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

Summary report

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AUSTRALIA

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Cover photographs

Front cover: Mabunji Rangers and Norm Duke tracking down interesting molluscs during the 2018 field surveys (photo: Jock Mackenzie).

Back cover: Aerial view during the 2018 field surveys (photo: Jock Mackenzie).

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Executive summary

Key findings

- Mass dieback of mangrove ecosystems in Australia’s Gulf of Carpentaria occurred over a period of three to four months in late 2015.
- The event was synchronous along 2,000 km of southern Gulf shorelines with at least 551 km of shoreline showing notable dieback. A total of 76.5 km^2 of mangrove ecosystems were lost, which was around 6% of mangrove cover in the area.
- The primary cause of this mass dieback event was a sudden and temporary drop in sea level associated with a severe El Niño in 2015–2016. Sea levels dropped by up to 0.4–0.5 m for a period of 5–6 months (April to October 2015).
- The dominant mangrove canopy species, *Avicennia marina* var. *eucalyptifolia*, was most severely affected by the dieback. These mangroves suffered from extreme moisture stress at higher elevation ecotones bordering the expansive saltpans between highest tide levels and mean sea level.
- Approximately 39.4 million trees died, releasing an estimated 820,895 tonnes of carbon.
- Rates of sea level rise are extreme in the Gulf, but mangroves in many areas had responded by progressively spreading up the tidal profile while maintaining their protective shoreline fringing stands. However, there were abundant signs of the consequences of sea level rise with shoreline erosion and loss of sea-edge mangrove trees coupled with saltpan scouring and terrestrial retreat.
- Tropical cyclones had localised severe impacts hindering mangrove recovery by pushing wrack piles of dead mangrove wood across areas, destroying recovering trees and seedlings, coupled with destructive shoreline scouring and erosion.
- A previously undetected, earlier mass dieback of mangroves was also discovered to have occurred in late 1982 under similar circumstances to that in 2015. Furthermore, its extent and widespread synchronicity were comparable. The 1982 dieback was associated also with a severe El Niño Southern Oscillation (ENSO) event co-incident with an extreme drop in sea level.
- These new findings reveal the occurrence of a 33-year interval collapse recovery cycle defined by widespread mass dieback events in 1982 and 2015. Recovery from the earlier event took 10–15 years depending on the localised impacts from severe storms and flooding. However, there are serious questions surrounding future recovery trajectories.
- The occurrence of these dieback events has allowed us to develop a sea level stress index with defined threshold levels for lethal and sublethal impacts on mangrove stands in the Gulf. This index is furthermore correlated with the Southern Oscillation Index from which there may be several weeks warning of imminent future mass mangrove dieback events in Australia’s remote Gulf of Carpentaria.

In late 2015, 7650 ha of mangroves died along more than 2000 km of coastline in the Gulf of Carpentaria

The significance of the mass dieback event was not recognised until early 2016 when images taken by local fishermen and environmental consultants showed the extent of mangrove death at a number of sites on both sides of the Gulf. Such an occurrence had never been reported before, and the cause was not immediately recognised. The Australian Government's National Environmental Science Program (NESP) funded James Cook University to conduct an urgent three-year research investigation into the mass dieback. We undertook aerial surveys and mapped the Gulf's shorelines to quantify the extent of the dieback; assessed estuaries by scoring changes to mangroves and tidal wetlands; and identified ongoing and emerging environmental issues that threaten mangrove ecosystems. We worked with local communities and Indigenous ranger groups from the Carpentaria Land Council Aboriginal Corporation in Queensland and the Mabunji Aboriginal Corporation in the Northern Territory.

Mass mangrove dieback was caused by a sudden, temporary drop in sea level

The 2015 dieback event was synchronous along approximately 2,000 km of the Gulf's coastline, killing more than 7,650 ha of mangroves. In 2015–2016, extreme high temperatures and prolonged drought conditions associated with a severe El Niño event affected the Gulf. However, these extreme weather conditions were not considered sufficient to so severely damage mangroves.

The upper edges of the mangrove zone, where mangroves at higher elevations border the saltpan–saltmarsh zone, were most affected by dieback. This indicated that the dieback event was connected to differences in elevation and changes in sea level. The El Niño event caused a sudden drop in sea levels across the western Pacific, with extreme drops in seawater levels of 0.3–0.5 m recorded in three ports at Milner Bay on Groote Island (NT), Karumba and Weipa (Queensland).

It is significant that mass mangrove dieback only occurred in the vicinity of Karumba, and not near the other Gulf ports. The drop in mean sea level at Karumba was especially severe with lowest extreme levels of around 0.4–0.5 m averaged over the six-month period from April to October 2015. The death of mangroves growing at the upper edges of the mangrove zone led to a seaward shift of the ecotone between the saltmarshes and mangroves to an elevation approximately 0.4–0.5 m lower – matching the drop in sea level at the port. The drop in sea levels induced severe moisture stress in the mangroves growing at higher elevations, and this led to their death. The dominant canopy species, *Avicennia marina* var. *eucalyptifolia* was particularly affected, noting that these forest stands typically have a functional root depth around 0.5 m.

A comparable, previously undetected mass dieback of mangroves was found to have occurred in 1982–1983

Whilst conducting these investigations into the 2015 mass dieback event, we also discovered an earlier comparable occurrence of mass mangrove dieback in late 1982. Both events, 33 years apart, were associated with particularly severe El Niño weather conditions – each causing extreme drops in sea level of up to 0.4–0.5 m for extended periods of 5–6 months. It is believed that this almost certainly confirms that higher placed mangrove stands died from a lack of seawater wetting. However, this situation was undoubtably exacerbated by both the extreme high temperatures and prolonged drought conditions observed in 2015–2016.

Finding evidence for the earlier mass dieback was made difficult by the remoteness of the region and the lack of anecdotal accounts, sea level data and historical aerial imagery. Therefore, several lines of enquiry were needed to confirm the discovery. These included available aerial imagery in 1978 and 1987–1989, measures of canopy density from the commencement of Landsat vegetation index (NDVI) readings in 1987–2020, uniquely comparable severe weather and sea level conditions in 1982 and 2015 as correlates also with the Southern Oscillation Index, and the size and age classes of mangrove canopy trees across the region.

Sea level rise is reducing the available area of mangrove habitat

Sea level rise has been relatively rapid in the Gulf region between 1993–2007, with rates of up to 12 mm per year exceeding the global average of around 8 mm per year. Shoreline erosion caused by rises in sea level had led to the loss of mature vegetation at lower elevations along the seaward fringe. Expansion of younger trees were notable in higher elevation zones. Rising sea levels also lead to sheet erosion in saltpans, gully erosion, the loss of saltmarsh vegetation and terrestrial retreat, whereby saline intrusion kills terrestrial trees in areas above the highest astronomical tides. The severity of mangrove dieback in the 37 estuaries we scored was strongly correlated with rising sea levels, especially terrestrial retreat and saltpan scouring.

Tropical cyclones and flooding are delaying mangrove recovery

Two severe cyclones occurred between the 2017 and 2019 aerial surveys. Tropical Cyclone Owen (Category 3) affected the area west of the Limmen Bight estuary and shoreline in December 2018, and Tropical Cyclone Trevor affected the Robinson, Calvert and Wearyan estuaries in March 2019. The collective impact of these storms caused serious damage to at least 600 km of Gulf shoreline. The types of damage ranged from shoreline erosion and retreat, sediment wash, root burial, dieback, new seedlings being scoured by wrack piles of trees that died in 2015, large patches of fallen and broken stems, and defoliation of the canopy.

In February 2019, severe flooding of the Flinders River further caused significant damage to estuarine tidal wetlands, including bank erosion and slumping, scouring and gullying in saltpan–saltmarsh areas and sediment deposition on seafront mudbanks where mangrove seedlings had become tentatively established in 2019.

The accumulation of impacts from tropical cyclones and flooding is likely to seriously impede, or even reverse, recovery in areas that are affected repeatedly.

A longer term collapse and recovery cycle in the Gulf

Based on our new findings, the distinctive, seemingly depauperate characteristics of mangrove stands in the Gulf can now be better explained. The newly recognised occurrence of a collapse–recovery cycle describes the processes that have shaped and formed key features of these mangroves including species biodiversity, stand structure, tree ages, biomass, and general appearance – as well as their role in nurturing dependent animals like commercial fish and crab stocks. This cycle in the Gulf is defined by the two severe collapse events of mass dieback 33 years apart in 1982 and 2015 (Figure 3).

These events have left the recovering shorelines highly vulnerable. Recovery following the earlier event was notably successful but this took around 15–20 years depending on subsequent damaging, localised weather events like cyclones and flooding. Canopy maturity in most areas was achieved 10–15 years before 2015 after which the current recovery phase was initiated. It is of primary interest that the 1982 damage had recovered naturally. However, since then several key driving factors have changed, notably the rising sea levels and the occurrence of more severe weather events. The expected increases in more damaging events means that the same recovery outcome cannot be guaranteed. And, there are also pertinent questions about the occurrence and increased frequency of future collapse events.

Management options in dealing with mass mangrove dieback and the collapse and recovery cycle

Key recommendations

Changing environmental conditions have the potential to pose severe and long-term threats to mangrove survival in the Gulf of Carpentaria. Strategies to ensure the long-term health and resilience of mangrove ecosystems can be pursued at the local, national and global scale. To be most effective, these strategies should be enacted concurrently:

1. Climate change abatement schemes enacted at national and global levels are needed to reduce the risk posed to mangrove ecosystems from flooding, sea level rise and more frequent and severe tropical storms and cyclones.
2. The resilience of mangrove communities and associated habitats will be strengthened by either removing or managing the impacts of local processes, such as feral pig damage, fires and weed invasions.
3. To deal with the likelihood of future collapse events, we strongly recommend there be a remedial strategy to keep affected trees alive during periods of extreme low moisture conditions that will kill them. Where healthy fringing stands are maintained, this will preserve valuable habitat as well as maintaining their carbon capture and protection of threatened shorelines. From our current studies, we now know the threshold low sea levels that will kill mangrove trees on these shorelines. And, we can devise a monitoring scheme to show when weather and sea level conditions become threatening. We therefore propose the supporting of a locally based response network of Indigenous rangers who can deliver life-sustaining watering when needed as part of an on-going program of regular maintenance of localised threats like feral pigs, weeds and fires. Where trees can be kept alive during inevitable collapse conditions then much of the progressive pressures like sea level rise can be managed far more effectively. In this case, prevention is both the most reliable response, and the cure.

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Acknowledgements

We acknowledge the Traditional Owners of the land and sea country where we conducted these studies, and we pay our respect to their Elders – past, present, and emerging. We acknowledge the important role the traditional land and sea country custodians continue to play in protecting the cultural, natural, and other values of tidal wetlands throughout the Gulf of Carpentaria region.

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

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The 2019 aerial survey was in large part funded by World Animal Protection[1] and Dr. Denise Hardesty at CSIRO owing to their interest in stranded marine debris like ghost nets along the 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 conduction of the surveys in 2017, 2018 and 2019. 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.

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[1] worldanimalprotection.org.au

1. Introduction

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 taken by local fishermen and environmental consultants emerged from this remote part of northern Australia. The images showed the affected area extended along more than 1000 km of shoreline where at least 7400 ha of mangroves had died (Figure 1), seemingly in a matter of months (Duke et al., 2017). Mangroves were reported as having notably severe dieback in a number of sites at widely separated locations on different sides of the Gulf (Duke et al., 2017).

