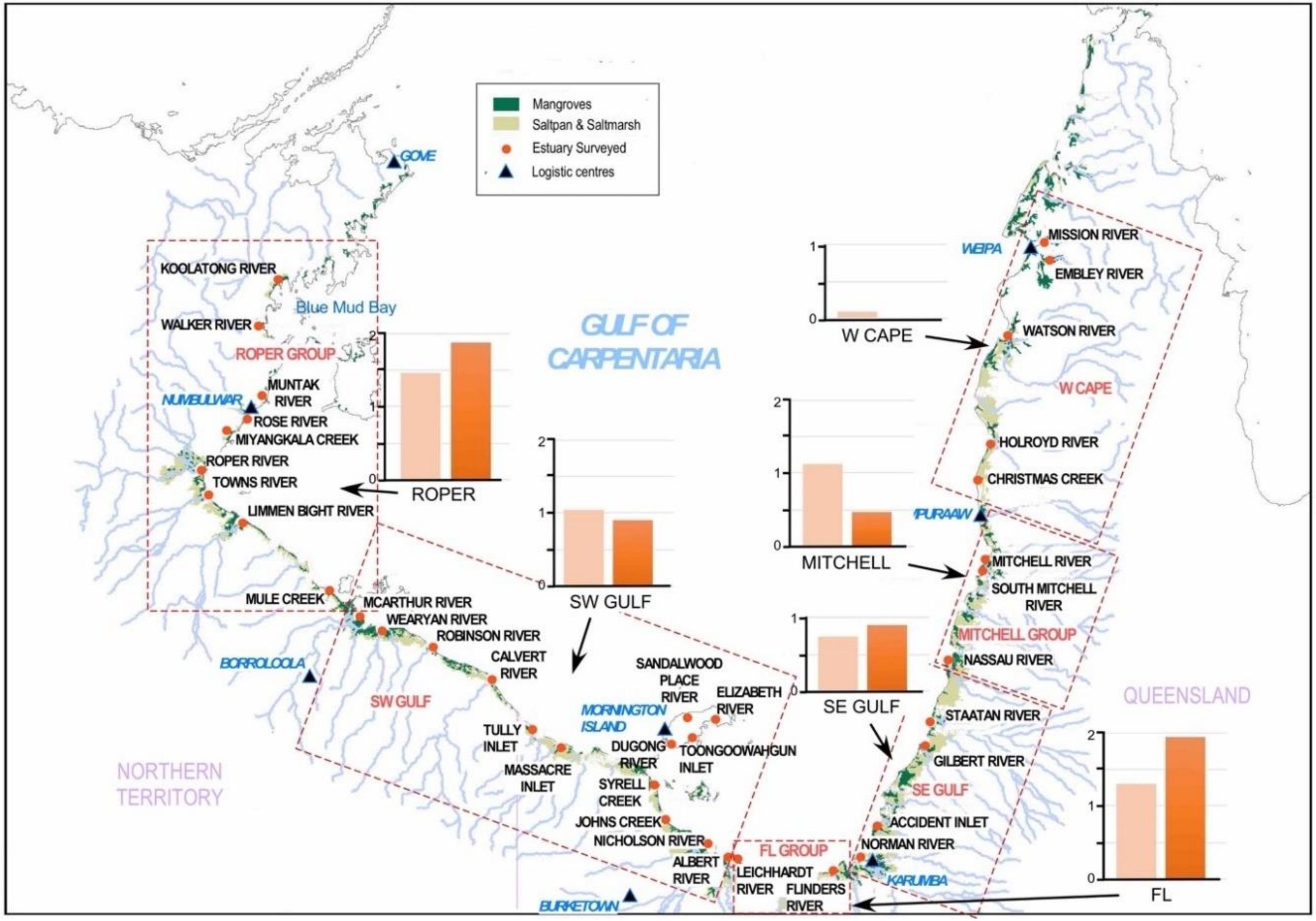

Figure 3.6. Levels of mangrove dieback severity scored in estuary mouths of six drainage divisions (CSIRO, 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i) in 2017 and 2019.

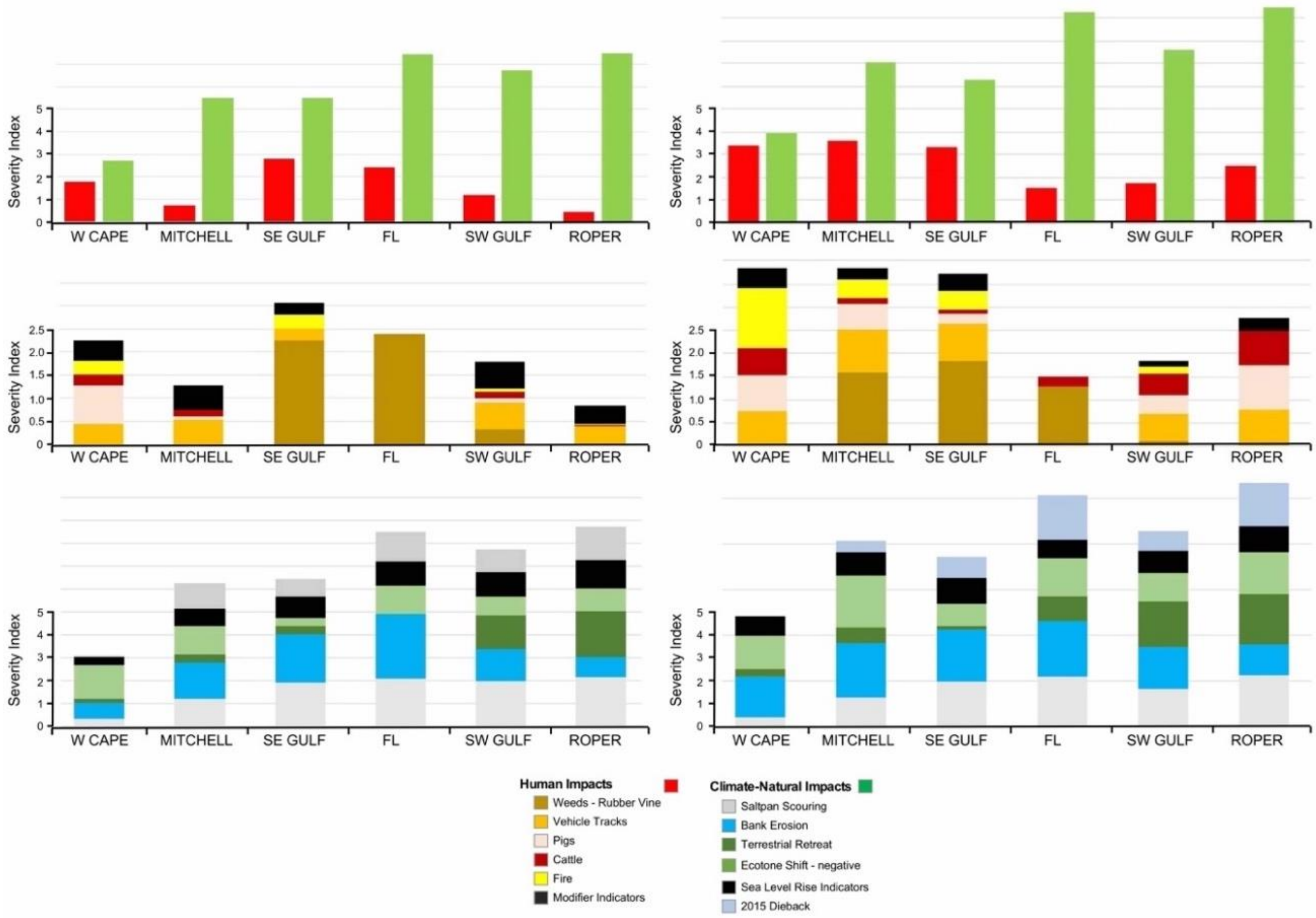

Figure 3.7. Based on the 31–37 estuaries, three levels of histogram graphs comparing severity scores for the six groupings of regional areas in 2017 (left) and 2019 (right), including top pair – human (red) and climate-natural (green) drivers; middle pair – dominant human drivers; and bottom pair – dominant climate-natural drivers.

By comparison, the dominant climate-natural impacts all appeared to increase in severity from eastern to western shorelines of the Gulf. This was the case for the 2015 mangrove dieback damage levels, as noted already, as also seen in two other indicators namely terrestrial retreat and saltpan scouring. Another two indicators, ecotone shift and bank erosion, were relatively high across all regions.

3.4.1 Individual site impacts

Specific observations for each of the key site locations have been listed in each of the estuary site data summaries (Figure 3.8 – Figure 3.10). As done for the regions, the same five highest human impacts and climate-natural impacts are displayed.

In general, overall trends and patterns with individual sites closely match those described for the regions. For instance, the estuarine and tidal wetland regional groupings with the highest direct Human Influences in order included the Mission and Norman systems. Notably those estuaries with active port facilities in their lower reaches.

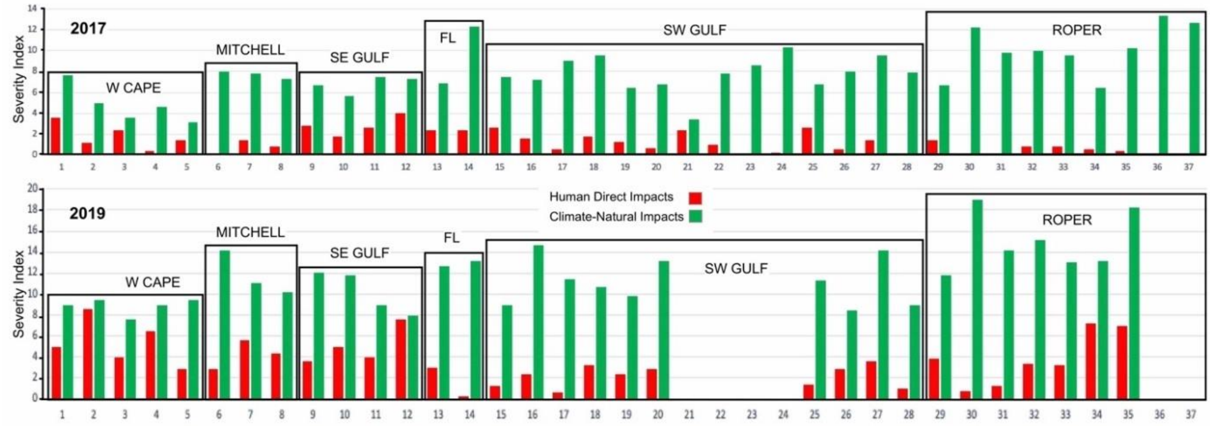

Figure 3.8. Comparing human and climate-natural impacts for 31–37 estuary mouth sites (Table 2.1, Figure 3.6).

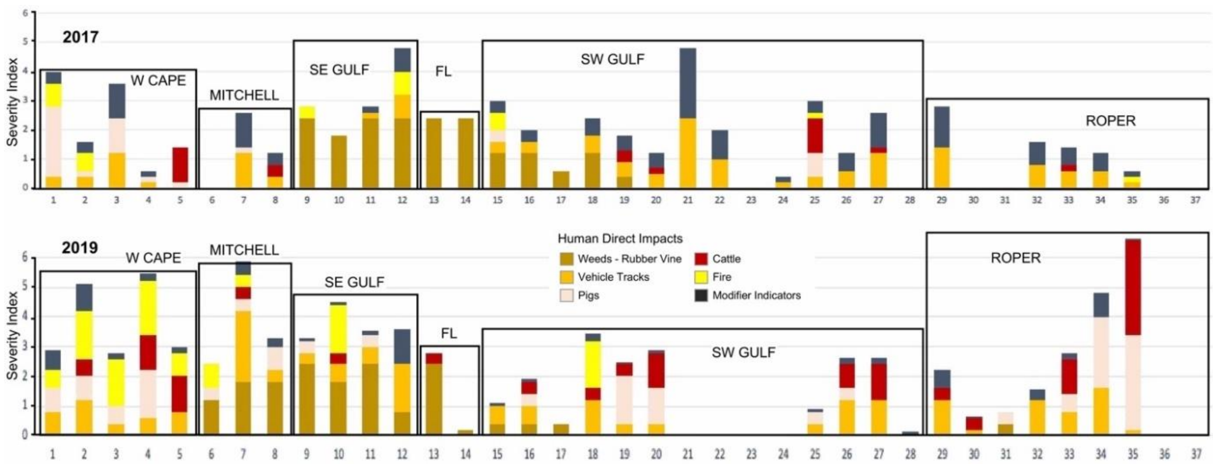

Figure 3.9. Comparing the five overall highest scoring impacts from human factors for 31–37 estuary study sites (Table 2.1, Figure 3.6).

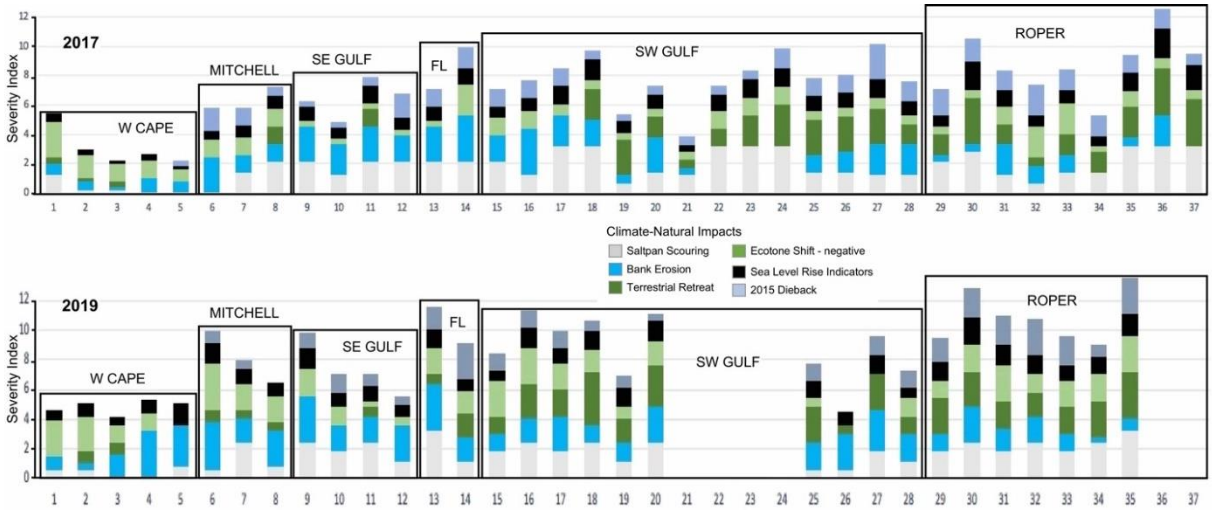

Figure 3.10. Comparing the five overall highest scoring impacts from climate–natural factors for 31–37 estuary study sites (Table 2.1, Figure 3.6).

3.4.2 Estuarine condition assessments

While human-related impacts are largely self-evident, like damage from access tracks (Figure 3.11), it has been useful to quantify their relative importance based on our visual characterisation of the severity of such effects (Table 3.2 and Table 3.3). Because the causes are evident, these observations potentially translate into tangible management recommendations for the limitation and constraint of particular harmful agents responsible.

However, this simple interpretation and identification of specific drivers may be confounded by multiple influences. While a detailed assessment is required to adequately unravel the roles of the various factors involved, there is preliminary evidence revealing the presence of likely relationships between responses and drivers (Table 3.4). These are considered indicative of the longer-term benefits to be gained from a detailed assessment of such monitoring data.

Figure 3.11. Access tracks across tidal wetlands damage delicate mangrove and saltmarsh plants with repercussions on the longer-term survival of these areas.

Table 3.2. Summary of threats and issues observed in 2017 for 37 estuarine locations within the Gulf of Carpentaria mangrove dieback study area (Table 2.1). Maximal scores marked with yellow shading. For further details, see Appendix 3.

	Driver type 2017	Human impact	Natural related	Sites scored	Mean score	Score sum
Human						
1	Structure loss*					
2	Direct loss*					
3	Altered hydrology*					
4	Encroachment*					
5	Access tracks*	X		24	0.69	16.6
6	Stock impacts	X		7	0.54	3.8
7	Feral damage	X		8	0.70	5.6
8	Pollutant impact					
9	Nutrient excess					
10	Fire scorch	X		7	0.51	3.6
11	Weed smother	X		11	1.67	18.4
	Modifier mean	**X**		**24**	**0.69**	**16.6**
Climate–natural						
1	Storm damage		X	8	0.96	7.7
2	Shoreline erosion*		X	18	0.95	17.1
3	Root burial*		X	13	0.50	6.5
4	Inner fringe collapse*		X			
5	Bank erosion*		X	32	1.56	49.9
6	Saltpan scouring*		X	34	1.87	63.6
7	Ecotone shift negative		X	37	0.96	35.4
8	Ecotone shift positive					
9	Depositional gain		X	31	0.78	24.1
10	Terrestrial retreat*		X	25	1.70	42.5
11	Light gaps		X	11	0.61	6.7
12	Altered hydrology		X	3	0.77	2.3
13	2015 dieback		X	33	1.12	37.1
	Sea level rise mean		**X**	**37**	**0.97**	**35.9**

Table 3.3. Summary of threats and issues observed in 2019 for 31 estuarine locations within the Gulf of Carpentaria mangrove dieback study area (Table 2.1). Maximal scores marked with yellow shading. Further details in Appendix 4.

	Driver type 2019	Human impact	Natural related	Sites scored	Mean score	Score sum
Human						
1	Structure loss*	X		8	1.05	8.4
2	Direct loss*	X		4	0.95	3.8
3	Altered hydrology*	X		4	0.85	3.4
4	Encroachment*	X		4	0.70	2.8
5	Access tracks*	X		25	0.84	21
6	Stock impacts	X		16	0.86	13.8
7	Feral damage	X		18	0.93	16.8
8	Pollutant impact	X		24	0.45	10.8
9	Nutrient excess	X		10	0.30	3
10	Fire scorch	X		9	1.20	10.8
11	Weed smother	X		13	1.26	16.4
	Modifier mean	**X**		**26**	**0.30**	**7.88**
Climate–natural						
1	Storm damage		X	15	1.40	21
2	Shoreline erosion*		X	22	1.02	22.5
3	Root burial*		X	23	0.90	20.6
4	Inner fringe collapse*		X	18	0.94	17
5	Bank erosion*		X	31	1.88	58.3
6	Saltpan scouring*		X	29	1.72	50
7	Ecotone shift negative		X	28	1.65	46.2
8	Ecotone shift positive		X	10	0.74	7.4
9	Depositional gain		X	29	1.06	30.7
10	Terrestrial retreat*		X	25	1.68	42
11	Light gaps		X	18	0.78	14
12	Altered hydrology		X	1	1.60	1.6
13	2015 dieback		X	24	1.30	31.1
	Sea level rise mean		**X**	**31**	**1.13**	**35.1**

*Table 3.4. Comparison of nine climate-natural indicators, including 2015–2016 mangrove dieback, observed in 2017 and 2019 aerial surveys showing similarities (correlations) in data scores between sampling periods. Significance levels for Pearson Correlations, 2-tailed test, as: *= 0.1, **= 0.05 and ***= 0.01. For the 31–37 estuaries and the six drainage region groupings (CSIRO, 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i).*

Indicator scored	Drainage region (N=6)	Individual estuary mouth (N=31)	Conclusion comparing 2017 and 2019
2015 dieback	0.544	0.0808	Different
Ecotone shift negative	0.3778	0.1497	Different
Shoreline erosion	0.1316	0.0434	Different
Bank erosion	0.629*	0.1696	Similar
Terrestrial retreat	0.7649**	0.3799**	Same
Saltpan scour	0.9317***	0.3651**	Same
Light gaps	0.6167	0.3512**	Same
Storm damage	0.2977	0.0001	Different
Depositional gain	0.8498***	0.425***	Same

For the climate–natural impacts, the habitat indicators reflect the delivery of regional and less localised drivers. These were identified and quantified based on the various responses observed. Specific examples include shoreline erosion; bank erosion, terrestrial retreat, and storm damage. In general, responsible drivers are expected to influence multiple response indicators. For instance, sea level rise is likely to affect at least both shoreline erosion and terrestrial retreat. In another example, storm damage might affect shoreline erosion; and be confounded by root burial and altered hydrology. Factors like fire were noted, but the effects were patchy (Figure 3.12).

Figure 3.12. Mangroves are very sensitive to fire. Frequent hot grassland burns during neap tide periods have devastating impacts, scorching and killing vulnerable edge stands.

Comparisons between survey dates (Table 3.5 and Table 3.6) show a number of matching score sets consistent with a generally comparable set of response indicators. Differences can be explained by damaging events between sampling dates.

Table 3.5. Summary of 2017 data on threats for 37 locations in the Gulf of Carpentaria mangrove dieback study area (Figure 3.6). Shaded human (pink shaded) and climate-natural (green shaded) issues identify the five most impacted sites, respectively. Shaded rows indicate the six drainage catchment regions (CSIRO, 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i).

Region		Gulf survey estuaries	Average	Cumulative	Cumulative rank	Human issues	Climate issues
W Cape	**1**	Mission River	0.70	11.2	7	3.6	7.6
	2	Embley River	0.39	6.2	33	1.2	5.0
	3	Watson River	0.38	6.0	34	2.4	3.6
	4	Holroyd River	0.31	5.0	36	0.4	4.6
	5	Christmas Creek	0.29	4.6	37	1.4	3.2
Mitchell	**6**	Mitchell River	0.50	8.0	27	0.0	8.0
	7	South Mitchell River	0.58	9.2	20	1.4	7.8
	8	Nassau River	0.51	8.1	26	0.8	7.3
SE Gulf	**9**	Staatan River	0.59	9.5	17	2.8	6.7
	10	Gilbert River	0.47	7.5	30	1.8	5.7
	11	Accident Inlet	0.63	10.1	13	2.6	7.5
	12	Norman River	0.71	11.3	5	4.0	7.3
F–L	**13**	Flinders River	0.58	9.3	19	2.4	6.9
	14	Leichhardt River	0.92	14.7	1	2.4	12.3
SW Gulf	**15**	Albert River	0.63	10.1	14	2.6	7.5
	16	Nicholson River	0.55	8.8	21	1.6	7.2
	17	John’s Creek	0.60	9.6	16	0.6	9.0
	18	Syrell Creek	0.71	11.3	6	1.8	9.5
	19	Massacre Inlet	0.48	7.7	29	1.3	6.4
	20	Tully Inlet	0.47	7.5	30	0.7	6.8
	21	Dugong River	0.36	5.8	35	2.4	3.4
	22	Toongoowahgun River	0.55	8.8	21	1.0	7.8
	23	Elizabeth River	0.54	8.6	23	0.0	8.6
	24	Sandalwood Place	0.66	10.5	11	0.2	10.3
	25	Calvert River	0.59	9.4	18	2.6	6.8
	26	Robinson River	0.54	8.6	23	0.6	8.0
	27	Wearyan River	0.68	10.9	8	1.4	9.5
	28	McArthur River	0.49	7.9	28	0.0	7.9
Roper	**29**	Mule Creek	0.51	8.1	25	1.4	6.7
	30	Limmen Bight River	0.76	12.2	4	0.0	12.2
	31	Towns River	0.61	9.8	15	0.0	9.8
	32	Roper River	0.68	10.8	9	0.8	10.0
	33	Miyangkala Creek	0.64	10.3	12	0.8	9.5
	34	Rose River	0.44	7.0	32	0.6	6.4
	35	Muntak River	0.66	10.6	10	0.4	10.2
	36	Walker River	0.83	13.3	2	0.0	13.3
	37	Koolatong River	0.79	12.6	3	0.0	12.6

Table 3.6. Summary of 2019 data on threats for 31 locations in the Gulf of Carpentaria mangrove dieback study area (Figure 3.6). Shaded human (pink shaded) and climate-natural (green shaded) issues identify the five most impacted sites, respectively. Shaded rows indicate the six drainage catchment regions (CSIRO, 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i).

Region		Gulf survey estuaries	Average	Cumulative	Cumulative rank	Human issues	Climate issues
W Cape	**1**	Mission River	0.58	13.9	21	5.0	8.9
	2	Embley River	0.75	18.0	5	8.6	9.4
	3	Watson River	0.48	11.6	28	4.0	7.6
	4	Holroyd River	0.64	15.4	17	6.4	9.0
	5	Christmas Creek	0.51	12.2	25	2.8	9.4
Mitchell	**6**	Mitchell River	0.71	17.0	7	2.8	14.2
	7	South Mitchell River	0.69	16.6	10	5.6	11.0
	8	Nassau River	0.61	14.6	19	4.4	10.2
SE Gulf	**9**	Staatan River	0.65	15.6	14	3.6	12.0
	10	Gilbert River	0.70	16.8	9	5.0	11.8
	11	Accident Inlet	0.54	13.0	23	4.0	9.0
	12	Norman River	0.65	15.5	16	7.6	7.9
F–L	**13**	Flinders River	0.65	15.7	13	3.0	12.7
	14	Leichhardt River	0.55	13.3	22	0.2	13.1
SW Gulf	**15**	Albert River	0.43	10.2	30	1.2	9.0
	16	Nicholson River	0.71	17.0	8	2.4	14.6
	17	John's Creek	0.50	12.0	27	0.6	11.4
	18	Syrell Creek	0.58	13.9	20	3.2	10.7
	19	Massacre Inlet	0.51	12.2	25	2.4	9.8
	20	Tully Inlet	0.67	16.0	12	2.8	13.2
	21	Dugong River					
	22	Toongoowahgun River					
	23	Elizabeth River					
	24	Sandalwood Place					
	25	Calvert River	0.53	12.7	24	1.4	11.3
	26	Robinson River	0.47	11.2	29	2.8	8.4
	27	Wearyan River	0.74	17.8	6	3.6	14.2
	28	McArthur River	0.42	10.0	31	1.0	9.0
Roper	**29**	Mule Creek	0.65	15.6	15	3.8	11.8
	30	Limmen Bight River	0.83	19.8	3	0.8	19.0
	31	Towns River	0.64	15.4	17	1.2	14.2
	32	Roper River	0.78	18.6	4	3.4	15.2
	33	Miyangkala Creek	0.68	16.2	11	3.2	13.0
	34	Rose River	0.85	20.4	2	7.2	13.2
	35	Muntak River	1.05	25.2	1	7.0	18.2
	36	Walker River					
	37	Koolatong River					

3.4.3 Shoreline condition assessment

3.4.3.1 Summary of survey scores

An assessment was made of mangroves and mangrove dieback along Gulf shorelines from 19,534 images taken in December 2017 every 100 metres from Weipa to Cape Barrow (the mouth of Blue Mud Bay; Figure 3.6). In total, 17,220 images, around 88.2%, showed clear views for assessments of shoreline features at ten frames per kilometre. Notably, mangroves bordered the seaward shoreline for 762.3 km or 44.3% of the coast. The number of mangrove shorelines varied throughout the Gulf, as depicted in Table 3.7, showing amounts in each of the six drainage regions (CSIRO, 2009a). While most of the western side of Cape York Peninsula (W Cape and Mitchell) had relatively fewer mangroves bordering the coastline (20% or less), shorelines in the south across to the western side had more than 50% with mangroves. The area with the greatest proportion (88.6%) was the shorelines of the Flinders–Leichhardt region.

Table 3.7. Summary of assessable shorelines showing total lengths of non-mangrove and mangrove vegetation facing the sea in the Gulf of Carpentaria study area surveyed (from Blue Mud Bay to just north of the Mitchell River; Figure 3.6). Regions are those used with the CSIRO NASY project (CSIRO, 2009a, 2009b, 2009c).

Assessable shoreline length (km)	W Cape*	Mitchell	SE Gulf	F–L	SW Gulf	Roper	Total
Total	**324.1**	**148.9**	**184.3**	**134.7**	**535.4**	**394.6**	**1722**
Non-mangrove	295.1	118.3	86.6	15.3	253.2	191.2	959.7
Mangrove	29.0	30.6	97.7	119.4	282.2	203.4	762.3
% mangrove	8.9	20.6	53.0	88.6	52.7	51.5	44.3

Note: * data from only a small southern part of the region.

3.4.4 Extent of shoreline dieback of mangroves

The extent of impacted shorelines across the Gulf as those shorelines observed having 2015–2016 mangrove dieback are displayed in Table 3.8 and Table 3.9, plus Figure 3.13.

Table 3.8. Summary of assessed shorelines showing total lengths of mangrove dieback in seaward fringing stands in the Gulf of Carpentaria (from Blue Mud Bay to just north of the Mitchell River; Figure 3.6). Regions are those used with the CSIRO NASY project (CSIRO, 2009a, 2009b, 2009c).

Shoreline length with mangrove dieback (km)	W Cape*	Mitchell	SE Gulf	F–L	SW Gulf	Roper	Total
None	12.1	11.0	26.7	32.5	69.5	40.9	211.2
1%–30%	5.2	10.7	40.2	69.8	162.5	96.8	379.4
30%–60%	4.2	4.1	16.2	15.4	38.7	35.4	109.9
60%–90%	5.5	2.7	8.7	1.5	9.4	23.4	45.3
90–100%	2.0	2.1	5.9	0.2	2.1	6.9	16.5
TOTAL assessed %	29.0	30.6	97.7	119.4	282.2	203.4	762.3
Dieback present	16.9	19.6	71.0	86.9	212.7	162.5	551.1
>30% dieback	11.7	8.9	30.8	17.1	50.2	65.7	171.7

Note: * data from only a small southern part of the region.

