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Assessing the Gulf of Carpentaria mangrove dieback 2017–2019

Volume 2: Field studies

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Cover photographs

Front cover: NESP researchers conducting field surveys in Qld (photo: Norm Duke).

Back cover: Mabunji rangers assisting with field surveys in the NT (photo: Norm Duke).

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Acronyms

AM ....*Avicennia marina*

ANSTO ....Australian Nuclear Science and Technology Organisation

CAFNEC ....The Cairns and Far North Environment Centre

CLCAC ....Carpentaria Land Council Aboriginal Corporation

DCA ....Department of Communications and the Arts

DBH ....Diameter Measured at Breast Height

DTA....................Digital Transformation Agency

GBR ....Great Barrier Reef

GHHP.................Gladstone Healthy Harbour Program

HAT....................Highest Astronomical Tide

JCU....................James Cook University

MMP ....Mangrove Management Plan

MSL ....Mean Sea Level

NCCARF ....National Climate Change Adaptation Research Facility

NDVI ....Normalized Difference Vegetation Index

NESP ....National Environmental Science Program

NRM ....Natural Resources Management

NT ....Northern Territory

PCCC ....Port Curtis Coral Coast

Qld ....Queensland

SE ....South-East

S-VAM ....Shoreline Video Assessment Method

SW ....South-West

TC ....Tropical Cyclone

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

TUMRA ....Traditional Use of Marine Resources Agreements

WPSQ ....Wildlife Preservation Society Queensland

Abbreviations

Cape ....Cape York Peninsula

Gulf....................Gulf of Carpentaria

Vol. 1 ....Duke N.C., Mackenzie J., Kovacs J., Staben G., Coles, R., Wood A., & Castle Y. (2020) *Assessing the Gulf of Carpentaria mangrove dieback 2017–2019. Volume 1: Aerial surveys*. James Cook University, Townsville, 226 pp.

W Cape.............Western Cape

Acknowledgements

We thank and acknowledge the Traditional Owners of the land and sea country where we conducted these studies, 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 (Figure 0.1) continue to play in protecting the cultural, natural, and other values of tidal wetlands throughout the Gulf of Carpentaria region (Figure 0.2).

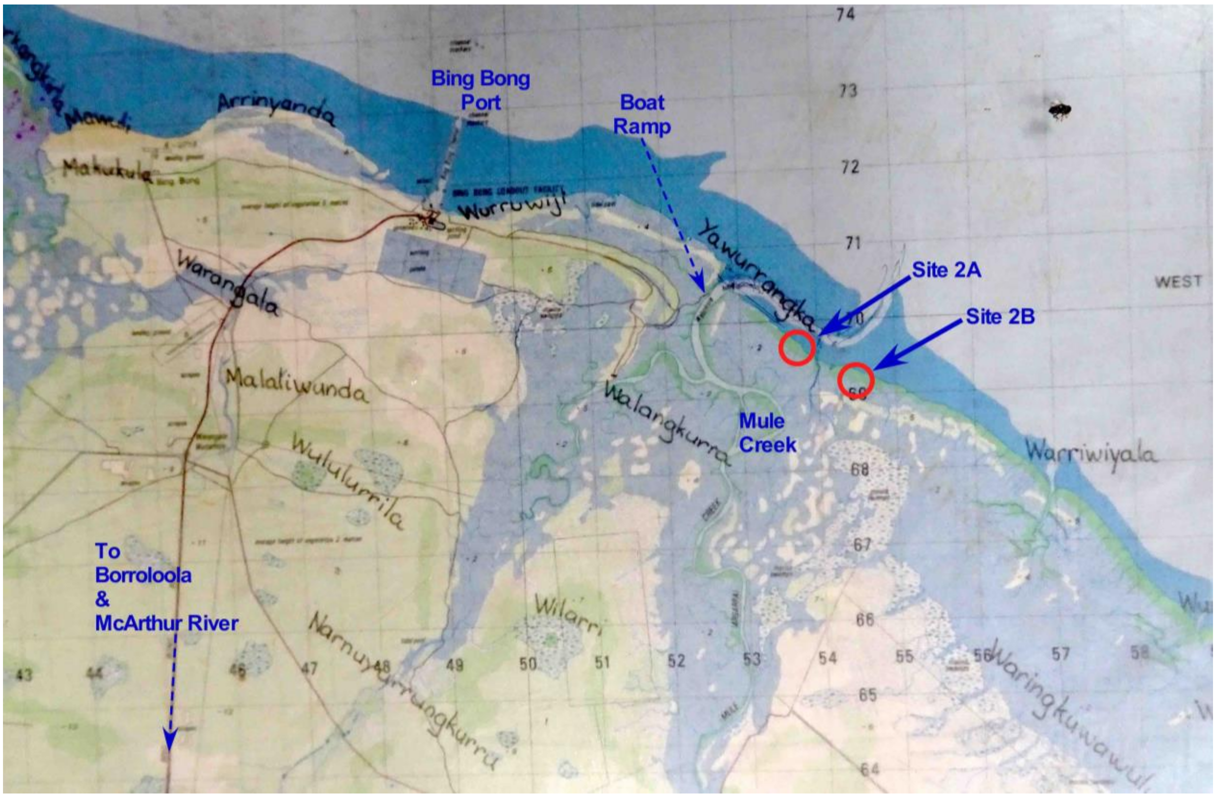

Figure 0.1. “This is our country … long time” say Il-Anthawirrayarra rangers with the Mabunji Aboriginal Corporation based in Borroloola. Annotations carefully scrawled in black pen across well-used, modern-day topographic maps literally brings home the profound message to visitors that this seemingly remote and isolated place is well-known Aboriginal homeland – as Traditional Owners of this south-west part of the Gulf of Carpentaria. Red circles mark the locations of field sites at Mule Creek (near Yawurrangka) used in these NESP investigations (Figure 5.2); blue text show other reference information. This homeland message applies to all Gulf land and sea country impacted by the 2015–2016 mass mangrove dieback. The local people are passionate about identifying external influences that threaten their natural and cultural heritage.

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We (Figure 0.3) further acknowledge our great appreciation for the assistance and support provided by Lindsay Hutley, Apanie Wood and Adam Bourke (Charles Darwin University), and John Kovacs and Ysabel Castle (Nipissing University). We especially thank the accomplished pilots with Cloncurry Mustering Company for navigating us safely and efficiently in the conduct of these aerial and field surveys.

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Survey data is available at eatlas.org.au.

Figure 0.3. A time for reflection after the fieldwork is completed.

Executive summary

1. This, Volume 2, documents the major findings of community meetings, ranger training sessions, publication outcomes and field studies – all concerning the mass dieback of mangroves that occurred in the Gulf of Carpentaria in late 2015. As with the studies listed in Volume 1, these in Volume 2 were also led by Dr Norm Duke with Jock Mackenzie from James Cook University (JCU) TropWATER Centre MangroveWatch Hub.
2. Field studies provided crucial validation of observations made from aerial surveys plus these on-ground studies added further significant insights of the impacts and subsequent changes that occurred across the Gulf coastline up to late 2019 – being four years after the severely damaging event in late 2015 (Figure 0.4).

Figure 0.4. Field studies were used to closely investigate the 2015–2016 mangrove dieback across the Gulf of Carpentaria from Queensland to the Northern Territory.

3. The overall statistics of the 2015–2016 mass dieback event in Australia's Gulf of Carpentaria include: dieback period of 3–4 months in late 2015; dieback area of 76.5 km^2 (Vol. 1: Table 3.1); 551 km of shorelines had dieback spread across 2,000 km of the Gulf (Vol. 1: Table 3.8); dieback of canopy trees dominated by *Avicennia marina* var. *eucalyptifolia*; based on 3,636 trees measured in field sites (Table 3.3); with dieback area tree densities ~5,152 stems/ha, equates to ~39.4 million trees having died with a total carbon content (above and below ground) for average sized trees of ~20.8 kg – equating

to ~820,895 tC released. Details surrounding the event are listed in the section ‘The mass dieback of Gulf mangroves in late 2015 – a summary’ (p. 8).

4. Project investigations were conducted in consultation with local communities and Indigenous ranger groups, particularly including 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 0.5) and Limmen Bight River. A series of training sessions were conducted with each of the ranger groups for their monitoring of estuarine shoreline condition in their areas (Figure 0.6) using the MangroveWatch shoreline video assessment method (S-VAM; Figure 0.7). In conjunction with these training sessions, we held public meetings for community members to both consult with and advise locals about these NESP investigations and our key findings. These meetings had the unexpected benefit to our partnership with rangers by raising their standing and status amongst their wider local communities.

5. Field studies primarily focused on shoreline fringing stands dominated by the Grey Mangrove *Avicennia marina* var. *eucalyptifolia*. And, while these trees were those most commonly impacted by the 2015–2016 mangrove dieback, this was mostly because of their overwhelming presence in the prevailing harsh climatic conditions of the region. Site selections were based on aerial surveys which had established that mangroves bordering estuarine banks were notably less affected. Transects were set up across impacted shoreline fringing stands to record vegetation present, stand structural parameters like the canopies of *A. marina* and under canopies of shrubby Club Mangrove *Aegialitis annulata*, the condition of these vegetation types including the 2015–2016 mangrove dieback, and the corresponding sediment elevation levels for each plant.

Figure 0.5. In situ discussions with local rangers helped explain our investigations while sharing knowledge of the event. This meeting was in transect 2 during October 2018.