Figure 1. 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. This image shows Transect 1A in the Northern Territory in October 2018.

Such an occurrence had never been reported before, and the cause was not immediately recognised. There were many questions about the potential cause but what became clear was the lack of a known responsible factor, such as a severe storm or a large chemical spill. Because of the remoteness of the region, the mass event was likely restricted to a relatively small number of environmental factors.

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 of any of these factors having 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. The dramatic response of mass dieback implied that some factor exceeded a tipping point for the survival of these mangrove forests.

The Australian Government's National Environmental Science Program (NESP) funded James Cook University's TropWATER Centre to conduct an urgent three-year research investigation into the mass dieback. The objective was to elaborate on the circumstances surrounding the event; to map the extent of mangrove death; 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 residents and the wider group of stakeholders in Queensland and the Northern Territory. Our observations were made during investigations from 2017 to 2019 in the areas shown in Figure 2. This summary report was compiled from the two extended technical reports detailing the aerial surveys (Duke et al., 2020a) and field studies (Duke et al. 2020b).

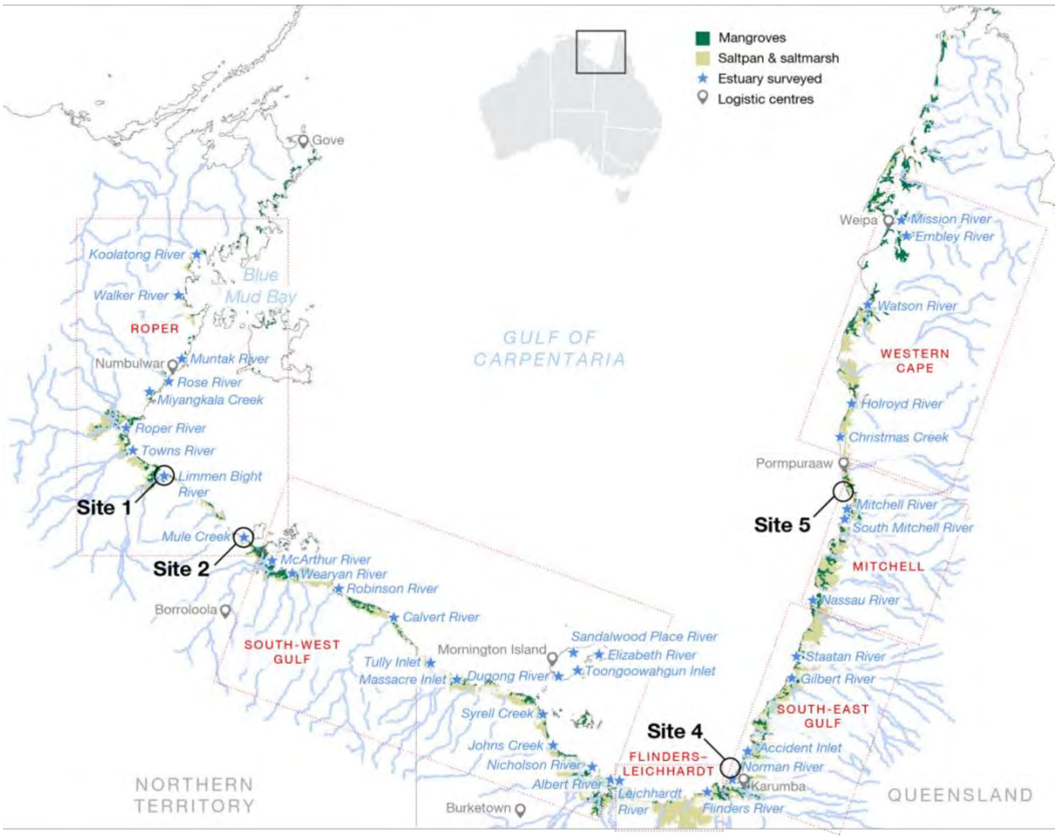


Figure 2. The locations of the four field study sites in the Gulf of Carpentaria representing the affected shorelines from Queensland to the Northern Territory. Also shown are the 37 estuaries surveyed in the six regional drainage areas, from Mission River in Weipa, Queensland, to Koolatong River in Blue Mud Bay, Northern Territory. Dashed rectangles show estuaries and shorelines according to the CSIRO NASY project (CSIRO, 2009a–i).

2. Summary of findings

We confirmed the timing of the dieback event was synchronous along approximately 2 000 km of the Gulf's coastline (Figure 3). In all, around 7650 ha of mangroves died, which is about 6% of mangrove cover in the affected area (Table 1). The upper edges of the mangrove zone, where mangroves growing at higher elevations border the saltpan–saltmarsh zone, were most affected by dieback (Figure 4). This observation indicated that the dieback event in these tidal wetlands was somehow connected to differences in elevation and changes in sea level.

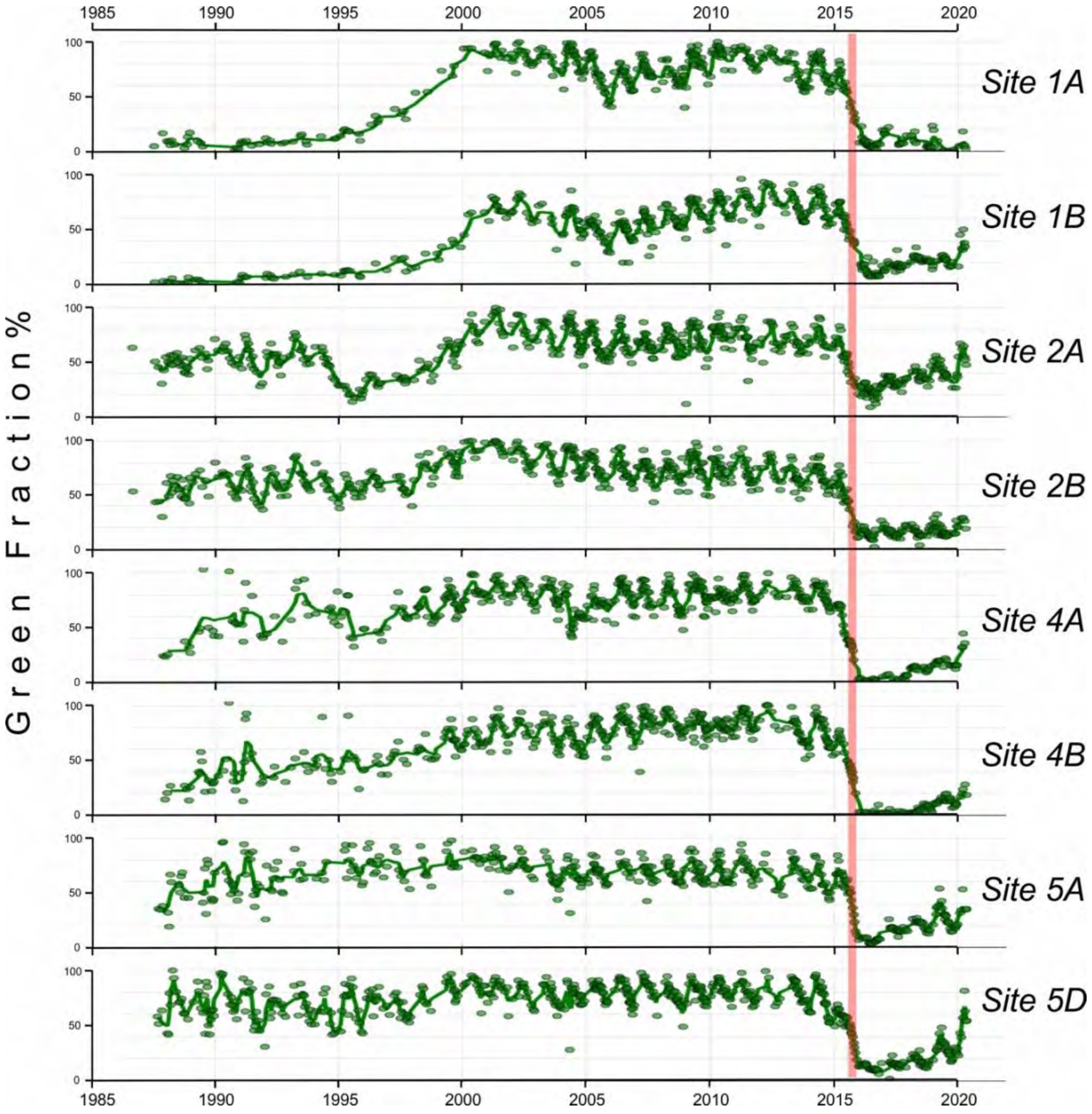


Figure 3. Time series plots of green fractional cover estimates from Landsat for the eight transect locations at the four field sites (see Figure 2) in the Northern Territory (sites 1 and 2) and Queensland (sites 4 and 5) from 1987 to 2020. The red line indicates the synchronous timing of the late 2015 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.

Table 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; see Figure 2), including intact mangroves, mangroves affected by the 2015–2016 dieback, and saltpan–saltmarsh. Regions are mostly those used with the CSIRO NASY project (CSIRO 2009a, b, c).

Vegetation units	W Cape*	Mitchell	SE Gulf	Flinders–Leichhardt	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 West Cape region.