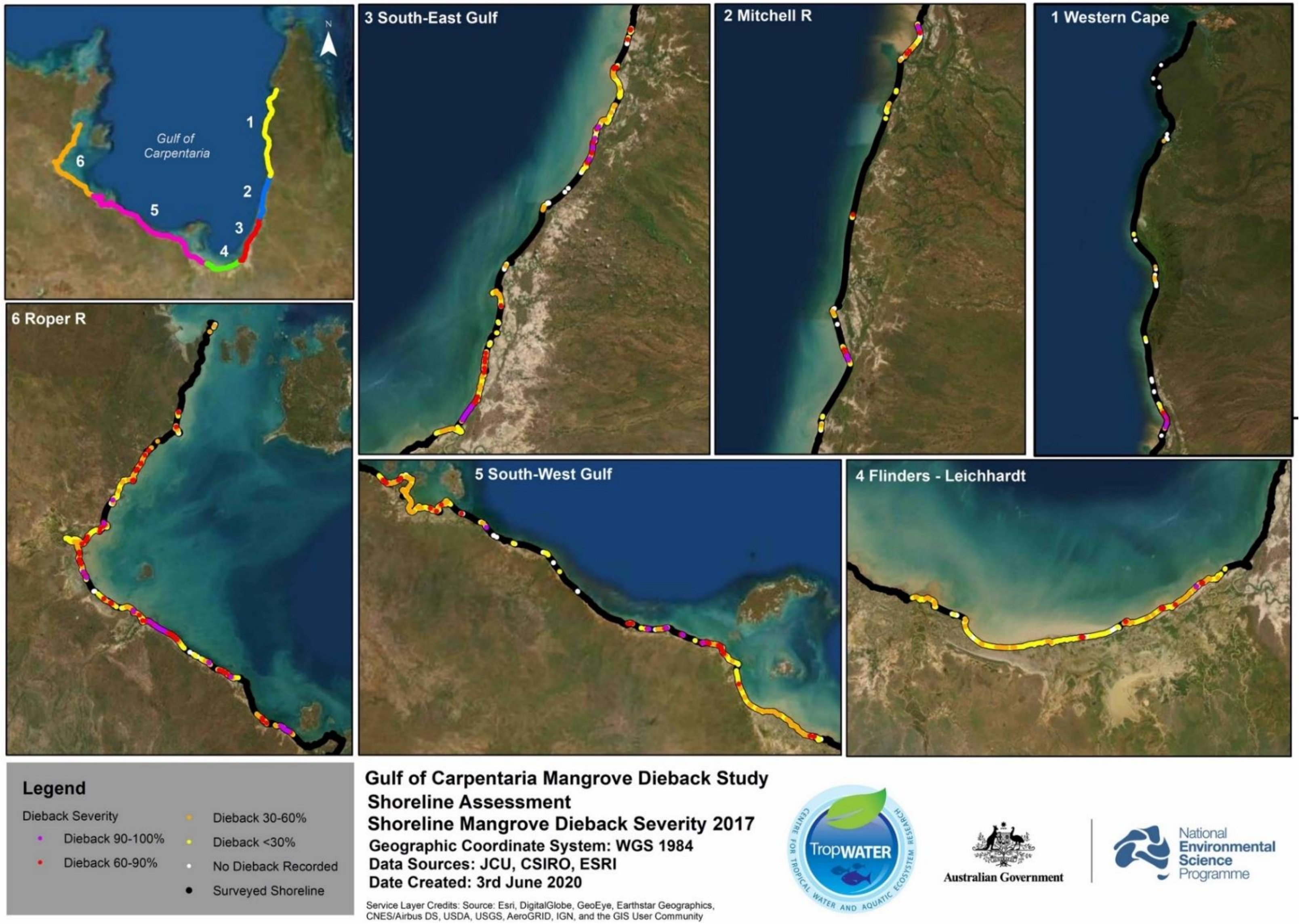

Figure 3.13. Mapped shorelines, showing mangroves and the extent of dieback severity classes for each of the six drainage regions (Figure 3.6).

In total, 551.1 km (72.3%) of mangrove shorelines showed some level of dieback impact. The region with the least amount of dieback was the Western Cape with 16.9 km (58.5%) – this being restricted to shoreline fringing stands in the southern extremity (Figure 3.13). By contrast, there were greater losses in all five other regions – ranging from 64.1%–79.9% of seaward edge mangrove stands. It was notable that these losses to the shoreline fringe were at the 'back' or upper edge at the saltpan-mangrove ecotone – mostly not reaching the seaward edge. The distinctive result was that most shorelines (97.5%) had intact surviving seaward stands. And, 72.2% of impacted shorelines maintained their seaward fringe. This augers well for the longer-term recovery of these shorelines since surviving vegetation offers some protection from exposure to large waves, strong winds, and storm conditions.

Table 3.9. Summary of assessed shorelines showing proportions of lengths of mangrove dieback in sea-facing fringing stands in the Gulf of Carpentaria (from Blue Mud Bay to just north of the Mitchell River; Figure 3.6). Regions are those used with the CSIRO NASY project (CSIRO, 2009a, 2009b, 2009c).

% shoreline length with mangrove dieback	W Cape*	Mitchell	SE Gulf	F–L	SW Gulf	Roper	Total
None	41.7	35.9	27.3	27.2	24.6	20.1	27.7
1%–30%	17.9	35.0	41.1	58.5	57.6	47.6	49.8
30%–60%	14.5	13.4	16.6	12.9	13.7	17.4	14.4
60%–90%	19.0	8.8	8.9	1.3	3.3	11.5	5.9
90%–100%	6.9	6.9	6.0	0.2	0.7	3.4	2.2
Dieback present	58.3	64.1	72.7	72.8	75.4	79.9	72.3
>30% dieback	40.3	29.1	31.5	14.3	17.8	32.3	22.5

Note: * data from only a small southern part of the region.

Moderate to severe levels of dieback (>30%) were recorded along 171.7 km (22.5%) of mangrove shorelines. Relatively similar amounts (14.3%–40.3%) of this level of dieback were observed in each of the six regions. It is significant that the shoreline extent impacted was at least 2,000 km in length from Queensland to the Northern Territory.

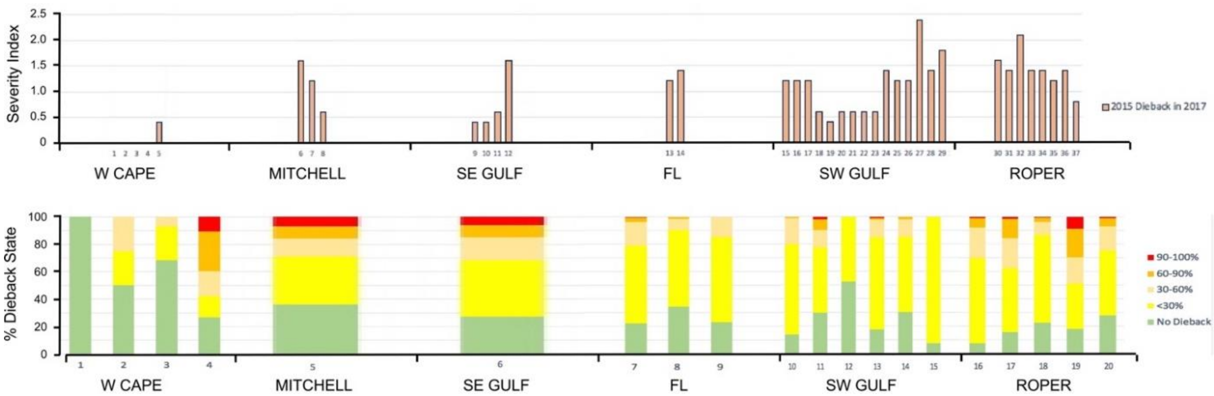

Figure 3.14. Distribution of 2015–2016 mangrove dieback across the six drainage regions of the Gulf of Carpentaria (Figure 1.4) scored in estuary surveys as overall severity (top graph; numbers refer to estuaries in Table 3.5 and in shoreline assessments as proportions of dieback extent – no dieback, 1%–30%, 30%–60%, 60%–90% and 90%–100% loss of the seaward fringing zone (lower graph; numbers refer to the region shoreline or subsections within each region).

The most severe impact of 90%–100% loss occurred along 16.5 km (2.2%) of the seaward fringe zone, and these losses were present in all six Gulf regions. The maximum coast length of this highest level of impact was 6.9 km (3.4%) in the Roper region and 5.9 km (6.0%) in the South East Gulf.

Aerial assessments of the distribution of 2015–2016 mangrove dieback are summarised in Figure 3.13. Findings from the shoreline assessments of extent are compared with estuary severity scores (see *Region and site summary data* section; Figure 3.14). The overall conclusion has been that the dieback was unusually widespread and patchy with variable levels of impact severity affecting mangroves around estuary mouths, although greater levels of damage were scored along seaward fringing shorelines. The Western Cape region was less affected with a transition from non-affected shorelines towards the north to higher levels in the south. Moderate to extreme dieback levels were recorded in all regions. The extent of dieback and the high levels of severity recorded with these studies had never been recorded before from a single event.

4. Discussion about remote assessment findings

4.1 Enhanced appreciation of the vulnerability of tidal wetlands

Observations and data from mapping and aerial surveys have defined and characterised the mass dieback of mangroves in the Gulf of Carpentaria that occurred in 2015–2016. The occurrence of this event was first raised in earlier published accounts, including Duke (2017), Duke et al. (2017), and Van Oosterzee & Duke (2017). Current JCU surveys both confirm these prior findings and greatly extend upon them with additional observations and further informative conclusions. These surveys have focused particularly on the extent of dieback, its severity, its timing, and its cause. They have also quantified other salient characteristics like the predominance of dieback at upper zone limits of seaward mangrove fringes rather than amongst mangroves bordering estuarine reaches. Such additional observations have greatly enhanced our understanding of the dieback event and the potentially influential factors like rapidly rising sea levels, extreme high temperatures, low moisture (semi-arid) weather conditions, frequent and severe cyclones, massive flooding events, occurring in the typical, low relief setting surrounding the broad, shallow gulf. Climate-related anomalies at the time were described by Harris et al. (2017).

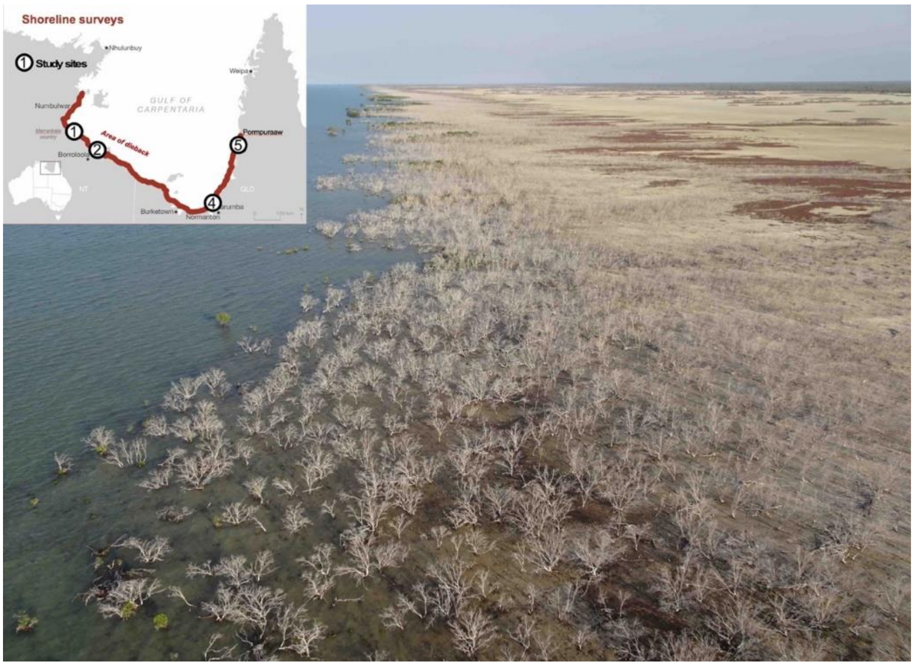

Figure 4.1. This image shows dead shoreline three years after the 2015–2016 event (Limmen Bight shoreline at site 1, Northern Territory, 2018). The inset shows the extent of the impacted shoreline along with four study site locations (Figure 2.1) where detailed field investigations assessed topography, vegetation and fauna (described in Vol. 2). Note: the state of degradation of dead trees at the time was such that they were standing and holding small twigs on branches.

Table 4.1. A brief summary of environmental observations associated with the 2015–2016 mass mangrove dieback event in Australia's Gulf of Carpentaria (Duke et al., 2017), updated in 2019.

General observations	Observed impact	Likely cause	Recovery or degradation	Consequences
Mangrove condition – extent	Dieback of 8,000 ha widespread over 1500 km	Regional applied factors	3-years post event degradation appears to outweigh recovery	Likely to influence fisheries catches, enhanced sediment mobilisation
Mangrove condition – timing	Dieback occurrence synchronous	Single unusual event	Negative localised influences of severe storms and flooding	Shorelines habitats at risk where they share threats
Mangrove condition – biodiversity	Dieback of multiple mangrove species	Setting factor, e.g. species zonation	Recovery and degradation rates of wood and roots vary for each species.	Some species are at risk of local extinction.
Mangrove condition – tidal elevation	Dieback at higher elevation zones and of taller plants	Factor related to tidal elevation	Because taller trees affected most, there is reduced erosion and exposure resilience of surviving stands	The loss of entire foreshore fringing stands, likely to take many decades to recover, if at all.
Extreme events – natural variability	No widespread severe storms, cyclones, tsunamis, flooding, etc.	Not applicable	Subsequent cyclones and flooding are likely to cause severe damage to natural recovery	Disturbances likely to alter ecosystem replacement and turnover processes
Extreme events – anthropogenic	No widespread oil spills or other pollutant or sediment discharges	Not applicable	Not applicable	Reduced resilience of shoreline habitats
Extreme events – temperature climate and weather	Likely to be related but limited direct evidence	Extreme high temperatures	No subsequent events of comparably high temperatures	Vulnerable to future extreme high-temperature events
Extreme events – rainfall climate and weather	Likely to be related but limited direct evidence	Prolonged drought and extreme low rainfall	No subsequent events of comparably low rainfall	Vulnerable to future periods of low rainfall
Extreme events – sea level rise	Likely to be related but limited direct evidence	Rising sea levels up to 3x's the global average	Rising sea levels are likely to affect recovery trajectories	Saline inundation, erosion of terrestrial edge habitats plus scouring of saltmarsh-saltpan
Extreme events – sea level drop	Very likely related	Temporary sea level drop of 20 cm Sept-Dec 2015	No subsequent events	Damage to shoreline integrity and exposure resilience

[a] *source* Hope et al., 2016

As noted, a distinguishing feature of the 2015–2016 dieback of mangroves in the Gulf of Carpentaria was its synchronous occurrence along more than 2,000 km of coastline (Figure 3.4). But, the condition of mangrove forests over the period of 1987–2017 was also important. While each time series had unique localised influences, it was evident that canopy cover generally followed an expansion or recovery trajectory from 1987 to around 2000 – particularly noticeable in site 1. A key question arising from this observation concerned the condition of mangroves, if any, in these locations prior to 1987. There were two possibilities, either these shoreline fringing sites had been expanding seaward, or they were recovering from a similar, possibly synchronous dieback event before 1987. Our investigation of historical Landsat imagery answered this question, in part, where dense fringing mangrove stands were present in imagery from 1972 to 1978 (Figure 3.5). And, the mangroves shown in the time series of images from 1989 to 2018 for each of the sites matched the condition depicted in the green fraction plots (Figure 3.4). This provides reasonable evidence for an earlier regional-scale impacting event similar to that in 2015–2016 had occurred between 1978 and 1987.

The observations of driving factors mentioned in this report described the range of processes likely responsible for those conditions influencing tidal wetland habitats. A listing of significant observations regards the 2015–2016 mass mangrove dieback event are provided in Table 4.1. Key questions include how severely had the Gulf coastline been impacted by dieback, and what factors contributed to the sudden event? Was this instance of large-scale dieback influenced or caused by climate change, and what is the likelihood of its re-occurrence? One inescapable truth is the realisation that mangrove ecosystems are indeed more vulnerable than had been appreciated earlier.

The studies with this project confirm prior findings and add significant new observations to better explain the causes and circumstances under which the 2015–2016 event occurred. As it happens, the deductions made in this first volume broadly define the circumstances surrounding this event with its unusual occurrence of sudden and severe mangrove dieback. Also identified was the range of influencing factors starting with the environmental setting influenced by rapidly rising sea levels, extreme high temperatures, low moisture (semi-arid) weather conditions, frequent and severe cyclones, massive flooding events, and typically low relief topography facing the large shallow gulf. These shorelines generally appeared to be unusually vulnerable to severe weather events. And, it is of grave concern that the damaging factors are expected to increase in intensity as temperatures continue to rise.

Furthermore, Laurence et al. (2011) indicated that saltmarsh and mangroves were in Australia’s top ten most vulnerable ecosystems and that sea-level rise, extreme weather events, and changes to water balance and hydrology were ranked as the three most likely threats. These predictions appear to be broadly consistent with the impact of the 2015–2016 event and subsequent accumulative impacts. It seems likely these areas of typically stressed tidal wetlands in the Gulf have been only the first to reach the tipping point to mass dieback as climate conditions become more variable, altered and damaging.

With the loss of so many mangrove trees (76.5 km^2 with this one incident), the retreat of shorelines might be expected to follow as overall sea levels rise (Figure 4.2). But, by how much? Has there been any recovery? The occurrence of such a large-scale disturbance to shoreline mangroves has raised serious concerns about the consequences on shoreline mangroves and the growing risks these habitats face as threatening pressures escalate

(Harris et al., 2018). This raises the urgency to better understand the key drivers of such major disturbance events – and how their influences might be minimised.

4.2 Aerial survey observations and the potential causal factors

The timing of the mangrove dieback event strongly suggests it was linked to the severe El Niño event of 2015–2016 – the 3rd most severe event in Australia's instrumental climate record (Hope et al., 2016; Harris et al., 2017). Arguably the likely key factor responsible for the mass dieback appears to have been the temporary 20 cm drop in sea level that reduced levels of tidal inundation over several months in late 2015 (Duke et al., 2017). However, matters were slightly complicated by the coincidence also of other climate factors stressful to mangroves, including unprecedented high air temperatures and prolonged drought with low moisture conditions persisting over the previous four years (Figure 4.3).

The impacts of such a short term 'pulse' event (rapid drop in sea level, elevated temperatures, monsoonal failure) was amplified by a longer-term climatic 'press' driven by decades of air and ocean warming (Harris et al., 2018) and sea level rise (Church et al., 2009; Hobday & Lough, 2011). Weather data gathered from eight meteorological stations spread across the Gulf south coast region (Numbulwar, Ngukurr, Borroloola, Centre Island, Macarthur River Mine, Mornington Island, Burketown, Normanton) showed mean temperatures rose by around 0.9 °C over the previous 50 years, and that temperatures during late 2015 exceeded all previous records (Figure 4.3a). While concurrent rainfall levels were mostly below average over the four years previous to 2015, over the last 50 years, there was no distinguishable trend in mean rainfall (Figure 4.3b).

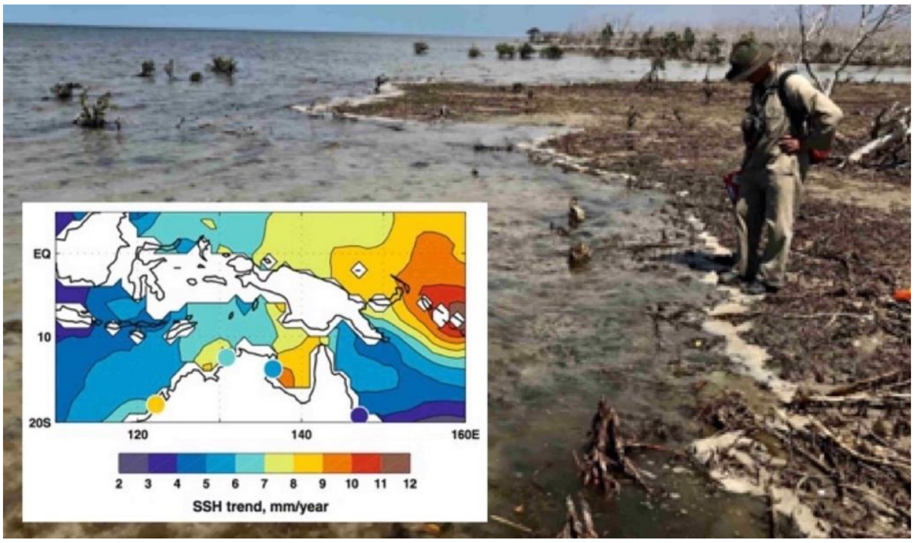

Figure 4.2. Shoreline erosion occurs when sea edge trees are lost, as seen in the Gulf of Carpentaria (Limmen Bight shoreline at site 1 (Figure 0.7), Northern Territory, in 2018). Surviving plants are unable to resist strong winds and waves that regularly buffet exposed shorelines. Seedling re-establishment is seemingly too slow and unable to keep up. This can be due to rising sea levels, but at a local scale further impacts a caused by severe cyclones. Inset: Sea level trends estimated from satellite altimeter data from January 1993 to December 2007 in the region. Comparable sea level data from tide gauge data from the National Tidal Centre are indicated by the coloured circles.

There was, however, a significant long-term rise in sea level recorded across three monitoring stations (Milner Bay on Groote Island, Karumba and Weipa; Figure 4.3c). This trend had a mean 3.65 mm/yr rise in sea level over the previous 25 years. These data were detrended based on this rise to further emphasis the unusually low sea levels at the time of the mass dieback in 2015. The reduced sea levels were a notable consequence of the particularly severe El Niño event depicted in Southern Oscillation Index measures (Figure 4.3d).

Sea levels are particularly sensitive to changes in climatic conditions, including atmospheric wind forcing (Wyrtki, 1984, 1985). When a severe El Niño event occurs, such as with the 2015–2016 event, the prevailing wind field collapses (Oliver & Thomson, 2011). In southern tropical latitudes, this results in prevailing south-easterly trade winds being reversed by strong westerly winds. These unusual atmospheric conditions force warm surface waters from the western to the eastern side of the Pacific Ocean for as long as the severe El Niño conditions persist. During such an event, sea levels in the western Pacific will be notably lower (up to 20 cm), and in the eastern Pacific, they will be correspondingly higher, and warmer. These times also often have unusually large numbers of more severe tropical cyclones.

Because severe El Niño conditions bring about such significant changes to sea level whilst also bringing other extreme climatic conditions like drought and heatwave, they will understandably also have a strong influence on mangrove forests. Tidal wetland habitats already under extreme pressure from steadily rising sea levels are vulnerable to additional 'pulse' events. The 2015–2016 mass dieback of mangroves has therefore been considered a classic 'press-pulse' response as described by Harris et al. (2018) for this and other ecosystems across Australia, both marine and terrestrial. Available moisture, vapour pressure, temperature and sea level across the Gulf of Carpentaria up to and during the dieback event were all consistent with a failure in the monsoon's normal arrival that year. These were likely to have influenced the widespread occurrence of hypersaline sediment porewater, resulting in severe mortality of mangroves as conditions exceeded plant tolerances. These conditions are likely to have resulted in the sudden rapid decline in mangrove cover during November-December 2015 (Figure 3.4) which persisted into the dry season of 2016. Similar circumstances were reported by Lovelock et al. (2015) for mangrove stands on the semi-arid Western Australian coastline, except that the drop in sea levels was not as large as that experienced in the Gulf. Nevertheless, the low sea levels had corresponded with the 2015–2016 El Niño event, resulting in enhanced soil salinity, some loss of mangrove cover and slow recovery. In this instance, the impacted area was two orders of magnitude smaller than the event in the Gulf of Carpentaria.

In summary, observations from the Gulf of Carpentaria reveal a complex interplay of at least four environmental factors, namely the sea level drop, a lengthy drought, low rainfall, and a heatwave – all associated with the severe El Niño. This combination of drivers forced a severe short-term response exceeding the physiological and ecological tolerance of mangrove plants driving this vulnerable habitat into a significantly degraded state – perhaps irreversibly with the on-going pressure of rising sea levels.

Mangroves of the semi-arid, wet-dry tropical Gulf of Carpentaria coastline exist at or near the limit of their local distributional positions in terms of tolerance to seasonal aridity, air and sea surface temperatures, and porewater salinity. This habitat was therefore highly susceptible to this particular climate press. At the time of the mass dieback, mean air temperatures and sea surface temperatures had increased by 1.64 and 1.56 ºC, respectively, since 1910.

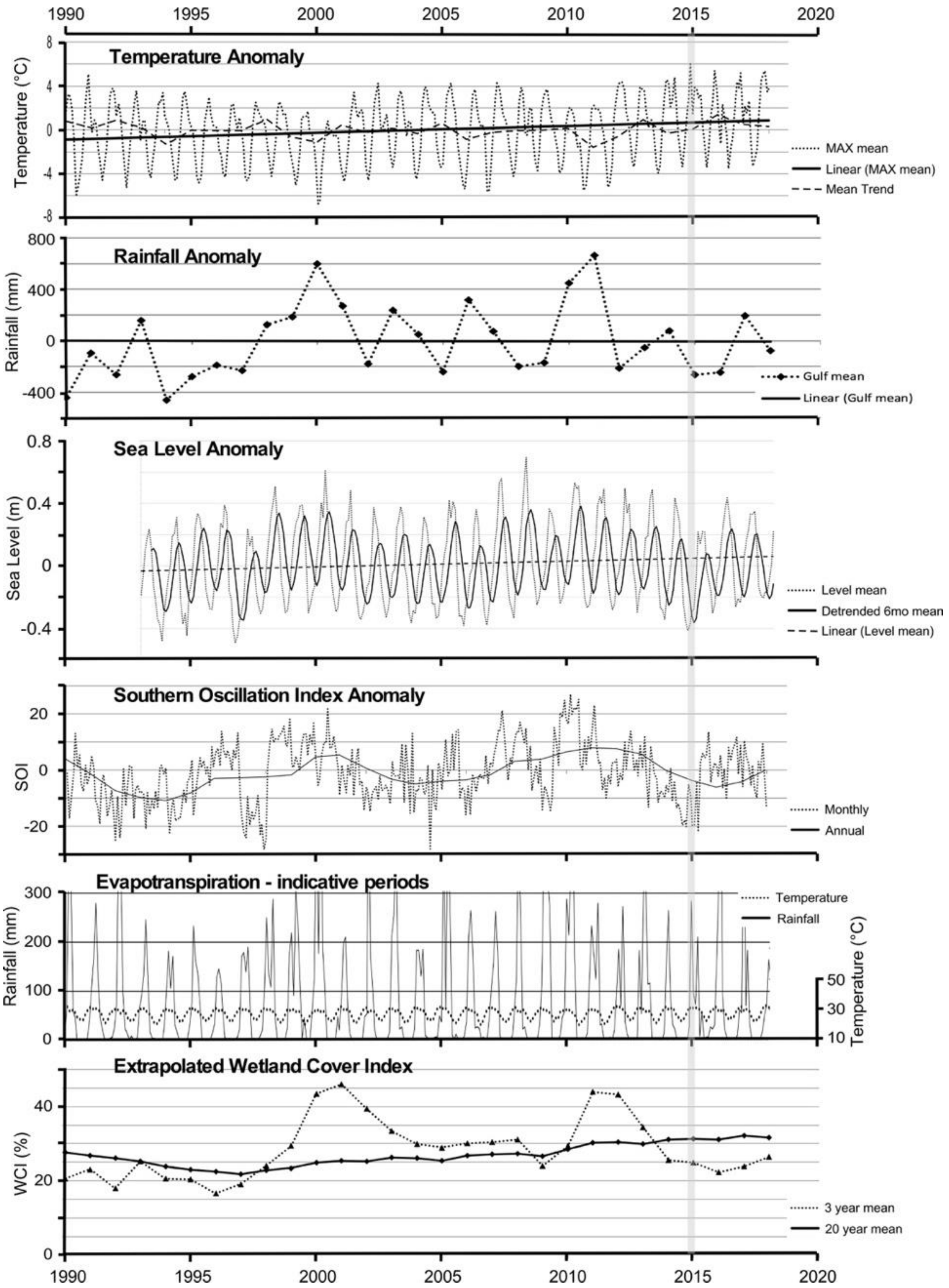

Figure 4.3. The condition of climate and environmental factors up to and after the 2015 mangrove dieback event (grey vertical line) in the Gulf of Carpentaria. Data were sourced online, mostly from the Australian Bureau of Meteorology. Factors showing anomalies were calculated using the 1990–2019 reference period and include (top to bottom): a) temperature monthly and annual mean maxima plus the overall trend; b) rainfall annual means plus the overall trend; c) sea level monthly means, the overall trend, and the detrended six-monthly means; d) the Southern Oscillation Index monthly and annual means; e) indicative levels of evapotranspiration shown as periods when the temperature exceeded rainfall at respective scales; and f) wetland cover index levels deduced from its rainfall correlate (Duke et al., 2019a) using three and 20-year running means.

It is pertinent to compare these climatic conditions to the previous instance of a short-term (less than six months) significant drop in sea level as observed with the very severe 1982–1983 El Niño event (Lukas et al., 1984; Wyrtki, 1984, 1985; Oliver & Thompson, 2011). On that occasion, however, no record of mangrove condition was reported, although we do know now that there was severe dieback between 1978 and 1987 (Figure 3.5). What we do know is that the 1982–1983 pulse event did not appear to have coincided with equivalent amplified temperatures as recorded with the 2015–2016 event, nor was this earlier event accompanied by monsoonal failure. We believe it is critically important towards understanding the cause of such mass dieback of mangroves, to confirm whether there was an earlier widespread event of mass dieback in the Gulf.

While key primary findings were the occurrence of dieback over a broad geographic area, its synchronous occurrence, and its involvement of multiple mangrove species (Figure 1.1). These observations (Table 4.2) were considered justification for ruling out a number of key processes, specifically replenishment and localised factors, and a lack of evidence for large-scale human-related extreme events, like a large oil spill. These investigations into the cause were therefore directed towards understanding more about the influences and changes in sea level and climate. These points are explored further in Vol. 2.

Should there have been similar past dieback events with different associated factors, then it may be possible to develop and refine a predictive model by focusing on the variables in common between events. For example, a testable assumption might be that a drop in sea level was the primary factor causing mass dieback? If not, then it would be a combination of environmental factors, as mentioned. One tangible line of enquiry relies on the comparative mapping of historical remote sensing imagery (satellite views, airborne photography) of mangroves condition with climate variables – and developing a timeline for this and other mass dieback events. Currently, there has been a lack of appropriate historical imagery, leaving this conclusion pending.