6. Eight transects were set up in four representative locations of damaged shoreline fringing stands of mangroves across the Gulf region (Figure 0.8 – Figure 0.10). A standard experimental design was applied 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 (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 ~90%–100% loss of shoreline mangrove fringe (as severely impacted), while the other had ~60%–80% loss of mangrove fringe (as moderately impacted). As such, the transects were characterised by their relative amounts of surviving seaward fringes. And, each was backed by impacted dead trees up the tidal profile to the ubiquitous broad saltpans – typical of Gulf shorelines.
7. These transect elevation profiles showed common characteristics in mangrove distributions between sites for upper tidal range vegetation and the relationships between ecotone positions and elevation levels. For instance, there was general agreement between transects in the reference markers, including ~MSL around 1.52 ± 0.04 m where ~HAT was taken as the zero reference. This elevation range was consistent with approximately half the reported tidal ranges recorded in port tide gauges around the Gulf.

Figure 0.6. 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.

8. Transect vegetation zones measured in the field showed the zone of dieback (Figure 0.11) was consistently at the upper tidal range (back edge) of shoreline fringe stands with a mean elevation range around 0.44 ± 0.04 m – as the difference between pre- and post-impact elevations of the upper fringe ecotone (Table 3.2). 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. For these

reasons, the dieback impact was characterised by the reduction in elevation from the prior vegetation ecotone at the rear edge of shoreline fringing mangroves. It was of particular interest that the pre-impact ecotone, not the post-impact limit, 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.

9. As noted above, the most likely hypothesis for the cause of this instance of mass dieback was the temporary drop in sea level measured in port tide gauges. Using these port records, we derived a stress index that helped explain how the situation in 2015 was exceptional and rare. The presumed stress on mangrove trees was based on their sensitivity to moisture deficit when inundation by daily tidal flooding might be significantly reduced as shown in tide gauge records. This index was calculated as the multiple of severity times duration to quantify the conditions caused by extremely low sea levels during 1985 to 2019. The conditions calculated were most extreme in 2015. Furthermore, the extreme mean low levels were equivalent to the decrease in elevation between pre- and post-impact dieback elevation levels.

Figure 0.7. Instruction on MangroveWatch monitoring importantly involved hands-on use of the equipment with the aim of building autonomy as well as a local capacity for effective habitat monitoring. This session was with the Il-Anthawirrayarra rangers of the Mabunji Aboriginal Corporation in Mule Creek estuary in September 2019.

10. Tree dendrochronology studies in progress demonstrated that mangrove stands in shoreline fringes had unusually young trees. Stand demography estimates were consistent with these sites being relatively highly disturbed vegetation where most stems

were 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.

11. Field observations also included regular sightings of dead and degraded old tree stumps amongst sea edge fringing stands. The presence of these older stumps is further consistent with the succession deductions already noted above. As such, the next question was whether these stumps might represent a common earlier dieback event. The answer to this question represents another objective posed in the on-going investigations mentioned concerned with age determinations of wood samples from sites across the Gulf.

Figure 0.8. 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 a severe Category 3 Tropical Cyclone Owen in December 2018.

12. Transect mollusc faunae were understandably also influenced by the mass dieback. Our results show there was a greater diversity of 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 with the percentage of dead canopy trees ($P<0.01$) and the percentage of lost living biomass ($P<0.05$) with the mangrove dieback. However, the relationships between fauna and mangrove dieback were notably complex when looking at individual families. Some like the Neritids followed the patterns described above, while others like some of the Potamids appeared to follow an opposite trajectory suggesting their apparent 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*.

13. Several drivers of change were recorded during these investigations, including rainfall, sea level rise, cyclones, flooding, and the sudden drop in sea level. However, only rainfall, sea level rise, and the sudden drop in sea level were recognised 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 dieback loss of fringing trees where the amount of mangrove loss was matched in timing and severity by the extreme low sea levels recorded in port tide gauge records.

Figure 0.9. For field studies, a brief summary of achievements in sites in Queensland during August 2018.

14. Cyclones and flooding can have considerable impacts on mangrove and tidal wetlands, but the distribution and timing of these impacts are characteristically localised. These impacts around the Gulf shorelines are further recognised as more intense in some sections of coastline – in notable 'hot spots'. Therefore, these influences on 2015–2016 dieback are considered additive being patchy and manifest as accumulative impacts with serious disruptive influences on longer-term recovery. This has been demonstrated by the impacts of two severe cyclones in the Northern Territory in 2018–2019, which caused significant damage to recovery processes, especially to sites around Mule Creek. Areas of 2015–2016 dieback revisited in late 2019 were notably stripped bare of seedling recruits and re-sprouting stems (Figure 0.12), where wrack piles of dead stems had been washed across these tidal wetlands (Figure 0.13), 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 0.14).

Figure 0.10. For field studies, a brief summary of achievements in sites in the Northern Territory during October 2018.

Figure 0.11. 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.*

The mass dieback of Gulf mangroves in late 2015 – a summary

This summary lists our latest findings regards the 2015–2016 mangrove mass dieback event in Australia's Gulf of Carpentaria. Our observations were made during investigations from 2017 to 2019. We describe this unusual event and list the influencing factors observed, including one now considered the primary cause. Also described are further significant damaging events contributing additional and accumulative impacts onto these already stressed remote shorelines fringed largely by mangroves.

1. Mangroves were reported having notably severe dieback in a number of sites at widely separated locations on different sides of the Gulf of Carpentaria (the Gulf) in early 2016 (Duke et al., 2017). Our current investigations confirmed the timing of this dieback event was synchronous along ~2,000 km of the Gulf coastline (Vol. 1: Figure 3.4). Such an occurrence had never been reported before, and the cause was not immediately recognised. Because of the remoteness of the region, the mass damaging event was likely restricted to a relatively small number of environmental factors. The dramatic response of mass dieback implied that some factor exceeded a tipping point for the survival of these mangrove forests.
2. In all, around 7,650 ha of mangroves died with this single event (Vol. 1: Table 3.1), being ~6% of mangroves in impacted areas of the Gulf. Areas were measured from change detection of vegetation mapping, comparing satellite imagery between April 2015 and April 2016 for affected tidal wetlands (Vol. 1: Figures 1.1, 3.2, 5.21, 5.32, 5.46, 5.54, and 5.98).
3. Dieback specifically occurred at the upper edges of shoreline fringing mangrove stands (Figure 2.2). These were the higher elevation mangrove zone margins bordering the saltpan–saltmarsh zone within these tidal wetlands. Such circumstances indicated that this instance of dieback was somehow connected to changes in elevation levels of sea level – noting that upper zone edge stands were those most affected.
4. The occurrence of dieback affected multiple mangrove species, specifically *Avicennia marina* (grey mangrove – the most common mangrove in the Gulf and widely distributed around mainland Australia). Other common species include *Rhizophora stylosa* (stilt-rooted mangrove – a tropical shoreline species) and *Ceriops australis* (yellow mangrove – a drought-resistant tropical species). On occasion, dieback was concurrent along with multiple ecotone divisions between vegetation units by the occurrence of multiple dieback fronts at the upper zonation margins of each species zone (Vol. 1: Figure 1.1 inset).
5. These changes to ecotone margins were consistent with sudden alterations in shoreline elevation or sea level. Such factors have fundamental influences on mangrove distributions. While direct human-related factors like cutting and major oil spills were discounted because of the remoteness of the location, the lack of vessel traffic, and the scale of the impacted area – so to were indirect human-related factors like pathogens or insect damage.
6. The coincident survival of low height species including 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. However, those plants affected all had one physical character in common – they were taller (species-specific) above one metre in height (Table 3.4).

7. Green Fraction time series plots confirmed the timing of dieback was in late 2015, and that it was synchronous across the Gulf (Vol. 1: Figure 3.4). These plots showed further that since 1987 these shorelines had been following an apparent recovery trajectory with stable full canopies only established around 2000. This was consistent with there being an earlier occurrence of dieback prior to 1987.
8. Comparisons of historical satellite imagery (Vol. 1: Figure 3.5) showed the loss and depletion of shoreline mangrove fringing stands as seen in 2015–2016 had occurred earlier between 1978 and 1987. This was the first confirmation of an earlier mass dieback event. As observed in 2015–2016, this earlier dieback occurred in both the Northern Territory and Queensland.
9. At the time, severe El Niño weather conditions were experienced in the region, particularly along the north-east coast of Queensland where extreme high-water temperatures resulted in severe bleaching of coral reefs along the northern Great Barrier Reef (Hughes et al., 2017). This notable event was coincident with the severe dieback of mangroves in the Gulf (Duke et al., 2017).

Figure 0.12. During aerial surveys in 2019, we revisited the same site near the seaward edge of Transect 1A (see Figure 0.11) to find few standing dead Avicennia marina *trees and a much-reduced under-canopy – as the consequence of severe Category 3 Tropical Cyclone Owen between visits.*

10. The extreme weather conditions with the 2015–2016 El Niño event affected the Gulf area, where extremely high temperatures and prolonged drought conditions were experienced (Harris et al., 2017). However, these extreme weather conditions were not considered sufficient to severely damage mangroves. So, the sudden drop in sea level across the western Pacific region associated with this El Niño event warranted greater attention. The drop in sea level was evident in Gulf port tide gauge records where extreme low water levels of 20–40 cm occurred in three ports (Figure 4.4 and Figure 4.5) including 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 there (Table 3.1) corresponded with the loss in elevation in the areas of dieback measured in each of the field transects, but especially for the Karumba transects (Table 3.2 and Table 3.3).