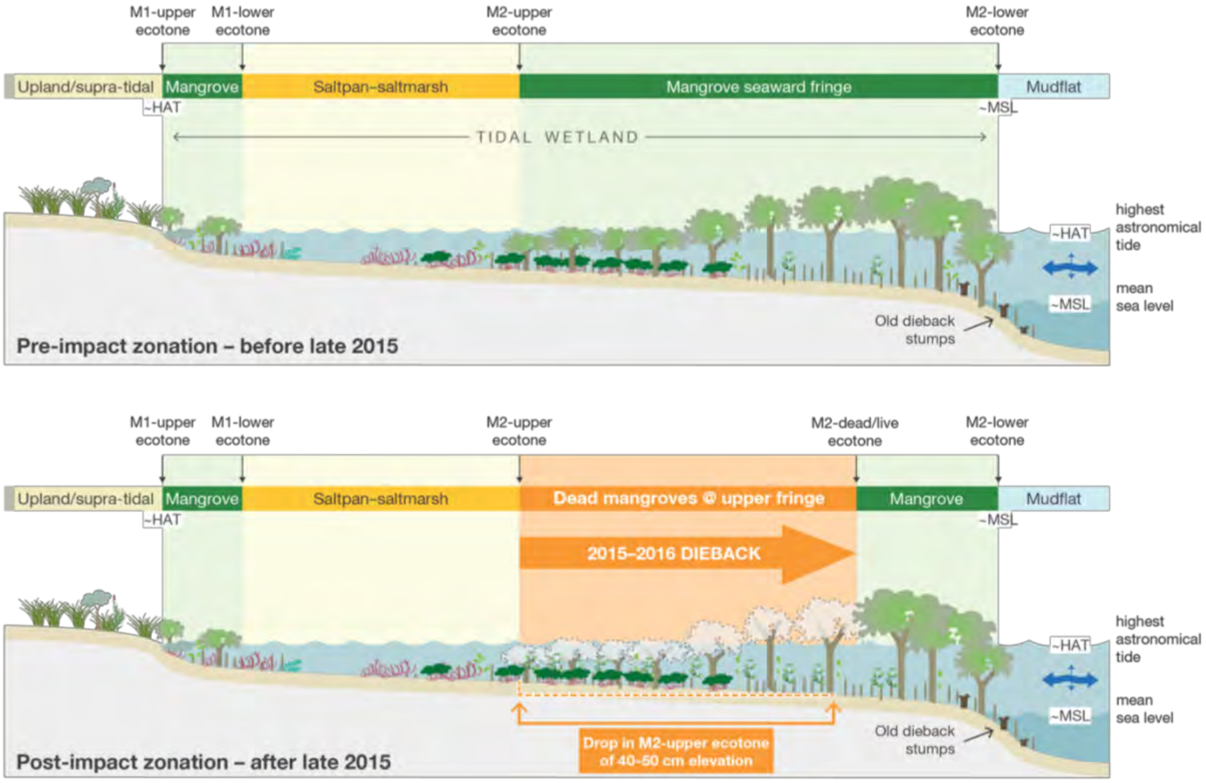
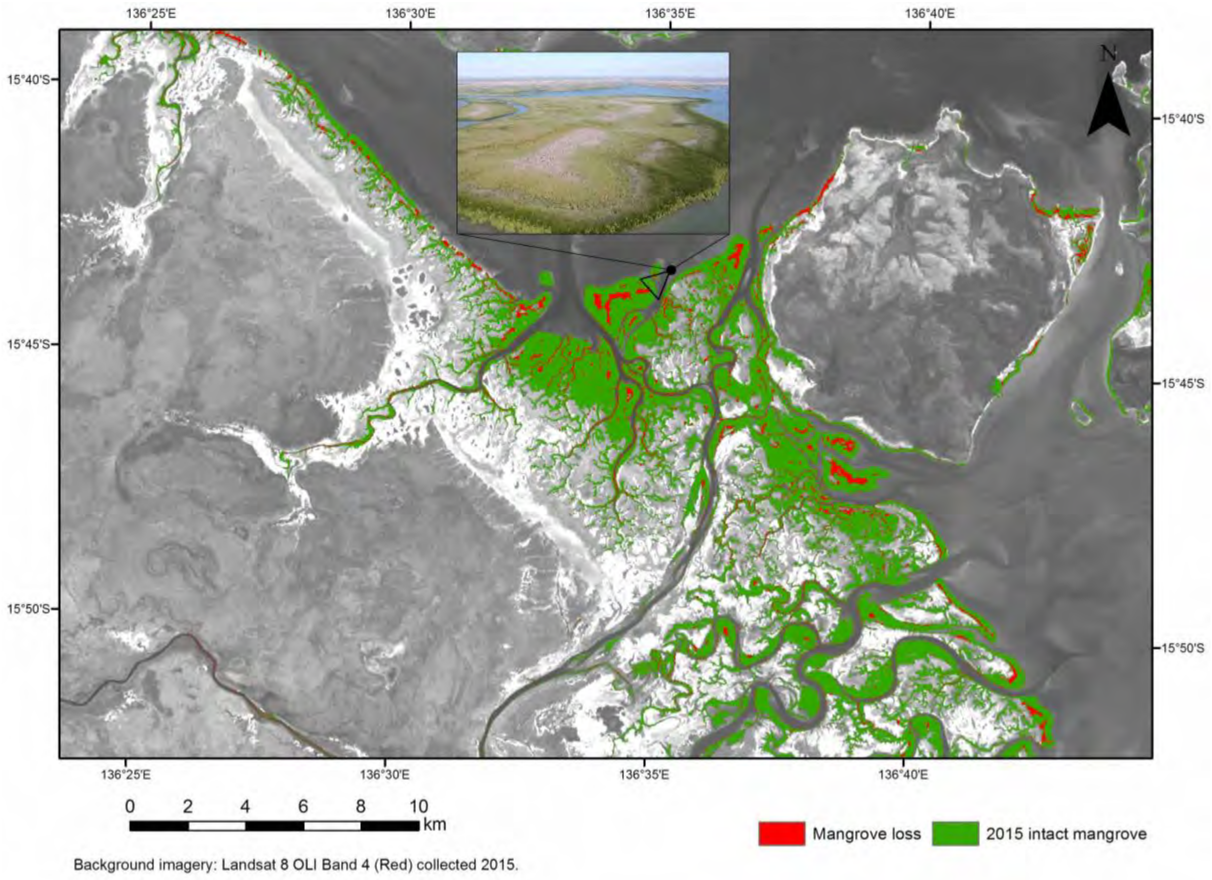


Figure 4. Characteristics used in field studies to define elevations and distances along transects as vegetation ecotones along the upper half of the tidal range – the niche of the tidal wetland zone. The profile images depict a relatively arid shoreline as in the Gulf of Carpentaria, before and after the severe impact of 2015–2016 dieback of the seaward mangrove fringe. As there were few obvious changes in the approximate highest astronomical tide (~HAT) and approximate mean sea level (~MSL) ecotones, damage severity could be quantified by the retreat seaward of the M2-upper ecotone to the M2-dead/live ecotone position.

In some places, we observed multiple dieback fronts at the upper margins of adjoining species zones (Figure 5, inset image). Such changes to ecotone margins were consistent with a sudden loss of moisture, as might be experienced with the temporary lowering of sea level – recognising that sea level fundamentally influences mangrove zonal distributions. Because of the remoteness of the location, the scale of the area affected and the lack of vessel traffic, we discounted direct human activities such as tree cutting or major oil spills, as well as indirect human-related factors like the introduction of pathogens or insect damage.



Background imagery: Landsat 8 OLI Band 4 (Red) collected 2015.

Figure 5. This image shows the coast around the mouth of the McArthur River and Centre Island just south of Mule Creek in the Northern Territory. Mangrove dieback (in red) was notable amongst surviving mangroves, with the greatest impacts occurring along seaward shorelines rather than in estuaries. 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.*

Multiple mangrove species were affected, but especially *Avicennia marina* (grey mangrove), the most common mangrove in the Gulf and widely distributed around mainland Australia. Other common species affected were *Rhizophora stylosa* (stilt-rooted mangrove; a tropical shoreline species) and *Ceriops australis* (yellow mangrove; a drought-resistant tropical species). The survival of low-height species such as the shrub mangrove *Aegialitis annulata* (club mangrove; a widely tolerant tropical species) and various shrubby succulent saltmarsh plants showed that the impact was to some extent species-specific. It may be no coincidence that shorter plants suffered least from the mass dieback event. It was likely that shorter plants might survive better when moisture was suddenly lacking from the drop in sea level experienced in late 2015 (Table 2).

Table 2. Summary of potential drivers of mangrove dieback for the eight transects 1A, 1B, 2B, 2A, 4A, 4B, 5A and 5D at field sites 1, 2, 4 and 5 (see Figure 2).

Attribute	1A	1B	2B	2A	4A	4B	5A	5D
Tidal range (m)	2	2	2.2	2.2	3.3	3.3	2.6	2.6
Sea level rise 1993–2007*	9.2	9.2	9.0	9.0	8.2	8.2	7.8	7.8
Cyclones 1995–2015**	0	0	2	2	0	0	4	4
Annual rainfall (mm)	843	843	843	843	750	750	965	965
Sea level drop (m) 2015/7	0.333	0.333	0.333	0.333	0.465	0.465	0.351	0.351

Sources: * Church at al. (2009); ** BOM website (accessed Feb 2020).

Green fraction time-series plots confirmed that the dieback occurred in late 2015, and that it was synchronous across the Gulf (Figure 3). These plots also showed that, since 1987, the vegetation along these shorelines had been following an apparent trajectory towards recovery after a previous disturbance, with stable, full canopies only established around 2000. This suggested that there was an earlier occurrence of dieback prior to 1987. When we compared historical satellite imagery (Figure 6) we found that the loss and depletion of seaward-fringing mangroves as seen in 2015–2016 had occurred earlier between 1978 and 1987. This was the first confirmation of an earlier mass dieback event. This earlier dieback event was also widespread, occurring in both the Northern Territory and Queensland.

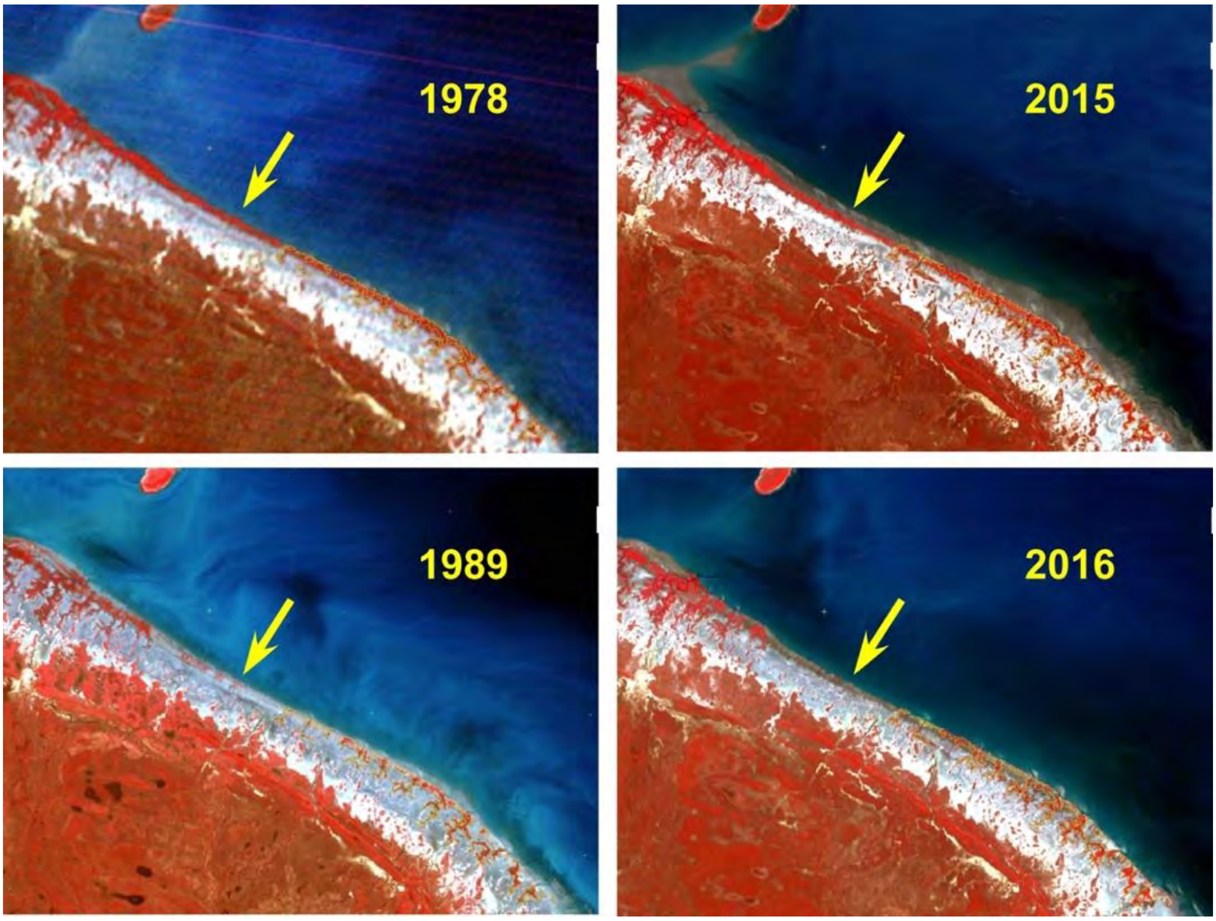


Figure 6. Selected time series comparisons show losses of shoreline mangroves (in false red colour) as seen in Landsat imagery. These compare the known 2015–2016 incident (right-side images) with those likely much earlier between 1978 and 1989 (left-side images). These views show the same severely affected shoreline just east of the Limmen Bight River mouth. 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, the foreshore fringing stand followed a recovery trajectory.