An important climate variable was rainfall. Mangroves require freshwater input from rainfall delivered directly, or as catchment runoff, tidal flooding, or groundwater flows (Duke, et al., 2019a). However, since the southern hemisphere, wet season anomaly of 2010–2011, the Gulf of Carpentaria coastline had experienced significantly below average mean annual rainfalls (Figure 4.3b). The wet seasons of 2014–2015 and 2015–2016 yielded rainfall anomalies of -586 and -295 mm in the Borroloola area of the southern Gulf coastline. In this 'pulse period', monsoons were of short duration, inducing low cloud cover, high radiation levels, elevated air temperatures (Figure 4.3a), vapour pressure deficits, and high evaporation rates (Hope et al., 2016). Had these stressors become particularly acute leading into the late dry season of 2015 (Oct to Nov) – the period when the mass dieback event became prominent?

These findings were inconclusive, however. Firstly, note that low rainfall levels (Figure 4.3b) had not resulted in mangrove dieback on previous occasions when rainfall conditions were similarly low, like during the mid 1990s. Furthermore, note the indicative evapotranspiration periods (Figure 4.3e) also had no specific correlative links to the mass dieback event. Secondly, this observation was supported by an assessment of the wetland cover index (WCI), as the percentage of mangrove cover versus the total area of tidal wetlands (Duke et al., 2019a). For the Gulf dieback event in 2015, the derived annual estimates of the WCI varied between 28.14% and 28.86% during the 2013–2016 period. By comparison, those measured from available mapping data at the time (Duke et al., 2017) were around 27.1%.

This meant that the observed extremes in rainfall did not appear to account for the overall losses observed, of around 6% of mangrove cover. Therefore, the dieback response did not appear to be related to shorter-term low levels of rainfall prior to the mass dieback event in late 2015.

It appears that moisture levels due to rainfall had been maintained within normal limits for these otherwise resilient trees. In fact, during the previous 25 years, the proportion of mangrove extent had risen overall from ~20% to just more than 30% (Figure 4.3f). This suggests that any downward pressure of recent drier weather conditions is considered unlikely to have had a strong influence on the mass dieback of mangroves in 2015–2016.

Accordingly, these weather variables can be largely excluded as a primary cause since the unusual conditions surrounding the dieback event had not been sufficiently extreme to explain the severe response observed. Therefore, the current view is that it is considered unlikely that the mass dieback would have occurred had it not been for the temporary 20 cm drop in sea level. This left at least one significant question. Was the drop in sea level alone sufficient to have caused the mass dieback event? Or, had the impact of the temporary drop in sea level been enhanced by the extreme climatic conditions at the time? In either case, the co-occurrence of weather and sea level influences were notably coincident for the 2015–2016 mass dieback event – so, at this time, such a likelihood cannot be ruled out.

Table 4.2. Deductions from the environmental forensic evaluation of the 2015 mass mangrove dieback event in Australia's Gulf of Carpentaria (Duke et al., 2017), based on the four levels of influencing processes that define the occurrence, extent and character of tidal wetlands.

	Regional drivers, local impacts		Disturbance and responses	
Evidence observed	Shoreline topographic setting plus sea level	Climate variability	Regional mangrove forest replenishment with small-scale disturbances	Localised disturbances exceeding the ambient range
Mass dieback widespread – synchronous occurrence, not species-specific	Likely	Likely	Small-scale human & natural factors excluded.	Local human & natural factors excluded – no severe weather event, no large oil spill, etc.
Highest records of air temperature	Likely	Period of high moisture stress. Unlikely primary factor, as temperatures not beyond survival range & not specifically synchronous with mass dieback.	Excluded	Excluded
Prolonged drought period	Likely	Period of high moisture stress. Unlikely primary factor, as deduced. Wetland Cover Index from longer-term rainfall data indicated no dieback & event not specifically synchronous with dieback.	Excluded	Excluded
Higher elevation zones – dieback of taller vegetation mostly	Severe moisture stress at higher tidal inundation zones.	Co-factor moisture stress – primary influence unlikely.	Excluded	Excluded
Temporary drop of 20 cm in sea level correlated with synchronous mass dieback	Apparent severe moisture stress associated with lack of tidal flooding into higher elevation zones.	Co-factor moisture stress – excluded as the likely primary factor.	Excluded	Excluded

4.3 Aerial observations of the influences of rising sea levels

Sea level rise has been relatively rapid in the Gulf region in recent decades (Church et al., 2009) – with regional rates (up to 12 mm/yr) exceeding global averages (~8 mm/yr). As mangroves are intimately dependent on sea levels, they are likely to have responded in recognisable ways as levels rose. And, this has been reflected in the indicators scored during this study (Table 3.2 and Table 3.3), like shoreline erosion (loss of lower elevation, seaward fringing mature vegetation around mean sea level), saltpan scouring (sheet erosion of saltpan sediments, loss of saltmarsh vegetation, gully erosion), and terrestrial retreat (loss of terrestrial trees with saline intrusion above the highest astronomical tides, edge erosion and scouring, expansion of mangrove seedlings upland). The significant two-way correlations between a number of physical factors and response indicators are displayed in Table 4.3. These correlations highlight a number of possibly linked indicators and drivers.

*Table 4.3. Comparisons of climate-natural indicator data for both 2017 and 2019 aerial surveys. The data were evaluated in two ways – by using individual severity scores for each indicator for 37 estuaries, and by averaging scores grouped for the six drainage regions (Figure 1.4). Significance levels for Pearson Correlations, 2-tailed test, as: *= 0.1, **= 0.05 and ***= 0.01.*

Indicator	Factor/indicator	2017		2019	
		N=6	N=37	N=6	N=31
2015 dieback	Sea level rise	0.5523	0.4032***	0.7649***	0.2103
2015 dieback	Terrestrial retreat	0.2197	0.0637	0.6108	0.2515*
2015 dieback	Saltpan scour	0.6765*	0.0378	0.4347	0.3147*
Terrestrial retreat	Sea level rise	0.6924*	0.3917**	0.7317**	0.446***
Saltpan scour	Sea level rise	0.743**	0.1401	0.6275*	0.2519
Shoreline erosion	Storm damage	0.8236**	0.1797	0.0597	0.0044
Storm damage	Cyclone frequency	-0.0043	0.0174	0.6316*	0.0154
Bank erosion	Depositional gain	0.7513**	0.1422	0.6749*	0.132

Importantly, a notable positive correlation with sea level rise was the severity of the 2015 mangrove dieback around individual estuaries (Figure 4.4). This relationship suggests that where sea level rises were greatest, the sensitivity of estuarine and shoreline mangroves to sudden drops in sea level would also be greater. Therefore, in places generally where the resilience of mangroves was appreciably weakened, then any additional event, like the sudden drop in sea level has resulted in greater damage. This may be difficult to quantify and evaluate further, but these results do suggest that the poorer condition of shoreline trees curbs their ability to respond to higher rates of sea level rise. And, this would reduce their ability to re-locate upland. This poses a serious threat to the longer-term survival of tidal wetlands faced with rapidly rising sea levels.

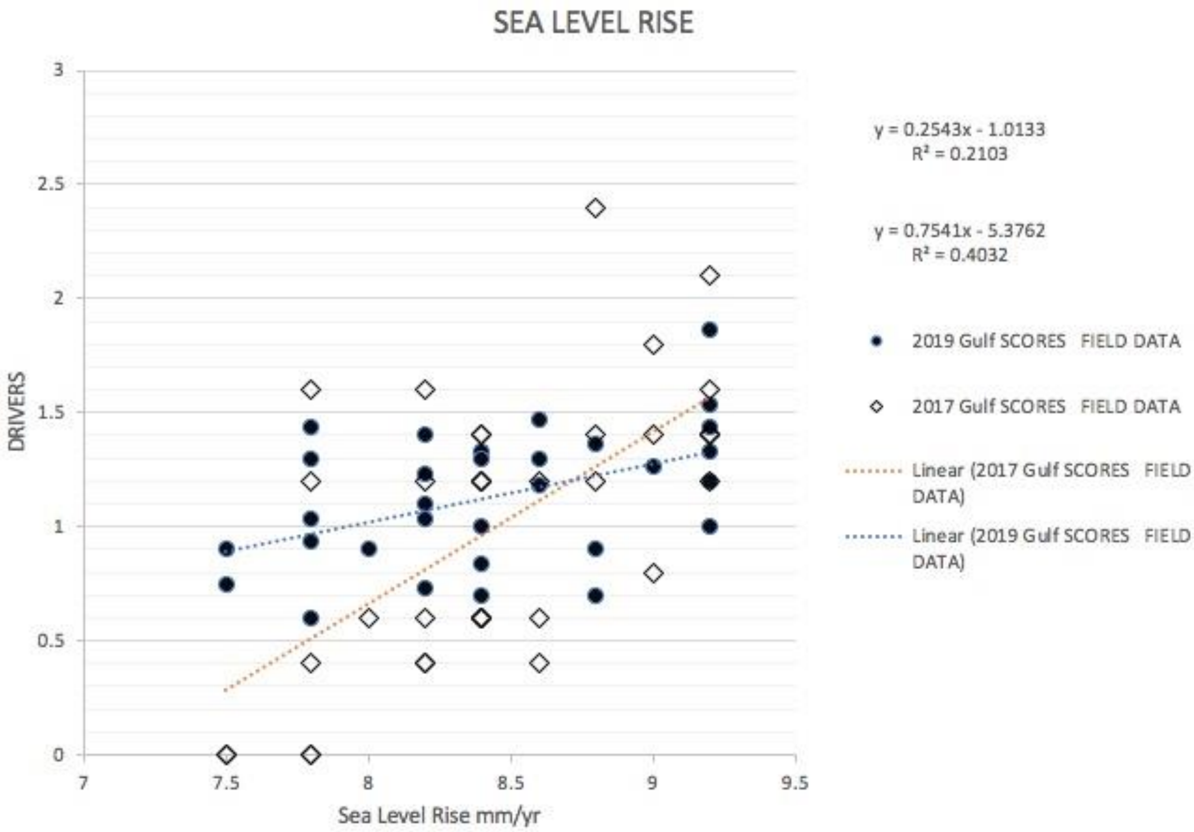

Figure 4.4. Plot of 2015 mangrove dieback (driver) and sea level rise (Church et al., 2009; Hobday & Lough, 2011) showing a significant relationship in 2017 estuary severity scores (Table 4.3). Scored with surveys in 2017 and 2019 for the 31–37 estuarine mouth sites.

Other indicator severity scores for the 31–37 estuaries and six region groupings also had significant positive correlations with rising sea levels, notably terrestrial retreat, and saltpan scouring (Table 4.3, Figure 4.5). While no such correlation was found between sea level rise and shoreline erosion, this was consistent with the observation of other more random factors directly impacting sea edge stands, such as the harsh localised weather conditions associated with severe tropical cyclones and flooding events. This suggests that the impacts on upland mangrove and saltmarsh-saltpan zones were largely due to rising sea levels.

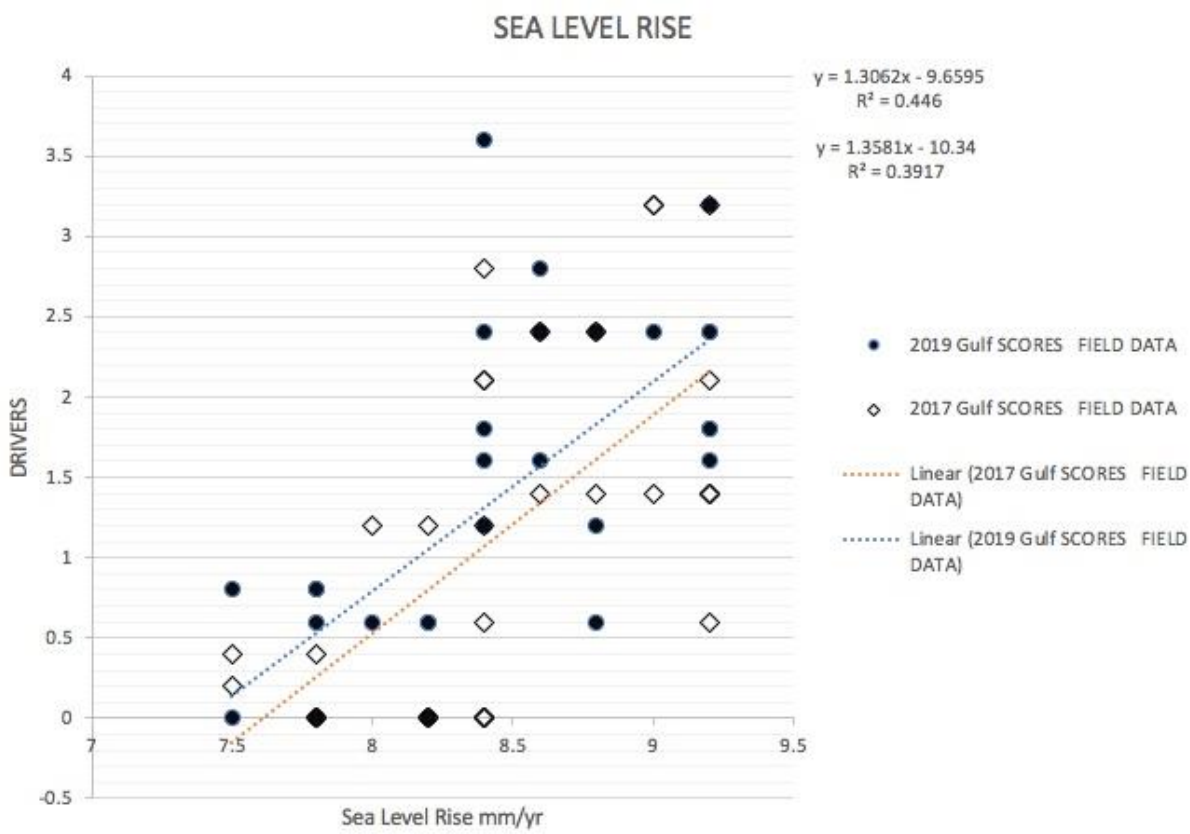

Figure 4.5. Plot of 2015 terrestrial retreat (driver) and sea level rise (Church et al., 2009; Hobday & Lough, 2011) showing significant relationships in 2017 and 2019 estuary severity scores (Table 4.3). Scored with surveys in 2017 and 2019 for the 31–37 estuarine mouth sites.

These data identify a number of shoreline changes taking place that are current and threatening. They are collectively indicative of an increasing threat in raising stress levels on not only mangrove shorelines, but also on adjacent marine habitats in the Gulf.

4.4 The influences of severe tropical cyclones and flooding

Cyclones and flooding events are added threats to mangrove shorelines. The positive correlation with sea level rise and the 2015 mangrove dieback implies that Gulf shorelines have become increasingly vulnerable. As sea level rise then the added impacts of additional harmful events become more influential and severe. In this way, where the resilience of mangrove shorelines have been weakened appreciably, then any additional event, like the sudden drop in sea level will result in greater damage. This may be difficult to quantify and evaluate, but the current findings do suggest that as the condition of shoreline habitats become poorer then their ability to respond to threats like rising rates of sea level will rapidly reduce their ability to re-locate upland. This situation poses a serious threat to the longer-term survival of tidal wetlands faced with rising sea levels. As such, it is not only the ability of these habitats to respond to rising sea levels alone but rather to the total combination of threatening factors, including severe flooding events and tropical cyclones.

Tropical cyclones cause damage that is localised and dependent on severity, plus other factors like tide levels at the time of impact. As such, the impacts are not evenly distributed around the Gulf, and there are ‘hot spot’ shoreline sections where the frequency of cyclones are higher (Figure 2.14). On the whole, the Gulf experiences one notable cyclone every two years. But, the occurrence of particularly severe cyclones (Category 3 and above) come in possible clusters every 30 years or so, and they mostly occurred on the Northern Territory side of the Gulf. Intervening cyclones and those in Queensland were mostly in the minor categories (Category 2 or less).

Figure 4.6. Exposed shoreline mangroves were uprooted, and those further inshore were mostly fatally stripped of foliage by Category 4 Tropical Cyclone Trevor in February 2019.

It was significant for this investigation that two severe cyclones occurred between the 2017 and 2019 aerial surveys, including TC Owen (Category 3) affecting the area west of the Limmen estuary and shoreline in December 2018, and TC Trevor (Category 4) affecting the Robinson, Calvert and Wearyan estuaries in March 2019 (Figure 4.6). The collective impact of these storms caused severe damage to around 600 km of Gulf shoreline. The types of damage ranged from shoreline erosion and retreat, sediment wash root burial dieback, wrack piles of 2015 dieback and scour, large patches of fallen and broken stems, and defoliation of canopy leaving estuary edge exposed trees intact.

Flooding was particularly severe in the Flinders River during February 2019. The impacts downstream in estuarine tidal wetlands included damaging bank erosion and slumping, serious scouring and gullying across saltmarsh-saltpan areas, and significant depositional gain where young seedlings were observed widely around the mouth occupying seafront mudbanks. There was a significant correlation between bank erosion and depositional gain indicators (Table 4.3) consistent with the cause being the same environmental driver – flooding. In addition, the unusual feature of severe gullying, notably evident between smaller mangrove-lined tributaries, suggested that mangrove-slowed flows redirected excessive flooding levels to instead track across less vegetated areas, eroding and cutting new channels across more open areas, in order to reach larger estuarine channels.

The longer-term impact of the accumulation of all these severe events is likely to greatly impede and even reverse recovery processes taking place in impacted places. Limited recovery had been observed generally with re-sprouting of damaged trees and some re-establishment of seedlings of canopy trees, described in the Vol. 2. However, these severe events resulted in the scouring of 2015 damaged sites. For cyclones, the surge of large waves and strong winds caused the mobilisation of dead wood that further aided the removal of seedlings and survivors, leaving re-impacted sites relatively bare and lifeless.

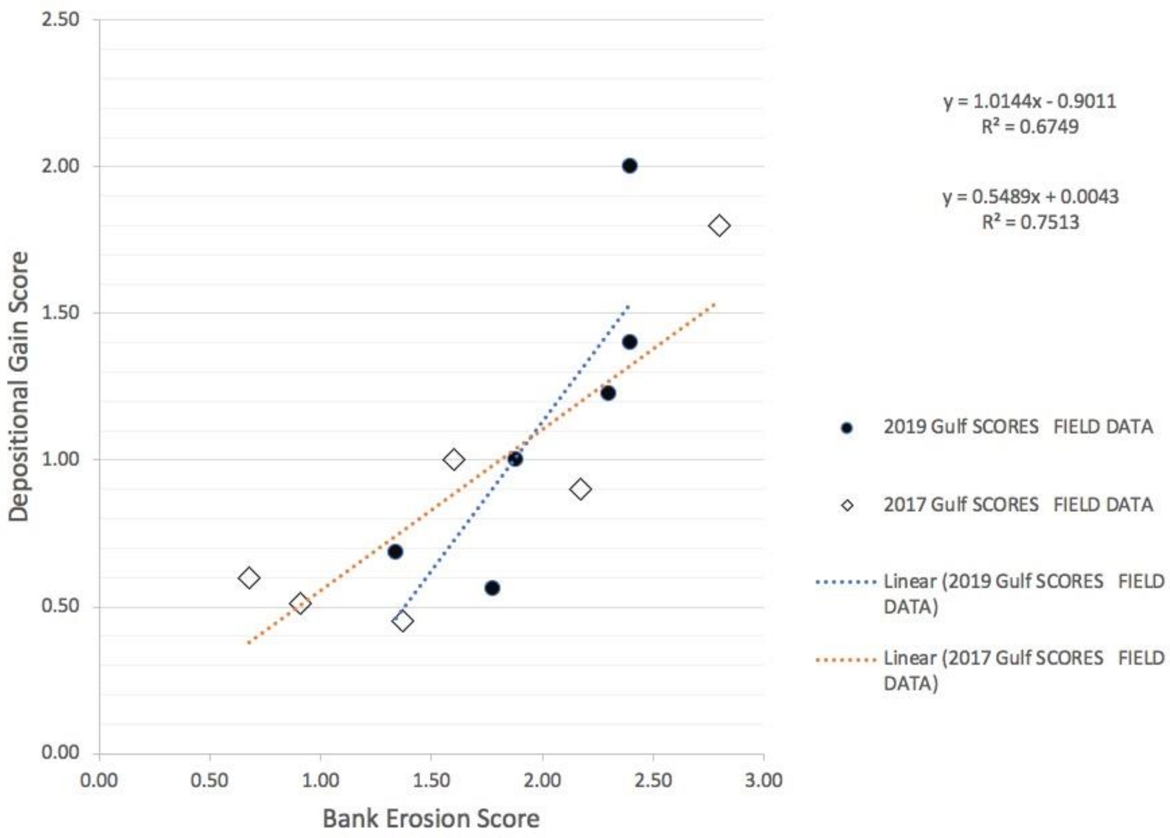

Figure 4.7. Plot comparing bank erosion and depositional gain with a relationship implying a link with flooding impacts as bank scouring and sediment relocated leads to the emergence of depositional banks and their colonisation by mangrove seedlings and saplings.

The observations made during this project document both the 2015 mass dieback of mangroves along Gulf shorelines, as well as a number of subsequent accumulative damaging events of severe cyclones and flooding up to 2019. This assessment identified a significant positive relationship between the severity of bank erosion and depositional gain (Figure 4.7).

The implications for management and environmental policymakers can be divided into two strategies. One must be to deal with the cause at a national and regional level with climate change abatement. The concurrent and equally important strategy is to deal with the symptoms and to focus on building greater resilience in struggling natural ecosystems so they can better adapt to and accommodate the rapidly changing environmental conditions.

4.5 Evidence from mapping and aerial surveys of an earlier dieback event

As mentioned, there are several pieces of evidence suggesting that the 2015–2016 mass dieback event was not unprecedented since there appears to have been an earlier occurrence. An additional event would provide definitive information on the cause, and it would allow future occurrences to be predicted.

While this point will be investigated further with the field studies, a summary from these aerial surveys provides a review of the current status. This evidence includes:

1. Satellite imagery showing a substantive loss of mangroves prior to 1987 (Figure 3.5).
2. Green fraction plots across the Gulf region (Figure 3.4) showing mostly depleted shorelines in 1987 that then recover afterwards up until 2020. The demonstrated recovery trajectory shows that these severely damaged fringing mangrove forests had recovered naturally over that time period.
3. Aerial observations of degraded dead stumps fronting and amongst mangrove shorelines across the region. It is important to determine when these trees died. The approach taken by this project also has been to secure additional funding to have the wood from these stumps analysed and carbon dated, as noted further in the field studies (in Vol. 2).
4. A series of publications about the prior occurrence of a severe but temporary drop in sea level during the 1982–1983 severe El Niño event (Lukas et al., 1984; Wyrtki, 1984, 1985; Oliver & Thompson, 2011). No observations were made of mangrove condition at the time. However, there was a link because of the likely common causal factor being similar to the temporary drop in sea level associated with the severe El Niño in 2015–2016.

4.6 Concluding remarks regards aerial surveys and mapping

Significant progress, more refined direction and significant new observations have been crucial outcomes from these mapping and aerial surveys. These findings start with the notably increased area of mangrove dieback than previously reported, the better description of the influential factors involved, and further evidence of the cause. All these considerations will be reported on further, and summarised, in Vol. 2. With the additional results from the field studies, we will complete this synthesis and assessment of the 2015–2016 mangrove dieback event. This will be done along with our listing of successful efforts in engaging and training local Aboriginal ranger groups across the Gulf, as well as our production of outcomes with community public meetings plus communication products.

5. Region and site summary data

In this section, information is summarised as both background knowledge and as project results for the six drainage regions (CSIRO, 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i) and the 37 estuaries surveyed in 2017 and 2019. These data have been used in analyses and assessments of the 2015 mangrove dieback in Australia's Gulf of Carpentaria.

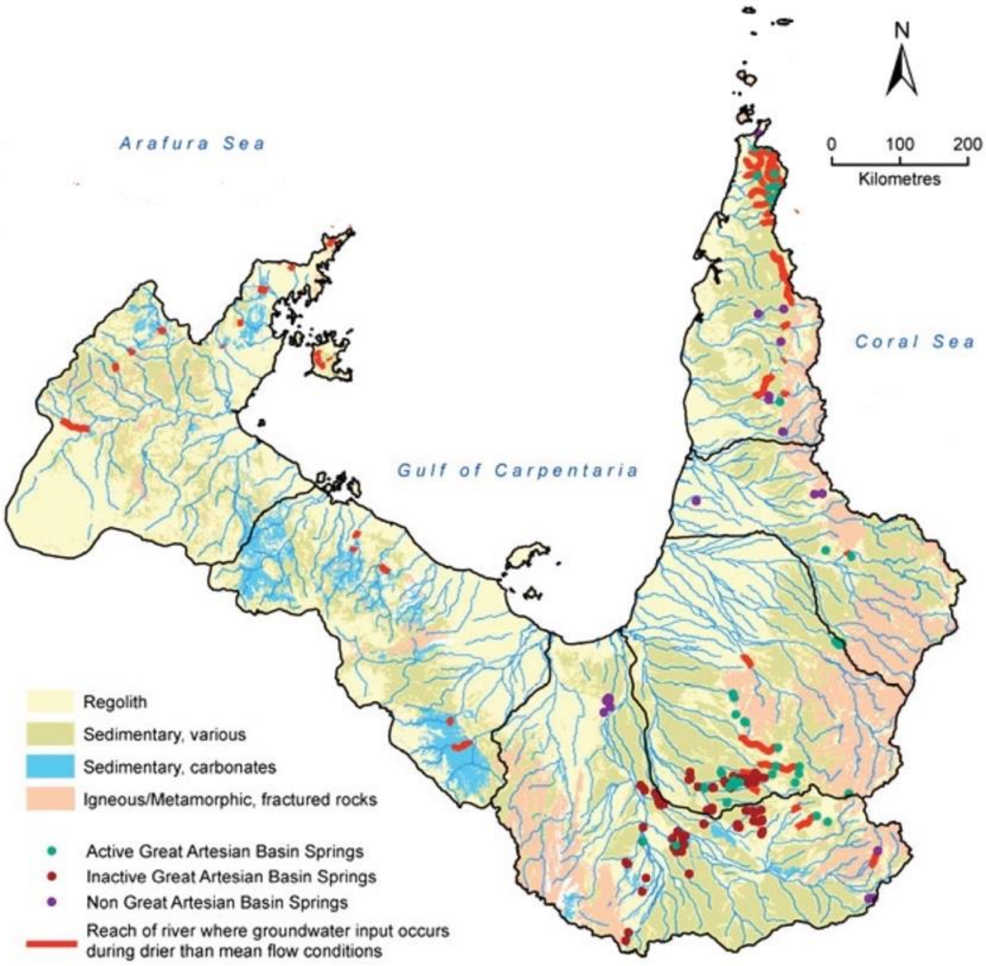

Figure 5.1. Map of six catchment sub-basin shorelines for estuarine tidal wetland areas surveyed in the Gulf of Carpentaria in 2017 and 2019 (source: CSIRO, 2009a, 2009b, 2009c, 2009d, 2009e, 2009f, 2009g, 2009h, 2009i).

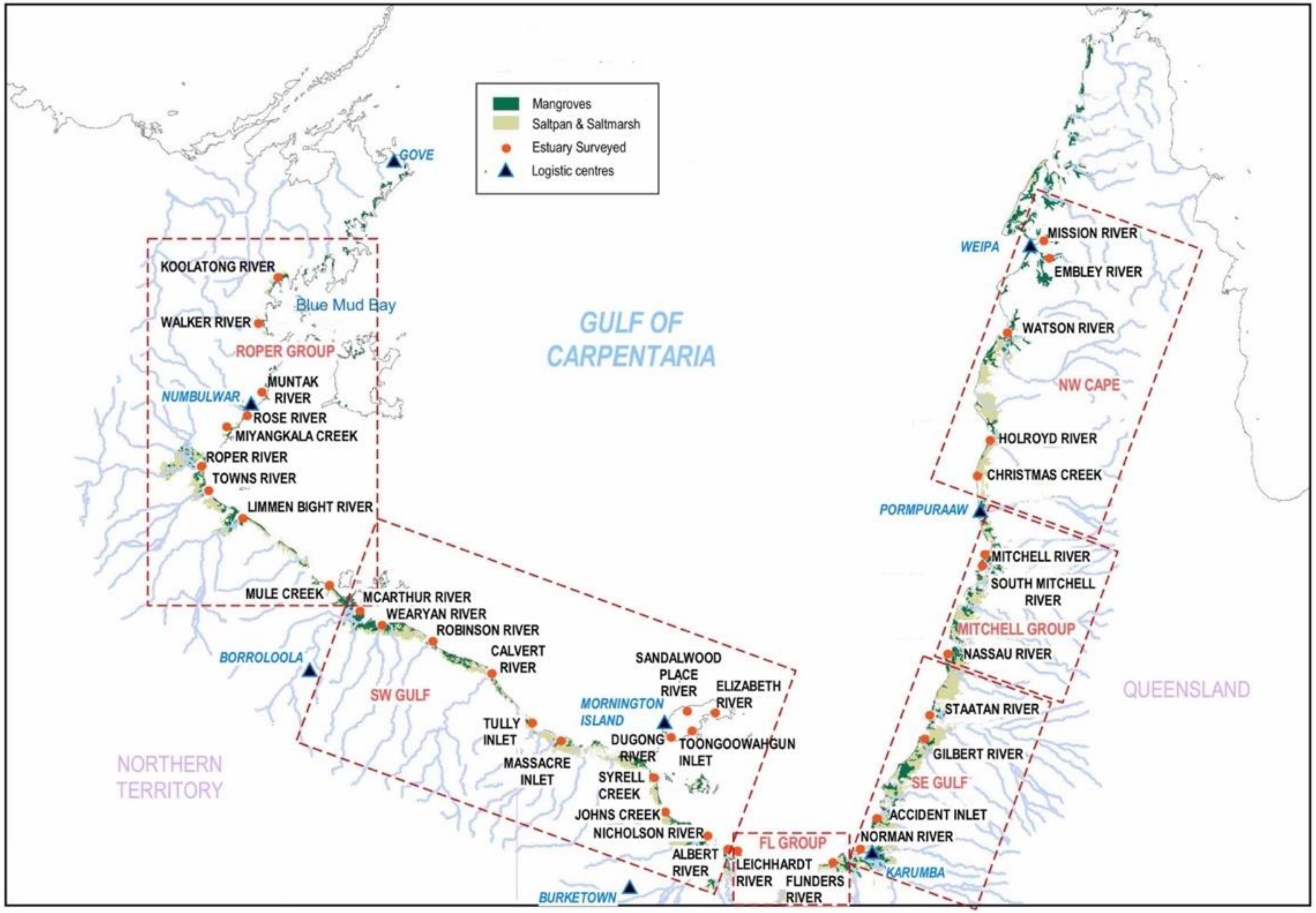

Figure 5.2. Locations of 37 estuaries included in the aerial surveys in 2017 and 2019. These are grouped into each of the six drainage regions in the Gulf of Carpentaria depicted in Figure 4.4.