11. Furthermore, a comparable link between such 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). On that occasion, 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 with this study, and there had been comparably severe dieback at the time between 1978 and 1987 (Figure 3.5). These observations provide convincing evidence of the earlier occurrence of mass mangrove dieback.

Figure 0.13. 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.*

12. As it stands, while these new discoveries make a compelling case for an earlier occurrence of severe mangrove dieback, they were also consistent with the cause being the sudden drop in sea level. Such an occurrence means that it might be possible to predict or anticipate future events. The evidence for a prior occurrence includes historical satellite imagery back to 1972; the recovery (or re-establishment) trajectory for shoreline mangroves around the Gulf since 1987 shown in 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.

13. Furthermore, additional evidence from these field studies document a distinctive demographic structure of seaward fringing mangroves across the Gulf (Figure 5.8, Figure 5.15, Figure 5.22, Figure 5.29, Figure 5.36, Figure 5.43, Figure 5.50, and Figure 5.57). The average tree age appeared to be much younger than those observed in other places (Duke, 2013; Mackenzie & Duke, 2011). Although our assessment of tree age was incomplete for this report, there were reliable indications that mangrove trees of Gulf shorelines had a mean age around 9–10 years with maximal age individuals around 20–30 years (Figure 5.8, Figure 5.15, Figure 5.22, Figure 5.29, Figure 5.36, Figure 5.43, Figure 5.50, and Figure 5.57). Should these deductions be confirmed, it suggests 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 accumulative 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 the recovery of fringing mangrove stands damaged in 2015–2016?

14. Sea level rise has been relatively rapid in the Gulf region between 1993–2007 (Church et al., 2009; Church & White, 2011) – with rates (up to 12 mm/yr) exceeding global averages by ~8 mm/yr. As mangroves are intimately dependent on sea level they are likely to have responded in recognisable ways scored during this study, like shoreline erosion (loss of lower elevation, seaward fringing mature vegetation around mean sea level; Vol. 1: Figure 2.15), saltpan scouring (sheet erosion of saltpan sediments, loss of saltmarsh vegetation, gully erosion; Vol. 1: Figure 2.22), and terrestrial retreat (loss of terrestrial trees with saline intrusion above the highest astronomical tides, edge erosion and scouring, expansion of mangrove seedlings upland; Vol. 1: Figure 2.16). These indicator severity scores for the 37 estuaries confirm these expectations with strong correlations with rising sea levels, especially terrestrial retreat (Vol. 1: Figure 4.5) and saltpan scouring (Vol. 1: Table 2.8). While no such correlation was found with sea level rise and shoreline erosion, this was consistent with a number of other factors directly impacting 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 disrupting the progressive influences of sea level rise on fringing mangroves.

15. A notable positive correlation with sea level rise was the 2015 mangrove dieback (Vol. 1: Table 2.8, Figure 4.4). This relationship suggests that where sea level rises were greatest, then the impact on mangroves to sudden drops in sea level would also be greater. Therefore, in places generally where the resilience of mangroves was weakened appreciably, then 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 do suggest that the poorer condition of shoreline trees responding to rising rates of sea level rise may reduce their ability to re-locate upland. This poses a serious threat to the longer-term survival of tidal wetlands faced with rising sea levels.

16. Field studies also showed that for several transects the relative size of trees decreased from larger trees at the seaward edge to smaller trees at the higher elevation back edge of the fringe zone (Figure 3.4). This ordering of size classes was consistent with younger trees at higher elevation levels and the situation expected with steadily rising sea levels.

17. Tropical cyclones could be distinguished by the damage they cause being local and dependent on severity, along with other factors like tide levels at the time of impact (Vol. 1: Figures 0.6, 0.7, 2.13, 4.6, 5.86, 5.89, 5.92, and 5.112). Furthermore, the impacts were not evenly distributed around the Gulf since there are 'hot spot' shoreline sections, where the frequency of cyclones had been higher (Vol. 1: Figure 2.14). On the whole, the Gulf experiences one notable cyclone ever two years. But, the occurrence of particularly severe cyclones (Category 3 and above) come in periodic clusters every 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 categories (Category 2 or less).

18. 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 (Vol. 1: Figure 0.7) in December 2018, and TC Trevor (Category 4) affecting the Robinson (Vol. 1: Figures 0.6, 4.6 and 5.89), Calvert (Vol. 1: Figure 2.13) and Wearyan (Vol. 1: Figure 5.92) estuaries in March 2019. 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 2015 dieback and scour, large patches of fallen and broken stems, and defoliation of canopy leaving estuary edge exposed trees intact.

Figure 0.14. 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 this was contributing to further damage and dieback of survivors and recovering plants.

19. Flooding was notably 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 (Vol. 1: Figures 2.23, 5.26, and 5.48), and significant depositional gain where young seedlings were observed widely around the mouth occupying seafront mudbanks (Vol. 1: Figures 2.20 and 5.24). There

was a significant correlation between bank erosion and depositional gain indicators (Vol. 1: Figure 4.7) 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, show 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.

20. The longer-term influence of such accumulative impact factors is likely to seriously impede and even reverse recovery processes taking place in sites of repeated impact. Such outcomes were observed during these investigations. Recovery of 2015–2016 impacted sites had been observed generally in 2018 where damaged trees had re-sprouted, and there was the notable establishment of seedlings of replacement canopy trees. However, subsequent severe tropical cyclones in late 2018 and early 2019 impacted Northern Territory sites resulting in significant damage to 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 dieback stems were mobilised, running over and scouring seedlings and survivors alike. These sites were seriously degraded and left relatively more bare and lifeless (Figure 0.11 and Figure 0.12).

21. In summary, the observations made during this NESP project document both the 2015–2016 mass dieback of mangroves along Gulf shorelines, as well as a number of subsequent accumulative impacts of damaging events of severe cyclones and flooding up to 2019.

22. The implications for management and environmental policymakers can be divided into two strategies. One deals with the cause 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 accumulative local human-related impact factors like feral pig damage, scorching by fires and smothering by weeds. 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.

1. Introduction and extended observations

In this, Volume 2, we document and present the findings from field studies investigating the 2015–2016 incident of mass mangrove dieback in the Gulf of Carpentaria (Figure 1.1). Volume 2 also includes a summarised account of publications, meetings attended and formal presentations as additional project outcomes for both engaging and informing project end users and stakeholders.

Figure 1.1. Eight transects were established and studied in the four field sites in the Gulf of Carpentaria representing the breadth of impacted areas from Queensland to the Northern Territory.

For the research part of this project, it was critical to firstly validate observations made from mapping studies and aerial surveys. And then, to extend key lines of investigation already initiated into the cause, and whether such a severe incident might be repeated in the future.

2. Research methods for field surveys

2.1 Study area and survey sites

Field studies were conducted in four locations across the Gulf of Carpentaria (Figure 2.1). The selection of locations was based initially on the widely placed instances of severe dieback of the mangrove fringe. Each of these locations of mangrove dieback was distinguishable and concurrent having occurred at the same time in 2015–2016.

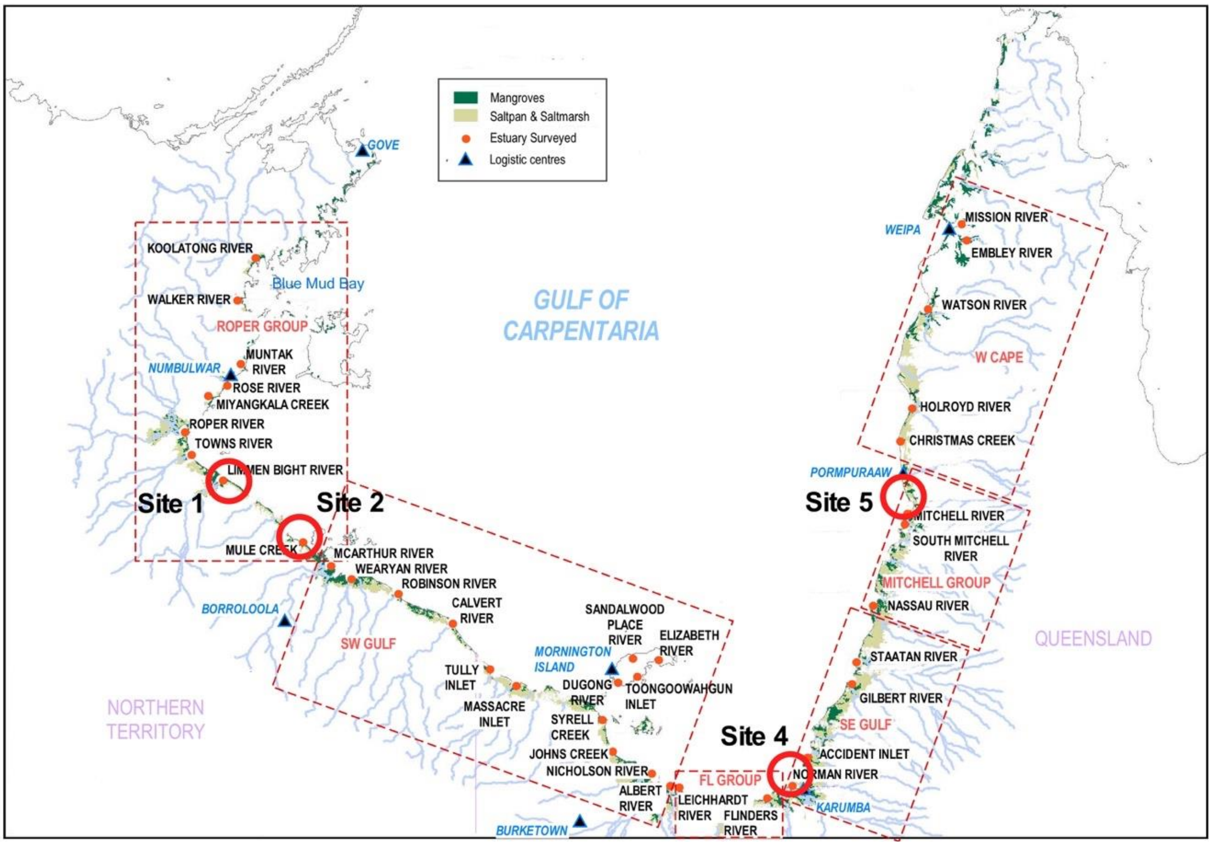


Figure 2.1. The locations of the four field study sites in the Gulf of Carpentaria representing the impacted shoreline from Queensland to the Northern Territory. Also shown are the 37 estuaries scored from the six regional drainage areas (CSIRO, 2009a-i) used in Volume 1 of this report.