2.1 The influence of El Niño on the dieback event

In 2015–2016, severe El Niño weather conditions were experienced in the region, particularly along the north-east coast of Queensland. Extreme high water temperatures resulted in severe bleaching of coral reefs along the northern Great Barrier Reef (Hughes et al., 2017). The El Niño event affected the Gulf area, which experienced extreme high temperatures and prolonged drought conditions (Harris et al., 2017), but these extreme weather conditions were not considered sufficient to severely damage mangroves. The sudden drop in sea level across the western Pacific region associated with this El Niño event did, however, warrant greater attention.

The drop in sea level was evident in tide gauge records of Gulf ports. Extreme low water levels of 20–40 cm occurred in three ports (Figure 13) at Milner Bay on Groote Island (NT), Karumba and Weipa (Queensland). Only one of these ports, Karumba in the Norman River, was in close proximity to an area of severe dieback. The drop in sea level at this port was especially extreme and the low levels recorded there (Table 3) corresponded to the difference in elevation across the dieback zone – from the upper saltmarsh–mangrove ecotone to the seaward extent of dieback in the shoreline mangrove zone of each transect, especially those near to Karumba (Table 4 and Table 5).

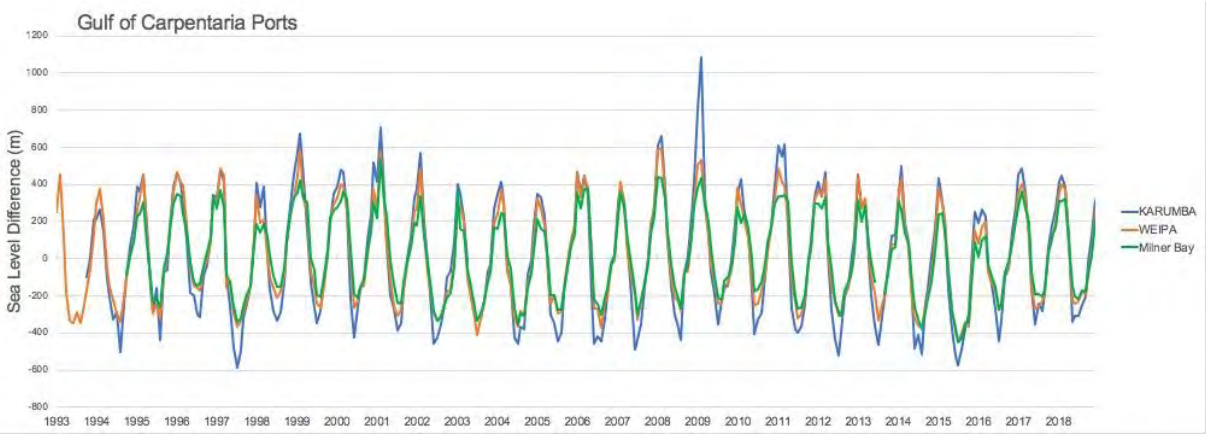


Figure 7. The time series of the difference between monthly sea levels and their five-year running averages for three Gulf of Carpentaria port tide gauges for Milner Bay (Groote Island) in the Northern Territory, and Karumba and Weipa in Queensland from 1993 to 2018. These differences tend to normalise the data, to remove the influence of sea level rise and to emphasise relative extreme events. Note the extreme minimum level for Karumba in 2015–2016 was comparable with that in 1997–1998. However, while these data show the relative differences in severity of the extreme events, there remained a question regards the duration of each extreme low event.

*Table 3. Descriptive attributes for the eight Gulf transects 1A, 1B, 2B, 2A, 4A, 4B, 5A and 5D. *Height (= elevation) readings were negative. Note: HAT was treated as the zero reference point for both elevation and distance. See Figure 2 for locations and Figure 4 for explanation of the codes used. Mean values are displayed in Table 4.*

Attribute	1A	1B	2B	2A	4A	4B	5A	5D
Distance (m)								
Tidal wetland width – MSL-HAT	572	790	374	210	581	651	196	483
Mangrove fringe width – MSL-M2upper	170	181	155	131	240	397	81	191
Dieback width – M2dead/live-M2upper	168	137	155	92	225	290	81	130
% Mangrove fringe lost	98.7	75.6	100	70.2	93.8	72.9	100	68.1
Tidal wetland slope – dist. / elevation	369	564	256	144	395	449	113	294
Pre-impact fringe slope – dist. / elevation	486	223	307	185	318	486	188	278
Dieback zone slope – dist. / elevation	553	312	310	238	345	594	190	407
Elevation (m)								
Tidal wetland elevation – MSL-HAT	1.55	1.40	1.46	1.46	1.47	1.45	1.73	1.64
Pre-impact upper fringe * – M2upper	1.19	0.65	0.98	0.78	0.74	0.67	1.24	0.90
Impact upper fringe * – M2dead/live	1.50	1.06	1.46	1.15	1.37	1.14	1.73	1.26
Mangrove fringe elevation – MSL-M2upper	0.36	0.75	0.49	0.68	0.73	0.78	0.49	0.74
Dieback elevation – M2dead/live-M2upper	0.31	0.41	0.48	0.37	0.63	0.47	0.49	0.35

*Table 4. Means of the descriptive attributes for the eight transects. Note: HAT was treated as the zero reference point for both elevation and distance. * indicates means with <5% variance. See Figure 4 for explanations of codes used. Values for individual transects are displayed in Table 3.*

Attribute	mean	SE	% variance
Distance (m)			
Tidal wetland width – MSL-HAT	482	74	15
Mangrove fringe width – MSL-M2upper	193	33	17
Dieback width – M2dead/live-M2upper	160	24	15
% Mangrove fringe lost	84.9	5.1	6.0
Tidal wetland slope – dist. / elevation	323	54	17
Pre-impact fringe slope – dist. / elevation	309	42	14
Dieback zone slope – dist. / elevation	369	50	14
Elevation (m)			
Tidal wetland elevation – MSL-HAT	1.55	0.04	2.6*
Pre-impact upper fringe * – M2upper	-0.89	0.06	7.2
Impact upper fringe * – M2dead/live	-1.33	0.06	4.5*
Mangrove fringe elevation – MSL-M2upper	0.63	0.06	10.1
Dieback elevation – M2dead/live-M2upper	0.44	0.04	8.9

Table 5. Measures of mangrove structure and condition for the eight transects 1A, 1B, 2B, 2A, 4A, 4B, 5A and 5D. Dominant species: AM = Avicennia marina*; AA =* Aegialitis annulata*. Shaded columns are those most severely affected by dieback (90–100% dead).*

Attribute	1A	1B	2B	2A	4A	4B	5A	5D
Canopy								
Trees measured	213	311	173	209	281	304	89	230
Dominant species	AM	AM	AM	AM	AM	AM	AM	AM
Total density (stems/m^2)	0.679	0.937	0.619	0.966	0.488	0.657	0.275	0.325
% dead trees	93.3	68.5	94.9	52.4	83.9	66.2	90.9	49.6
Tree height mean (m)	1.5	1.5	1.9	1.4	2.3	2.1	1.6	2.9
Tree height max. (m)	4.3	3.6	6.0	4.2	8.8	8.5	7.8	9.6
Stem diam. mean (cm)	5.3	4.1	7.3	5.2	5.7	5.2	7.9	7.4
Max. stem diam. (cm)	18.1	20.5	33.4	23.5	25.9	21.7	18.6	22.0
Avg tree biomass (kg)	28.3	20.1	64.3	30.1	36.1	29.4	68.3	56.6
Tree carbon total tC/ha (=<2015)	77.8	92.6	153.9	139.2	75.1	86.6	95.0	92.2
Tree carbon dead tC/ha (=>2016)	75.8	37.3	148.6	70.0	70.8	53.8	93.4	62.9
Under-canopy								
Shrubs/saplings measured	59	672	259	632	693	3698	62	855
Dominant species	AA	AM	AA	AA	AA	AM	AM	AM
Total density (stems/m^2)	0.270	3.360	1.177	2.995	2.530	1.628	0.689	4.290
% dead shrubs/saplings	55.6	6.8	83.4	20.5	0.1	0.3	0	2.7
Shrub height mean (m)	0.25	0.34	0.18	0.28	0.46	0.46	0.50	0.59

A comparable link between a temporary drop in sea levels and a severe El Niño event (Cane, 1983; Rasmussen & Wallace, 1983) was recorded much earlier in 1982–1983 (Lukas et al., 1984; Wyrtki, 1984, 1985; Oliver & Thompson, 2011). While much was noted concerning the impacts on climate, agriculture and seabirds (Allan, 1983; Schreiber & Schreiber, 1984), no observations of mangrove dieback were reported. The earlier condition of these mangroves was investigated as part of this study, and there had been comparably severe dieback at the time between 1978 and 1987 (Figure 6). These observations provide convincing evidence of the earlier occurrence of mass mangrove dieback.

These new discoveries made a compelling case for the sudden drop in sea level being the cause of the earlier occurrence of severe mangrove dieback. This means that it may be possible to predict or anticipate future events. The evidence for a prior occurrence includes historical satellite imagery back to the 1972; the recovery (or re-establishment) trajectory for shoreline mangroves around the Gulf since 1987 shown in the green fraction plots; the young age of mangrove stands; the presence of old degraded stumps of earlier mangrove trees fronting existing shoreline stands; and those prior publications describing the temporary drop in sea level associated with a similarly severe El Niño event in 1982–1983 (e.g., Wyrtki, 1985). This means it is highly likely that comparably widespread severe damage and loss of mangroves had gone unrecognised in this remote part of northern Australia.

2.2 Sea level rise

Sea level rise has been relatively rapid in the Gulf region between 1993–2007 (Church et al., 2009; Church & White, 2011), with rates of up to 12 mm per year exceeding the global average of about 8 mm per year. Mangrove ecosystems are intimately dependent on sea level and they are likely to have responded in the recognisable ways investigated during this study, such as shoreline erosion (loss of seaward-fringing mature vegetation at lower elevations around mean sea level; Figure 8); saltpan scouring (sheet erosion of saltpan sediments, loss of saltmarsh vegetation, gully erosion; Figure 9); and terrestrial retreat (loss of terrestrial trees with saline intrusion above the highest astronomical tides, edge erosion and scouring, expansion of mangrove seedlings upland; Figure 10).

Figure 8. Shoreline erosion and retreat of tidal wetlands occurs when trees on the sea edge are lost. Unlike the specially adapted, sprawling trees along the sea edge, the lanky trees in the inner stands are unable to resist the 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.

Figure 9. Surface sheet erosion is another consequence of additional water in an estuary. As with terrestrial retreat, saline intrusion and mangrove encroachment, this impact is associated with rising sea levels. In this case, greater water volumes inundate upper saltpan areas and regular tidal flooding and drainage result in sheet erosion and scouring of surface sediments. In extreme instances, saltmarsh vegetation, including natural layers of microphytobenthos, have been unable to establish. The whole inundated area is scoured, leaving bare sediments and pools of residual waters.