5.1 Western Cape region

Maps of the region (Figure 5.3) and the main regional characteristics are listed (Table 5.1).

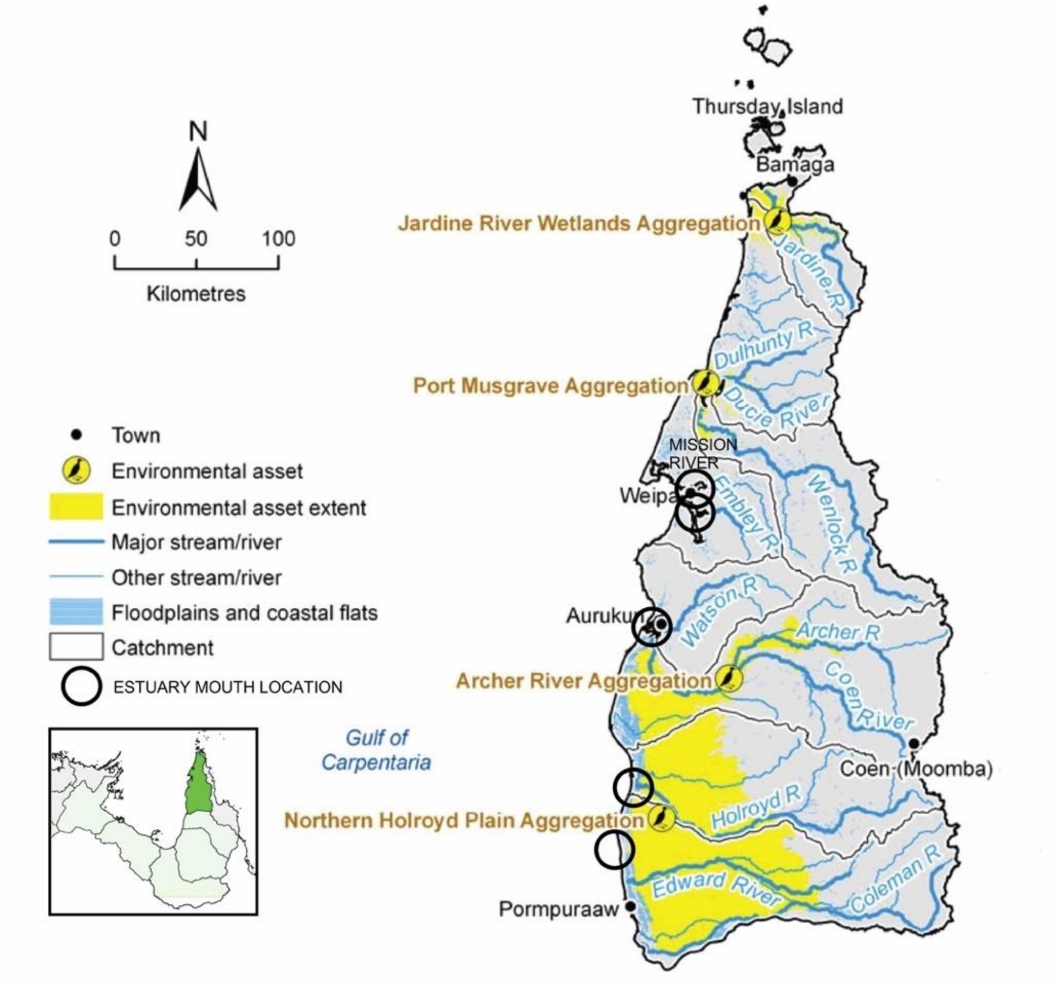

Figure 5.3. Major rivers, streams, towns and settlements in the Western Cape region (CSIRO, 2009i). See inset for location within the Gulf of Carpentaria. Lower estuaries surveyed with this study include Mission River, Embley River, Watson River, Holroyd River, and Christmas Creek (north of Edward River).

Table 5.1 Features of the Western Cape region. Source, in part: CSIRO (2009i).

Feature	Western Cape region
Total drainage area (km^2)	66,766
Maximal relief (m)	814
Mean annual temperature (°C), range	27.0, 22.4–31.7
Mean annual rainfall (mm)	1,417
Mean annual runoff (mm)	479
Volume of streamflow (TL/y)	32
Tidal influence, mean range in metres	Local, 1.9
Number of important wetlands	10
Future flows with climate change (-2030)	Possible decrease
Northern shoreline coordinate	-10.687516; 142.531376
Southern shoreline coordinate	-15.103986; 141.630043
Proportion of catchment drainage in study	32.2%
Severe tropical cyclones since 1995	> 8
Average sea level rise (mm/yr)	7.7
Mangrove species diversity	24
Mangrove Wetland Cover Index	44.7%
2015 mangrove dieback severity – estuary mouths	0.08 (max. 0.4), minimal to absent
2015 shoreline mangrove dieback – >30% lost	zero

Dieback mapping

Maps presented in this report are regional summary displays taken from the project GIS file of the complete study area in the Gulf of Carpentaria (Figure 5.4). Mapping and quantification of 2015–2016 mangrove dieback plus mangrove and saltpan–saltmarsh areas were undertaken for intertidal areas from just north of the Mitchell region in the east, extending west to the southern part of the Roper region. The Western Cape region only had 2015–2016 mangrove dieback at its southern extremity (Table 5.2). This area was included in the Mitchell region map (Figure 4.6).

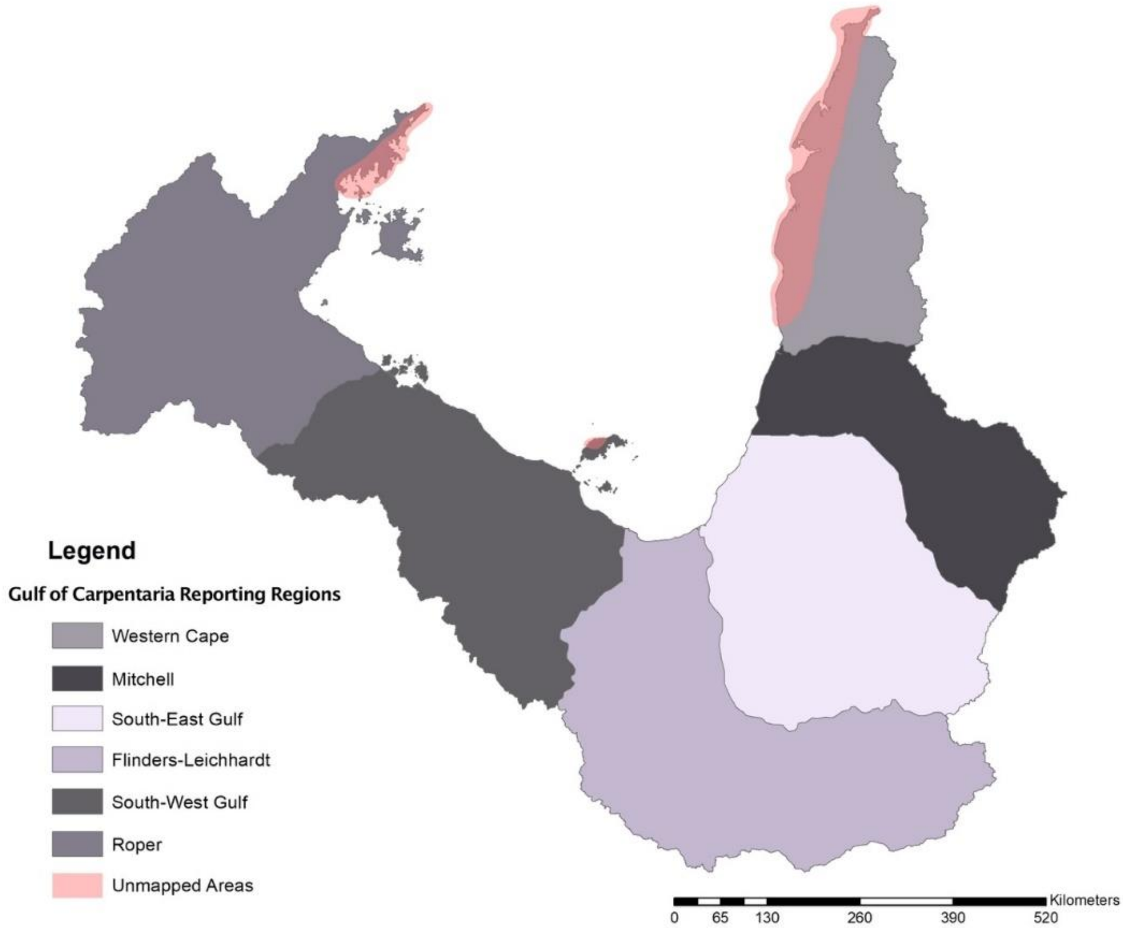

Figure 5.4. Mapping areas of mangrove dieback extend mostly across regions south and west of the Western Cape Region. See Mitchell Region mapping for dieback areas at the far southern extremity of this region.

Table 5.2. Tidal wetland areas from mapping of the Western Cape region.

Western Cape region	
Mangrove (km^2): 15.8	2015 dead mangrove (km^2): 1.6
Tidal wetland (+ saltmarsh & pans) (km^2): ~41.4	% 2015 dead mangrove: 10.0%

5.1.1 Mission River lower estuary

Figure 5.5. Mouth of the Mission River 12 September 2019.

Information about the lower section of this estuary (Figure 5.5) is shown in Table 5.3.

Table 5.3. Mission River site information.

Location of mouth: -12.6201 °S; 141.8372 °E	Aerial survey dates: 1 Dec 2017; 12 Sep 2019
Catchment area (km^2): 1,290	Tidal wetland total area (km^2): 41.7
Estuary length (km): 32.8	Saltmarsh and saltpan area (km^2): 10.8
Tidal range (m): ~2.1	Mangrove area (km^2): 30.9
Close-by major cyclones since 1995: at least 2	Mangrove Wetland Cover Index: 74.2%
Recent sea level rise: ~7.5 mm/yr	Mangrove species numbers: no data

Figure 5.6. Damage from access tracks, a notable issue for the Mission River estuary.

Figure 5.7. Satellite image (Google Earth) showing the Mission River estuary.

The location is shown in Figure 5.7 and observed issues listed in Figure 5.6 and Table 5.4.

Table 5.4. Mission River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	3.6	5.0
Weed smothering	0	0
Access tracks, roads and boat ramps	0.4	0.8
Feral presence, damage and tracks	2.4	0.8
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0.8	0.6
Direct modification >>>	*0.4*	*0.7*
CLIMATE–NATURAL	7.6	8.9
Saltpan scouring	1.2	0.6
Bank erosion	0.8	0.9
Terrestrial retreat	0.4	0
Ecotone shift negative	2.4	2.4
2015 mangrove dieback	0	0
Sea level rise indicators >>>	*0.6*	*0.8*

Note: yellow shaded areas highlight maximal severity indicators.

5.1.2 Embley River lower estuary

Figure 5.8. Mouth of the Embley River 12 September 2019.

Information about the lower section of this estuary (Figure 5.8) is shown in Table 5.5.

Table 5.5. Embley River site information.

Location of mouth: -12.6676 °S; 141.8297 °E	Aerial survey dates: 1 Dec 2017; 12 Sep 2019
Catchment area (km^2): 2,076	Tidal wetland total area (km^2): 168.6
Estuary length (km): 38.4	Saltmarsh and saltpan area (km^2): 105.8
Tidal range (m): ~2.1 m	Mangrove area (km^2): 62.8
Close-by major cyclones since 1995: zero	Mangrove Wetland Cover Index: 37.2%
Recent sea level rise: ~7.5 mm/yr	Mangrove species numbers: at least 25

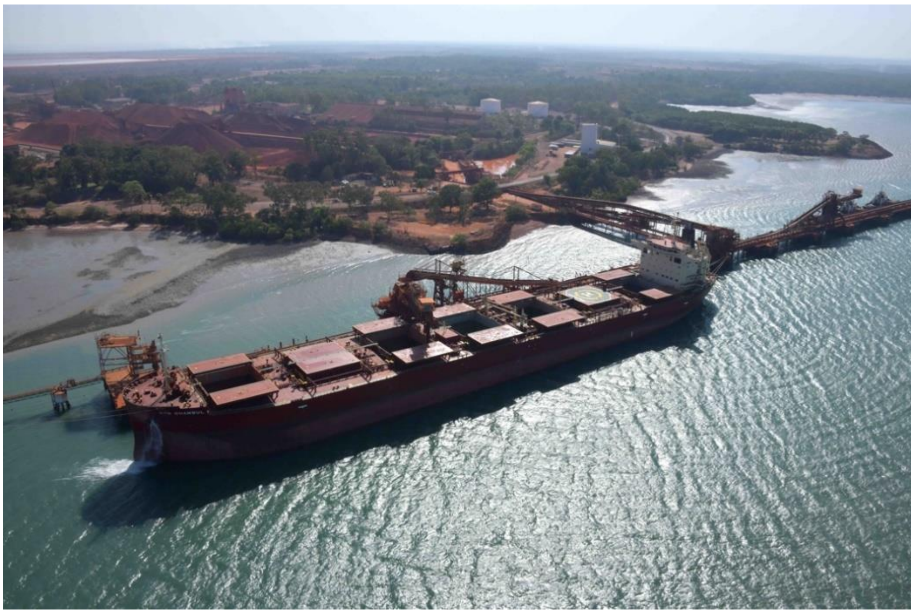

Figure 5.9. Shoreline modification, a notable issue for the Embley estuary.

Figure 5.10. Satellite image (Google Earth) showing the Embley River estuary.

The location is shown in Figure 5.10 and observed issues listed in Figure 5.9 and Table 5.6.

Table 5.6. Embley River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**1.2**	**8.6**
Weed smothering	0	0
Access tracks, roads and boat ramps	0.4	1.2
Feral presence, damage and tracks	0.2	0.8
Stock presence, damage and tracks	0	0.6
Fire impacts, scorched and dead mangroves	0.6	1.6
Direct modification >>>	***0.4***	***0.92***
CLIMATE–NATURAL	**5.0**	**9.4**
Saltpan scouring	0.2	0.6
Bank erosion	0.6	0.4
Terrestrial retreat	0.2	0.8
Ecotone shift negative	1.6	2.4
Sea level rise indicators >>>	***0.3***	***0.9***
2015 mangrove dieback	0	0

Note: yellow shaded areas highlight maximal severity indicators.

5.1.3 Watson River lower estuary

Figure 5.11. Mouth of the Watson River, Archer Bay 12 September 2019.

Information about the lower section of this estuary (Figure 5.11) is shown in Table 5.7.

Table 5.7. Watson River site information.

Location of mouth: -13.3465 °S; 141.6612 °E	Aerial survey dates: 1 Dec 2017; 12 Sep 2019
Catchment area (km^2): 16,310	Tidal wetland total area (km^2): 99.8
Estuary length (km): 37.5	Saltmarsh and saltpan area (km^2): 52.1
Tidal range (m): ~1.7 m	Mangrove area (km^2): 47.7
Close-by major cyclones since 1995: zero	Mangrove Wetland Cover Index: 47.8%
Recent sea level rise: ~7.8 mm/yr	Mangrove species numbers: no data

Figure 5.12. Shoreline changes at the mouth, a notable issue for the Watson River estuary.

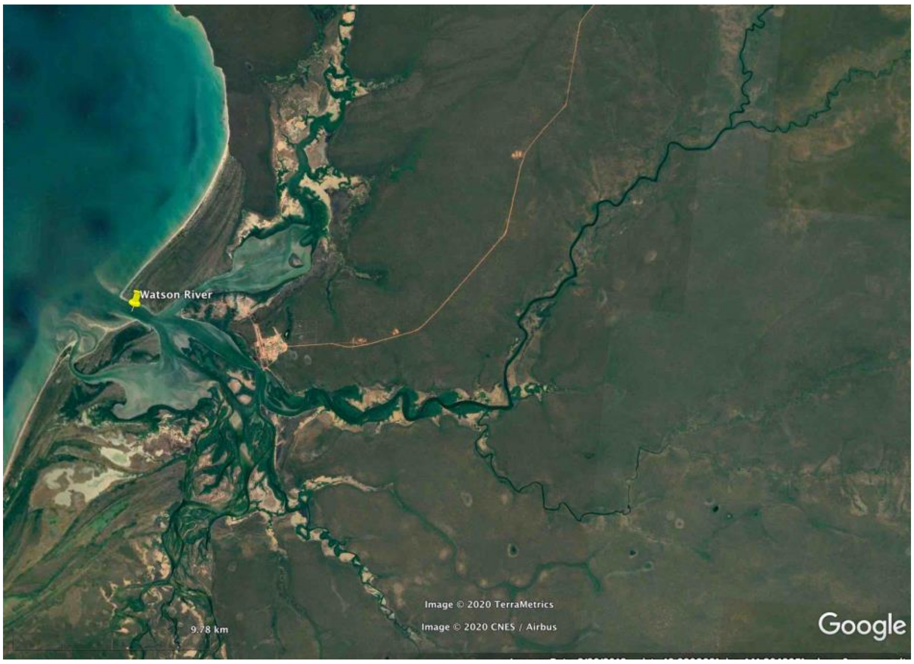

Figure 5.13. Satellite image (Google Earth) showing the Watson River estuary.

The location is shown in Figure 5.13 and observed issues listed in Figure 5.12 and Table 5.8.

Table 5.8. Watson River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**2.4**	**4.0**
Weed smothering	0	0
Access tracks, roads and boat ramps	1.2	0.4
Feral presence, damage and tracks	1.2	0.6
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0	1.6
Direct modification >>>	***1.2***	***0.2***
CLIMATE–NATURAL	**3.6**	**7.6**
Saltpan scouring	0.2	0
Bank erosion	0.2	1.6
Terrestrial retreat	0.4	0.8
Ecotone shift negative	1.2	1.2
Sea level rise indicators >>>	***0.24***	***0.6***
2015 mangrove dieback	0	0

Note: yellow shaded areas highlight maximal severity indicators.

5.1.4 Holroyd River lower estuary

Figure 5.14. Mouth of the Holroyd (Kirke) River 12 September 2019.

Information about the lower section of this estuary (Figure 5.14) is shown in Table 5.9.

Table 5.9. Holroyd (Kirke) River site information.

Location of mouth: -14.1633 °S; 141.5945 °E	Aerial survey dates: 1 Dec 2017; 12 Sep 2019
Catchment area (km^2): 1,365	Tidal wetland total Aaea (km^2): 63.4
Estuary length (km): 42.8	Saltmarsh and saltpan area (km^2): 60.1
Tidal range (m): ~1.9 m	Mangrove area (km^2): 3.3
Close-by major cyclones since 1995: at least 4	Mangrove Wetland Cover Index: 5.3%
Recent sea level rise: ~7.8 mm/yr	Mangrove species numbers: no data

Figure 5.15. Damage from access tracks and bank erosion, notable issues in the Holroyd.

Figure 5.16. Satellite image (Google Earth) showing the Holroyd River estuary.

The location is shown in Figure 5.16 and observed issues listed in Figure 5.15 and Table 5.10.

Table 5.10. Holroyd River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.4**	**6.4**
Weed smothering	0	0
Access tracks, roads and boat ramps	0.2	0.6
Feral presence, damage and tracks	0.2	1.6
Stock presence, damage and tracks	0	1.2
Fire impacts, scorched and dead mangroves	0	1.8
Direct modification >>>	**0.2**	**0.3**
CLIMATE–NATURAL	**4.6**	**9.0**
Saltpan scouring	0	0
Bank erosion	1	3.2
Terrestrial retreat	0	0
Ecotone shift negative	1.2	1.2
Sea level rise indicators >>>	**0.5**	**0.9**
2015 mangrove dieback	0	0

Note: yellow shaded areas highlight maximal severity indicators.

5.1.5 Christmas Creek lower estuary

Figure 5.17. Mouth of Christmas Creek 13 September 2019.

Information about the lower section of this estuary (Figure 5.17) is shown in Table 5.11.

Table 5.11 Christmas Creek site information.

Location of mouth: -14.5448 °S; 141.5412 °E	Aerial survey dates: 2 Dec 2017; 13 Sep 2019
Catchment area (km^2): 437	Tidal wetland total area (km^2): 8.2
Estuary length (km): 3.0	Saltmarsh and saltpan area (km^2): 7.5
Tidal range (m): ~1.9 m	Mangrove area (km^2): 0.7
Close-by major cyclones since 1995: at least 2	Mangrove Wetland Cover Index: 8.8%
Recent sea level rise: ~7.8 mm/yr	Mangrove species numbers: no data

Figure 5.18. Bank erosion and ecotone shift loss is an issue in Christmas Creek estuary.

Figure 5.19. Satellite image (Google Earth) showing Christmas Creek estuary.

The location is shown in Figure 5.19 and observed issues listed in Figure 5.18 and Table 5.12.

Table 5.12. Christmas Creek lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**1.4**	**2.8**
Weed smothering	0	0
Access tracks, roads and boat ramps	0	0.8
Feral presence, damage and tracks	0.2	0
Stock presence, damage and tracks	1.2	1.2
Fire impacts, scorched and dead mangroves	0	0.8
Direct modification >>>	**0**	**0.2**
CLIMATE–NATURAL	**3.2**	**9.4**
Saltpan scouring	0	0.8
Bank erosion	0.8	2.8
Terrestrial retreat	0	0
Ecotone shift negative	0.8	0
Sea level rise indicators >>>	**0.2**	**1.4**
2015 mangrove dieback	0.4	0

Note: yellow shaded areas highlight maximal severity indicators.

5.2 Mitchell region

Maps of the region (Figure 5.20) and the main regional characteristics are listed (Table 5.13).

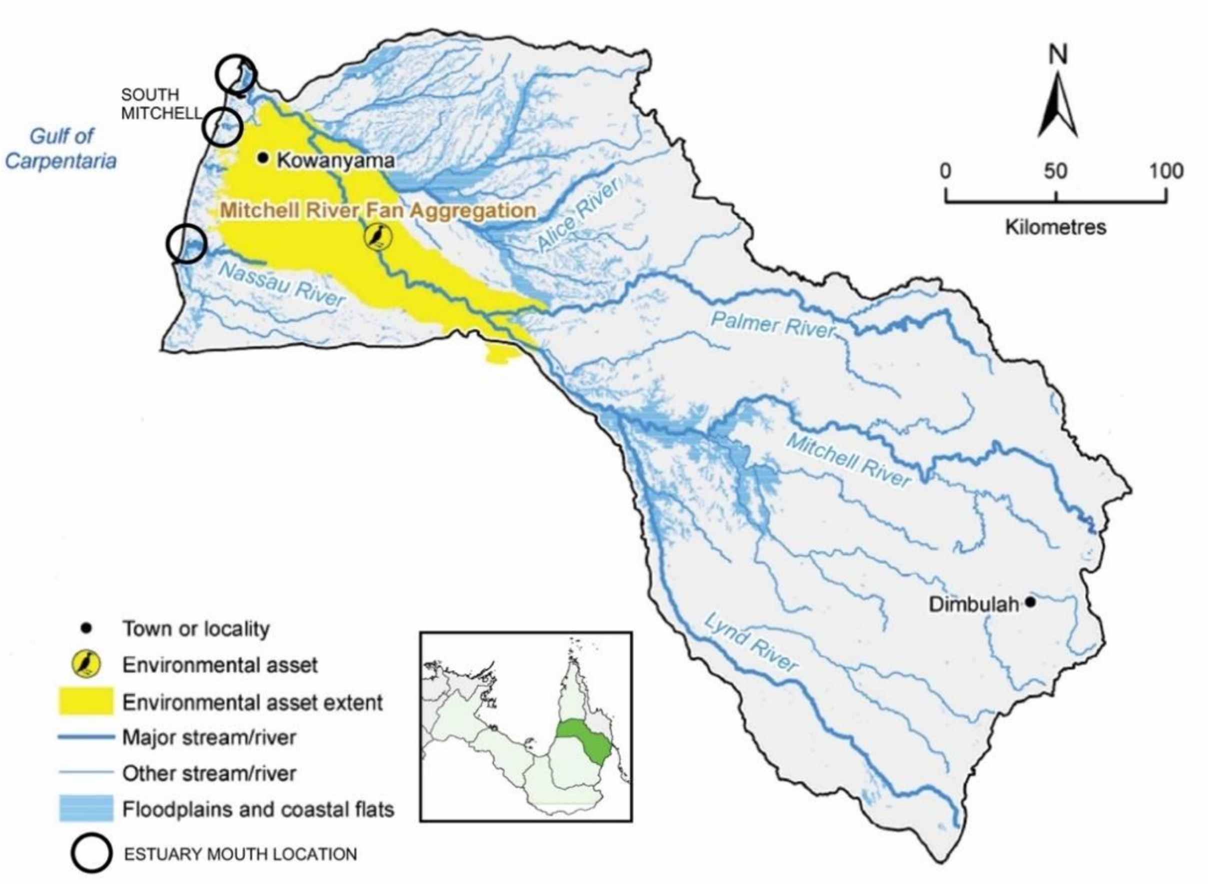

Figure 5.20. Major rivers, streams, towns and settlements in the Mitchell region (CSIRO, 2009h). See inset for location within the Gulf of Carpentaria. Lower estuaries surveyed with this study include Mitchell River, South Mitchell River and Nassau River.

Table 5.13. Features of the Mitchell region. Source, in part: CSIRO (2009i).

Feature	Mitchell region
Total drainage area (km^2)	72,229
Maximal relief (m)	1,355
Mean annual temperature (°C), range	27.0, 19.7–34.7
Mean annual rainfall (mm)	965
Mean annual runoff (mm)	198
Volume of streamflow (TL/y)	14
Tidal influence, mean range in metres	Significant, 2.6
Number of important wetlands	4
Future flows with climate change (-2030)	Possible decrease
Northern shoreline coordinate	-15.103986; 141.630043
Southern shoreline coordinate	-16.273342; 141.34466
Proportion of catchment drainage in study	99.5%
Severe tropical cyclones since 1995	> 11
Average sea level rise (mm/yr)	15 likely
Mangrove species diversity	9 (10 possible)
Mangrove Wetland Cover Index	27.5%
2015 mangrove dieback severity – estuary mouths	1.13 (max. 1.6), moderate to severe
2015 shoreline mangrove dieback – >30% lost	7.9 km (25.8%)

Dieback mapping

Distribution of dieback and remaining mangroves shown in Figure 5.21 and Table 5.14.

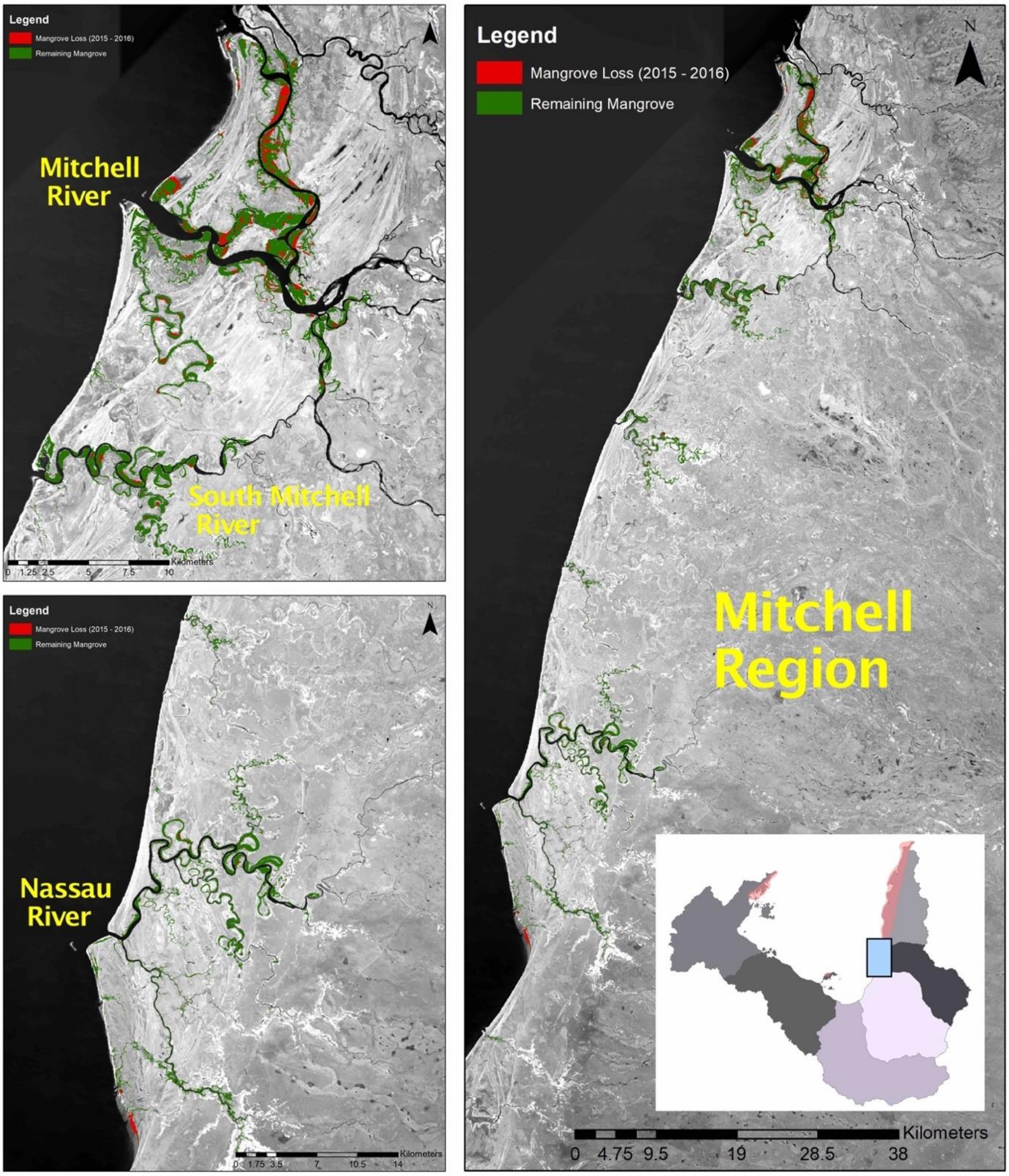

Figure 5.21. Mapped areas of mangrove dieback for the Mitchell region, plus the southern part of the Western Cape region.