Further specific observations of the dieback also determined that the field investigations were to focus on seaward facing shorelines since mangroves along estuarine channels and waterways were generally less affected (for example, see Vol. 1: Figures 1.1 and 3.2; Duke et al., 2017).

There were two major periods of field studies taking account of the logistic challenges associated with working in distantly separated locations in this remote part of Australia. These studies started with the two locations in Queensland during 4–10 August 2018 and then moved onto those in the Northern Territory during 11–17 October 2018. The aim was to have these study dates as close as possible, so the data from all field sites on post-impact vegetative condition and elevation profiles were comparable.

2.2 Transect studies

A total of eight transects, perpendicular to the shoreline were established at the four shoreline sites across the Gulf of Carpentaria (Table 2.1; Figure 2.1). These included matched pairs of two condition treatments for each of two severity levels of 90%–100% and 60%–80% dieback of mangrove fringes (Figure 2.2; Vol. 1: Figure 2.2). This experimental design enabled the comparison of each site with each of these impact conditions and the importance of established foreshore vegetation. In each of the four sites, one transect had little or no surviving seaward mangrove fringe (e.g., Figure 5.6) while the second transect had a significantly wider surviving seaward mangrove fringe (e.g., Figure 5.13). One aim was to evaluate the relative recovery status for sites depending on the width of surviving fringes. Another aim was to investigate reasons for different impact severity levels and whether these depended on particular site characteristics. Aerial surveys clearly showed that severity levels varied within locations and throughout the impacted region (Vol. 1: Figure 3.13).

Table 2.1. Locations of field transects for paired sites in each of four locations of severe (90%–100%) and moderate (~60%–80%) severity of 2015 mangrove dieback in Queensland (Qld) and the Northern Territory (NT).

State	Site #	Transect locations	Latitude S	Longitude E	Type
NT	1A	Limmen – Roper region	-15.146215°	135.788778°	90%–100%
	1B		-15.171145°	135.836993°	60%–80%
	2B	Mule – Roper region	-15.650919°	136.441971°	90%–100%
	2A		-15.647369°	136.434148°	60%–80%
Qld	4A	Karumba – SE Gulf	-17.422561°	140.853576°	90%–100%
	4B		-17.340024°	140.896250°	60%–80%
	5A	Mitchell north – W Cape	-15.027324°	141.665424°	90%–100%
	5D		-14.996538°	141.660919°	60%–80%

The tidal wetland terrain of much of the Gulf was typically complex because of the historical interplay of mangrove-lined, dendritic tidal channels and remnant chenier mounds and ridges – as records of past conditions of shoreline topography and sea level. Remnant mounds were often vegetated and distinguished by plants of the supratidal zone. And, these raised patches each had beach wash zones indicative of the highest reach of tidal waters (Figure 2.3), marking convenient, albeit approximate levels of highest astronomical tides (~HAT). In complement to this primary reference position, a second reference position at the sea edge of mangroves was taken as a proxy relative to mean sea level (~MSL). These two positions conveniently bracket and define the tidal wetland zone as the upper half of the tidal range normally occupied by mangroves and saltpan–saltmarsh habitat (Duke et al., 2019a). The two marker positions were convenient and useful comparative reference points for these investigations of field sites in this remote region of Australia. So, despite these investigations lacking the budget for more precise measurement of universal elevation data, these proxy reference positions provided an effective comparison of elevation levels and vegetation condition amongst the study transects.

Each transect was based or anchored at the nominal Highest Astronomical Tide (~HAT) level of the highwater benchmark at each transect 'head' (Figure 2.2, Figure 2.3, and Figure 2.5). The location of the head position was chosen so that a straight line transect could be taken to the fringing mangrove stand, and to the sea edge at the proxy position of mean sea level (~MSL). As noted, these two common reference points were established for each of the eight Gulf transects.

Furthermore, the locations of three additional 'internal' ecotone position markers (Figure 2.2 and Figure 2.3) between ~HAT and ~MSL of the tidal wetland zone were recorded for each transect, including the landward fringing mangrove to the saltpan–saltmarsh position (M1-lower); the lower elevation limit of saltpan–saltmarsh bordering the upper dieback mangrove edge (M2-upper); and the lower elevation limit of mangrove dieback (M2-dead/live).

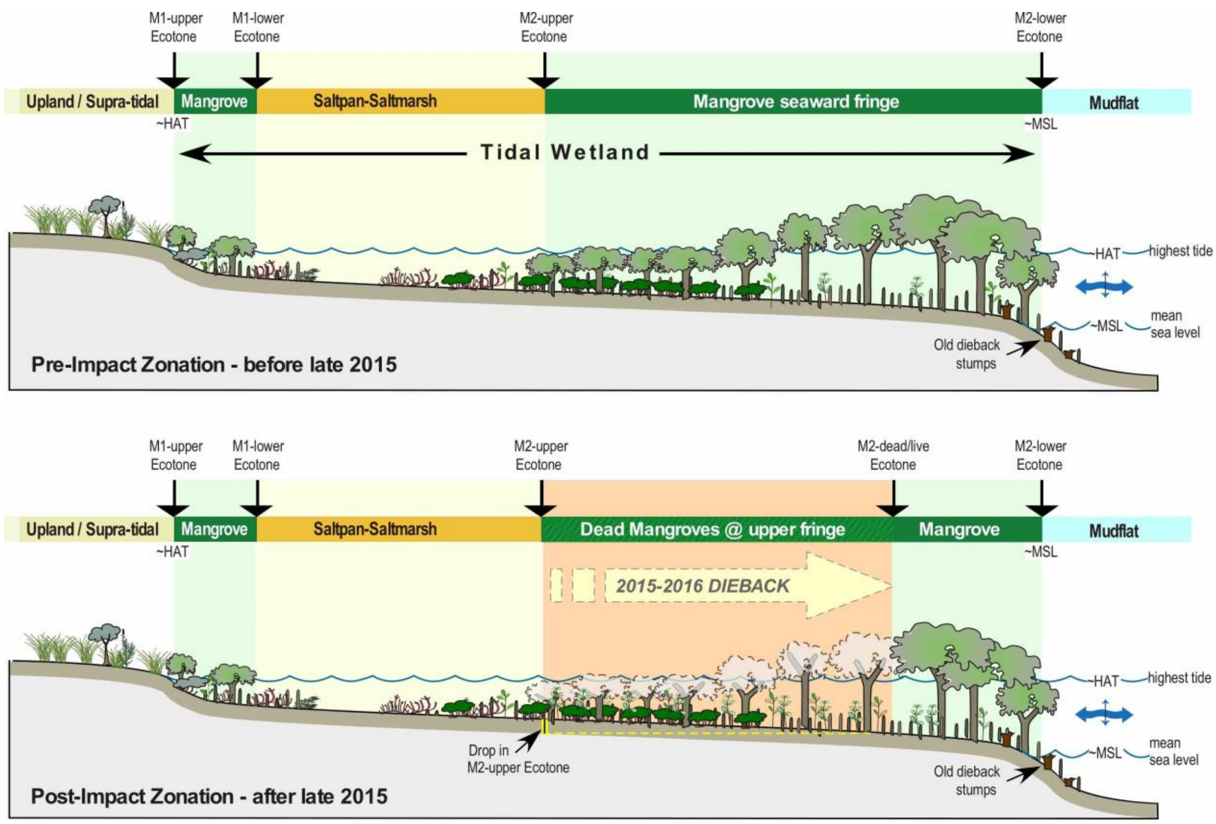


Figure 2.2. Characteristics used in field studies to define elevations and distances along transects as vegetation ecotones along the upper half of the tidal range – the niche of the tidal wetland zone. The profile images depict a relatively arid shoreline as in the Gulf of Carpentaria, before and after the severe impact of 2015–2016 dieback of the seaward mangrove fringe. As there were few obvious changes in ~HAT and ~MSL ecotones, damage severity could be quantified by the retreat seaward of the M2-upper ecotone to the M2-dead/live ecotone position.

Transect locations were usefully identified using National Map[1] (Australian Government, 2020). This is an online map-based tool to allow easy access to spatial data from Australian government agencies. It was an initiative of the Department of Communications and the Arts (DCA) now currently managed by the Digital Transformation Agency (DTA) and the software

[1] nationalmap.gov.au

has been developed by Data61 working closely with the DCA, Geoscience Australia and other government agencies.