Figure 10. Terrestrial retreat, coupled with saline intrusion, is marked by dieback of supratidal terrestrial vegetation, possible encroachment by seedling mangroves, and erosion along the highest seawater margins. This impact comes as a direct consequence of progressively rising sea levels. Such an occurrence is considered a valuable indicator. Because it depends on elevation, the breadth of affected sites might be greatest in areas of low-relief terrain.

The severity of mangrove dieback in the 37 estuaries we scored was strongly correlated with rising sea levels, especially terrestrial retreat (Figure 11) and saltpan scouring (Table 6). While we found no correlation between sea level rise and shoreline erosion, a number of other factors directly affected sea-fringing stands, like the localised harsh weather conditions associated with flooding and severe tropical cyclones. These latter events are likely to cause deposition of sediments along shorelines which will disrupt the progressive influences of sea level rise on fringing mangroves.

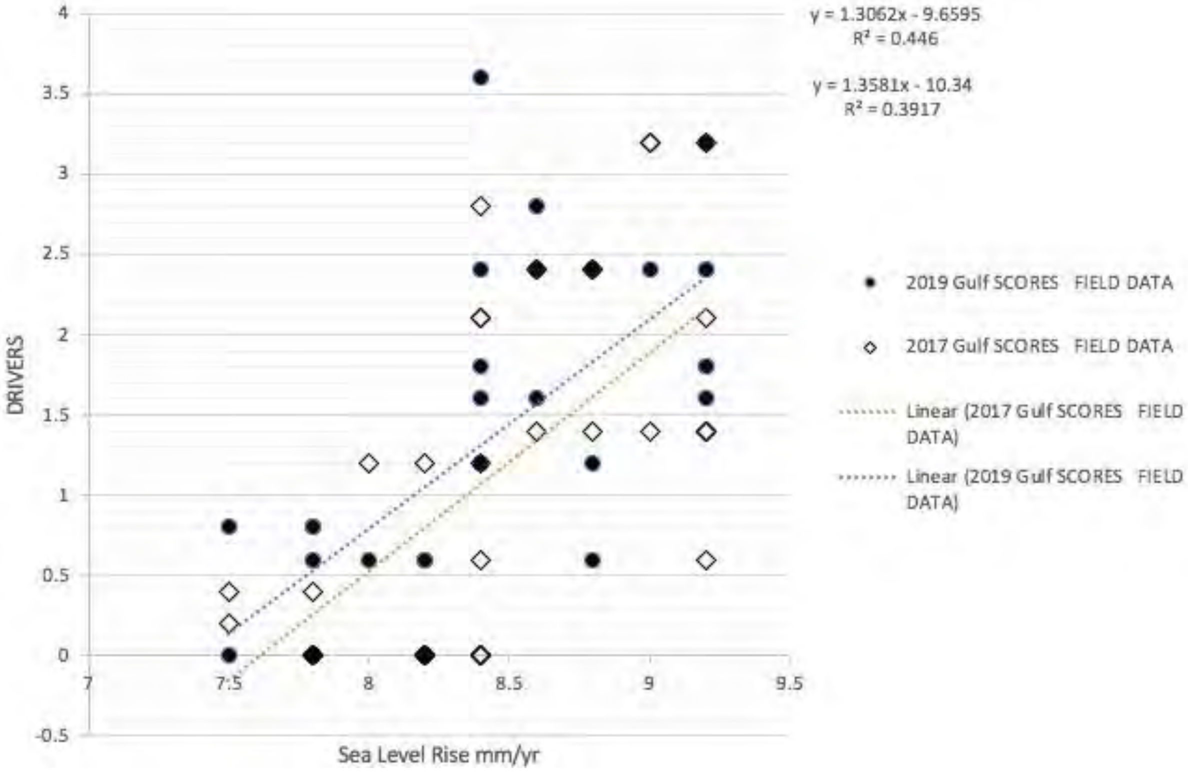


Figure 11. Plot of 2015 terrestrial retreat (driver) and sea level rise (Church et al., 2009; Hobday & Lough, 2011) showing significant relationships between the 2017 and 2019 estuary severity scores (see Table 6). Scored by surveys in 2017 and 2019 for the 31–37 estuarine mouth sites.

*Table 6. Comparisons of climate-natural indicator data for the 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 by the six drainage regions (see Figure 2). Significance levels for Pearson correlations, 2-tailed test, are * = 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

There was a notable positive correlation between sea level rise and the severity of the 2015 mangrove dieback (Table 6, Figure 12). This suggests that the impact of sudden drops in sea level on mangroves are greatest where sea level rises have also been greatest. Therefore, in places where the resilience of mangroves has been weakened, any additional event like a sudden drop in sea level would result in greater damage. This may be difficult to quantify and evaluate further but our findings suggest that the poorer condition of shoreline trees caused by increasing rates of sea level rise may reduce their ability to colonise further upland. This poses a serious threat to the longer-term survival of tidal wetlands faced with rising sea levels.

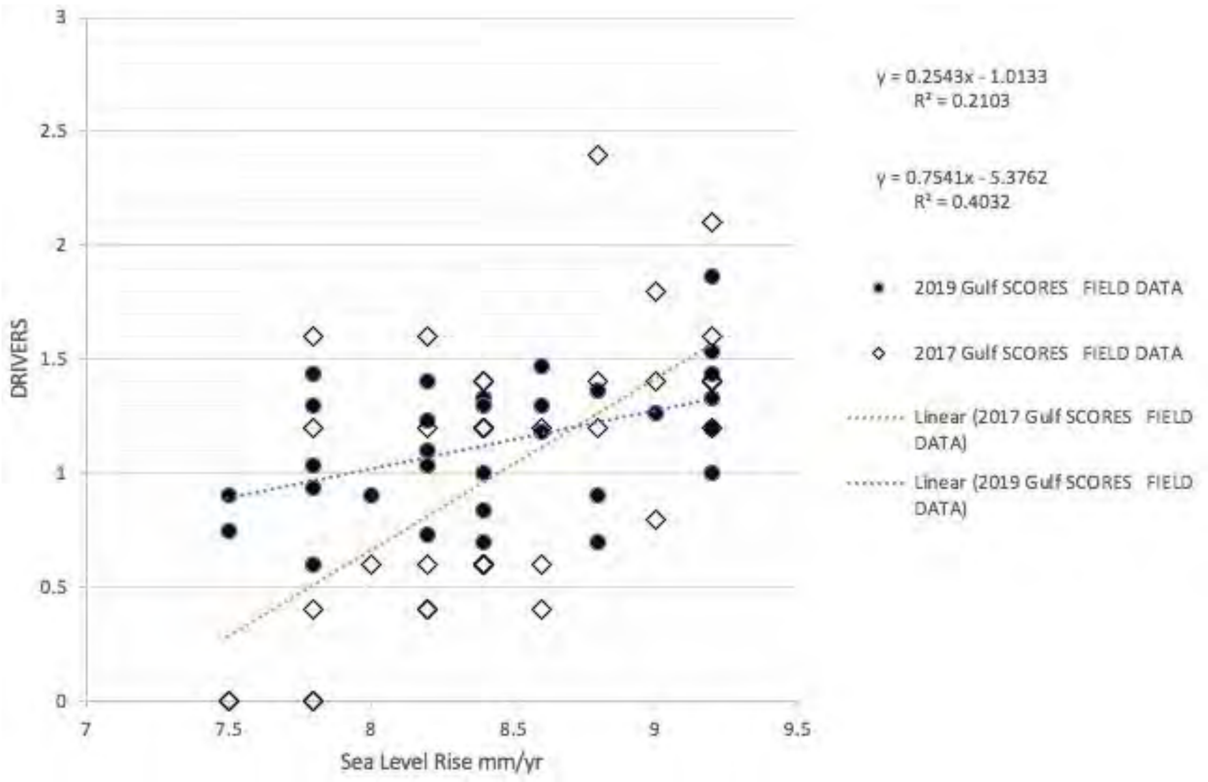


Figure 12. Plot of 2015 mangrove dieback (driver) and sea level rise (Church et al., 2009; Hobday & Lough, 2011) showing a significant relationship with the 2017 estuary severity scores (see Table 6). Scored by surveys in 2017 and 2019 for the 31–37 estuarine mouth sites.

2.3 Mangrove demography

Field studies also showed that, for several transects, the relative sizes of trees decreased as elevation increased, with larger trees at the seaward edge and smaller trees at higher elevations along the rear edge of the fringe zone (Figure 13). This ordering of size classes was consistent, with younger trees at higher elevations a reflection of the steadily rising sea levels in the Gulf.

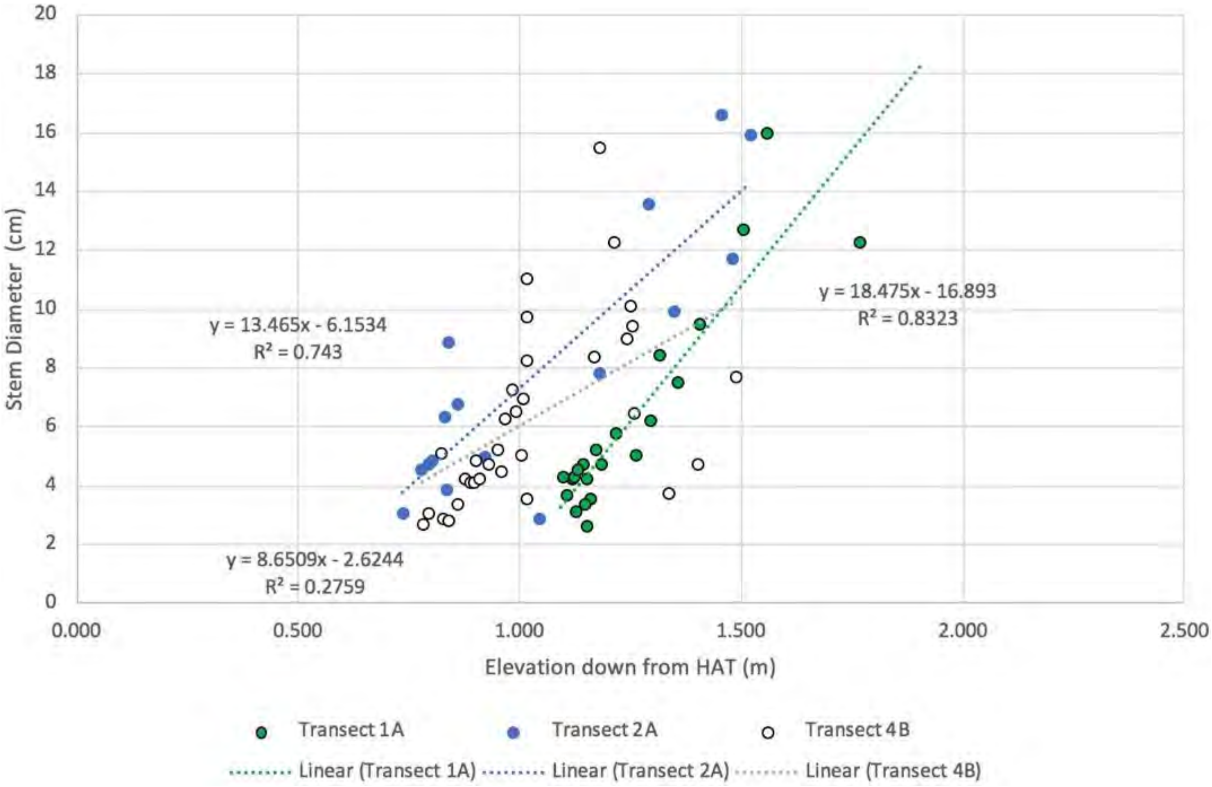


Figure 13. Mean size of canopy trees along transects 1A, 2A and 4B compared with elevation height. These data show the condition of the mangrove fringe as it was before the 2015–2016 dieback. There were significant positive relationships with elevation measured down from ~HAT. These show a relationship where smaller, younger trees were found higher up the tidal zone of sites on either side of the Gulf.