Table 5.14. Tidal wetland areas from mapping of the Mitchell region.

Mitchell region	
Mangrove (km²): 85.8	2015 dead mangrove (km²): 7.1
Tidal wetland (+ saltmarsh & pans) (km²): 308.8	% 2015 dead mangrove: 8.2%

5.2.1 Mitchell River lower estuary

Figure 5.22. Mouth of the Mitchell River 13 September 2019.

Information about the lower section of this estuary (Figure 5.22) is shown in Table 5.15.

Table 5.15. Mitchell River site information.

Location of mouth: -15.2004 °S; 141.591 °E	Aerial survey dates: 2 Dec 2017; 13 Sep 2019
Catchment area (km^2): 65,278	Tidal wetland total area (km^2): 198.4
Estuary length (km): 26.3	Saltmarsh and saltpan area (km^2): 137.0
Tidal range (m): ~2.2 m	Mangrove area (km^2): 61.4
Close-by major cyclones since 1995: at least 4	Mangrove Wetland Cover Index: 31.0%
Recent sea level rise: ~7.8 mm/yr	Mangrove species numbers: no data

Figure 5.23. Shoreline mangroves severely damaged by the 2015 dieback often have surviving shrubby, low stature plants, like saltmarsh species and the club mangrove Aegialtitis annulata*.*

Figure 5.24. Satellite image (Google Earth) showing the Mitchell River estuary.

The location is shown in Figure 5.24 and observed issues listed in Figure 5.23 and Table 5.16.

Table 5.16. Mitchell lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	0.0	2.8
Weed smothering	0	1.2
Access tracks, roads and boat ramps	0	0
Feral presence, damage and tracks	0	0.4
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0	0.8
Direct modification >>>	0	0
CLIMATE–NATURAL	8.0	14.2
Saltpan scouring	0	0.6
Bank erosion	2.4	3.2
Terrestrial retreat	0	0.8
Ecotone shift, negative	1.2	3.2
Sea level rise indicators >>>	0.6	1.3
2015 mangrove dieback	1.6	0.8

Note: yellow shaded areas highlight maximal severity indicators.

5.2.2 South Mitchell River lower estuary

Figure 5.25. Mouth of the South Mitchell River 2 December 2017.

Information about the lower section of this estuary (Figure 5.25) is shown in Table 5.17.

Table 5.17. South Mitchell River site information.

Location of mouth: -15.3578 °S; 141.5404 °E	Aerial survey dates: 2 Dec 2017; 13 Sep 2019
Catchment area (km^2): 794	Tidal wetland total area (km^2): 37.2
Estuary length (km): 20.8	Saltmarsh and saltpan area (km^2): 28.2
Tidal range (m): ~2.5 m	Mangrove area (km^2): 9.0
Close-by major cyclones since 1995: at least 4	Mangrove Wetland Cover Index: 24.1%
Recent sea level rise: ~7.8 mm/yr	Mangrove species numbers: no data

Figure 5.26. Scouring of saltpans, a notable issue for the South Mitchell estuary.

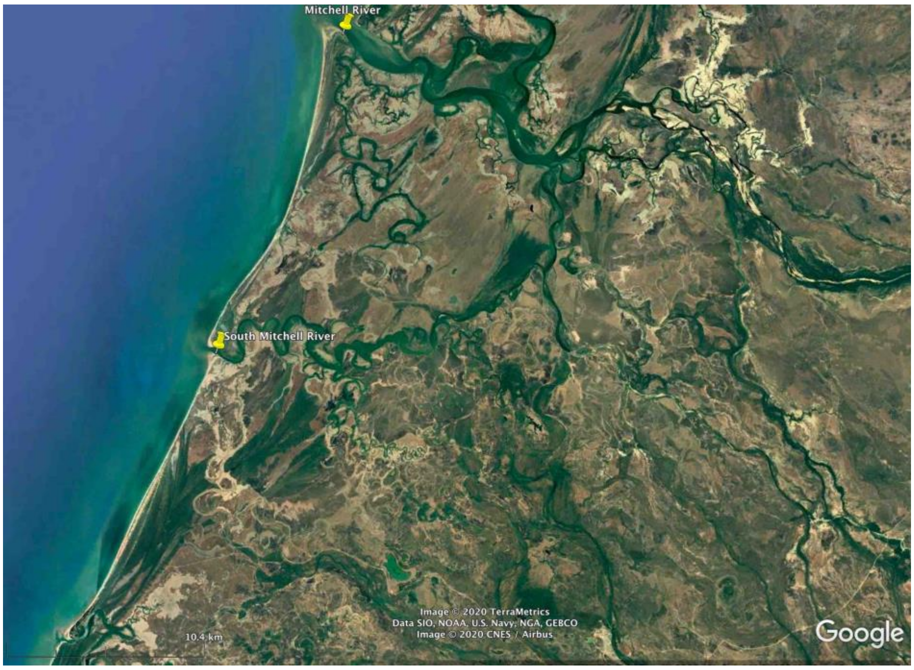

Figure 5.27. Satellite image (Google Earth) showing the South Mission River estuary.

The location is shown in Figure 5.27 and observed issues listed in Figure 5.26 and Table 5.18.

Table 5.18. South Mitchell River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	1.4	5.6
Weed smothering	0	1.8
Access tracks, roads and boat ramps	1.2	2.4
Feral presence, damage and tracks	0.2	0.4
Stock presence, damage and tracks	0	0.4
Fire impacts, scorched and dead mangroves	0	0.4
Direct modification >>>	1.2	0.5
CLIMATE–NATURAL	7.8	11.0
Saltpan scouring	1.4	2.4
Bank erosion	1.2	1.6
Terrestrial retreat	0	0.6
Ecotone shift, negative	1.2	1.8
Sea level rise indicators >>>	0.8	1.0
2015 mangrove dieback	1.2	0.6

Note: yellow shaded areas highlight maximal severity indicators.

5.2.3 Nassau River lower estuary

Figure 5.28. Mouth of the Nassau River 13 September 2019.

Information about the lower section of this estuary (Figure 5.28) is shown in Table 5.19.

Table 5.19. Nassau River site information.

Location of mouth: -15.9074 °S; 141.3952 °E	Aerial survey dates: 2 Dec 2017; 13 Sep 2019
Catchment area (km^2): 5,797	Tidal wetland total area (km^2): 135.3
Estuary length (km): 39.8	Saltmarsh and saltpan area (km^2): 102.6
Tidal range (m): ~3.0 m	Mangrove area (km^2): 32.7
Close-by major cyclones since 1995: at least 3	Mangrove Wetland Cover Index: 24.1%
Recent sea level rise: ~8.0 mm/yr	Mangrove species numbers: no data

Figure 5.29. Damage from bank erosion, a notable issue for the Nassau estuary.

Figure 5.30. Satellite image (Google Earth) showing the Nassau River estuary.

The location is shown in Figure 5.30 and observed issues listed in Figure 5.29 and Table 5.20.

Table 5.20. Nassau River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	0.8	4.4
Weed smothering	0	1.8
Access tracks, roads and boat ramps	0.4	0.4
Feral presence, damage and tracks	0	0.8
Stock presence, damage and tracks	0.4	0
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	0.4	0.3
CLIMATE–NATURAL	7.3	10.2
Saltpan scouring	2.1	0.8
Bank erosion	1.2	2.4
Terrestrial retreat	1.2	0.6
Ecotone shift, negative	1.2	1.8
Sea level rise indicators >>>	0.9	0.9
2015 mangrove dieback	0.6	0

Note: yellow shaded areas highlight maximal severity indicators.

5.3 South-East Gulf region

Maps of the region (Figure 5.31) and the main regional characteristics are listed (Table 5.21).

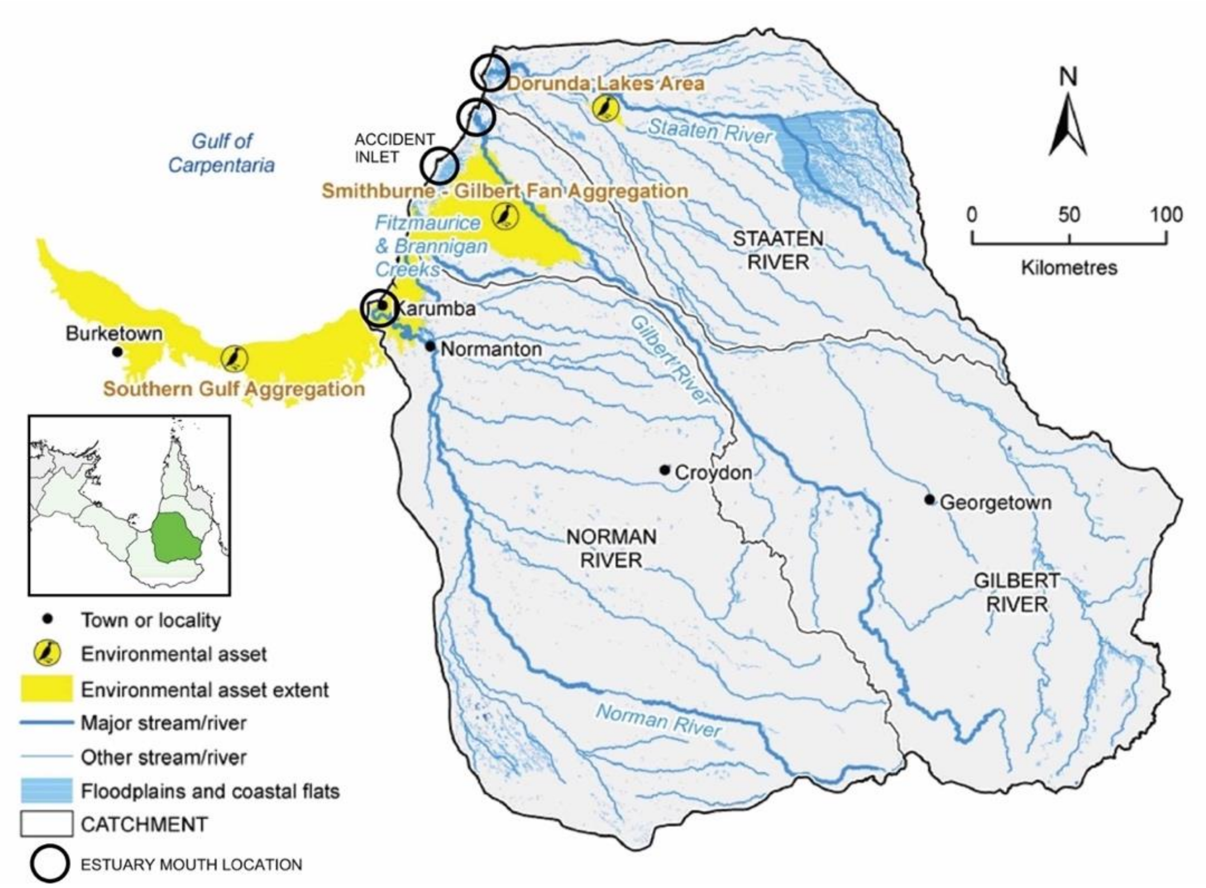

Figure 5.31. Major rivers, streams, towns and settlements in the South-East Gulf region (CSIRO, 2009g). See inset for location within the Gulf of Carpentaria. Lower estuaries surveyed with this study include Staatan River, Gilbert River, Accident Inlet, and Norman River.

Table 5.21. Features of the South-East Gulf region. Source, in part: CSIRO (2009i).

Feature	South-East Gulf region
Total drainage area (km^2)	122,094
Maximal relief (m)	1,068
Mean annual temperature (°C), range	26.6, 19.7–33.6
Mean annual rainfall (mm)	750
Mean annual runoff (mm)	110
Volume of streamflow (TL/y)	13
Tidal influence, mean range in metres	Significant, 3.3
Number of important wetlands	6
Future flows with climate change (-2030)	Possible increase
Northern shoreline coordinate	-16.273342; 141.34466
Southern shoreline coordinate	-17.480796; 140.764011
Proportion of catchment drainage in study	97.8%
Severe tropical cyclones since 1995	> 14
Average sea level rise (mm/yr)	8.4
Mangrove species diversity	11 likely
Mangrove Wetland Cover Index	9.8%
2015 mangrove dieback severity – estuary mouths	0.75 (max. 1.6), moderate to severe
2015 shoreline mangrove dieback – >30% lost	30.8 km (31.5%)

Dieback mapping

Distribution of dieback and remaining mangroves shown in Figure 5.32 and Table 5.22.

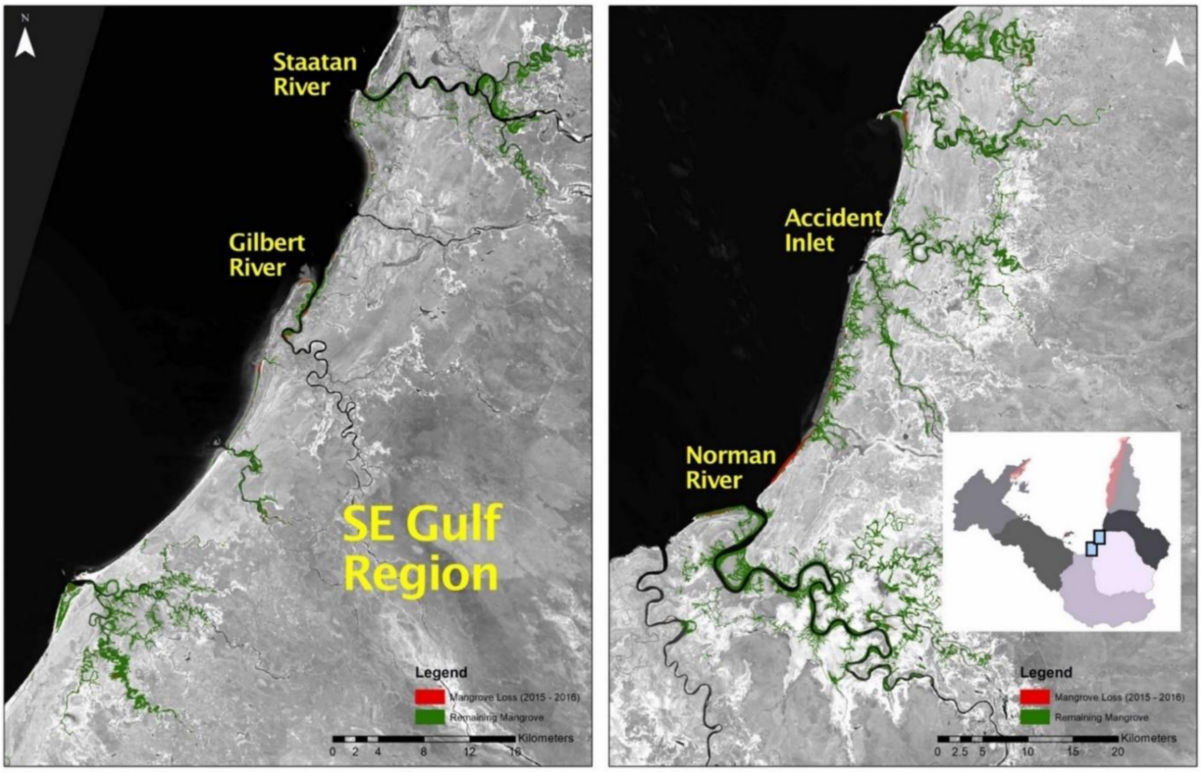

Figure 5.32. Mapped areas of mangrove dieback for the South-East Gulf region.

Table 5.22. Tidal wetland areas from mapping of the South-East Gulf region.

South-East Gulf region	
Mangrove (km^2): 211.3	2015 dead mangrove (km^2): 4.0
Tidal wetland (+ saltmarsh & pans) (km^2): ~1,.830	% 2015 dead mangrove: 1.9%

5.3.1 Staatan River lower estuary

Figure 5.33. Mouth of the Staatan River 14 September 2019.

Information about the lower section of this estuary (Figure 5.33) is shown in Table 5.23.

Table 5.23. Staatan River site information.

Location of mouth: -16.401 °S; 141.296 °E	Aerial survey dates: 3–4 Dec 2017; 14 Sep 2019
Catchment area (km^2): 25,722	Tidal wetland total area (km^2): 190.6
Estuary length (km): 23.0	Saltmarsh and saltpan area (km^2): 171.3
Tidal range (m): ~3.3 m	Mangrove area (km^2): 19.3
Close-by major cyclones since 1995: at least 5	Mangrove Wetland Cover Index: 10.1%
Recent sea level rise: ~8.2 mm/yr	Mangrove species numbers: no data

Figure 5.34. Damage from bank erosion, a notable issue for the Staatan estuary.

Figure 5.35. Satellite image (Google Earth) showing the Staatan River estuary.

The location is shown in Figure 5.35 and observed issues listed in Figure 5.34 and Table 5.24.

Table 5.24. Staatan River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	2.8	3.6
Weed smothering	2.4	2.4
Access tracks, roads and boat ramps	0	0.4
Feral presence, damage and tracks	0	0.4
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0.4	0
Direct modification >>>	0	0.1
CLIMATE–NATURAL	6.7	12.0
Saltpan scouring	2.1	2.4
Bank erosion	2.4	3.2
Terrestrial retreat	0	0
Ecotone shift, negative	0.4	1.8
Sea level rise indicators >>>	*1.0*	1.4
2015 mangrove dieback	0.4	1.0

Note: yellow shaded areas highlight maximal severity indicators.

5.3.2 Gilbert River lower estuary

Figure 5.36. Mouth of the Gilbert River 14 September 2019.

Information about the lower section of this estuary (Figure 5.36) is shown in Table 5.25.

Table 5.25. Gilbert River site information.

Location of mouth: -16.5575 °S; 141.2695 °E	Aerial survey dates: 3–4 Dec 2017; 14 Sep 2019
Catchment area (km^2): 42,148	Tidal wetland total area (km^2): 97.0
Estuary length (km): 39.3	Saltmarsh and saltpan area (km^2): 88.4
Tidal range (m): ~3.3 m	Mangrove area (km^2): 8.6
Close-by major cyclones since 1995: at least 5	Mangrove Wetland Cover Index: 8.8%
Recent sea level rise: ~8.2 mm/yr	Mangrove species numbers: no data

Figure 5.37. Bank erosion and depositional gain, notable issues for the Gilbert estuary.

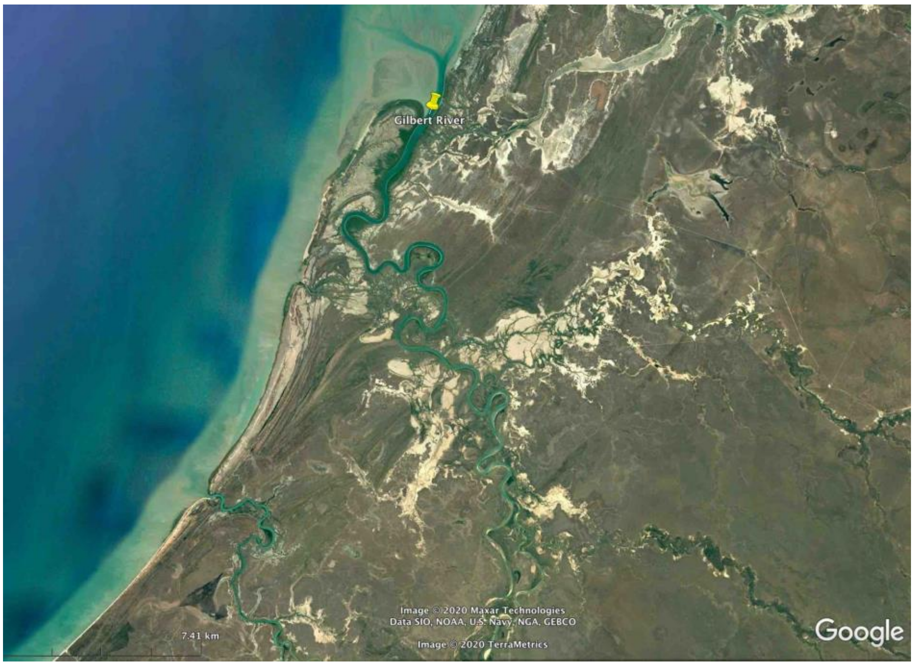

Figure 5.38. Satellite image (Google Earth) showing the Gilbert River estuary.

The location is shown in Figure 5.38 and observed issues listed in Figure 5.37 and Table 5.26.

Table 5.26. Gilbert River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	1.8	5.0
Weed smothering	1.8	1.8
Access tracks, roads and boat ramps	0	0.6
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0.4
Fire impacts, scorched and dead mangroves	0	1.6
Direct modification >>>	0	0.1
CLIMATE–NATURAL	5.7	11.8
Saltpan scouring	1.2	1.8
Bank erosion	2.1	1.8
Terrestrial retreat	0	0
Ecotone shift, negative	0.4	1.2
Sea level rise indicators >>>	0.7	1.0
2015 mangrove dieback	0.4	1.2

Note: yellow shaded areas highlight maximal severity indicators.

5.3.3 Accident Inlet estuary

Figure 5.39. Mouth of Accident Inlet 14 September 2019.

Information about the lower section of this estuary (Figure 5.39) is shown in Table 5.27.

Table 5.27. Accident Inlet site information.

Location of mouth: -17.1834 °S; 140.9389 °E	Aerial survey dates: 3–4 Dec 2017; 14 Sep 2019
Catchment area (km^2): 1889	Tidal wetland total area (km^2): 71.2
Estuary length (km): 27.4	Saltmarsh and saltpan area (km^2): 67.5
Tidal range (m): ~3.3 m	Mangrove area (km^2): 3.7
Close-by major cyclones since 1995: at least 4	Mangrove Wetland Cover Index: 5.1%
Recent sea level rise: ~8.2 mm/yr	Mangrove species numbers: no data

Figure 5.40. Bank erosion, pan scouring and weeds, notable issues for the Accident estuary.

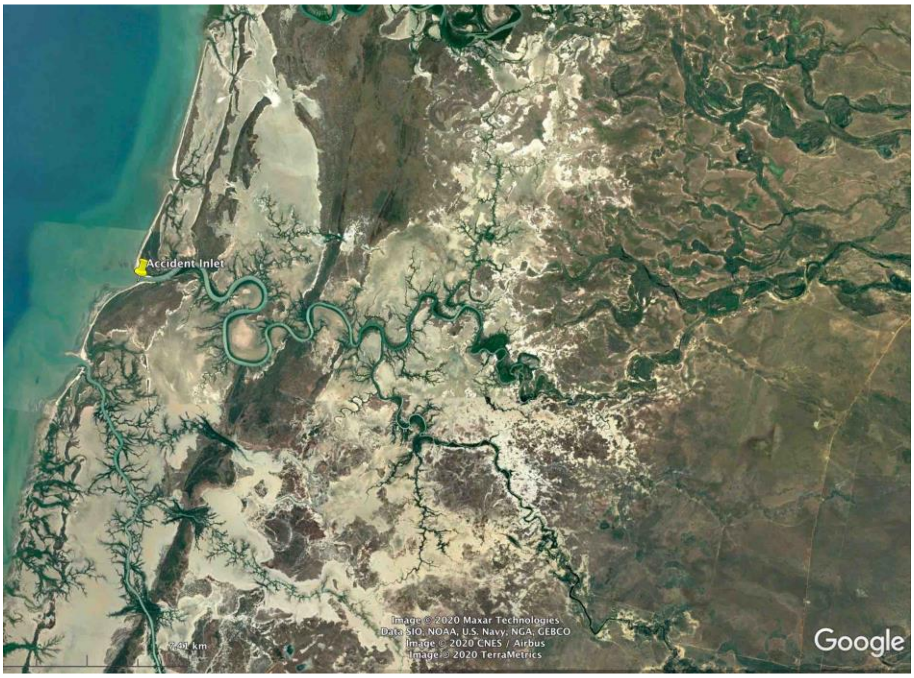

Figure 5.41. Satellite image (Google Earth) showing Accident Inlet estuary.

The location is shown in Figure 5.41 and observed issues listed in Figure 5.40 and Table 5.28.

Table 5.28. Accident inlet estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	2.6	4.0
Weed smothering	2.4	2.4
Access tracks, roads and boat ramps	0.2	0.6
Feral presence, damage and tracks	0	0.4
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	0.2	0.1
CLIMATE–NATURAL	7.5	9.0
Saltpan scouring	2.1	2.4
Bank erosion	2.4	1.8
Terrestrial retreat	1.2	0.6
Ecotone shift, negative	0.4	0.4
Sea level rise indicators >>>	1.22	1.1
2015 mangrove dieback	0.6	0.8

Note: yellow shaded areas highlight maximal severity indicators.

5.3.4 Norman River lower estuary

Figure 5.42. Mouth of the Norman River 14 September 2019.

Information about the lower section of this estuary (Figure 5.42) is shown in Table 5.29.

Table 5.29. Norman River site information.

Location of mouth: -17.464 °S; 140.8194 °E	Aerial survey dates: 3–4 Dec 2017; 14 Sep 2019
Catchment area (km^2): 49,588	Tidal wetland total area (km^2): 392.8
Estuary length (km): 102.4	Saltmarsh and saltpan area (km^2): 337.5
Tidal range (m): ~3.3 m	Mangrove area (km^2): 55.2
Close-by major cyclones since 1995: zero	Mangrove Wetland Cover Index: 14.1%
Recent sea level rise: ~8.2 mm/yr	Mangrove species numbers: no data

Figure 5.43. Shoreline modification and access tracks, notable issues for the Norman estuary.

Figure 5.44. Satellite image (Google Earth) showing the Norman River estuary.

The location is shown in Figure 5.44 and observed issues listed in Figure 5.43 and Table 5.30.

Table 5.30. Norman River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**4.0**	**7.6**
Weed smothering	2.4	0.8
Access tracks, roads and boat ramps	0.8	1.6
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0.8	0
Direct modification >>>	***0.8***	***1.2***
CLIMATE–NATURAL	**7.3**	**7.9**
Saltpan scouring	2.1	1.2
Bank erosion	1.8	2.4
Terrestrial retreat	0	0
Ecotone shift, negative	0.4	0.6
Sea level rise indicators >>>	***0.9***	***0.7***
2015 mangrove dieback	1.6	0.6

5.4 Flinders–Leichhardt region

Maps of the region (Figure 5.45) and the main regional characteristics are listed (Table 5.31).

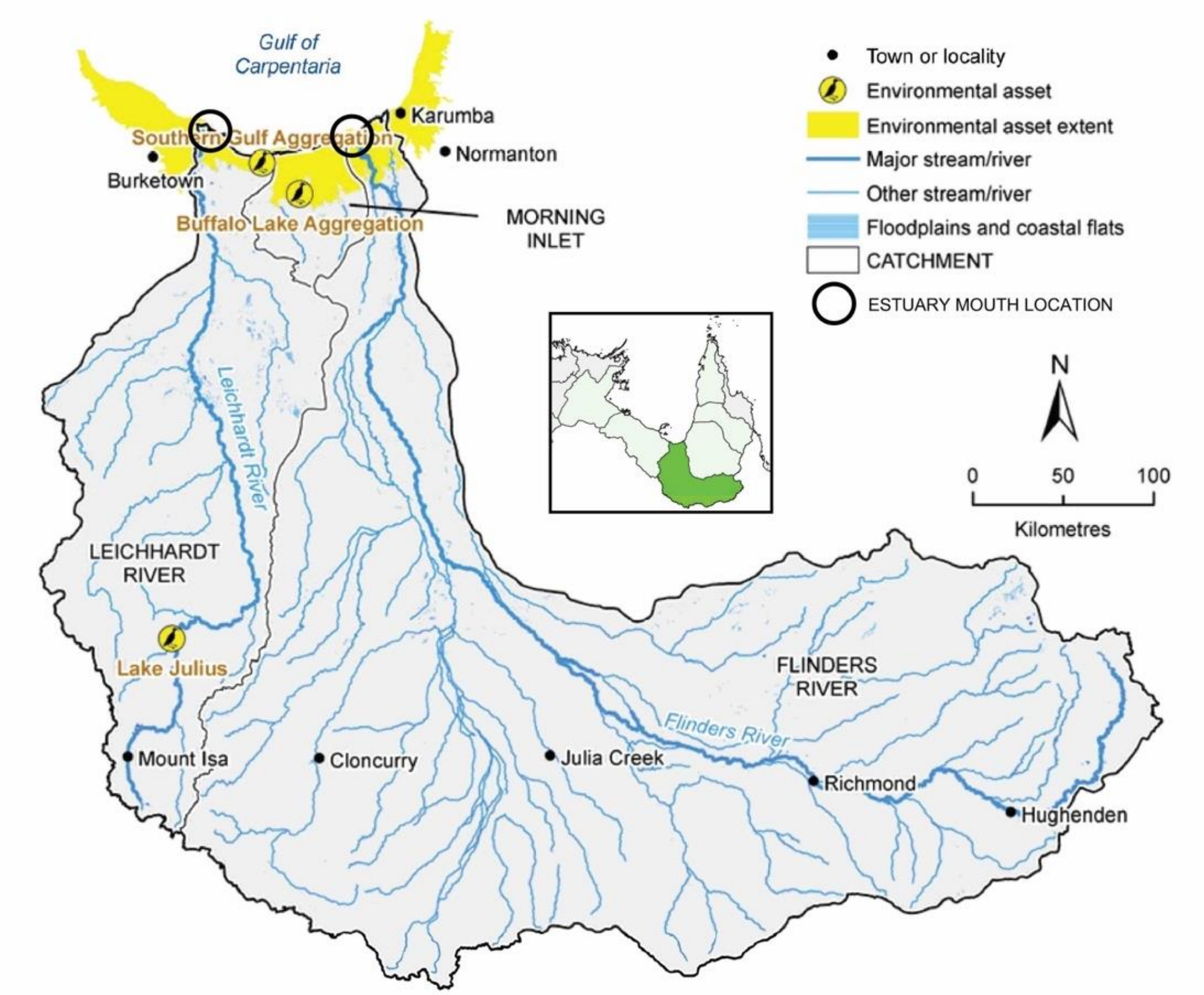

Figure 5.45. Major rivers, streams, towns and settlements in the Flinders–Leichhardt region (CSIRO, 2009f). See inset for location within the Gulf of Carpentaria. Lower estuaries surveyed with this study include Flinders River and Leichhardt River.