2.3 Transect vegetation assessments – long plot method

Long plots were used to describe and quantify mangrove and saltmarsh vegetation along each transect. This method was essentially a transect plot developed specifically for rapid and practical assessment of mangrove forests. Long plots were essentially narrow, 1–4 m wide, continuous forest plots laid out in this Gulf study perpendicular to the shoreline. This was done because the specific location of 2015–2016 dieback appeared associated with the tidal range and elevation.

The long plot method (Figure 2.4) allowed the plot width to be adjusted during the survey depending on stem density of particular sections along the transect. As long as an accurate account of plot width was recorded, then changes in stem densities did not significantly slow or diminish the characterisation of transect vegetation. In practice, where there were closely spaced trees, plots were narrower (<2 m wide) than where trees were larger and further apart (>2 m wide). These measurements were achievable and successfully collected within a day for each transect.

Figure 2.3. The 'head' of Transect 1A with measuring tape to the 30-metre mark (next to rotary laser on its tripod) showing the alignment towards the seaward mangrove fringe. Note the expansive saltpan – a common feature of these Gulf transects.

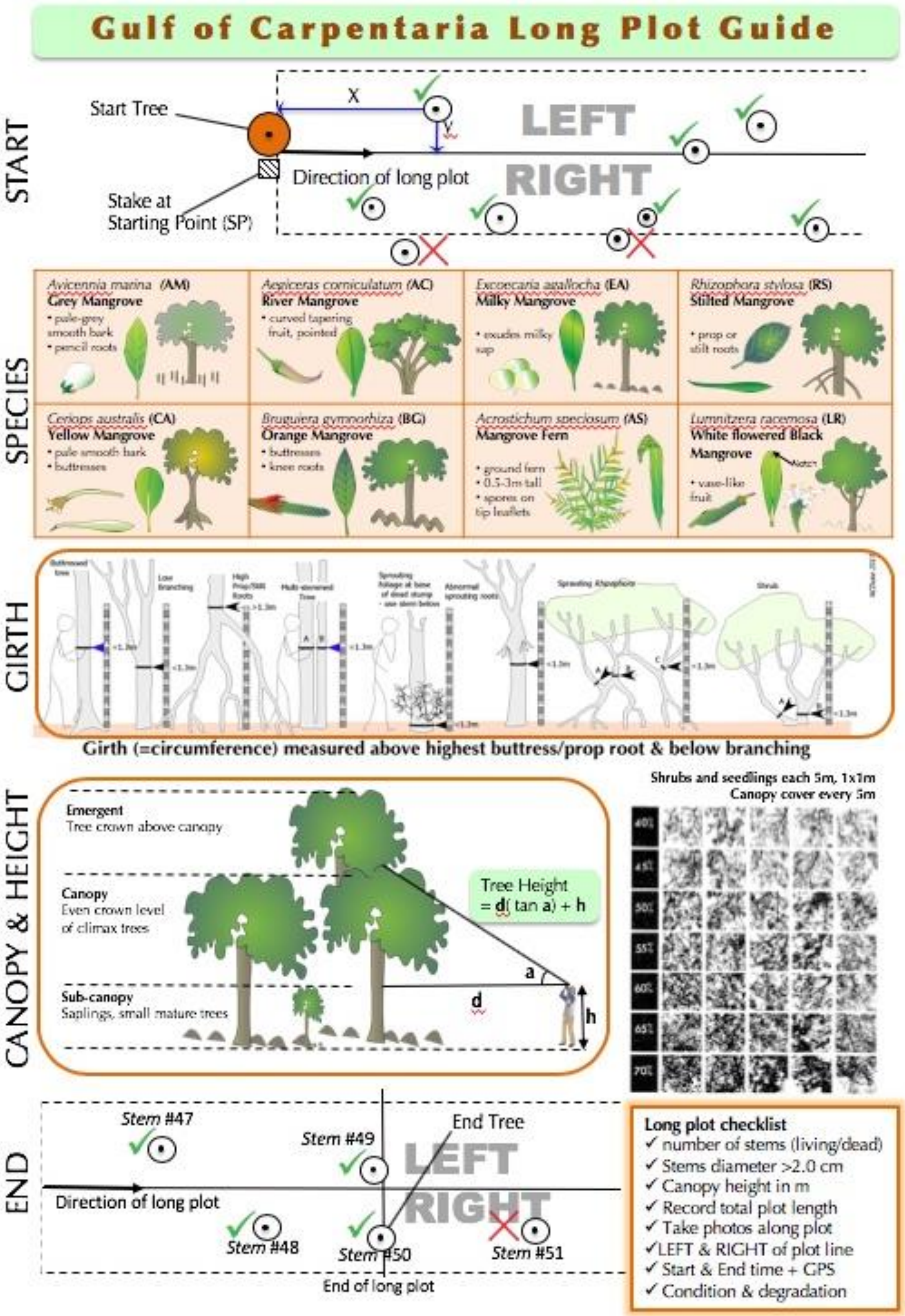


Figure 2.4. Summary of the long plot method used in field studies for measurement of forest structural characters along transects in the Gulf of Carpentaria.

2.4 Transect setup

Specific steps in setting up each transect (Figure 2.4) included:

1. Selection of the 'head' of the transect to establish its starting point (Figure 2.3 and Figure 2.5). The head was marked with a permanent hardwood stake just above the highest tidal wash zone (~HAT). A second hardwood stake was installed 30 metres along the transect line to consolidate the alignment of the transect in a direction running perpendicular towards the nearest part of the seaward shoreline edge (~MSL).
2. Details and descriptive information about the location were recorded on datasheets for each transect, including the GPS location coordinates for each of the hardwood markers, and the seaward edge – as well as intermediate reference points. Temporary intermediate markers were used along the transect to provide working reference points while measures were taken from each end position of 100 m transect tapes laid along the ground. Transect measuring tapes were laid out all the way from the head marker to the sea edge amongst or just beyond the last trees.

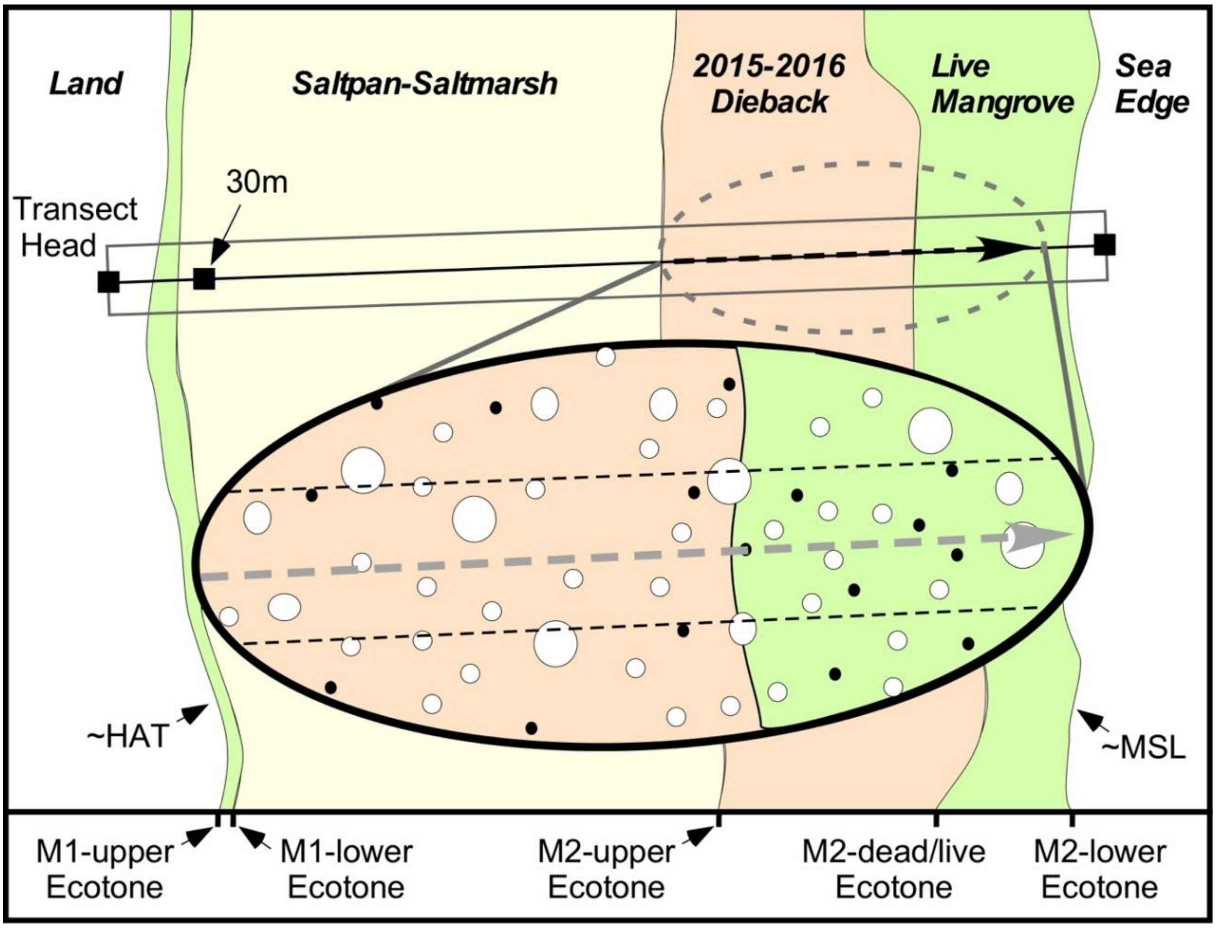


Figure 2.5. Characteristics of transect layout showing the 'head' and reference markers along with key vegetation ecotones across the upper half of the tidal range – the regular niche of the tidal wetland zone. The oval inset shows a portion of the idealised transect swath and its capture of representative trees and shrubs (circles). This view of a tidal wetland shoreline depicts a relatively arid setting as in the Gulf of Carpentaria with moderate impact of 2015–2016 dieback of the seaward mangrove fringe. Damage severity was quantified as the proportion of the mangrove shoreline fringe zone (M2-upper to ~MSL) that died.