Additional evidence from our field studies documented a distinctive demographic structure of seaward-fringing mangroves across the Gulf (Figure 14). The average tree age appeared to be much younger than that observed in other places (Duke, 2013; Mackenzie & Duke, 2011). There were reliable indications that mangrove trees along the Gulf's shorelines appeared to have a mean age around 9–10 years, with the oldest individuals around 20–30 years (Figure 14).

Although our assessment of tree age was incomplete at the time of writing[2], our data further suggested that these Gulf shorelines have suffered repeated instances of severe mangrove dieback followed by three decades of recovery. While this does imply that natural recovery of the damage caused by the 2015–2016 event may occur, there are also the cumulative impacts of other factors to consider. A key question is how have environmental conditions changed since 1982–1983? And how will these factors now influence recovery of fringing mangrove stands damaged in 2015–2016?

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[2] Age estimates depend largely on carbon dating analyses and other assessments being made in collaboration with researchers at the Australian Nuclear Science and Technology Organisation (ANSTO). The results were not available for this final report due to the recent pandemic restrictions. In the interim we have based age estimates on several factors including the number of lamina bands recorded in stem wood sections. The relative ages of these trees corresponds to stem diameter measures seen in Figure 14.

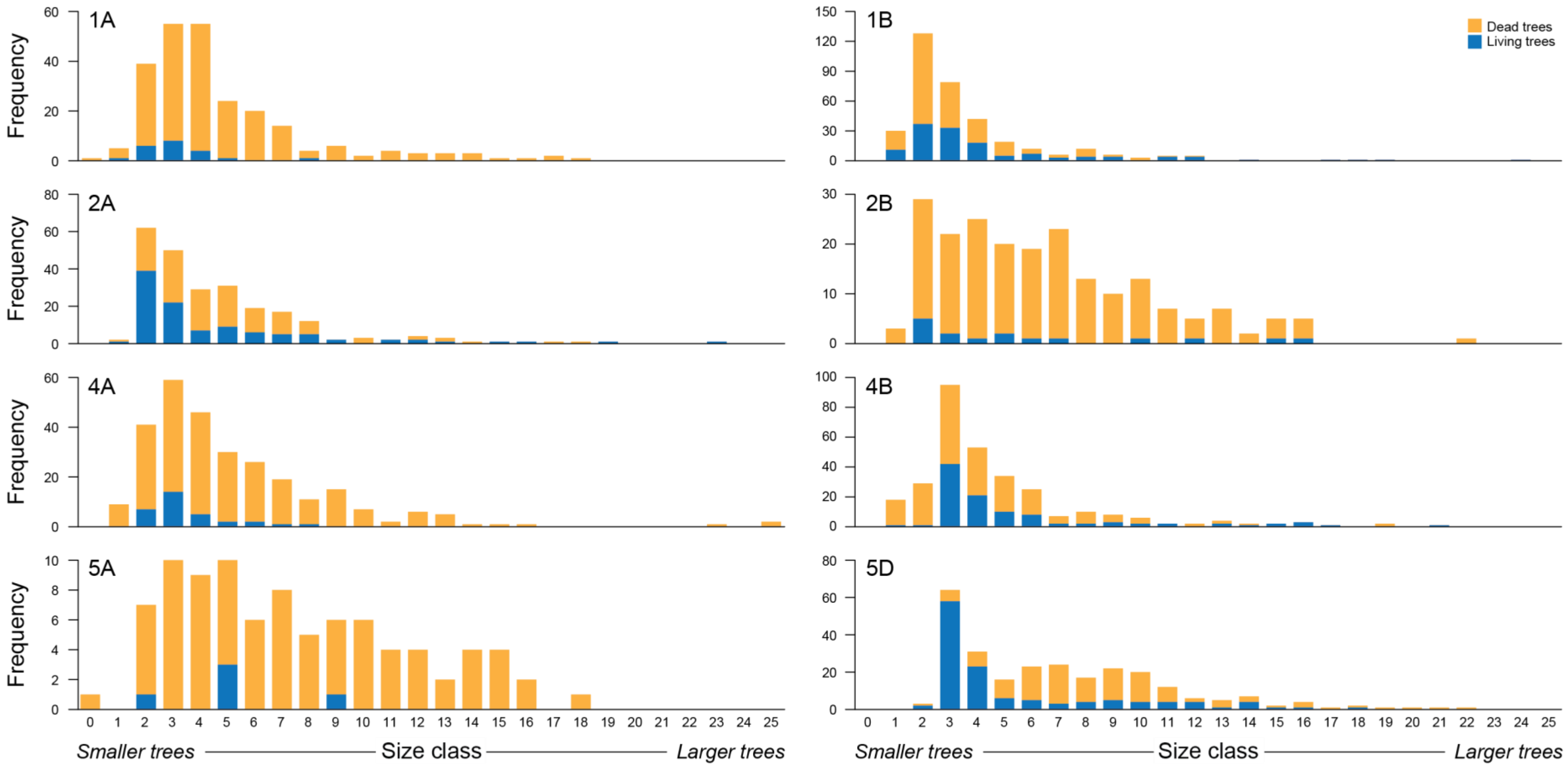

Figure 14. Size (cm) frequency of vegetation along Transects 1 and 2 (in October 2018), and 4 and 5 (in August 2018) showing live and dead plants. Trees died mostly in late 2015. Notably, the smaller (younger) individuals had greatest survivorship.

2.4 The impact of tropical cyclones on mangrove recovery

A significant outcome of these investigations has been the reporting of previously unrecognised but notable impacts on the habitats along the Gulf of Carpentaria's shorelines in both Queensland and the Northern Territory. Two severe cyclones occurred between the 2017 and 2019 aerial surveys. Tropical Cyclone Owen (Category 3) affected the area west of the Limmen estuary and shoreline (Figure 15) in December 2018 and Tropical Cyclone Trevor (Category 4) affected the Robinson, Calvert and Wearyan estuaries in March 2019 (Figure 16–Figure 18). The collective impact of these storms caused serious 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 trees that died in 2015 and scour, large patches of fallen and broken stems, and defoliation of the canopy.

Figure 15. The impact on the Limmen shoreline of Category 3 Tropical Cyclone Owen in December 2018 on 2015–2016 dieback areas. This is more evident by comparing this 'after' image taken in September 2019 with the image taken 'before' in September 2018 (Figure 1). Standing dead stems and seedling recruits have been scoured and dumped inland. Note the piles of wood wrack evident as grey patches in the centre foreground and extending into the distance.

Figure 16. 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 cumulative impacts.

Figure 17. Exposed shoreline mangroves were uprooted and those further inshore were mostly fatally stripped of foliage by Category 4 Tropical Cyclone Trevor in February 2019.

Figure 18. Strong cyclones cause severe damage to mangrove forests. Damaged shorelines may recover but only after several decades and provided that seedlings can rapidly re-establish amongst the dead, damaged and uprooted trees.

The damage caused by tropical cyclones was local and dependent upon the cyclone's severity. The level of damage was also influenced by other factors such as tide levels at the time of impact (Figure 15–Figure 18). The impacts of cyclones were not evenly distributed around the Gulf since there are 'hot spot' sections of shoreline where the frequency of cyclones had been greater (Figure 19). On the whole, the Gulf experiences one notable cyclone every two years. Particularly severe cyclones (Category 3 and above) occur in periodic clusters each 30 years or so, and they mostly occurred on the NT side of the Gulf. Intervening cyclones and those in Queensland were mostly of minor strength (Category 2 or lower).

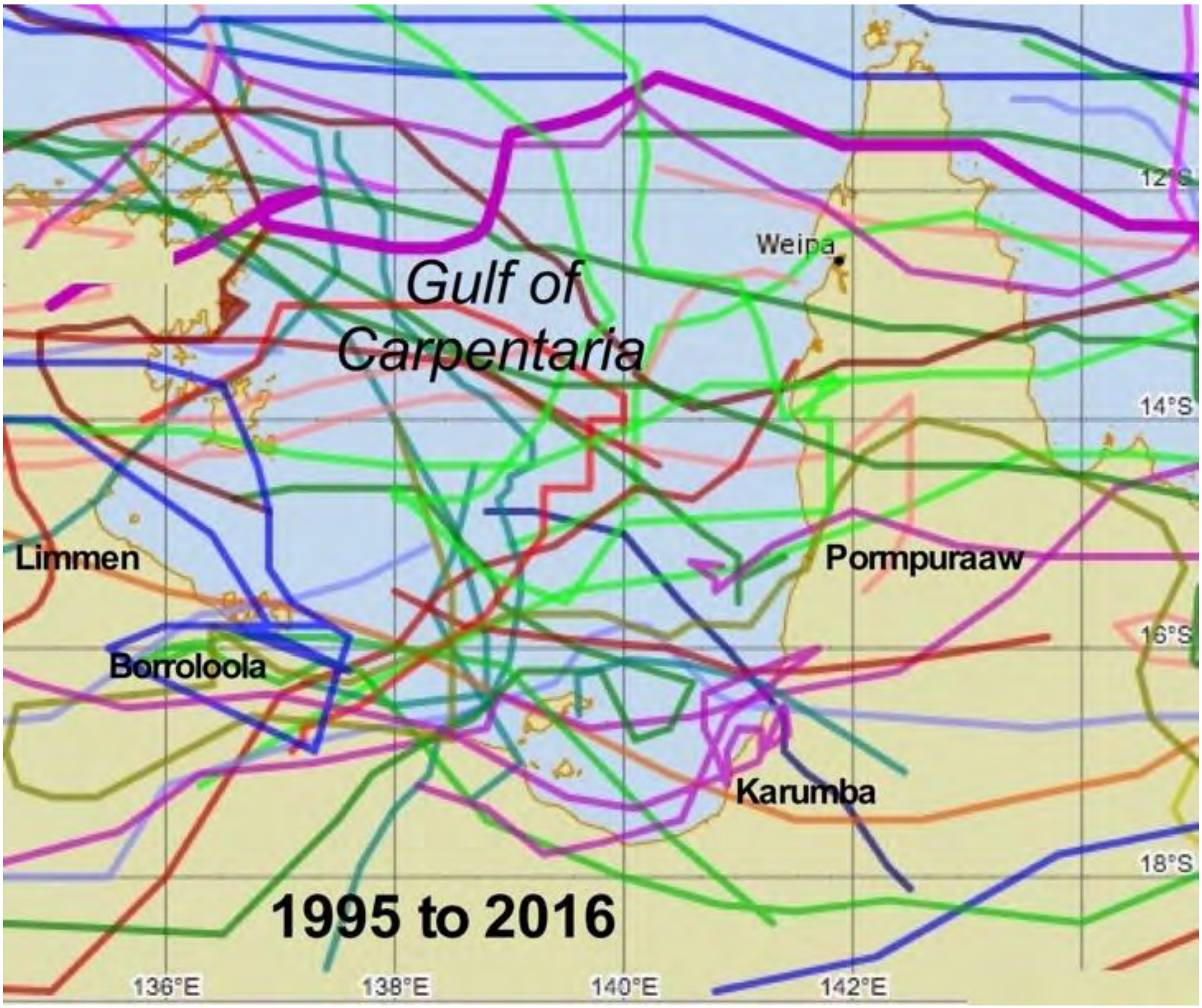

Figure 19. Cyclones are a common feature in the Gulf of Carpentaria. This figure shows tracks of cyclones in the region during the 20 years up to 2015 (BOM website, accessed 2019), with around one cyclone every two years. Although cyclones have a regional influence, the damage caused by these events is mostly localised. This was exemplified further where some shorelines suffered notably less than other sections. Note the intense cyclone activity around Borroloola shorelines in particular.