Table 5.31. Features of the Flinders–Leichhardt region. Source, in part: CSIRO (2009i).

Feature	Flinders–Leichhardt region
Total drainage area (km^2)	145,223
Maximal relief (m)	1,078
Mean annual temperature (°C), range	27.0, 21.3–32.7
Mean annual rainfall (mm)	493
Mean annual runoff (mm)	44
Volume of streamflow (TL/y)	6
Tidal influence, mean range in metres	Significant, 3.4
Number of important wetlands	6
Future flows with climate change (-2030)	Possible increase
Eastern Shoreline Coordinate	-17.480796; 140.764011
Western Shoreline Coordinate	-17.573194; 139.774519
Proportion of catchment drainage in study	97.8%
Severe tropical cyclones since 1995	> 2
Average sea level rise (mm/yr)	8.4
Mangrove species diversity	7
Mangrove Wetland Cover Index	20.4%
2015 mangrove dieback severity – estuary mouths	1.30 (max. 1.4), severe
2015 shoreline mangrove dieback – >30% lost	17.1 km (14.3%)

Dieback mapping

Distribution of dieback and remaining mangroves shown in Figure 5.46 and Table 5.32.

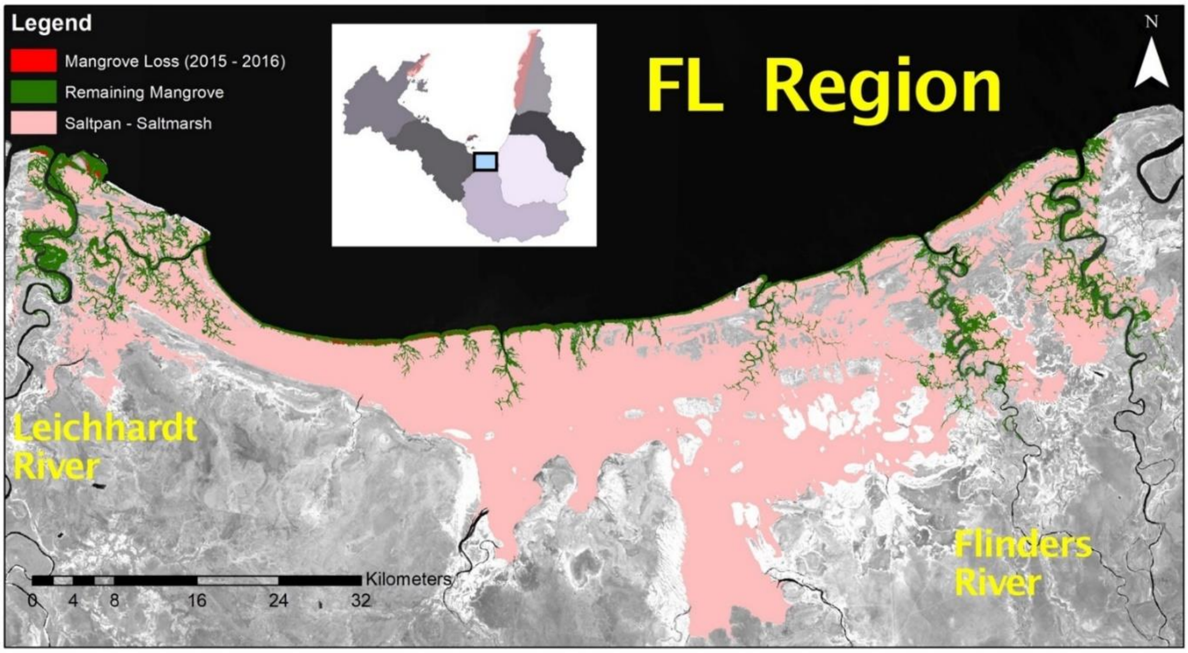

Figure 5.46. Mapped areas of mangrove dieback for the Flinders–Leichhardt Region.

Table 5.32. Tidal wetland areas from mapping of the Flinders–Leichhardt region.

Flinders–Leichhardt Region	
Mangrove (km^2): 172.9	2015 dead mangrove (km^2): 4.0
Tidal wetland (+ saltmarsh & pans) (km^2): 1,369.4	% 2015 dead mangrove: 2.3%

5.4.1 Flinders River lower estuary

Figure 5.47. Mouth of the Flinders River 15 September 2019.

Information about the lower section of this estuary (Figure 5.47) is shown in Table 5.33.

Table 5.33. Flinders River site information.

Location of mouth: -17.5977 °S; 140.595 °E	Aerial survey dates: 5 Dec 2017; 15 Sep 2019
Catchment area (km^2): 109,460	Tidal wetland total area (km^2): 320.8
Estuary length (km): 74.2	Saltmarsh and saltpan area (km^2): 286.2
Tidal range (m): ~3.3 m	Mangrove area (km^2): 34.6
Close-by major cyclones since 1995: at least 1	Mangrove Wetland Cover Index: 10.8%
Recent sea level rise: ~8.2 mm/yr	Mangrove species numbers: at least 7

Figure 5.48 Scour damage from recent flooding, a notable issue in the Flinders estuary.

Figure 5.49. Satellite image (Google Earth) showing the Flinders River estuary.

The location is shown in Figure 5.49 and observed issues listed in Figure 5.48 and Table 5.34.

Table 5.34. Flinders River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**2.4**	**3.0**
Weed smothering	2.4	2.4
Access tracks, roads and boat ramps	0	0
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0.4
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0***	***0***
CLIMATE–NATURAL	**6.9**	**12.7**
Saltpan scouring	2.1	3.2
Bank erosion	2.4	3.2
Terrestrial retreat	0	0.6
Ecotone shift, negative	0.4	1.8
Sea level rise indicators >>>	***1.0***	**1.2**
2015 mangrove dieback	1.2	1.5

Note: yellow shaded areas highlight maximal severity indicators.

5.4.2 Leichhardt River lower estuary

Figure 5.50. Mouth of the Leichhardt River 15 September 2019.

Information about the lower section of this estuary (Figure 5.50) is shown in Table 5.35.

Table 5.35. Leichhardt River site information.

Location of mouth: -17.5787 °S; 139.7944 °E	Aerial survey dates: 5 Dec 2017; 15 Sep 2019
Catchment area (km^2): 32,568	Tidal wetland total area (km^2): 79.7
Estuary length (km): 70.5	Saltmarsh and saltpan area (km^2): 59.3
Tidal range (m): ~3.5 m	Mangrove area (km^2): 20.4
Close-by major cyclones since 1995: at least 1	Mangrove Wetland Cover Index: 25.6%
Recent sea level rise: ~8.4 mm/yr	Mangrove species numbers: no data

Figure 5.51. Mangrove dieback from 2015, a notable issue in the Leichhardt estuary.

Figure 5.52. Satellite image (Google Earth) showing the Leichhardt River estuary.

The location is shown in Figure 5.52 and observed issues listed in Figure 5.51 and Table 5.36.

Table 5.36. Leichhardt River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	2.4	0.2
Weed smothering	2.4	0.2
Access tracks, roads and boat ramps	0	0
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	*0*	*0*
CLIMATE–NATURAL	12.3	13.1
Saltpan scouring	2.1	1.2
Bank erosion	3.2	1.6
Terrestrial retreat	0	1.6
Ecotone shift, negative	2.1	1.5
Sea level rise indicators >>>	*1.1*	*0.8*
2015 mangrove dieback	1.4	2.4

Note: yellow shaded areas highlight maximal severity indicators.

5.5 South-West Gulf region

Maps of the region (Figure 5.53) and the main regional characteristics are listed (Table 5.37).

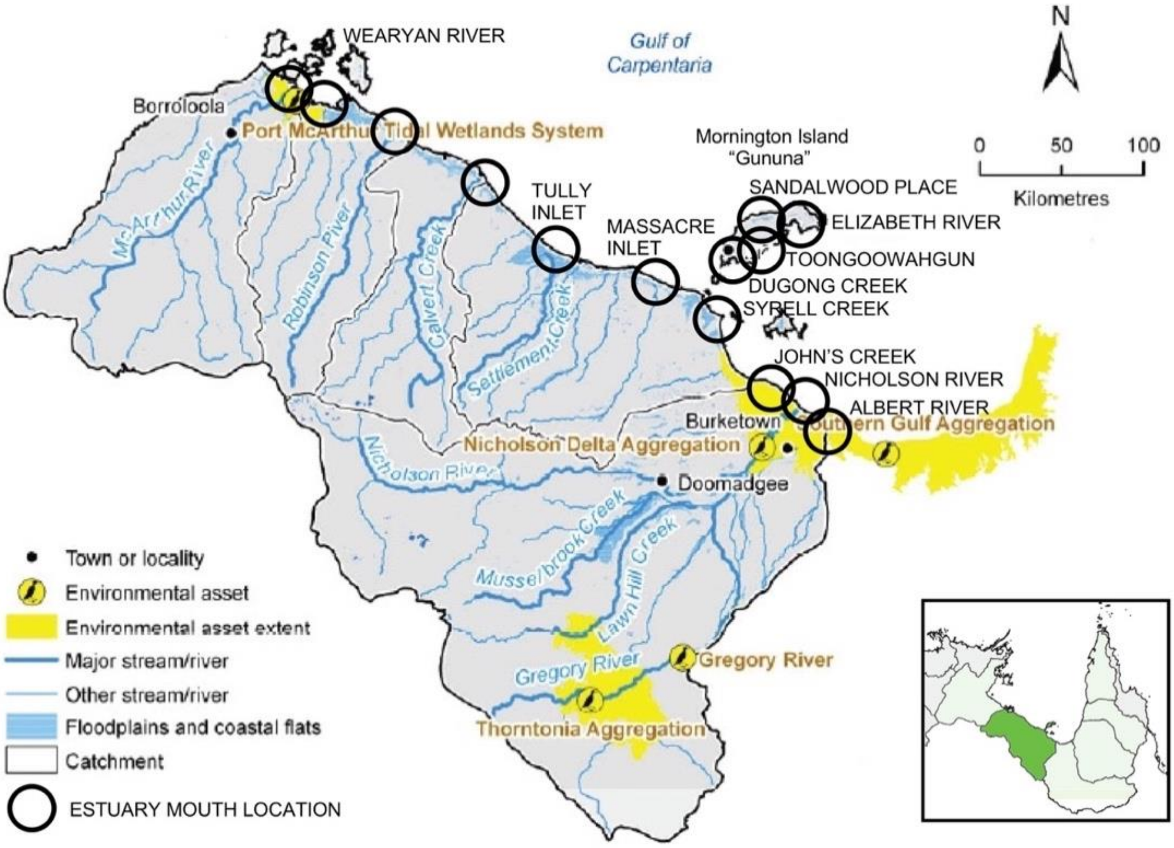

Figure 5.53. Major rivers, streams, towns and settlements in the South-West Gulf region (CSIRO, 2009e). See inset for location within the Gulf of Carpentaria. Lower estuaries surveyed with this study include Albert River, Nicholson River (Pascoe Inlet), John's Creek, Syrell Creek, Dugong Creek, Toongoowahgun River, Elizabeth River, Sandalwood Place, Massacre Inlet, Tully Inlet, Calvert River, Robinson River, Wearyan River, and McArthur River.

Table 5.37. Features of the South West Gulf region. Source, in part: CSIRO (2009i).

Feature	South-West Gulf
Total drainage area (km^2)	111,890
Maximal relief (m)	431
Mean annual temperature (°C), range	28.0, 22.1–33.9
Mean annual rainfall (mm)	670
Mean annual runoff (mm)	89
Volume of streamflow (TL/y)	10
Tidal influence, mean range in metres	Significant, 3.2
Number of important wetlands	12
Future flows with climate change (-2030)	Possible decrease
Eastern Shoreline Coordinate	-17.573194; 139.774519
Western Shoreline Coordinate	-15.670915; 136.471575
Proportion of catchment drainage in study	82.2%
Severe tropical cyclones since 1995	> 35
Average sea level rise (mm/yr)	8.9
Mangrove species diversity	9 (10 likely)
Mangrove Wetland Cover Index	20.3%
2015 mangrove dieback severity – estuary mouths	1.04 (max. 2.4), moderate to very severe
2015 shoreline mangrove dieback – >30% lost	50.2 km (17.8%)

Dieback mapping

Distribution of dieback and remaining mangroves shown in Figure 5.54 and Table 5.38.

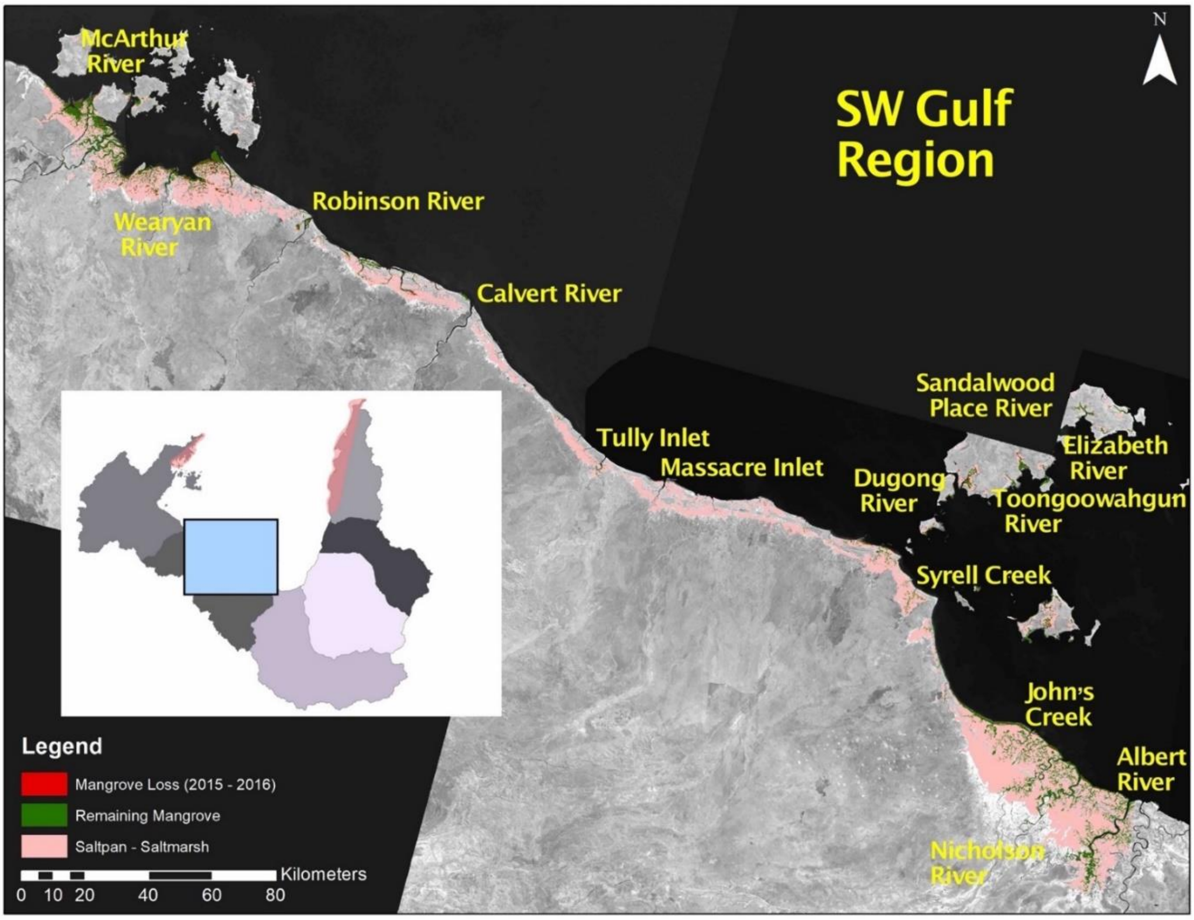

Figure 5.54. Mapped areas of mangrove dieback for the South-West Gulf region.

Table 5.38. Tidal wetland areas from mapping of the South-West Gulf region.

South-West Gulf region	
Mangrove (km^2): 482.2	2015 dead mangrove (km^2): 40.3
Tidal wetland (+ saltmarsh & pans) (km^2): 2,559.3	% 2015 dead mangrove: 8.4%

5.5.1 Albert River lower estuary

Figure 5.55. Mouth of the Albert River 15 September 2019.

Information about the lower section of this estuary (Figure 5.55) is shown in Table 5.39.

Table 5.39. Albert River site information.

Location of mouth: -17.5744 °S; 139.7559 °E	Aerial survey dates: 5 Dec 2017; 15 Sep 2019
Catchment area (km^2): 20,941	Tidal wetland total area (km^2): 229.2
Estuary length (km): 49.9	Saltmarsh and saltpan area (km^2): 218.5
Tidal range (m): ~3.5 m	Mangrove area (km^2): 10.7
Close-by major cyclones since 1995: zero	Mangrove Wetland Cover Index: 4.7%
Recent sea level rise: ~8.4 mm/yr	Mangrove species numbers: 12

Figure 5.56. Damage from access tracks and bank erosion, notable issues for the Albert.

Figure 5.57. Satellite image (Google Earth) showing the Albert River estuary.

The location is shown in Figure 5.57 and observed issues listed in Figure 5.56 and Table 5.40.

Table 5.40. Albert River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**2.6**	**1.2**
Weed smothering	1.2	0.4
Access tracks, roads and boat ramps	0.4	0.6
Feral presence, damage and tracks	0.4	0
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0.6	0
Direct modification >>>	***0.4***	***0.1***
CLIMATE–NATURAL	**7.5**	**9.0**
Saltpan scouring	2.1	1.8
Bank erosion	1.8	1.2
Terrestrial retreat	0	1.2
Ecotone shift, negative	1.2	2.4
Sea level rise indicators >>>	***0.8***	***0.7***
2015 mangrove dieback	1.2	1.2

Note: yellow shaded areas highlight maximal severity indicators.

5.5.2 Nicholson River (Pascoe Inlet) lower estuary

Figure 5.58. Mouth of the Nicholson River (Pascoe Inlet) 15 September 2019.

Information about the lower section of this estuary (Figure 5.58) is shown in Table 5.41.

Table 5.41. Nicholson River site information.

Location of mouth: -17.507 °S; 139.6051 °E	Aerial survey dates: 5 Dec 2017; 15 Sep 2019
Catchment area (km^2): 27,959	Tidal wetland total area (km^2): 111.4
Estuary length (km): 35.4	Saltmarsh and saltpan area (km^2): 102.6
Tidal range (m): ~3.5 m	Mangrove area (km^2): 8.8
Close-by major cyclones since 1995: at least 1	Mangrove Wetland Cover Index: 7.9%
Recent sea level rise: ~8.4 mm/yr	Mangrove species numbers: no data

Figure 5.59. Damage from access tracks, a notable issue for the Nicholson estuary.

Figure 5.60. Satellite image (Google Earth) showing the Nicholson River estuary.

The location is shown in Figure 5.60 and observed issues listed in Figure 5.59 and Table 5.42.

Table 5.42. Nicholson River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**1.6**	**2.4**
Weed smothering	1.2	0.4
Access tracks, roads and boat ramps	0.4	0.6
Feral presence, damage and tracks	0	0.4
Stock presence, damage and tracks	0	0.4
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0.4***	***0.1***
CLIMATE–NATURAL	**7.2**	**14.6**
Saltpan scouring	1.2	2.4
Bank erosion	3.2	1.6
Terrestrial retreat	0	2.4
Ecotone shift, negative	1.2	2.4
Sea level rise indicators >>>	***0.9***	***1.3***
2015 mangrove dieback	1.2	1.2

Note: yellow shaded areas highlight maximal severity indicators.

5.5.3 John's Creek lower estuary

Figure 5.61. Mouth of John's Creek 17 September 2019.

Information about the lower section of this estuary (Figure 5.61) is shown in Table 5.43.

Table 5.43. John's Creek site information.

Location of mouth: -17.3956 °S; 139.4513 °E	Aerial survey dates: 6 Dec 2017; 17 Sep 2019
Catchment area (km^2): 113	Tidal wetland total area (km^2): 130.2
Estuary length (km): 12.2	Saltmarsh and saltpan area (km^2): 125.8
Tidal range (m): ~3.6 m	Mangrove area (km^2): 4.5
Close-by major cyclones since 1995: at least 1	Mangrove Wetland Cover Index: 3.4%
Recent sea level rise: ~8.4 mm/yr	Mangrove species numbers: no data

Figure 5.62. Bank erosion, a notable issue for John's estuary.

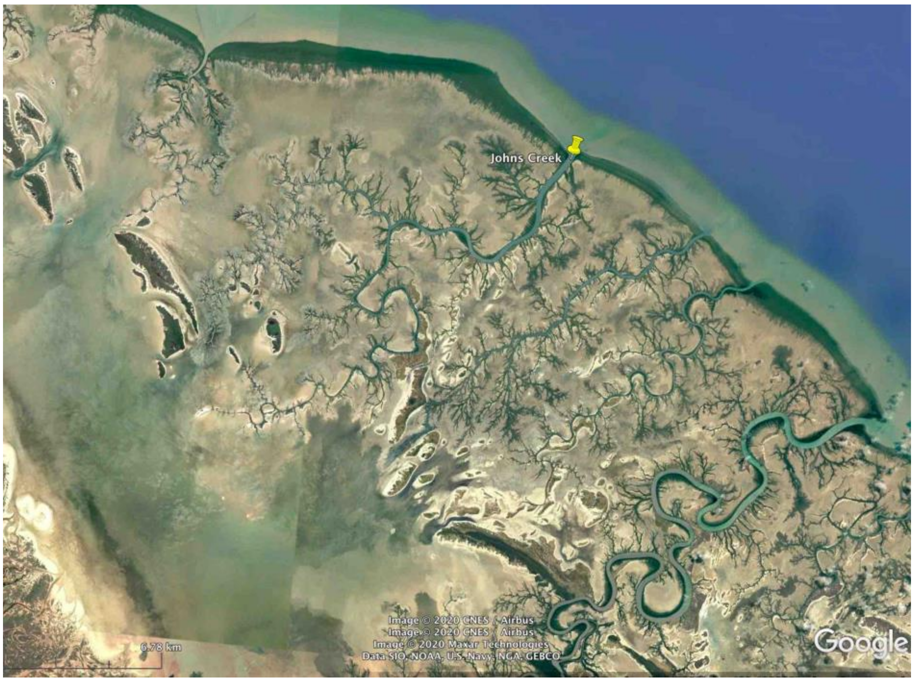

Figure 5.63. Satellite image (Google Earth) showing John's Creek estuary.

The location is shown in Figure 5.63 and observed issues listed in Figure 5.62 and Table 5.44.

Table 5.44. John’s Creek lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.6**	**0.6**
Weed smothering	0.6	0.4
Access tracks, roads and boat ramps	0	0
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0***	***0***
CLIMATE–NATURAL	**9.0**	**11.4**
Saltpan scouring	3.2	1.8
Bank erosion	2.1	2.4
Terrestrial retreat	0	1.8
Ecotone shift, negative	0.7	1.8
Sea level rise indicators >>>	***1.3***	***1***
2015 mangrove dieback	1.2	1.2

Note: yellow shaded areas highlight maximal severity indicators.

5.5.4 Syrell Creek lower estuary

Figure 5.64. Mouth of Syrell Creek 17 September 2019.

Information about the lower section of this estuary (Figure 5.64) is shown in Table 5.45.

Table 5.45. Syrell Creek site information.

Location of mouth: -17.0043 °S; 139.0924 °E	Aerial survey dates: 6 Dec 2017; 17 Sep 2019
Catchment area (km^2): 344	Tidal wetland total area (km^2): 58.3
Estuary length (km): 4.7	Saltmarsh and saltpan area (km^2): 56.5
Tidal range (m): ~3.6 m	Mangrove area (km^2): 1.8
Close-by major cyclones since 1995: at least 2	Mangrove Wetland Cover Index: 3.0%
Recent sea level rise: ~8.4 mm/yr	Mangrove species numbers: no data

Figure 5.65. Damage from grass fires, a notable issue for the Syrell estuary.

Figure 5.66. Satellite image (Google Earth) showing Syrell Creek estuary.

The location is shown in Figure 5.66 and observed issues listed in Figure 5.65 and Table 5.46.

Table 5.46. Syrel Creekl lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**1.8**	**3.2**
Weed smothering	1.2	0
Access tracks, roads and boat ramps	0.6	1.2
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0.4
Fire impacts, scorched and dead mangroves	0	1.6
Direct modification >>>	***0.6***	***0.2***
CLIMATE–NATURAL	**9.5**	**10.7**
Saltpan scouring	3.2	2.4
Bank erosion	1.8	1.2
Terrestrial retreat	2.1	3.6
Ecotone shift, negative	0.6	1.5
Sea level rise indicators >>>	***1.4***	***1.3***
2015 mangrove dieback	0.6	0.6

Note: yellow shaded areas highlight maximal severity indicators.

5.5.5 *Massacre Inlet estuary*

Figure 5.67. Mouth of Massacre Inlet 17 September 2019.

Information about the lower section of this estuary (Figure 5.67) is shown in Table 5.47.

Table 5.47. Massacre Inlet site information.

Location of mouth: -16.738 °S; 138.3355 °E	Aerial survey dates: 6 Dec 2017; 17 Sep 2019
Catchment area (km^2): 647	Tidal wetland total area (km^2): 66.6
Estuary length (km): 7.9	Saltmarsh and saltpan area (km^2): 65.3
Tidal range (m): ~3.2 m	Mangrove area (km^2): 1.2
Close-by major cyclones since 1995: at least 6	Mangrove Wetland Cover Index: 1.9%
Recent sea level rise: ~8.6 mm/yr	Mangrove species numbers: no data

Figure 5.68. Pan scouring and terrestrial retreat, notable issues for the Massacre estuary.

Figure 5.69. Satellite image (Google Earth) showing Massacre Inlet estuary.

The location is shown in Figure 5.69 and observed issues listed in Figure 5.68 and Table 5.48.

Table 5.48. Massacre Inlet estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**1.3**	**2.4**
Weed smothering	0.4	0
Access tracks, roads and boat ramps	0.5	0.4
Feral presence, damage and tracks	0	1.6
Stock presence, damage and tracks	0.4	0.4
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0.5***	***0.1***
CLIMATE–NATURAL	**6.4**	**9.8**
Saltpan scouring	0.6	1.2
Bank erosion	0.6	1.2
Terrestrial retreat	2.4	1.6
Ecotone shift, negative	0.5	0.8
Sea level rise indicators >>>	***0.8***	***1.3***
2015 mangrove dieback	0.4	0.8

Note: yellow shaded areas highlight maximal severity indicators.

5.5.6 Tully Inlet estuary

Figure 5.70. Mouth of Tully Inlet 17 September 2019.

Information about the lower section of this estuary (Figure 5.70) is shown in Table 5.49.

Table 5.49. Tully Inlet site information.

Location of mouth: -16.6776 °S; 138.158 °E	Aerial survey dates: 6 Dec 2017; 17 Sep 2019
Catchment area (km^2): 4,362	Tidal wetland total area (km^2): 20.8
Estuary length (km): 6.5	Saltmarsh and saltpan area (km^2): 20.7
Tidal range (m): ~3.0 m	Mangrove area (km^2): 0.1
Close-by major cyclones since 1995: at least 5	Mangrove Wetland Cover Index: 0.5%
Recent sea level rise: ~8.6 mm/yr	Mangrove species numbers: no data

Figure 5.71. Tracks from feral animals and stock, notable issues for the Tully estuary.

Figure 5.72. Satellite image (Google Earth) showing Tully Inlet estuary.

The location is shown in Figure 5.72 and observed issues listed in Figure 5.71 and Table 5.50.

Table 5.50. Tully Inlet estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.7**	**2.8**
Weed smothering	0	0
Access tracks, roads and boat ramps	0.5	0.4
Feral presence, damage and tracks	0	1.2
Stock presence, damage and tracks	0.2	1.2
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0.5***	***0.1***
CLIMATE–NATURAL	**6.8**	**13.2**
Saltpan scouring	1.4	2.4
Bank erosion	2.4	2.4
Terrestrial retreat	1.4	2.8
Ecotone shift, negative	0.5	1.6
Sea level rise indicators >>>	***1.0***	***1.5***
2015 mangrove dieback	0.6	0.4

Note: yellow shaded areas highlight maximal severity indicators.

5.5.7 Dugong River lower estuary, Mornington Island

Figure 5.73. Mouth of Dugong River (Boyorunga) 7 December 2017.

Information about the lower section of this estuary (Figure 5.73) is shown in Table 5.51.

Table 5.51. Dugong River site information.