3. Elevation levels were recorded at 20–30 m intervals or more frequently where there were notable changes in topography or there were notable changes in vegetation type and condition. Levels were made using a Topcon construction surveyors rotating laser and staff (Figure 2.6). Where it was necessary to relocate the laser instrument, additional reference points were taken for each transition point providing offset measures to link each series of measurements. Elevation levels were recorded all the way from the head marker to the sea edge amongst or just beyond the last trees.
4. Vegetation was scored for species, stem diameter, height, condition as well as distance along the transect and distance left or right of the measuring tape (Figure 2.7). Trees were scored in 30 m sections within a fixed distance from the measuring tape depending on stand density. The width was mostly set at two metres, but on occasion, this was reduced to one metre or up to four metres wide as necessary.
5. Along each transect, at each 30-metre interval or at ecotone points, photographs were taken at four square directions to the transect line – towards the sea, 90 degrees to the right, back towards the 'head' and 90 degrees to the left. At these same points, canopy photos were taken using a camera with a fisheye lens.

In this way, vegetation structure and condition along transects were quantified using recognised stand descriptors, including species; ecotones; structural form; the height of individual trees; stem diameter of individual trees; plot area; density of trees; condition of trees and habitat; comments on canopy foliage; as well as the extent of 2015–2016 dieback.

Figure 2.6. Elevation levels were made using a Topcon rotary laser with a range of around 500 metres depending on the density of vegetation.

Special consideration was taken in measuring stem diameters because slight differences in these measures could create considerable differences and errors in calculations of biomass and carbon content when using allometric equations. While terrestrial forestry practice recommended that stem diameter be measured at 1.3 m above the ground – as diameter measured at breast height (DBH) – this was found to be impractical in these and other mangrove forests. For example, for more than 50% of tree species measured in studies of south-western Pacific mangrove stands (Duke, 2013), DBH could not be applied literally. It was considered inappropriate to use this rule in the measurement of stem diameter of tree and shrubs in these mangrove forests. The difficulties encountered included the common occurrence of multiple stems, short height mature trees and shrubs (<1.3 m), multiple forms of plant types (shrubs and trees), low branching (<1.3 m), and high placed roots and buttresses (>1.3 m). Therefore, a more appropriate standard was applied in these studies of mangroves in the Gulf. This mangrove standard rule for measurement of stem diameter was adaptable and effective by following the rule of measuring stem diameters above highest prop roots and buttresses and below lowest branching. Accordingly, specific examples of different stem (girth) measurements for different stems are illustrated in the long plot method summary sheet (Figure 2.4).

2.5 Biomass and carbon estimations

Calculations of biomass and carbon content of individual trees and stands of trees (above and below ground) relied on the use of appropriate and confirmed allometric equations (Komiyama et al., 2008). These equations use the relationship between plant structural measures (like stem diameter and height) and the dry weight of the key components. These equations were dependent on mangrove species, but these differences could be captured in a common equation where wood densities defined species variability (Komiyama et al., 2005; Chave et al., 2005).

Figure 2.7. The transect measuring tape provided the reference from which to quantify mangrove vegetation structure and condition across each tidal wetland profile.

2.6 Wood sampling and tree coring – a study in progress

An investigation into wood cores of dieback impacted mangrove trees was initiated using wood samples collected during these field studies in the Gulf of Carpentaria. The studies could not be completed for this final report, however, on the strength of the results gained, a supportive grant from the Australian Nuclear Science and Technology Organisation (ANSTO) was awarded for the high-level analytical work required, including elemental scans and carbon dating. These studies are expected to significantly enhance this project's outcomes. The results will be reported upon and published at a later date.

During this investigation, tree stem wood cores were sampled from Grey Mangroves, *Avicennia marina* var. *eucalyptifolia* – the dominant mangrove tree species in the Gulf – and the one most impacted by the 2015–2016 mass dieback. As noted, samples were collected during field surveys in 2018 from the same locations across the Gulf region.

Wood samples included both living and dead trees – as trees that died during the 2015–2016 dieback event and others that had survived. Dead trees were sampled as slices of the main stem (Figure 2.8) around 20–30 cm above the ground but below major stem branching. Live trees were sampled, taking a 2 cm diameter core at a similar position. Cores were taken from the outer surface to the tree centre and through to the opposite side, where possible. Living trees were otherwise unharmed. Sample locations and other details were recorded, and samples were stored in a dry state in readiness for assessment and analyses.

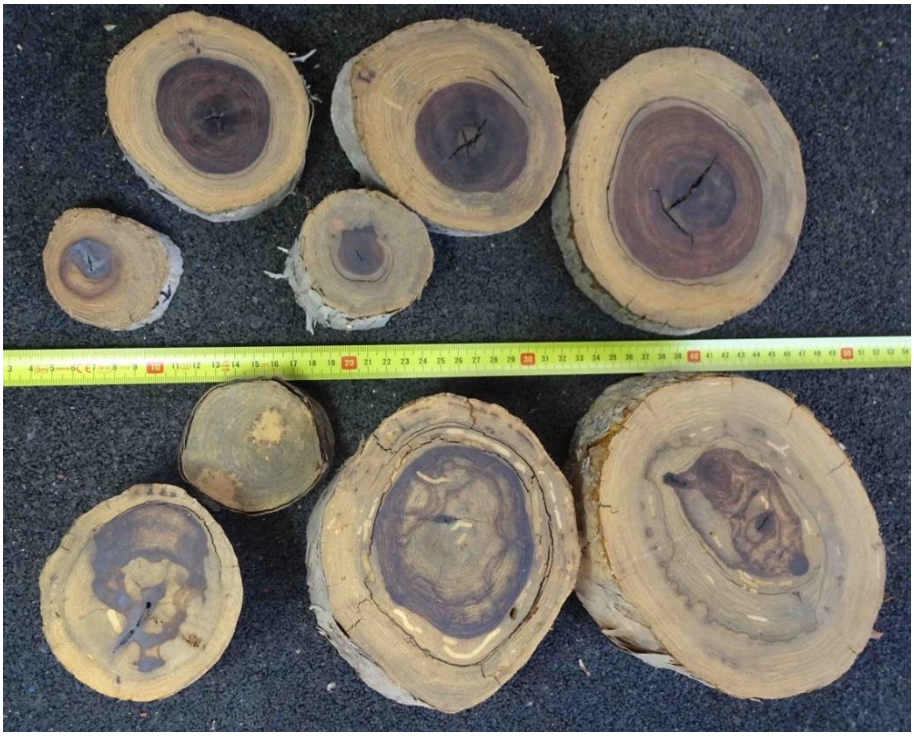


Figure 2.8. Stem section samples from dead trees killed in the 2015–2016 dieback incident were taken at each of the eight Gulf transects in 2018.

Wood cores and sections from 28 trees were cut and sanded to best display cross-section radial sections of tree centre to bark edge. Where possible the number of laminae (as de facto wood rings) crossing, each of three radial sections was counted and averaged for each individual tree. These ‘ring’ measures were prepared as time interval series as individual sequences for each tree. In addition, the sequence position of dark stained wood seen in the wood sections was also recorded for each individual tree (Figure 2.8). These stained sections will be checked since they may represent ‘event scars’ where such staining might be a response by trees during periods of severe stress.

Wood fragment samples were also collected from each of the eight transects in recognition of the common occurrence of degraded dead stumps in all locations. The presence and frequency of dead stumps indicated there had been significant earlier dieback. The question we are asking is whether these were the result of localised factors like storm damage, or was it related to an earlier widespread concurrent event like the 2015–2016 mass dieback event (Figure 2.9). Samples were taken for carbon dating to be also done with the ANSTO grant.

Figure 2.9. Making sense of a dire and chaotic situation.

2.7 The sampling of molluscan fauna

Molluscs were sampled at the lower edge of seaward mangrove stands at each of the eight Gulf transects. In moderately impacted sites, this meant that sampling was done amongst remnant living mangrove stands, while most severely affected sites had no living canopy trees (see *Transect summary data* section). The question was whether there were any notable differences in fauna present in these often quite different environmental conditions. And, how had these fauna responded with site recovery three- and four-years post-impact. Sampling was accomplished using live animal sampling, identification and counts of molluscs present in three 1 m^2 quadrats along with a broader assessment to determine local biodiversity.

3. Results of field studies and communication

3.1 Transect profiles, vegetation present and 2015–2016 mangrove dieback

The four widely distributed study sites in the Gulf of Carpentaria each shared common types and severity of impacts resulting from the 2015–2016 mangrove dieback event (Figure 2.2). These impacts included the severe dieback and loss of fringing mangrove forests bordering Gulf shorelines. Dieback occurred commonly at the rear or upland side of the dense seaward fringing stand of mangrove trees and shrubs. In most sites, the mangrove fringe was backed by broad and flat saltpan–saltmarsh plains. The maximal tidal reach extended from the mangrove fringe and across the saltpans often much further inland. In many locations, the upland terrestrial margin was more than a kilometre from the mangrove sea edge.