2.5 The impact of flooding on mangrove recovery

Severe flooding of the Flinders River occurred in February 2019. The impacts downstream in estuarine tidal wetlands included damaging bank erosion and slumping; serious scouring and gullying across saltpan–saltmarsh areas (Figure 20 and Figure 21); and significant depositional gain around the mouth of the river where young seedlings occupied seafront mudbanks (Figure 22 and Figure 23). There was a significant correlation between bank erosion and depositional gain indicators (Figure 24) 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, showed that excessive flow events take the line of least resistance, with flows redirected across open saltpan, eroding and cutting new channels to reach larger drainage channels to the sea.

Figure 20. Flood damage is indicated by bank erosion, uprooted trees, scouring of saltmarsh, and tree remains in estuarine tributaries.

Figure 21. Scouring of saltpans, a notable issue for the South Mitchell estuary.

Figure 22. Depositional gain occurs when mangrove seedlings and saplings occupy accreting mudbanks that exceed elevations above mean sea level. Because sediment deposition can be associated with periodic flood events, the expanding vegetation canopy is often stepped and incremental.

Figure 23. Depositional gain at the mouth, a notable issue for the Koolatong estuary.

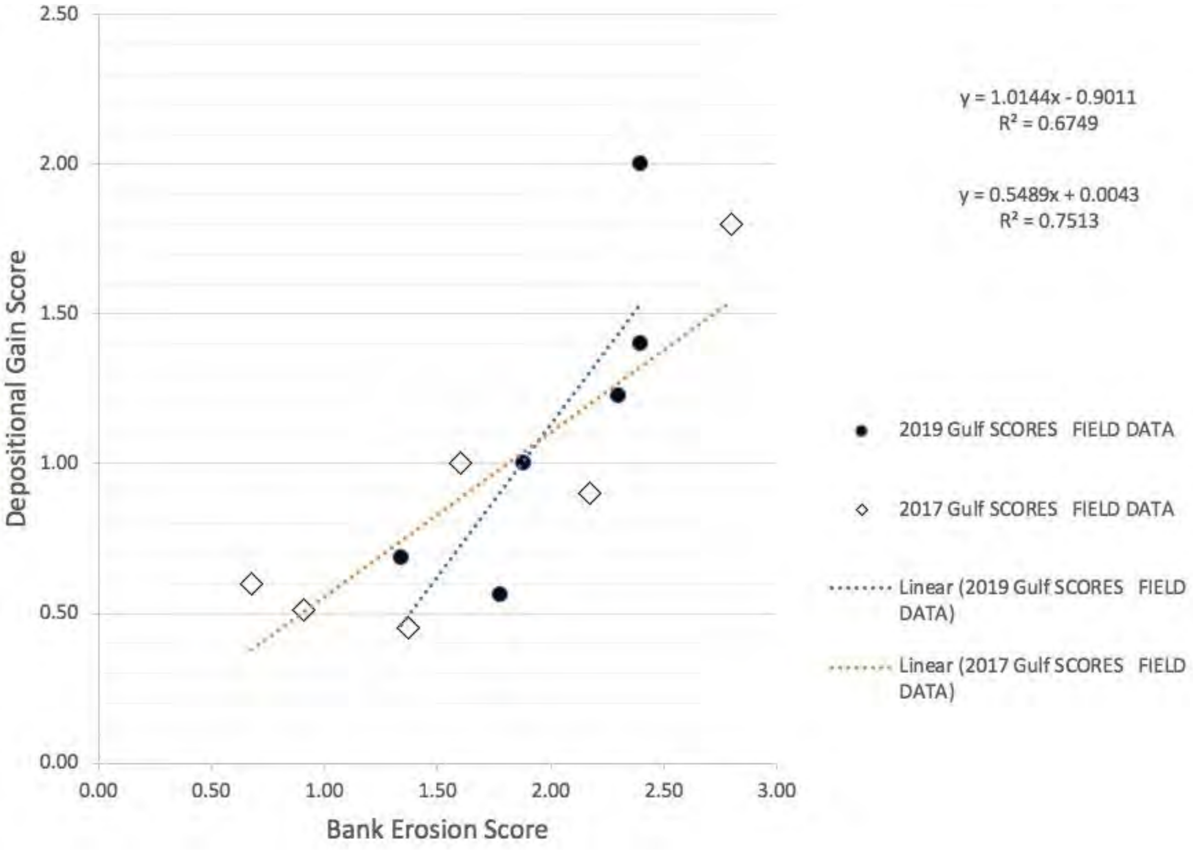

Figure 24. Plot comparing bank erosion and depositional gain. Their relationship implies a link between flooding impacts, such as bank scouring, and relocated sediment, which leads to the emergence of depositional banks and their colonisation by mangrove seedlings and saplings.

The accumulation of impacts from tropical cyclones and flooding is likely to seriously impede, or even reverse, recovery in areas that are affected repeatedly. Such outcomes were observed during these investigations. Recovery of sites affected in 2015–2016 were observed generally in 2018. Damaged trees had re-sprouted and there was notable establishment of seedlings to replace canopy trees. However, subsequent severe tropical cyclones in late 2018 and early 2019 resulted in significant damage to Northern Territory sites, and the 2015–2016 dieback areas in particular. The accompanying storm surge of large waves and strong winds not only eroded and uprooted shoreline trees, but wood piles of broken and dead stems were mobilised, running over and scouring seedlings and survivors alike. These sites were seriously degraded, and left relatively more bare and lifeless (Figure 25 and Figure 26).

Figure 25. During field surveys in October 2018, dead Avicennia marina *trees were mostly standing and intact with under-canopy shrubs of* Aegialitis annulata *and scattered saltmarsh, as seen near the seaward edge of Transect 1A in the Northern Territory.*

Figure 26. During aerial surveys in 2019, we revisited the same site near the seaward edge of Transect 1A (see Figure 25) to find few standing dead Avicennia marina *trees and a much reduced under-canopy; a consequence of severe Tropical Cyclone Owen between visits.*

Box 1. Management implications

There are two strategies that can be adopted by managers and environmental policy makers to help ensure the long-term health and resilience of mangrove ecosystems in the Gulf of Carpentaria.

The first strategy deals with the cause of mangrove dieback by attempting to remove or limit the harmful, changing environmental conditions at a national and global level with schemes like climate change abatement.

The second strategy focuses on improving resilience in threatened, struggling mangrove habitats by reducing, where possible, the cumulative effects of local impacts such as feral pig damage, scorching by fires and smothering by weeds. This strategy has three components including a regional monitoring network, a rapid response mangrove watering strategy, and the implementation of locally based land management practices. These components are described briefly as follows.

1. ***A regional environmental monitoring network.*** Since we identified one or more key trigger factors in this report, starting with the drop in sea level, the suggested plan is to continuously monitor sea level along with other factors at automated recording stations around the Gulf region. This array would complement and extend upon existing continuous monitoring recording stations of ports and the Australian Bureau of Meteorology. While local NRM regional groups need to be involved, the environmental monitoring stations could be installed, serviced and maintained by local Indigenous ranger teams as part of their land and sea custodianship roles. Recorded measures like sea level would be monitored on a daily to weekly basis. When sea levels drop below a recognised exceedance level (identified in this investigation) then a response team would be deployed as required to implement the next level response action.
2. ***A rapid response mangrove watering strategy.*** The response team would effectively deploy a temporary, landscape-scale watering system designed to keep desiccated mangroves alive during periods of acute stress – as depicted in the monitoring stations. This would likely take place over a 2–3-month time frame. The scale and the technical actions required would be determined in such a way as to reduce and prevent mangrove dieback – especially in critical areas known to suffer severe shoreline damage – identified and located also during these investigations. This working response to a sea level drop would operate under the expectation that such significant drops in sea level may occur anytime during any 10-year period. This component would also include an evaluation and review process after each deployment to refine successful practices and improve future responses.
3. ***On-going efforts to build resilience in natural mangrove ecosystems.*** As noted already, there needs to be on-going improved local management efforts to install and implement mangrove-friendly practices. Suggested practices include limiting controlled fires to periods of spring tides when mangroves are wetted, removal of weeds smothering mangrove verges bordering upland vegetation, and removal of feral pigs that dig up wetland plants interfacing between mangrove and freshwater flooded lands. Each of these actions will improve the resilience of mangrove systems where they must migrate upland with rising sea levels if they are to survive. These actions need to be done in full cooperation with landowners and regional NRM groups while on-ground works could be lead and assisted by Indigenous rangers.

To be effective, these strategies need to be concurrent and applied with all haste. The damaging influences are clearly active and they are already causing serious longer-term consequences for mangrove survival.

3. Investigations undertaken

3.1 Shoreline mapping and aerial surveys

Our mapping of the Gulf's shorelines located dieback areas and quantified the associated vegetation units, specifically areas of mangroves, saltpan and saltmarsh, and the 2015–2016 mangrove dieback. We used green fraction time series plots of canopy vegetation condition to show that the dieback event occurred in late 2015, and this period was synchronous across the Gulf (Figure 3). The affected area extended from Blue Mud Bay in the Northern Territory to just north of the northern Mitchell River mouth in Queensland. Mapping showed that dieback mostly occurred in fringing mangroves along the shoreline rather than along the banks bordering estuarine reaches upstream. Specifically, dieback areas consistently occurred at the rear or upper edge of the shoreline mangrove fringe.

Aerial surveys were conducted in consultation with local communities and Indigenous ranger groups, including the Carpentaria Land Council Aboriginal Corporation in Queensland (Figure 27) and the Mabunji Aboriginal Corporation in the Northern Territory. The aim of aerial shoreline surveys was to systematically record and investigate the presence of 2015 mangrove dieback, the overall condition of shorelines, the processes affecting the mangrove vegetation, and the health of tidal wetlands along the Gulf's shorelines and in the mouths of major estuarine systems (Figure 28). These surveys were repeated in 2017 and 2019.

Figure 27. Aboriginal rangers joined our aerial surveys to give advice about their country and to learn about our surveys of the 2015–2016 mangrove dieback.

Figure 28. 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.

A key outcome of the aerial surveys was a baseline database of more than 19,534 geotagged oblique images taken in 2017 and 2019 that cover every metre of shoreline, plus a series of inland profiles extending to the upper limits of tidal inundation in 37 estuarine outlets. 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. The number of images taken were roughly equal in number for shorelines and estuarine entrances. 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.

3.2 Estuary assessments

Estuary assessments include summaries for estuarine entrances based on our scoring of changes to mangroves and tidal wetlands generally. Observed threats and management issues were listed in terms of 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.