Location of mouth: -16.7083 °S; 139.2071 °E	Aerial survey dates: 7 Dec 2017
Catchment area (km^2): 158	Tidal wetland total area (km^2): 29.1
Estuary length (km): 6.3	Saltmarsh and saltpan area (km^2): 15.6
Tidal range (m): ~3.6 m	Mangrove area (km^2): 13.5
Close-by major cyclones since 1995: zero	Mangrove Wetland Cover Index: 46.4%
Recent sea level rise: ~8.4 mm/yr	Mangrove species numbers: at least 8

Figure 5.74. Scouring across saltpans, a notable issue for the Dugong estuary.

Figure 5.75. Satellite image (Google Earth) showing the Dugong River estuary.

The location is shown in Figure 5.75 and observed issues listed in Figure 5.74 and Table 5.52.

Table 5.52. Dugong River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**2.4**	
Weed smothering	0	
Access tracks, roads and boat ramps	2.4	
Feral presence, damage and tracks	0	
Stock presence, damage and tracks	0	
Fire impacts, scorched and dead mangroves	0	
Direct modification >>>	***2.4***	
CLIMATE–NATURAL	**3.4**	
Saltpan scouring	1.2	
Bank erosion	0.5	
Terrestrial retreat	0.6	
Ecotone shift, negative	0.5	
Sea level rise indicators >>>	***0.5***	
2015 mangrove dieback	0.6	

Note: yellow shaded areas highlight maximal severity indicators.

5.5.8 Toongoowahgun River lower estuary, Mornington Island

Figure 5.76. Mouth of Toongoowahgun River 7 December 2017.

Information about the lower section of this estuary (Figure 5.76) is shown in Table 5.53.

Table 5.53. Toongoowahgun River site information.

Location of mouth: -16.6405 °S; 139.3841 °E	Aerial survey dates: 7 Dec 2017
Catchment area (km^2): 153	Tidal wetland total area (km^2): 13.9
Estuary length (km): ---	Saltmarsh and saltpan area (km^2): 8.8
Tidal range (m): ~3.6 m	Mangrove area (km^2): 5.1
Close-by major cyclones since 1995: at least 3	Mangrove Wetland Cover Index: 36.8%
Recent sea level rise: ~8.4 mm/yr	Mangrove species numbers: no data

Figure 5.77. Scouring of saltpans and terrestrial retreat, notable issues for Toongoowahgun.

Figure 5.78. Satellite image (Google Earth) showing the Toongoowahgun River estuary.

The location is shown in Figure 5.78 and observed issues listed in Figure 5.77 and Table 5.54.

Table 5.54. Toongoowahgun River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**1.0**	
Weed smothering	0	
Access tracks, roads and boat ramps	1.0	
Feral presence, damage and tracks	0	
Stock presence, damage and tracks	0	
Fire impacts, scorched and dead mangroves	0	
Direct modification >>>	***1.0***	
CLIMATE–NATURAL	**7.8**	
Saltpan scouring	3.2	
Bank erosion	0	
Terrestrial retreat	1.2	
Ecotone shift, negative	1.2	
Sea level rise indicators >>>	***1.1***	
2015 mangrove dieback	0.6	

Note: yellow shaded areas highlight maximal severity indicators.

5.5.9 Elizabeth River lower estuary, Mornington Island

Figure 5.79. Mouth of the Elizabeth River 7 December 2017.

Information about the lower section of this estuary (Figure 5.79) is shown in Table 5.55.

Table 5.55. Elizabeth River site information.

Location of mouth: -16.4854 °S; 139.5576 °E	Aerial survey dates: 7 Dec 2017
Catchment area (km^2): 62	Tidal wetland total area (km^2): 10.6
Estuary length (km): 8.6	Saltmarsh and saltpan area (km^2): 6.6
Tidal range (m): ~3.6 m	Mangrove area (km^2): 4.0
Close-by major cyclones since 1995: at least 1	Mangrove Wetland Cover Index: 37.4%
Recent sea level rise: ~8.4 mm/yr	Mangrove species numbers: no data

Figure 5.80. Pan scouring and terrestrial retreat, notable issues for the Elizabeth estuary.

Figure 5.81. Satellite image (Google Earth) showing the Elizabeth River estuary.

The location is shown in Figure 5.81 and observed issues listed in Figure 5.80 and Table 5.56.

Table 5.56. Elizabeth River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.0**	
Weed smothering	0	
Access tracks, roads and boat ramps	0	
Feral presence, damage and tracks	0	
Stock presence, damage and tracks	0	
Fire impacts, scorched and dead mangroves	0	
Direct modification >>>	***0***	
CLIMATE–NATURAL	**8.6**	
Saltpan scouring	3.2	
Bank erosion	0	
Terrestrial retreat	2.1	
Ecotone shift, negative	1.2	
Sea level rise indicators >>>	***1.3***	
2015 mangrove dieback	0.6	

Note: yellow shaded areas highlight maximal severity indicators.

5.5.10 Sandalwood Place estuary, Mornington Island

Figure 5.82. Mouth of Sandalwood Place River 7 December 2017.

Information about the lower section of this estuary (Figure 5.82) is shown in Table 5.57.

Table 5.57. Sandalwood Place River site information.

Location of mouth: -16.4582 °S; 139.3582 °E	Aerial survey dates: 7 Dec 2017
Catchment area (km^2): 102	Tidal wetland total area (km^2): 24.7
Estuary length (km): ---	Saltmarsh and saltpan area (km^2): 18.6
Tidal range (m): ~3.6 m	Mangrove area (km^2): 6.1
Close-by major cyclones since 1995: at least 3	Mangrove Wetland Cover Index: 24.8%
Recent sea level rise: ~8.4 mm/yr	Mangrove species numbers: no data

Figure 5.83. Saltpan scouring, a notable issue in the Sandalwood estuary.

Figure 5.84. Satellite image (Google Earth) showing the Sandalwood Place River estuary.

The location is shown in Figure 5.84 and observed issues listed in Figure 5.83 and Table 5.58.

Table 5.58. Sandalwood Place River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.2**	
Weed smothering	0	
Access tracks, roads and boat ramps	0.2	
Feral presence, damage and tracks	0	
Stock presence, damage and tracks	0	
Fire impacts, scorched and dead mangroves	0	
Direct modification >>>	***0.2***	
CLIMATE–NATURAL	**10.3**	
Saltpan scouring	3.2	
Bank erosion	0	
Terrestrial retreat	2.8	
Ecotone shift, negative	1.2	
Sea level rise indicators >>>	***1.3***	
2015 mangrove dieback	1.4	

Note: yellow shaded areas highlight maximal severity indicators.

5.5.11 Calvert River lower estuary

Figure 5.85. Mouth of the Calvert River 17 September 2019.

Information about the lower section of this estuary (Figure 5.85) is shown in Table 5.59.

Table 5.59. Calvert River site information.

Location of mouth: -16.266 °S; 137.7442 °E	Aerial survey dates: 8 Dec 2017; 17 Sep 2019
Catchment area (km^2): 7,536	Tidal wetland total area (km^2): 11.5
Estuary length (km): 33.1	Saltmarsh and saltpan area (km^2): 10.4
Tidal range (m): ~2.4 m	Mangrove area (km^2): 1.1
Close-by major cyclones since 1995: at least 5	Mangrove Wetland Cover Index: 9.2%
Recent sea level rise: : ~8.6 mm/yr	Mangrove species numbers: at least 8

Figure 5.86. Damage from Cyclone Trevor, a notable issue in the Calvert estuary.

Figure 5.87. Satellite image (Google Earth) showing the Calvert River estuary.

The location is shown in Figure 5.87 and observed issues listed in Figure 5.86 and Table 5.60.

Table 5.60. Calvert River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	2.6	1.4
Weed smothering	0	0
Access tracks, roads and boat ramps	0.4	0.4
Feral presence, damage and tracks	0.8	0.4
Stock presence, damage and tracks	1.2	0
Fire impacts, scorched and dead mangroves	0.2	0
Direct modification >>>	*0.4*	*0.1*
CLIMATE–NATURAL	6.8	11.3
Saltpan scouring	1.4	0.6
Bank erosion	1.2	1.8
Terrestrial retreat	2.4	2.4
Ecotone shift, negative	0.6	0.6
Sea level rise indicators >>>	*1.0*	*1.2*
2015 mangrove dieback	1.2	1.2

Note: yellow shaded areas highlight maximal severity indicators.

5.5.12 Robinson River lower estuary

Figure 5.88. Mouth of the Robinson River 18 September 2019.

Information about the lower section of this estuary (Figure 5.88) is shown in Table 5.61.

Table 5.61. Robinson River site information.

Location of mouth: -16.0311 °S; 137.2683 °E	Aerial survey dates: 8 Dec 2017; 17 Sep 2019
Catchment area (km^2): 5,766	Tidal wetland total area (km^2): 2.7
Estuary length (km): 21.9	Saltmarsh and saltpan area (km^2): 1.2
Tidal range (m): ~2.3 m	Mangrove area (km^2): 1.4
Close-by major cyclones since 1995: at least 3	Mangrove Wetland Cover Index: 53.6%
Recent sea level rise: ~8.8 mm/yr	Mangrove species numbers:

Figure 5.89. Damage from Cyclone Trevor, a notable issue for the Robinson estuary.

Figure 5.90. Satellite image (Google Earth) showing the Robinson River estuary.

The location is shown in Figure 5.90 and observed issues listed in Figure 5.89 and Table 5.62.

Table 5.62. Robinson River site information.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.6**	**2.8**
Weed smothering	0	0
Access tracks, roads and boat ramps	0.6	1.2
Feral presence, damage and tracks	0	0.4
Stock presence, damage and tracks	0	0.8
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0.6***	***0.2***
CLIMATE–NATURAL	**8.0**	**8.4**
Saltpan scouring	1.4	0.6
Bank erosion	1.4	2.4
Terrestrial retreat	2.4	0.6
Ecotone shift, negative	0.6	0
Sea level rise indicators >>>	***1.0***	***0.9***
2015 mangrove dieback	1.2	0

Note: yellow shaded areas highlight maximal severity indicators.

5.5.13 Wearyan River lower estuary

Figure 5.91. Mouth of the Wearyan River 18 September 2019.

Information about the lower section of this estuary (Figure 5.91) is shown in Table 5.63.

Table 5.63. Wearyan River site information.

Location of mouth: -15.9139 °S; 136.8585 °E	Aerial survey dates: 9 Dec 2017; 18 Sep 2019
Catchment area (km^2): 3,704	Tidal wetland total area (km^2): 25.7
Estuary length (km): 32.0	Saltmarsh and saltpan area (km^2): 22.5
Tidal range (m): ~2.3 m	Mangrove area (km^2): 3.2
Close-by major cyclones since 1995: at least 2	Mangrove Wetland Cover Index: 12.6%
Recent sea level rise: ~8.8 mm/yr	Mangrove species numbers: at least 9

Figure 5.92. Cyclone damage plus bank erosion, notable issues for the Wearyan estuary.

Figure 5.93. Satellite image (Google Earth) showing the Wearyan River estuary.

The location is shown in Figure 5.93 and observed issues listed in Figure 5.92 and Table 5.64.

Table 5.64. Wearyan River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**1.4**	**3.6**
Weed smothering	0	0
Access tracks, roads and boat ramps	1.2	1.2
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0.2	1.2
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***1.2***	***0.2***
CLIMATE–NATURAL	**9.5**	**14.2**
Saltpan scouring	1.2	1.8
Bank erosion	2.1	2.8
Terrestrial retreat	2.4	2.4
Ecotone shift, negative	0.8	0
Sea level rise indicators >>>	***1.3***	***1.4***
2015 mangrove dieback	2.4	1.2

Note: yellow shaded areas highlight maximal severity indicators.

5.5.14 McArthur River lower estuary

Figure 5.94. Mouth of the McArthur River (Battan Branch) 18 September 2019.

Information about the lower section of this estuary (Figure 5.94) is shown in Table 5.65.

Table 5.65. McArthur River site information.

Location of mouth: -15.7105 °S; 136.6117 °E	Aerial survey dates: 9 Dec 2017; 18 Sep 2019
Catchment area (km^2): 20,139	Tidal wetland total area (km^2): 460.3
Estuary length (km): ---	Saltmarsh and saltpan area (km^2): 406.3
Tidal range (m): ~2.3 m	Mangrove area (km^2): 53.9
Close-by major cyclones since 1995: at least 2	Mangrove Wetland Cover Index: 11.7%
Recent sea level rise: ~8.8 mm/yr	Mangrove species numbers: at least 11

Figure 5.95. Bank erosion and access constructions, notable issues in the McArthur estuary.

Figure 5.96. Satellite image (Google Earth) showing the McArthur River estuary.

The location is shown in Figure 5.96 and observed issues listed in Figure 5.95 and Table 5.66.

Table 5.66. McArthur River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.0**	**1.0**
Weed smothering	0	0
Access tracks, roads and boat ramps	0	0
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0***	***0.1***
CLIMATE–NATURAL	**7.9**	**9.0**
Saltpan scouring	1.2	1.2
Bank erosion	2.1	1.8
Terrestrial retreat	1.4	1.2
Ecotone shift, negative	0.6	1.2
Sea level rise indicators >>>	***0.9***	***0.7***
2015 mangrove dieback	1.4	1.2

Note: yellow shaded areas highlight maximal severity indicators.

5.6 Roper region

Maps of the region (Figure 5.97) and the main regional characteristics are listed (Table 5.67).

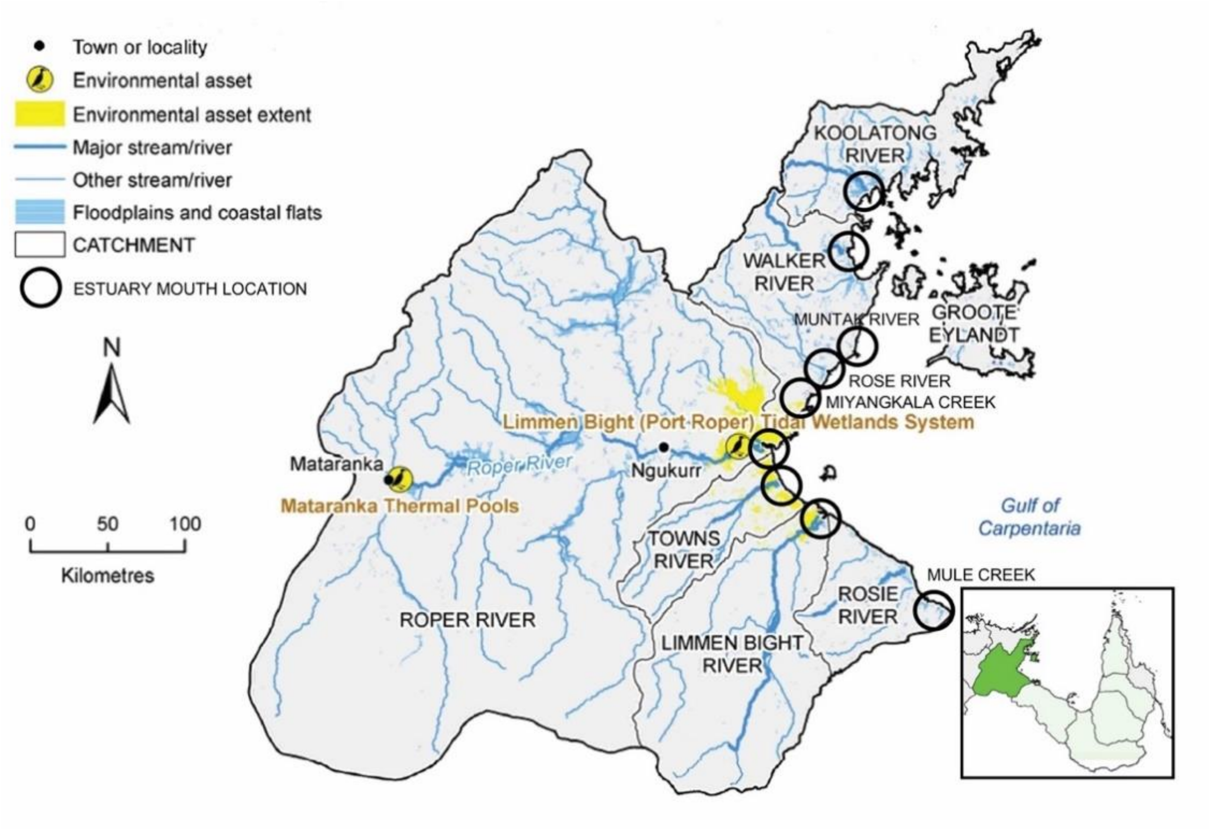

Figure 5.97. Major rivers, streams, towns and settlements in the Roper region (CSIRO, 2009d). See inset for location within the Gulf of Carpentaria. Lower estuaries surveyed with this study include Mule Creek, Limmen Bight River, Towns River, Roper River, Miyangkala Creek, Rose River, Muntak River, Walker River, and Koolatong River.

Table 5.67. Features of the Roper region. Source, in part: CSIRO (2009i).

Feature	Roper region
Total drainage area (km^2)	128,518
Maximal relief (m)	441
Mean annual temperature (°C), range	26.9, 21.3–32.4
Mean annual rainfall (mm)	843
Mean annual runoff (mm)	112
Volume of streamflow (TL/y)	14
Tidal influence, mean range in metres	Local, 2.1
Number of important wetlands	2
Future flows with climate change (-2030)	Possible decrease
Southern shoreline coordinate	-15.670915; 136.471575
Northern shoreline coordinate	-12.35059; 136.92761
Proportion of catchment drainage in study	94.6%
Severe tropical cyclones since 1995	> 14
Average sea level rise (mm/yr)	9.1
Mangrove species diversity	12 (13 likely)
Mangrove Wetland Cover Index	18.5%
2015 mangrove dieback severity – estuary mouths	1.46 (max. 2.1), moderate to very severe
2015 shoreline mangrove dieback – >30% lost	65.7 km (32.3%)

Dieback mapping

Distribution of dieback and remaining mangroves shown in Figure 5.98 and Table 5.68.

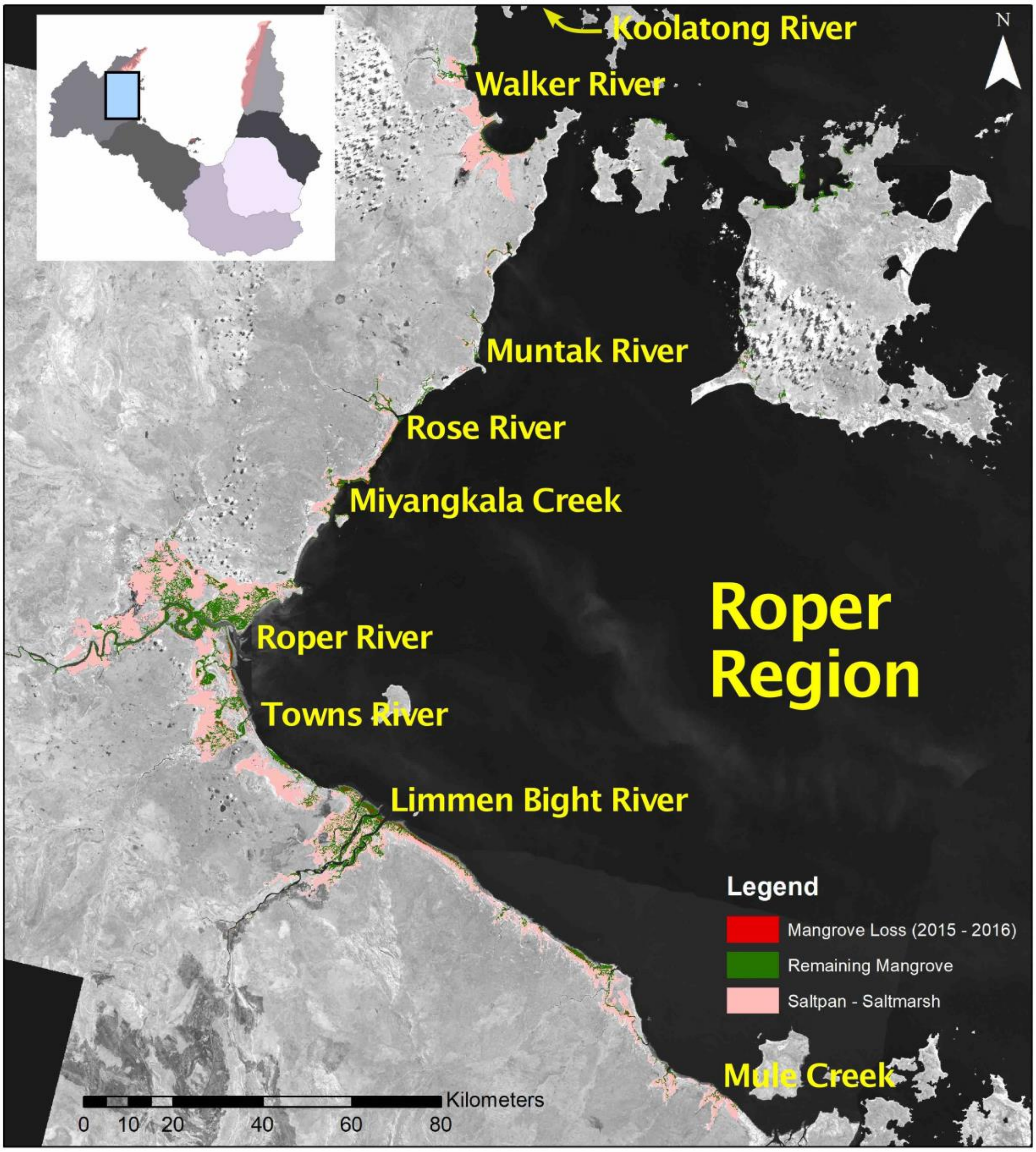

Figure 5.98. Mapped areas of mangrove dieback for the Roper region.

Table 5.68. Tidal wetland areas from mapping of the Roper region.

Roper region	
Mangrove (km^2): 374.8	2015 dead mangrove (km^2): 19.6
Tidal wetland (+ saltmarsh & pans) (km^2): 1,238.2	% 2015 dead mangrove: 5.2%

5.6.1 Mule Creek lower estuary

Figure 5.99. Mouth of Mule Creek 18 September 2019.

Information about the lower section of this estuary (Figure 5.99) is shown in Table 5.69.

Table 5.69. Mule Creek site information.

Location of mouth: -15.6394 °S; 136.425 °E	Aerial survey dates: 9 Dec 2017; 18 Sep 2019
Catchment area (km^2): 242	Tidal wetland total area (km^2): 20.6
Estuary length (km): 9	Saltmarsh and saltpan area (km^2): 19.5
Tidal range (m): ~2.2 m	Mangrove area (km^2): 1.1
Close-by major cyclones since 1995: at least 2	Mangrove Wetland Cover Index: 5.2%
Recent sea level rise: ~9.0 mm/y	Mangrove species numbers: no data

Figure 5.100. Terrestrial retreat and pan scouring, notable issues for the Mule estuary.

Figure 5.101. Satellite image (Google Earth) showing Mule Creek estuary.

The location is shown in Figure 5.101 and observed issues listed in Figure 5.100 and Table 5.70.

Table 5.70. Mule Creek lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**1.4**	**3.8**
Weed smothering	0	0
Access tracks, roads and boat ramps	1.4	1.2
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0.4
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***1.4***	***0.6***
CLIMATE–NATURAL	**6.7**	**11.8**
Saltpan scouring	2.1	1.8
Bank erosion	0.5	1.2
Terrestrial retreat	1.4	2.4
Ecotone shift, negative	0.5	1.2
Sea level rise indicators >>>	***0.8***	***1.3***
2015 mangrove dieback	1.8	1.6

Note: yellow shaded areas highlight maximal severity indicators.

5.6.2 Limmen Bight River lower estuary

Figure 5.102. Mouth of the Limmen Bight River 20 September 2019.

Information about the lower section of this estuary (Figure 5.102) is shown in Table 5.71.

Table 5.71. Limmen Bight River site information.

Location of mouth: -15.1153 °S; 135.7212 °E	Aerial survey dates: 9 Dec 2017; 18 Sep 2019
Catchment area (km^2): 22,855	Tidal wetland total area (km^2): 91.9
Estuary length (km): 63.6	Saltmarsh and saltpan area (km^2): 70.6
Tidal range (m): ~2.0 m	Mangrove area (km^2): 21.2
Close-by major cyclones since 1995: zero	Mangrove Wetland Cover Index: 23.1%
Recent sea level rise: ~9.2 mm/yr	Mangrove species numbers: at least 12

Figure 5.103. Shoreline erosion and retreat, a notable issue for the Limmen estuary.

Figure 5.104. Satellite image (Google Earth) showing the Limmen Bight River estuary.

The location is shown in Figure 5.104 and observed issues listed in Figure 5.103 and Table 5.72.

Table 5.72. Limmen Bight River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.0**	**0.8**
Weed smothering	0	0
Access tracks, roads and boat ramps	0	0.2
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0.4
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0***	***0.1***
CLIMATE–NATURAL	**12.2**	**19.0**
Saltpan scouring	2.8	2.4
Bank erosion	0.5	2.4
Terrestrial retreat	3.2	2.4
Ecotone shift, negative	0.5	1.8
Sea level rise indicators >>>	***1.9***	***1.9***
2015 mangrove dieback	1.6	2.0

Note: yellow shaded areas highlight maximal severity indicators.

5.6.3 Towns River lower estuary

Figure 5.105. Mouth of the Towns River 20 September 2019.

Information about the lower section of this estuary (Figure 5.105) is shown in Table 5.73.

Table 5.73. Towns River site information.

Location of mouth: -14.9142 °S; 135.4307 °E	Aerial survey dates: 10 Dec 2017; 20 Sep 2019
Catchment area (km^2): 4,755	Tidal wetland total area (km^2): 83.0
Estuary length (km): 19.5	Saltmarsh and saltpan area (km^2): 72.0
Tidal range (m): ~2.0 m	Mangrove area (km^2): 10.9
Close-by major cyclones since 1995: zero	Mangrove Wetland Cover Index: 13.2%
Recent sea level rise: ~9.2 mm/yr	Mangrove species numbers: at least 8

Figure 5.106. Damage from the 2015 mangrove dieback, a notable issue for the Towns estuary.

Figure 5.107. Satellite image (Google Earth) showing the Towns River estuary.

The location is shown in Figure 5.107 and observed issues listed in Figure 5.106 and Table 5.74.

Table 5.74. Towns River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.0**	**1.2**
Weed smothering	0	0.4
Access tracks, roads and boat ramps	0	0
Feral presence, damage and tracks	0	0.4
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0***	***0***
CLIMATE–NATURAL	**9.8**	**14.2**
Saltpan scouring	1.2	1.8
Bank erosion	2.1	1.6
Terrestrial retreat	1.4	1.8
Ecotone shift, negative	1.2	2.4
Sea level rise indicators >>>	***1.1***	***1.4***
2015 mangrove dieback	1.4	2.0

Note: yellow shaded areas highlight maximal severity indicators.

5.6.4 Roper River lower estuary

Figure 5.108. Mouth of the Roper River 20 September 2019.

Information about the lower section of this estuary (Figure 5.108) is shown in Table 5.75.

Table 5.75. Roper River site information.

Location of mouth: -14.7513 °S; 135.3968 °E	Aerial survey dates: 10 Dec 2017; 20 Sep 2019
Catchment area (km^2): 84,655	Tidal wetland total area (km^2): 175.9
Estuary length (km): ---	Saltmarsh and saltpan area (km^2): 92.0
Tidal range (m): ~2.1 m	Mangrove area (km^2): 83.9
Close-by major cyclones since 1995: at least 1	Mangrove Wetland Cover Index: 47.7%
Recent sea level rise: ~9.2 mm/yr	Mangrove species numbers: at least 13

Figure 5.109. Damage from the 2015 mangrove dieback, a notable issue for the Roper estuary.

Figure 5.110. Satellite image (Google Earth) showing the Roper River estuary.

The location is shown in Figure 5.110 and observed issues listed in Figure 5.109 and Table 5.76.

Table 5.76. Roper River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.8**	**3.4**
Weed smothering	0	0
Access tracks, roads and boat ramps	0.8	1.2
Feral presence, damage and tracks	0	0
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0.8***	***0.4***
CLIMATE–NATURAL	**10.0**	**15.2**
Saltpan scouring	0.6	2.4
Bank erosion	1.2	1.8
Terrestrial retreat	0.6	1.6
Ecotone shift, negative	2.1	1.2
Sea level rise indicators >>>	***0.8***	***1.3***
2015 mangrove dieback	2.1	2.4

Note: yellow shaded areas highlight maximal severity indicators.

5.6.5 Miyangkala Creek lower estuary

Figure 5.111. Mouth of Miyangkala Creek 20 September 2019.

Information about the lower section of this estuary (Figure 5.111) is shown in Table 5.77.

Table 5.77. Miyangkala Creek site information.

Location of mouth: -14.4398 °S; 135.6077 °E	Aerial survey dates: 10 Dec 2017; 20 Sep 2019
Catchment area (km^2): 396	Tidal wetland total area (km^2): 10.6
Estuary length (km): 3.8	Saltmarsh and saltpan area (km^2): 9.8
Tidal range (m): ~2.2 m	Mangrove area (km^2): 0.8
Close-by major cyclones since 1995: at least 2	Mangrove Wetland Cover Index: 7.8%
Recent sea level rise: ~9.2 mm/yr	Mangrove species numbers: no data

Figure 5.112. Damage from a decade-old severe storm, a notable issue in the Miyangkala estuary.

Figure 5.113. Satellite image (Google Earth) showing Miyangkala Creek estuary.

The location is shown in Figure 5.113 and observed issues listed in Figure 5.112 and Table 5.78.

Table 5.78. Miyangkala Creek lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	0.8	3.2
Weed smothering	0	0
Access tracks, roads and boat ramps	0.6	0.8
Feral presence, damage and tracks	0	0.6
Stock presence, damage and tracks	0.2	1.2
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	*0.6*	*0.2*
CLIMATE–NATURAL	9.5	13.0
Saltpan scouring	1.4	1.8
Bank erosion	1.2	1.2
Terrestrial retreat	1.4	1.8
Ecotone shift, negative	2.1	1.8
Sea level rise indicators >>>	*0.9*	*1.0*
2015 mangrove dieback	1.4	2.0

Note: yellow shaded areas highlight maximal severity indicators.