3.1.1 Validation of aerial survey findings

All findings made from aerial survey assessments were confirmed in the field study transects. These observations were made in recognition of it being three years since the dieback event. Mangroves of fringing stands had suffered notable dieback along their saltpan–saltmarsh edges. The species dominating each site was *A. marina*, the Grey Mangrove. Most dead trees had died standing, and there were few signs of there being any physical damage associated with the 2015–2016 dieback event. This included the lack of any consistent accumulations of sediment or erosion around stem bases nor there being any consistent smothering or exposure of emergent breathing roots (pneumatophores).

3.1.2 Elevation profiles

The aim of this assessment of field observations was ultimately to identify whether any factors might explain the types of changes observed. The key descriptive attributes for each transect are summarised in Table 3.1 and Table 3.2, and listed in the *Transect summary data* section. The length of the transects varied from 196–790 m, representing a notably conservative measure of the width of the tidal wetland zone. The relative elevation range of the tidal wetland varied from 1.4–1.73 m with a mean of 1.5 ± 0.04 (1X SE) m. This value broadly equated to half the tidal range for the region (Table 3.1 and Table 3.2). In a specific example, the two transects in the Karumba area (4A and 4B) had a mean range of 1.47 m, while the reported tidal range for the local port was 3.3 m. This was consistent with the view that mangroves mostly occupy only the upper half of the tidal range (Duke et al., 1998).

The width of the seaward fringing stand of mangroves varied from 81 to 397 m. The proportion impacted by the 2015–2016 dieback varied from 68.1% to 100%. For the two treatments, this varied with severely impacted 93.8% to 100% and moderately impacted 68.1% to 75.6%.

*Table 3.1. Descriptive attributes for Transects 1A, 1B, 2B, 2A, 4A, 4B, 5A, and 5D (also see Transect summary data). *Height (elevation) readings were negative. Note: HAT was treated as the zero reference point for both elevation and distance. See Figure 2.2 for an explanation of the codes used. Mean values are displayed in Table 3.2.*

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 3.2. Means of the descriptive attributes for the eight transects (also see Transect summary data). Note: HAT was treated as the zero reference point for both elevation and distance. * indicates means with <5% variance. See Figure 2.2 for explanations of the codes used. Values for individual transects are displayed in Table 3.1.*

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

Where transects had zero elevation levels at each HAT marker, the MSL-HAT values (Figure 2.2) defined the entire elevation range of the tidal wetland zone (the upper half of the tidal range) with closely comparable elevations around 1.52 m for these transect profiles. While the position of this zone depends on sea level, tidal range, and topography, the three 'intermediate' ecotone markers between (M1-lower, M2-upper, and M2-dead/live; Figure 2.2) are thought to be influenced by rainfall (Duke et al., 2019a) and possibly another external factor associated with the dieback. As such, the prior position of M1-lower and M2-upper positions depended on longer-term rainfall conditions. And, most notable amongst these ecotones was the observation that the 2015–2016 mangrove dieback event almost entirely involved an extreme shift and lowering of the 'M2-upper' ecotone to a new location defined as the 'M2-dead/live' ecotone position – at least in the short term. It was significant that the damaging agent was no longer affecting transect vegetation during the field investigations.

The extent of dieback could also be equated to the elevation range of impacted sections along the transects, with a mean of 0.44 ± 0.04 (1X SE) m. This amount quantified the decrease in the tidal range observed in the upper elevation limit (M2-upper to M2-dead/live) of mangroves in seaward fringe stands. It also quantifies the degree of stress on mangroves in terms of the decrease in the tidal range needed to affect such a change. And, as shown earlier in Table 3.1, sea levels were extremely low over a five-month period in 2015 from June to October. For the Karumba area, sea levels were measured around 0.47 m below the 5-year running monthly average. The dieback elevation range near Karumba was averaged for the two transects there at around 0.57 m. This evidence of comparable amounts of sea level change for the physical driver attribute and the measured vegetation response is further consistent with the compelling case for the primary cause of the 2015–2016 instance of mass mangrove dieback being the drop in sea level.

3.1.3 Vegetation structure and diversity

The distribution of mangrove and saltmarsh vegetation across the tidal wetland zone (~HAT to ~MSL, Figure 2.2) is defined and constrained by location, climate, and physical characteristics of the shoreline (Duke, 2006). For the eight Gulf transects, these extended across extremely low relief shorelines with slopes between 1:113 and 1:564 (Table 3.1 and Table 3.2). Mangroves growing across these broad upper tidal transects (196–790 m wide) distinctively occupied only part of the tidal slope. As noted, these were characterised mostly by the relatively wide seaward facing fringe (81–397 m wide), defined in this study by two 'intermediate' ecotones, M2-upper (saltpan–saltmarsh interface with mangrove) and ~MSL (mangrove interface with the open sea). The 2015–2016 dieback characteristically impacted large portions of the mangrove fringe zone – defined between ecotones M2-upper and M2-dead/live. For two transects, the entire fringe of mature trees had died, depicted by M2-dead/live equalling the ~MSL ecotone.

The structure and condition of vegetation along the eight transects are summarised in Table 3.3. Each mangrove stand was characterised by a combination of canopy and under-canopy plants. Canopy plants were notably dominated by mature *A. marina* trees with only occasional additional species like *Rhizophora stylosa*. Under-canopy plants were dominated by mature shrubs of *Aegialitis annulata* plus saplings and seedlings of *A. marina*. Significant numbers of individual plants within each grouping were measured and scored. The number varied between transects because of the sometimes very different densities found in some locations (Table 3.3). There were notably lower densities of canopy trees in severely impacted sites. This was mostly comparable with under-canopy plants.

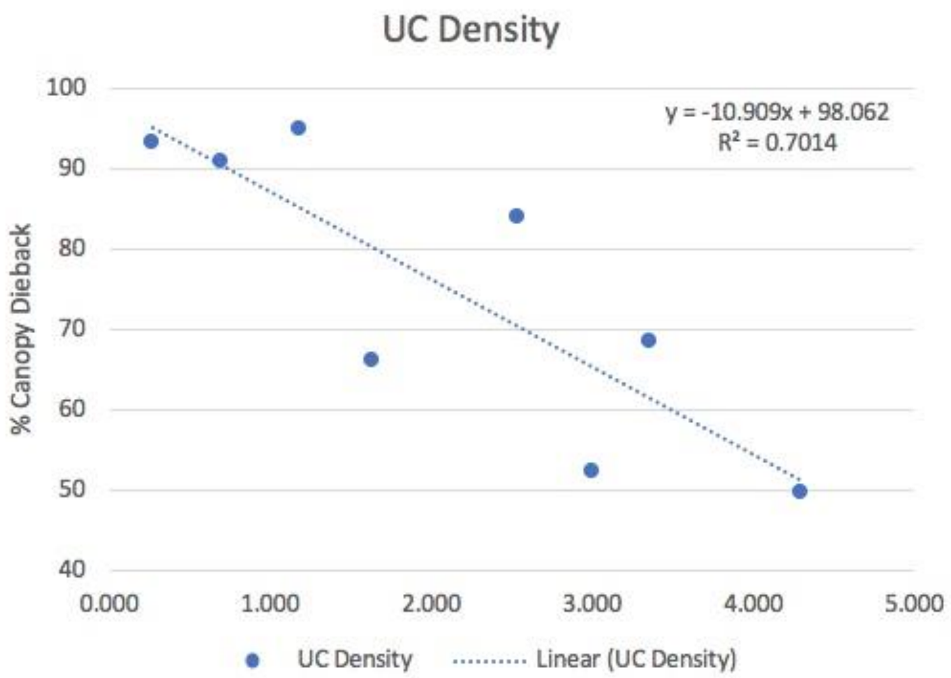
Canopy trees of *A. marina* were mostly relatively low in stature with mean heights between 1.4 and 2.9 m (1.9 ± 0.2 (1X SE)) with mean stem diameters between 4.1 and 7.9 cm (6.0 ± 0.5 (1X SE)). Taller trees were present with maximal heights of 3.6–9.6 m (6.6 ± 0.8 (1X SE)) and maximal stem diameters of 18.1–33.4 cm (23.0 ± 1.7 (1X SE)). Under-canopy shrubs of *A. annulata* and saplings of *A. marina* had a mean height of 0.18–0.59 m. These figures, along with the measures of density, describe relatively low stature vegetation in thicket-like stands was indicative that these sites were commonly influenced by high levels of disturbance.

Table 3.3. Measures of mangrove structure and condition for Transects 1A, 1B, 2B, 2A, 4A, 4B, 5A and 5D (also see Transect summary data). Dominant species: AM = Avicennia marina*; AA =* Aegialitis annulata*. Shaded columns are those with 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

Canopy trees prior to the 2015–2016 dieback event were estimated having relatively low levels of the total biomass of 75.1–153.9 tC/ha. By comparison, the total biomass of *A. marina* on South-Western Pacific Islands was around 250–484 tC/ha (Duke, 2013) and 65–501 tC/ha in SE Asia including India (Komiyama et al., 2008; Pandey et al., 2013). The losses in mangrove biomass with the 2015–2016 dieback event were 40.3–98.3% – understandably comparable to losses in decreased spatial extent. Based on the total mapped extent of mangrove loss around 7,650 ha (Table 3.1), the extrapolated level lost with the dieback incident would be around 13,695,846 tC.