Measures of shoreline status were used to identify and quantify dominant environmental drivers. We used a pragmatic classification system developed by Duke and Mackenzie (Duke et al., 2020a) to quantify 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 as the emerging dominant environmental issues in response to changing global climate and rising sea levels.

We compiled observations of current drivers of change and severity of impacts for 37 major estuarine sites, from east to west: 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, Tully 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 (Figure 2).

Our data provide overall information on the condition of critical shoreline ecosystems in the Gulf, and the severe changes taking place in them. The current shoreline and estuarine evaluations identified more than 30 issues affecting tidal wetland and shoreline habitats. Some were associated with rising sea levels and severe and frequent storms. Others were caused by feral animals and 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. Generalised, severe impacts like terrestrial retreat and shoreline erosion increased from eastern to south-western estuaries and respective sections of shoreline, consistent with an increasing trend of sea level rise.

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.

3.3 Field studies

Field studies provided crucial validation of observations made from aerial surveys. These on-ground studies added further significant insights of the impacts and subsequent changes that occurred across the Gulf coastline up to late 2019, four years after the severely damaging event in late 2015 (Figure 29).

Figure 29. Field studies were used to closely investigate the 2015–2016 mangrove dieback across the Gulf of Carpentaria from Queensland to the Northern Territory.

Project investigations were conducted in consultation with local communities and Indigenous ranger groups, particularly the Carpentaria Land Council Aboriginal Corporation in Queensland with their base stations in Normanton and Burketown, and the Mabunji Aboriginal Corporation in the Northern Territory with stations in Borroloola (Figure 30) and Limmen Bight River. We conducted a series of training sessions with each of the ranger groups before they began monitoring estuarine shoreline condition in their areas (Figure 31) using the MangroveWatch shoreline video assessment method (S-VAM; Figure 32). In conjunction with these training sessions, we held public meetings for community members to both consult with and advise locals about the NESP investigations and our key findings. These meetings had an unexpected benefit to our partnership of raising the standing and status of the rangers amongst their wider local communities.

Figure 30. In situ *discussions with local rangers helped explain our investigations while sharing knowledge of the event. This meeting was on Transect 2 during October 2018.*

Figure 31. NESP researchers provided instruction on MangroveWatch monitoring equipment with ranger groups in Queensland and the Northern Territory. This training session was with Il-Anthawirrayarra rangers of the Mabunji Aboriginal Corporation in Borroloola in September 2019.

Figure 32. Instruction on MangroveWatch monitoring involved hands-on use of the equipment, with the aim of building autonomy as well as local capacity for effective habitat monitoring. This session is with the Il-Anthawirrayarra rangers of the Mabunji Aboriginal Corporation in Mule Creek estuary in September 2019.

Field studies primarily focused on shoreline fringing stands dominated by the grey mangrove *Avicennia marina* var. *eucalyptifolia*. While these trees were those most commonly affected by the 2015–2016 mangrove dieback, this was mostly because of their overwhelming presence in the prevailing harsh climatic conditions of the region. Sites were selected based on aerial surveys, which had established that mangroves bordering estuarine banks were notably less affected. Eight transects were set up across affected shoreline fringing stands to record vegetation present; stand structural parameters like the canopies of *A. marina* and under-canopies of shrubby club mangrove *Aegialitis annulate*; the condition of these vegetation types including the 2015–2016 mangrove dieback; and the corresponding sediment elevation levels for each plant (Figure 33–Figure 35).

Figure 33. We revisited the field sites in September 2019 to learn about additional damaging events on the 2015–2016 dieback areas, as shown in field site 2 which was struck by severe Category 3 Tropical Cyclone Owen in December 2018.

MangroveWatch TropWATER JAMES COOK UNIVERSITY AUSTRALIA

Gulf of Carpentaria Mangrove Dieback Surveys August 2018

3 Mangrove Researchers & 2 Indigenous Rangers
2 locations, 5 sites & 6 days of data collection
2.4 km of elevation transects
904 mangrove trees measured over **2,457 m^2**
5,537 seedlings counted
19 wood samples
7 sediment cores
27 Fauna plots
1,877 molluscs counted
21 mangrove mollusc species from **14** families

Australian Government Department of the Environment
Northern Australia Environmental Resources Hub National Environmental Science Programme
CHARLES DARWIN UNIVERSITY
NORTHERN TERRITORY GOVERNMENT

Figure 34. For field studies, a brief summary of achievements in sites in Queensland during August 2018.

MangroveWatch TropWATER JAMES COOK UNIVERSITY AUSTRALIA

Gulf of Carpentaria Mangrove Dieback Surveys October 2018

4 Mangrove Researchers, 4 NT Gov Officers
& 4 Indigenous Rangers
2 locations, 4 sites & 6 days of data collection
1.8 km of elevation transects
828 mangrove trees measured over **1,223 m^2**
1,622 seedlings & saplings counted
21 wood samples
5 sediment cores sampled
13 Fauna plots
2115 molluscs counted
24 mangrove mollusc species from **12** families

Australian Government Department of the Environment
Northern Australia Environmental Resources Hub National Environmental Science Programme
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NORTHERN TERRITORY GOVERNMENT

Figure 35. For field studies, a brief summary of achievements in sites in the Northern Territory during October 2018.

A standard experimental design was used, with paired transects at each location. Transects were run from a highwater point at the head, directly towards the sea edge. This method captured common reference elevation levels for all sites while maximising coverage of the entire elevation range of the tidal wetland (i.e. mangroves plus tidal saltpan and saltmarsh vegetation), from approximately highest astronomical tide levels (~HAT) at the head to approximately mean sea level (~MSL) at the seaward edge of living mangrove trees. For transect pairs, one had about 90–100% loss of shoreline mangrove fringe (severely impacted) while the other had about 60–80% loss of mangrove fringe (moderately impacted). As such, the transects were characterised by their relative amounts of surviving seaward fringes and each was backed by dead trees up the tidal profile to the ubiquitous broad saltpans that are typical of Gulf shorelines.

Ecotone shift – the constant shifting of the ecotone between two vegetation types with changing climate variables – is a natural feature of mangrove vegetation (Duke et al. 2019). The 2015–16 dieback event constituted an extreme example of ecotone shift, characterised by a seaward retreat of the ecotone to a much lower elevation. The most likely hypothesis for the cause of this dieback event was the temporary drop in sea level measured in port tide gauges. The zone of dieback (Figure 4) was consistently at the upper tidal range (back edge) of the shoreline fringe stands, with a mean elevation range around 0.44 ± 0.04 m as the difference between the pre- and post-impact elevations of the upper fringe ecotone (Table 4). This range was notably consistent with mean anomalous low tide levels recorded in the tide gauge of Karumba port, the only port gauge in close proximity to an area of 2015–2016 dieback.

It was of particular interest that the elevation of the ecotone prior to the dieback event, rather than its limit after the event, was linked to regional levels of mean annual rainfall. For this and other reasons, the lack of rainfall was discounted as being primarily responsible for the 2015–2016 dieback response.

We used the port records to derive a stress index that helped to explain how the situation in 2015 was exceptional and rare. The presumed stress on mangrove trees was based upon their sensitivity to moisture deficit when inundation by daily tidal flooding might be significantly reduced. This index was calculated as the multiple of the severity of the drop in sea level times its duration, to quantify the conditions caused by extremely low sea levels between 1985 and 2019. The conditions calculated in 2015 were the most extreme. This extreme low in mean sea level was equivalent to the seaward shift of the ecotone between the saltmarsh-mangrove edge down through the seaward fringing mangroves to an elevation approximately 40 cm lower.

Tree dendrochronology studies (still in progress) showed that mangrove stands on shoreline fringes had unusually young trees. Stand demography estimates were consistent with these sites being relatively highly disturbed vegetation, where most stems appeared to be less than 20 years old. While specific age determinations are the subject of on-going investigations, the current findings show the relatively rapid turnover of these fringing mangrove stands. Our findings revealed a pattern of succession across transects with older trees at lower seaward edges and younger trees in higher tidal levels. This was consistent with the widespread influence of rising sea levels where mangrove trees display continual upward migration and succession.

Field observations also included regular sightings of old tree stumps amongst sea-edge fringing stands. The presence of these older stumps is further consistent with the succession of these stands. As such, the next question is whether these stumps might represent an earlier dieback event, which we will continue to investigate using age determinations of wood samples from sites across the Gulf.

Molluscs were also influenced by the mass dieback. Our results showed there was greater diversity of mollusc families in sites with greater densities of canopy trees ($P < 0.05$), and especially for under-canopy plants ($P < 0.001$). Conversely, there was a negative relationship between the percentage of dead canopy trees ($P < 0.01$) and the per cent of lost living biomass ($P < 0.05$) with the mangrove dieback. However, the relationships between fauna and mangrove dieback were complex when looking at individual families. Some families, like the Neritids, followed the patterns described above while other families, such as some of the Potamids, appeared to follow an opposite trajectory, suggesting a preference for disturbed habitat. In conclusion, it was consistent also that the molluscan fauna might include a range of specialist groups suited to the prevailing conditions, not unlike the already noted dominance of the habitat-forming, disturbance specialist of mangrove trees, *Avicennia marina*.

The structure and biodiversity of mangrove stands are influenced by local climate, so that stands in the Gulf are smaller in size and lower in biodiversity than mangroves in wetter sites along the east coast. We investigated several of the drivers that structure mangrove communities – including rainfall, sea level rise, cyclones, flooding and the sudden drop in sea level – to understand whether changes in these drivers had caused the dieback event. Only rainfall, sea level rise, and the sudden drop in sea level were recognised as having an impact on mangrove health in the results of our field studies.

Firstly, the influence of sea level rise had already been recognised for its influence on the succession of trees along the transects. Secondly, rainfall displayed a longer-term positive influence, where the width of mangroves was greater in wetter locations. Thirdly, the sudden drop in sea level had a significant positive relationship ($P < 0.01$) with the loss of fringing trees to dieback, where the amount of mangrove loss was related to the timing and severity of extremely low sea levels as recorded in port tide gauge records.

Cyclones and flooding can have considerable impacts on mangroves and tidal wetlands but the distribution and timing of these impacts are localised. Therefore, these influences on 2015–2016 dieback are considered additive, being patchy but with cumulative impacts that may disrupt longer term recovery. This was demonstrated by the impacts of two severe cyclones in the Northern Territory in 2018–2019 that caused significant damage to recovery processes, especially to sites around Mule Creek. Dieback areas revisited in late 2019 were notably stripped bare of seedling recruits and re-sprouting stems (Figure 26) where wrack piles of dead stems had been washed across these tidal wetlands (Figure 36), along with the erosion and re-deposition of sediments. The devastation was notable and severe, and it was expected to have long lasting consequences (Figure 37).

Figure 36. Between field surveys in 2018 and aerial surveys in 2019, we observed massive piles of dead Avicennia marina *trunks in rows and patches across the tidal zone, and especially at the highwater edge. The forces involved were demonstrated not only by the scouring of sediments and under-canopy plants but also by the flattening of short hardwood reference markers we had driven into the ground in 2018.*

Figure 37. The field studies provided a close up look at the processes of dieback and recruitment and how these shorelines were coping. For instance, it was evident that the sediment depositional conditions had changed once vegetation was gone and that this was contributing to further damage and dieback of survivors and recovering plants.

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