5.6.6 Rose River lower estuary

Figure 5.114. Mouth of the Rose River 20 September 2019.

Information about the lower section of this estuary (Figure 5.114) is shown in Table 5.79.

Table 5.79. Rose River site information.

Location of mouth: -14.2885 °S; 135.7344 °E	Aerial survey dates: 10 Dec 2017; 20 Sep 2019
Catchment area (km^2): 3,572	Tidal wetland total area (km^2): 21.6
Estuary length (km): 12.1	Saltmarsh and saltpan area (km^2): 16.0
Tidal range (m): ~2.2 m	Mangrove area (km^2): 5.6
Close-by major cyclones since 1995: at least 3	Mangrove Wetland Cover Index: 25.8%
Recent sea level rise: ~9.2 mm/yr	Mangrove species numbers:

Figure 5.115. Pan scouring and terrestrial retreat, notable issues for the Rose estuary.

Figure 5.116. Satellite image (Google Earth) showing the Rose River estuary.

The location is shown in Figure 5.116 and observed issues listed in Figure 5.115 and Table 5.80.

Table 5.80. Rose River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.6**	**7.2**
Weed smothering	0	0
Access tracks, roads and boat ramps	0.6	1.6
Feral presence, damage and tracks	0	2.4
Stock presence, damage and tracks	0	0
Fire impacts, scorched and dead mangroves	0	0
Direct modification >>>	***0.6***	***0.8***
CLIMATE–NATURAL	**6.4**	**13.2**
Saltpan scouring	1.4	2.4
Bank erosion	0	0.4
Terrestrial retreat	1.4	2.4
Ecotone shift, negative	0.4	1.8
Sea level rise indicators >>>	***0.7***	***1.2***
2015 mangrove dieback	1.4	0.8

Note: yellow shaded areas highlight maximal severity indicators.

5.6.7 Muntak River lower estuary

Figure 5.117. Mouth of the Muntak River 21 September 2019.

Information about the lower section of this estuary (Figure 5.117) is shown in Table 5.81.

Table 5.81. Muntak River site information.

Location of mouth: -14.1638 °S; 135.8817 °E	Aerial survey dates: 11 Dec 2017; 21 Sep 2019
Catchment area (km^2): 78	Tidal wetland total area (km^2): 4.8
Estuary length (km): 7.5	Saltmarsh and saltpan area (km^2): 3.8
Tidal range (m): ~2.1 m	Mangrove area (km^2): 1.0
Close-by major cyclones since 1995: at least 3	Mangrove Wetland Cover Index: 20.3%
Recent sea level rise: ~9.2 mm/yr	Mangrove species numbers: at least 11

Figure 5.118. Terrestrial retreat and pan scouring, notable issues for the Muntak estuary.

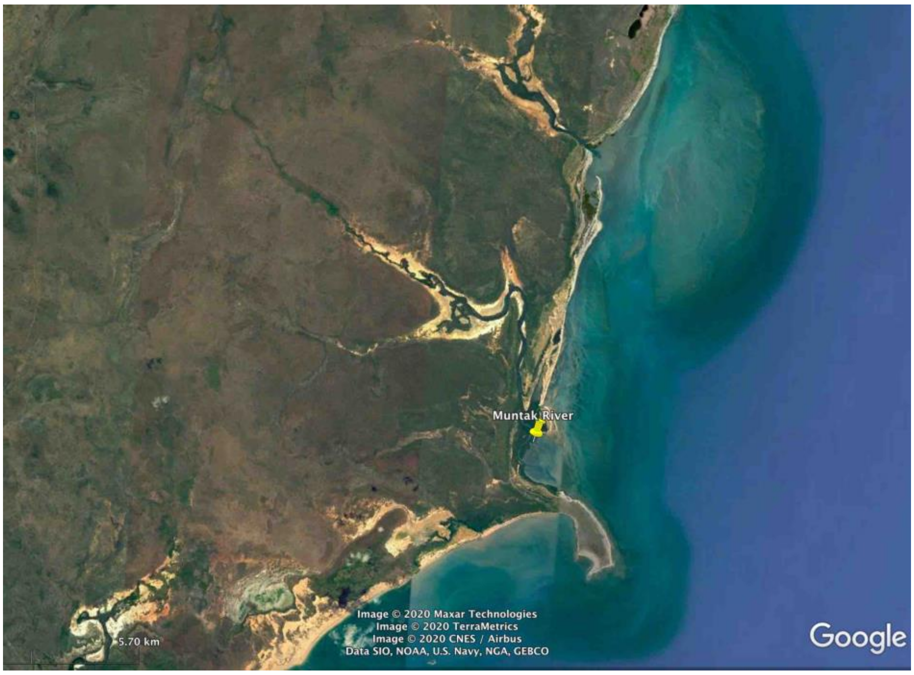

Figure 5.119. Satellite image (Google Earth) showing the Muntak River estuary.

The location is shown in Figure 5.119 and observed issues listed in Figure 5.118 and Table 5.82.

Table 5.82. Muntak River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.4**	**7.0**
Weed smothering	0	0
Access tracks, roads and boat ramps	0.2	0.2
Feral presence, damage and tracks	0	3.2
Stock presence, damage and tracks	0	3.2
Fire impacts, scorched and dead mangroves	0.2	0
Direct modification >>>	***0.2***	***0.1***
CLIMATE–NATURAL	**10.2**	**18.2**
Saltpan scouring	3.2	3.2
Bank erosion	0.6	0.8
Terrestrial retreat	2.1	3.2
Ecotone shift, negative	1	2.4
Sea level rise indicators >>>	***1.3***	***1.5***
2015 mangrove dieback	1.2	2.4

Note: yellow shaded areas highlight maximal severity indicators.

5.6.8 Walker River lower estuary

Figure 5.120. Mouth of the Walker River 11 December 2017.

Information about the lower section of this estuary (Figure 5.120) is shown in Table 5.83.

Table 5.83. Walker River site information.

Location of mouth: -13.5905 °S; 135.8369 °E	Aerial survey dates: 11 Dec 2017
Catchment area (km^2): 2,232	Tidal wetland total area (km^2): 19.4
Estuary length (km): 22.6	Saltmarsh and saltpan area (km^2): 16.3
Tidal range (m): ~1.8 m	Mangrove area (km^2): 3.1
Close-by major cyclones since 1995: at least 1	Mangrove Wetland Cover Index: 16.0%
Recent sea level rise: ~9.0 mm/yr	Mangrove species numbers: at least 16

Figure 5.121. Pan scouring and terrestrial retreat, notable issues for the Walker estuary.

Figure 5.122. Satellite image (Google Earth) showing the Walker River estuary.

The location is shown in Figure 5.122 and observed issues listed in Figure 5.121 and Table 5.84.

Table 5.84. Walker River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	0.0	
Weed smothering	0	
Access tracks, roads and boat ramps	0	
Feral presence, damage and tracks	0	
Stock presence, damage and tracks	0	
Fire impacts, scorched and dead mangroves	0	
Direct modification >>>	*0*	
CLIMATE–NATURAL	13.3	
Saltpan scouring	3.2	
Bank erosion	2.1	
Terrestrial retreat	3.2	
Ecotone shift, negative	0.7	
Sea level rise indicators >>>	*2.0*	
2015 mangrove dieback	1.4	

Note: yellow shaded areas highlight maximal severity indicators.

5.6.9 Koolatong River lower estuary

Figure 5.123. Mouth of the Koolatong River 11 December 2017.

Information about the lower section of this estuary (Figure 5.123) is shown in Table 5.85.

Table 5.85. Koolatong River site information.

Location of mouth: -13.2543 °S; 135.9474 °E	Aerial survey dates: 11 Dec 2017
Catchment area (km^2): 2,845	Tidal wetland total area (km^2): 13.8
Estuary length (km): 8.0	Saltmarsh and saltpan area (km^2): 8.7
Tidal range (m): ~2.0 m	Mangrove area (km^2): 5.1
Close-by major cyclones since 1995: at least 2	Mangrove Wetland Cover Index: 37.1%
Recent sea level rise: ~9.0 mm/yr	Mangrove species numbers: at least 14

Figure 5.124. Depositional gain at the mouth, a notable issue for the Koolatong estuary.

Figure 5.125. Satellite image (Google Earth) showing the Koolatong River estuary.

The location is shown in Figure 5.125 and observed issues listed in Figure 5.124 and Table 5.86.

Table 5.86. Koolatong River lower estuary severity scores for dominant indicators of change.

Dominant indicators	2017 survey	2019 survey
HUMAN	**0.0**	
Weed smothering	0	
Access tracks, roads and boat ramps	0	
Feral presence, damage and tracks	0	
Stock presence, damage and tracks	0	
Fire impacts, scorched and dead mangroves	0	
Direct modification >>>	***0***	
CLIMATE–NATURAL	**12.6**	
Saltpan scouring	3.2	
Bank erosion	0	
Terrestrial retreat	3.2	
Ecotone shift, negative	0.6	
Sea level rise indicators >>>	***1.7***	
2015 mangrove dieback	0.8	

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Appendix 1: Catchment descriptors for estuaries of the Gulf of Carpentaria study area

	ECY Survey Locations	Latitude S	Longitude E	Catchment (km^2)	River (km)	Estuary (km)	Mangroves (km^2)	Saltpan (km^2)	Saltm. (km^2)	WCI %	Mangrove species
1	Mission River	-12.6201	141.8372	1290	37	32.78	30.9	6.15	4.61	74.2	23
2	Embley River	-12.6676	141.8297	2076	54	38.38	62.78	27.47	78.33	37.2	25
3	Watson River	-13.3465	141.6612	16310	92	37.49	47.71	27.1	24.95	47.8	
4	Holroyd River	-14.1633	141.5945	1365	325	42.79	3.34	4.26	55.8	5.3	
5	Christmas Creek	-14.5448	141.5412	437	75.5	3.04	0.72	0.01	7.47	8.8	
6	Mitchell River	-15.2004	141.591	65278	750	26.31	61.42	9.55	127.45	31.0	
7	South Mitchell River	-15.3578	141.5404	794		20.76	8.98	0.6	27.63	24.1	
8	Nassau River	-15.9074	141.3952	5797		39.77	32.66	1.4	101.24	24.1	
9	Staatan River	-16.401	141.296	25722		22.98	19.3	22.5	148.82	10.1	
10	Gilbert River	-16.5575	141.2695	42148	877	39.25	8.58	23.26	65.15	8.8	
11	Accident Inlet	-17.1834	140.9389	1889		27.38	3.66	0.61	66.91	5.1	
12	Norman River	-17.464	140.8194	49588	420	102.36	55.24	4.05	333.46	14.1	
13	Flinders River	-17.5977	140.595	109460	1004	74.19	34.6	10.42	275.78	10.8	7
14	Leichhardt River	-17.5787	139.7944	32568	630	70.47	20.4	10.9	48.35	25.6	
15	Albert River	-17.5744	139.7559	20941		49.88	10.69	17.03	201.44	4.7	12*
16	Nicholson River	-17.507	139.6051	27959	725	35.43	8.77	2.39	100.23	7.9	
17	John's Creek	-17.3956	139.4513	113		12.2	4.46	0.68	125.1	3.4	
18	Syrell Creek	-17.0043	139.0924	344		4.67	1.77	0	56.52	3.0	
19	Massacre Inlet	-16.738	138.3355	647		7.89	1.24	11.27	54.07	1.9	
20	Tully Inlet	-16.6776	138.158	4362	142	6.48	0.1	0.93	19.72	0.5	
21	Dugong Creek	-16.7083	139.2071	158		6.28	13.51	0.16	15.43	46.4	8
22	Toongoowahgun Creek	-16.6405	139.3841	153			5.1	3.67	5.1	36.8	

	ECY Survey Locations	Latitude S	Longitude E	Catchment (km^2)	River (km)	Estuary (km)	Mangroves (km^2)	Saltpan (km^2)	Saltm. (km^2)	WCI %	Mangrove species
23	Elizabeth River	-16.4854	139.5576	62		8.61	3.96	0.1	6.52	37.4	
24	Sandalwood Place	-16.4582	139.3582	102			6.14	0.98	17.6	24.8	
25	Calvert River	-16.266	137.7442	7536	222	33.14	1.05	2.41	8.01	9.2	8
26	Robinson River	-16.0311	137.2683	5766	215	21.91	1.42	0.28	0.95	53.6	8
27	Wearyan River	-15.9139	136.8585	3704		32.01	3.24	2.57	19.89	12.6	9
28	McArthur River	-15.7105	136.6117	20139	521		53.94	32.22	374.1	11.7	11
29	Mule Creek	-15.6394	136.425	242		9	1.07	1.72	17.78	5.2	
30	Limmen Bight River	-15.1153	135.7212	22855		63.62	21.23	0.1	70.6	23.1	12
31	Towns Creek	-14.9142	135.4307	4755	84	19.45	10.94	0.01	72.01	13.2	8
32	Roper River	-14.7513	135.3968	84655	1010		83.88	8.16	83.88	47.7	13
33	Miyangkala Creek	-14.4398	135.6077	396		3.81	0.83	0.01	9.78	7.8	
34	Rose River	-14.2885	135.7344	3572		12.11	5.57	0.01	15.98	25.8	13
35	Muntak Creek	-14.1638	135.8817	78		7.48	0.97	0.01	3.8	20.3	11
36	Walker Creek	-13.5905	135.8369	2232	119	22.59	3.1	0.01	16.31	16.0	16
37	Koolatong Creek	-13.2543	135.9474	2845	92	8.03	5.13	0.01	8.68	37.1	14

Note: * denotes mangrove biodiversity survey findings in the Albert River estuary as part of MangroveWatch training with CLCAC Indigenous rangers from Burketown. This includes the reporting of new species for the region, *Acanthus ebracteatus* subsp. *ebarbatus*. Data variously sourced including the OzCoasts website, https://ozcoasts.org.au.

Appendix 2: Catchment descriptors for estuaries of the Gulf of Carpentaria study area

	GULF survey locations	Latitude S	Longitude E	Classification	Subclass	Land use	Condition
1	Mission River	-12.6201	141.8372	Tide dominated	Estuary	sparse	Nearly pristine
2	Embley River	-12.6676	141.8297	Tide dominated	Estuary	sparse	Largely unmodified
3	Watson River	-13.3465	141.6612	Tide dominated	Estuary	sparse	Nearly pristine
4	Holroyd River	-14.1633	141.5945	Wave dominated	Estuary	sparse	Nearly pristine
5	Christmas Creek	-14.5448	141.5412	Tide dominated	Estuary	sparse	Nearly pristine
6	Mitchell River	-15.2004	141.591	River dominated	Delta	sparse	Largely unmodified
7	South Mitchell River	-15.3578	141.5404	River dominated	Delta	sparse	Nearly pristine
8	Nassau River	-15.9074	141.3952	River dominated	Delta	sparse	Largely unmodified
9	Staatan River	-16.401	141.296	River dominated	Delta	sparse	Nearly pristine
10	Gilbert River	-16.5575	141.2695	River dominated	Delta	sparse	Nearly pristine
11	Accident Inlet	-17.1834	140.9389	River dominated	Delta	sparse	Nearly pristine
12	Norman River	-17.464	140.8194	River dominated	Delta	sparse	Largely unmodified
13	Flinders River	-17.5977	140.595	River dominated	Delta	sparse	Nearly pristine
14	Leichhardt River	-17.5787	139.7944	River dominated	Delta	sparse	Nearly pristine
15	Albert River	-17.5744	139.7559	River dominated	Delta	sparse	Nearly pristine
16	Nicholson River	-17.507	139.6051	River dominated	Delta	sparse	Nearly pristine
17	John’s Creek	-17.3956	139.4513	Tide dominated	Flat	sparse	Nearly pristine
18	Syrell Creek	-17.0043	139.0924	Tide dominated	Flat	sparse	Nearly pristine
19	Massacre Inlet	-16.738	138.3355	River dominated	Delta	sparse	Nearly pristine
20	Tully Inlet	-16.6776	138.158	River dominated	Delta	sparse	Nearly pristine
21	Dugong Creek	-16.7083	139.2071	Tide dominated	Flat	sparse	Nearly pristine
22	Toongoowahgun Creek	-16.6405	139.3841	Tide dominated	Flat	sparse	Nearly pristine

	GULF survey locations	Latitude S	Longitude E	Classification	Subclass	Land use	Condition
23	Elizabeth River	-16.4854	139.5576	River dominated	Delta	sparse	Nearly pristine
24	Sandalwood Place	-16.4582	139.3582	Tide dominated	Flat	sparse	Nearly pristine
25	Calvert River	-16.266	137.7442	River dominated	Delta	sparse	Nearly pristine
26	Robinson River	-16.0311	137.2683	River dominated	Delta	sparse	Nearly pristine
27	Wearyan River	-15.9139	136.8585	River dominated	Delta	sparse	Nearly pristine
28	McArthur River	-15.7105	136.6117	River dominated	Delta	sparse	Nearly pristine
29	Mule Creek	-15.6394	136.425	Tide dominated	Flat	sparse	Nearly pristine
30	Limmen Bight River	-15.1153	135.7212	River dominated	Delta	sparse	Nearly pristine
31	Towns Creek	-14.9142	135.4307	River dominated	Delta	sparse	Nearly pristine
32	Roper River	-14.7513	135.3968	Tide & river dominated	Estuary	sparse	Nearly pristine
33	Miyangkala Creek	-14.4398	135.6077	Tide & river dominated	Estuary	sparse	Nearly pristine
34	Rose River	-14.2885	135.7344	Tide dominated	Flat	sparse	Nearly pristine
35	Muntak Creek	-14.1638	135.8817	Tide dominated	Flat	sparse	Nearly pristine
36	Walker Creek	-13.5905	135.8369	Tide & river dominated	Delta	sparse	Nearly pristine
37	Koolatong Creek	-13.2543	135.9474	Tide & river dominated	Delta	sparse	Nearly pristine

Note: Data variously sourced including the OzCoasts website, https://ozcoasts.org.au.

Appendix 3: Severity scores for 37 estuary mouths in Gulf of Carpentaria study area observed during 1–11 December 2017.

	2017 Gulf survey locations	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Mission River					0.4	0	2.4			0.8	0	0	0.8	0		0.8	1.2	2.4		0.4	0.4	1.6	0	0
2	Embley River					0.4	0	0.2			0.6	0	0	0.6	0		0.6	0.2	1.6		1.2	0.2	0.6	0	0
3	Watson River					1.2	0	1.2			0	0	0.4	0.4	0		0.2	0.2	1.2		0.4	0.4	0.4	0	0
4	Holroyd River					0.2	0	0.2			0	0	0	1	0.4		1	0	1.2		0.6	0	0.4	0	0
5	Christmas Creek					0	1.2	0.2			0	0	0	0.4	0		0.8	0	0.8		0.4	0	0.4	0	0.4
6	Mitchell River					0	0	0			0	0	0.6	0	0.6		2.4	0	1.2		1.2	0	0.4	0	1.6
7	South Mitchell River					1.2	0	0.2			0	0	0	1.2	0.2		1.2	1.4	1.2		0.8	0	0.6	0	1.2
8	Nassau River					0.4	0.4	0			0	0	0	0	0		1.2	2.1	1.2		1	1.2	0	0	0.6
9	Staatan River					0	0	0			0.4	2.4	0	0	0.4		2.4	2.1	0.4		1	0	0	0	0.4
10	Gilbert River					0	0	0			0	1.8	0	0	0.4		2.1	1.2	0.4		1.2	0	0	0	0.4
11	Accident Inlet					0.2	0	0			0	2.4	0	0	0.4		2.4	2.1	0.4		0.4	1.2	0	0	0.6
12	Norman River					0.8	0	0			0.8	2.4	0	0	0.4		1.8	2.1	0.4		1	0	0	0	1.6
13	Flinders River					0	0	0			0	2.4	0	0	0.4		2.4	2.1	0.4		0.4	0	0	0	1.2
14	Leichhardt River					0	0	0			0	2.4	0	0	0.3		3.2	2.1	2.1		3.2	0	0	0	1.4
15	Albert River					0.4	0	0.4			0.6	1.2	0	0	0		1.8	2.1	1.2		1.2	0	0	0	1.2
16	Nicholson River					0.4	0	0			0	1.2	0	0	0		3.2	1.2	1.2		0.4	0	0	0	1.2
17	John’s Creek					0	0	0			0	0.6	0	0	1.2		2.1	3.2	0.7		0.6	0	0	0	1.2
18	Syrell Creek					0.6	0	0			0	1.2	0	0	0		1.8	3.2	0.6		1.2	2.1	0	0	0.6
19	Massacre Inlet					0.5	0.4	0			0	0.4	0	0	0.6		0.6	0.6	0.5		0.5	2.4	0	0.8	0.4
20	Tully Inlet					0.5	0.2	0			0	0	0	0	0		2.4	1.4	0.5		0.5	1.4	0	0	0.6
21	Dugong Creek					2.4	0	0			0	0	0	0	0		0.5	1.2	0.5		0	0.6	0	0	0.6

	2017 Gulf survey locations	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	12	13
22	Toongoowahgun Creek					1	0	0			0	0	0	0.5	0.6		0	3.2	1.2		0.5	1.2	0	0	0.6
23	Elizabeth River					0	0	0			0	0	0	0.5	0.6		0	3.2	1.2		0	2.1	0.4	0	0.6
24	Sandalwood Place					0.2	0	0			0	0	0	0.4	0		0	3.2	1.2		0.6	2.8	0	0.7	1.4
25	Calvert River					0.4	1.2	0.8			0.2	0	0	0	0		1.2	1.4	0.6		0	2.4	0	0	1.2
26	Robinson River					0.6	0	0			0	0	0	0	0		1.4	1.4	0.6		0.2	2.4	0	0.8	1.2
27	Wearyan River					1.2	0.2	0			0	0	0	0.6	0		2.1	1.2	0.8		0	2.4	0	0	2.4
28	McArthur River					0	0	0			0	0	0	0	0		2.1	1.2	0.6		0.6	1.4	0.6	0	1.4
29	Mule Creek					1.4	0	0			0	0	0	0	0		0.5	2.1	0.5		0.4	1.4	0	0	1.8
30	Limmen Bight River					0	0	0			0	0	0	3.2	0		0.5	2.8	0.5		0.4	3.2	0	0	1.6
31	Towns Creek					0	0	0			0	0	1.2	0.7	0		2.1	1.2	1.2		0.6	1.4	0	0	1.4
32	Roper River					0.8	0	0			0	0	0.6	1.4	0		1.2	0.6	2.1		1.4	0.6	0	0	2.1
33	Miyangkala Creek					0.6	0.2	0			0	0	0.8	0.6	0		1.2	1.4	2.1		0.6	1.4	0	0	1.4
34	Rose River					0.6	0	0			0	0	0	0.6	0		0	1.4	0.4		0.6	1.4	0.6	0	1.4
35	Muntak Creek					0.2	0	0			0.2	0	1.4	0.7	0		0.6	3.2	1		0	2.1	0	0	1.2
36	Walker Creek					0	0	0			0	0	0.6	1.4	0		2.1	3.2	0.7		0	3.2	0.7	0	1.4
37	Koolatong Creek					0	0	0			0	0	2.1	2.1	0		0	3.2	0.6		0.6	3.2	0	0	0.8

Note: Column numbers refer to indicator variables grouped as human impacts (pink shading, 1–11) and climate-natural impacts (green shading, 1–13) (Table 3.2).

Appendix 4: Severity scores for 31 estuary mouths in the Gulf of Carpentaria study area observed during 12–21 September 2019

	2019 Gulf survey locations	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Mission River	1	0	0.6	1	0.8	0	0.8	0	0.2	0.6	0	0	0.8	1	1.2	0.9	0.6	2.4	0	0.2	0	1.8	0	0
2	Embley River	2	0	0.8	0.6	1.2	0.6	0.8	0.8	0.2	1.6	0	0	1.2	0.6	1.8	0.4	0.6	2.4	0	0.4	0.8	1.2	0	0
3	Watson River	0.6	0	0	0	0.4	0	0.6	0.8	0	1.6	0	0.6	0	0	1.2	1.6	0	1.2	0	0.6	0.8	1.6	0	0
4	Holroyd River	0	0.8	0	0	0.6	1.2	1.6	0.4	0	1.8	0	0.8	0.6	0.6	1.2	3.2	0	1.2	0	0.8	0	0.6	0	0
5	Christmas Creek	0	0	0	0	0.8	1.2	0	0	0	0.8	0	0	1.6	1.6	1.8	2.8	0.8	0	0	0.8	0	0	0	0
6	Mitchell River	0	0	0	0	0	0	0.4	0.4	0	0.8	1.2	0	1.6	1.6	0	3.2	0.6	3.2	0	1.8	0.8	0.6	0	0.8
7	South Mitchell River	0	0	0	0	2.4	0.4	0.4	0.2	0	0.4	1.8	0.6	0.4	0.6	0.6	1.6	2.4	1.8	0	1.2	0.6	0.6	0	0.6
8	Nassau River	0	0	1	0	0.4	0	0.8	0.4	0	0	1.8	0.8	0.6	0.6	0.4	2.4	0.8	1.8	0.4	1.2	0.6	0.6	0	0
9	Staatan River	0	0	0	0	0.4	0	0.4	0.4	0	0	2.4	0	1.6	0.8	0.4	3.2	2.4	1.8	0	0.8	0	0	0	1
10	Gilbert River	0	0	0	0	0.6	0.4	0	0.2	0.4	1.6	1.8	1	1.8	0.8	0	1.8	1.8	1.2	0	1.8	0	0.4	0	1.2
11	Accident Inlet	0	0	0	0	0.6	0	0.4	0.4	0.2	0	2.4	0	1.2	0.6	0	1.8	2.4	0.4	0	0.8	0.6	0.4	0	0.8
12	Norman River	1.6	1	1	0.8	1.6	0	0	0.6	0.2	0	0.8	0.8	0	0.8	0	2.4	1.2	0.6	0	1.5	0	0	0	0.6
13	Flinders River	0	0	0	0	0	0.4	0	0	0.2	0	2.4	0	0.4	0	0	3.2	3.2	1.8	0.6	0.8	0.6	0.6	0	1.5
14	Leichhardt River	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0.6	0	1.6	1.2	1.5	0.4	3.2	1.6	0.6	0	2.4
15	Albert River	0	0	0	0	0.6	0	0	0.2	0	0	0.4	0	0	0	0	1.2	1.8	2.4	0.6	0.6	1.2	0	0	1.2
16	Nicholson River	0	0	0	0	0.6	0.4	0.4	0.4	0.2	0	0.4	1.2	0.8	0.8	0	1.6	2.4	2.4	0	1.8	2.4	0	0	1.2
17	John’s Creek	0	0	0	0	0	0	0	0.2	0	0	0.4	0	0	0	0	2.4	1.8	1.8	0.8	1.6	1.8	0	0	1.2
18	Syrell Creek	0	0	0	0	1.2	0.4	0	0	0	1.6	0	0	0	0	0.6	1.2	2.4	1.5	0	0.8	3.6	0	0	0.6
19	Massacre Inlet	0	0	0	0	0.4	0.4	1.6	0	0	0	0	0	1.6	1.6	0.6	1.2	1.2	0.8	0	0.4	1.6	0	0	0.8
20	Tully Inlet	0	0	0	0	0.4	1.2	1.2	0	0	0	0	0	0	0.8	0.4	2.4	2.4	1.6	1.2	1.2	2.8	0	0	0.4
21	Dugong Creek																								

	2019 Gulf survey locations	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	12	13
22	Toongoowahgun Creek																								
23	Elizabeth River																								
24	Sandalwood Place																								
25	Calvert River	0	0	0	0	0.4	0	0.4	0.6	0	0	0	2.4	0.7	1.6	0	1.8	0.6	0.6	0	0	2.4	0	0	1.2
26	Robinson River	0	0	0	0	1.2	0.8	0.4	0.4	0	0	0	2.4	1.2	0.6	0	2.4	0.6	0	0	0.6	0.6	0	0	0
27	Wearyan River	0	0	0	0	1.2	1.2	0	1.2	0	0	0	3	0	0	1.2	2.8	1.8	0	0	1.8	2.4	0	0	1.2
28	McArthur River	0.6	0	0	0	0	0	0	0.4	0	0	0	0.6	0	0	0	1.8	1.2	1.2	0	1.2	1.2	0.6	0	1.2
29	Mule Creek	1	1	0	0	1.2	0.4	0	0.2	0	0	0	0	0.8	0.8	0.6	1.2	1.8	1.2	0.6	0.4	2.4	0.4	0	1.6
30	Limmen Bight River	0	0	0	0	0.2	0.4	0	0.2	0	0	0	1.8	1.6	0.8	1.6	2.4	2.4	1.8	0.4	1.2	2.4	0.6	0	2
31	Towns Creek	0	0	0	0	0	0	0.4	0.4	0	0	0.4	0	1.6	1.2	0.6	1.6	1.8	2.4	0	0.6	1.8	0.6	0	2
32	Roper River	0.6	0	0	0	1.2	0	0	0.8	0.8	0	0	0	0.8	0.6	0.8	1.8	2.4	1.2	0	1.8	1.6	1.8	0	2.4
33	Miyangkala Creek	0	0	0	0	0.8	1.2	0.6	0.2	0.4	0	0	2.4	0.4	0.8	0	1.2	1.8	1.8	0	0.4	1.8	0.4	0	2
34	Rose River	1	1	0	0.4	1.6	0	2.4	0.6	0.2	0	0	1.8	0.8	0	1.2	0.4	2.4	1.8	0.6	0.4	2.4	0.6	0	0.8
35	Muntak Creek	0	0	0	0	0.2	3.2	3.2	0.4	0	0	0	0.8	0.4	0.8	0.8	0.8	3.2	2.4	1.8	0	3.2	0	1.6	2.4
36	Walker Creek																								
37	Koolatong Creek																								

Note: Column numbers refer to indicator variables grouped as human impacts (pink shading, 1–11) and climate-natural impacts (green shading, 1–13) (Table 3.3).

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