Of these plants, the 2015–2016 dieback event caused a significant impact on canopy trees with losses between 49.6% and 94.9% while under-canopy losses ranged between 0% and 83.4%. In fact, the density of under-canopy plants were negatively correlated with percent loss of canopy trees (r^2= 0.7014, n= 8, **P<0.05; Figure 3.1 top) and positively correlated with percent remaining of the living fringe (r^2= 0.6336, n= 8, **P<0.05; Figure 3.1 bottom). This showed that the remnant seaward fringe trees were having a positive influence on post-impact recovery measured three years after the impact. The transects with wider remaining live fringes had a significantly greater establishment of seedling recruits and survival of established under-canopy plants.



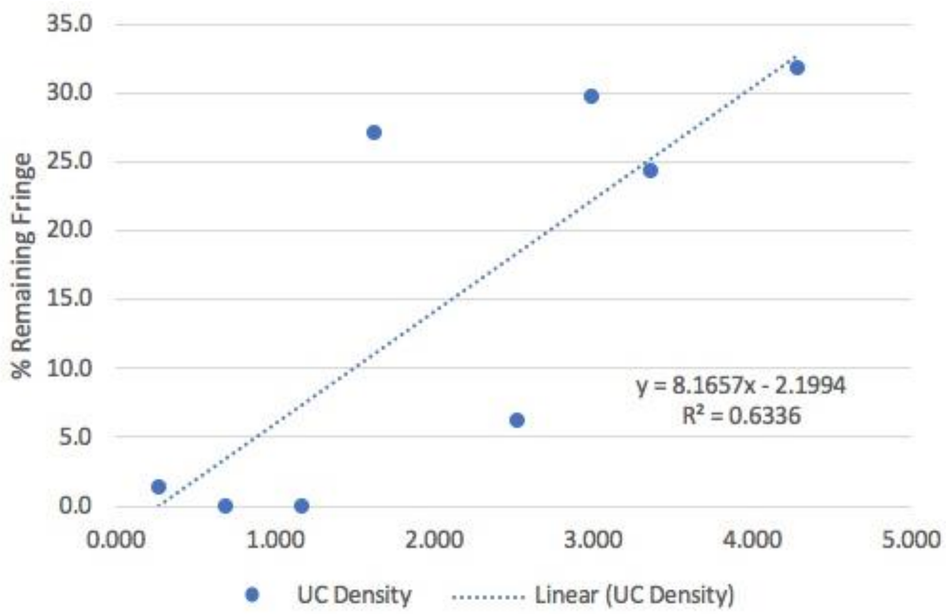


Figure 3.1. Density of under-canopy (UC) plants compared to the loss of canopy trees (top) and remaining living fringe width.

3.2 Links with external variables as drivers of change

As noted, the 2015–2016 dieback of mangroves was characterised by their retreat from the rear fringe edge ecotone (M2-upper to M2-dead/live; Figure 2.2). There were no additional occurrences of dieback at other profile positions along any of the eight transects. So the nature of this dieback event was unambiguous and distinct. The question is, what might have caused the dieback in this particular profile position?

Damage from cyclonic conditions, for example, could be discounted because these would have been evident at the seaward edge at very least. Factors like sea level rise, cyclones and tidal range listed in Table 3.4 showed no correlations with elevation levels or distance markers. But more importantly, there had never been such a widespread impact from even the most severe Gulf storm or flood event. Note that the impacted area of mangroves was recorded from more than 1,500 km of shoreline.

There were two factors with possible widespread influences, including the severe drought conditions at the time and the temporary drop in sea level. Both have been discussed in Vol. 1.

Firstly, the influence of rainfall and the drought conditions were notable at the time (Harris et al., 2017). Mean rainfall levels estimated for each transect (Table 3.4) were further compared with data gathered from the transects. The 2015–2016 loss of mangroves had a significant (r^2= -0.6326, n= 8, **$P<0.05$) negative relationship with rainfall where sites with higher rainfall were less impacted. As this was counter to the notion that unusually low rainfall influenced mangrove dieback, it was instead considered consistent with the idea that the low rainfall conditions had not had a major influence on this instance of mangrove dieback.

Table 3.4. Summary of potential drivers of mangrove dieback for Transects 1A, 1B, 2B, 2A, 4A, 4B, 5A and 5D (also see Transect summary data).

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).

And, as the derived sea level stress index demonstrated the co-incidence of the sea level drop with the mangrove damage, did the levels of extreme low conditions compare with the drop in the elevation of the impacted ecotone? Therefore, the specific question was, how did the extreme low sea level conditions in the port record compare with our field measurements for the eight transects?

The extent of impacted fringe losses was positively correlated with the estimated drop in sea level (Figure 2.2) for each transect (r^2= -0.6999, n= 8, **$P<0.05$). This finding was consistent with the influence of a major sea level drop being a likely cause of 2015–2016 mangrove dieback. This showed that where sea levels dropped most those sites had greater amounts of dieback. Most of all though, the strongest association was in the drop in elevation across dieback areas of around 0.44 m (Table 3.1 and Table 3.2) being equivalent to the tide gauge measures around 0.47 m as the extremely low levels of the sea during the event. This suggests that the timing and the severity between dieback and the sea levels were coincident.

These findings show that the factor positively linked with the 2015–2016 dieback of mangroves was the sudden drop in sea level. This was consistent with the coincident timing, the unusually high levels of the stress index derived from port sea level data, the likely reduced moisture levels expected with such an occurrence, plus the corresponding level of extreme low sea levels measured. Accordingly, this implies the mass dieback event was related to the sudden change in climatic conditions associated with the altered atmospheric conditions during the 2015–2016 severe El Niño event.

3.3 Observations on the demography of mangrove fringing stands

Detailed data on vegetation across all transects provides a comprehensive database from which to assess features of stand demography and changes taking place in these shoreline mangroves of the Gulf region. In total for all eight transects, 1,810 trees and shrubs were measured and counted in 3,636 m^2 of seaward fringing mangrove forests. These data have been summarised in the *Transect summary data* section and Appendix 1–Appendix 8.

These observations clearly depict the distribution along each transect of vegetation – it's structure and condition. As noted above, the 2015–2016 dieback was predominantly located at the upper edge of the seaward fringing mangrove stand. And, these fringing stands were dominated by one species of canopy tree, *Avicennia marina* var. *eucalyptifolia*. Furthermore, sites with seaward edge survivors had appreciably greater amounts of under-canopy dominated by both surviving shrubs of *Aegialitis annulata*, plus surviving and newly established saplings of *A. marina*. These measures quantify such conditions as being similar in all these Gulf field sites.

Stem diameter is a convenient and reliable measure of tree size (Figure 3.9). The significant (<0.01) negative relationship between tree size (~age) and density (Figure 3.2) shows these forested stands had normal structural relationships where larger older trees occurred in lower-density stands of these Gulf shorelines. And further, there was a relationship also between tree size and the wetland cover index from areas of mangroves and tidal wetlands mapped in studies (Figure 3.3). The significant (<0.01) positive relationship between tree size and the index showed these trees tended to be larger (and possibly older) in wetter parts of these Gulf shorelines. This implies that the survival of these trees was improved by increased levels of rainfall.

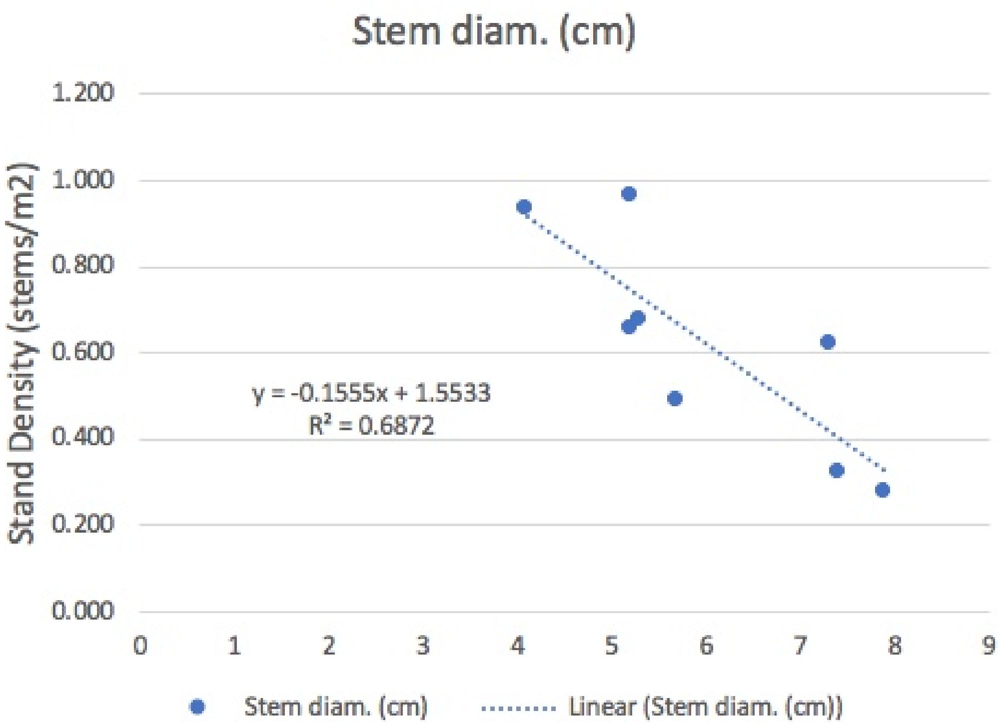


Figure 3.2. Mean stem diameter of canopy trees compared to the density of canopy trees of the eight Gulf transects.

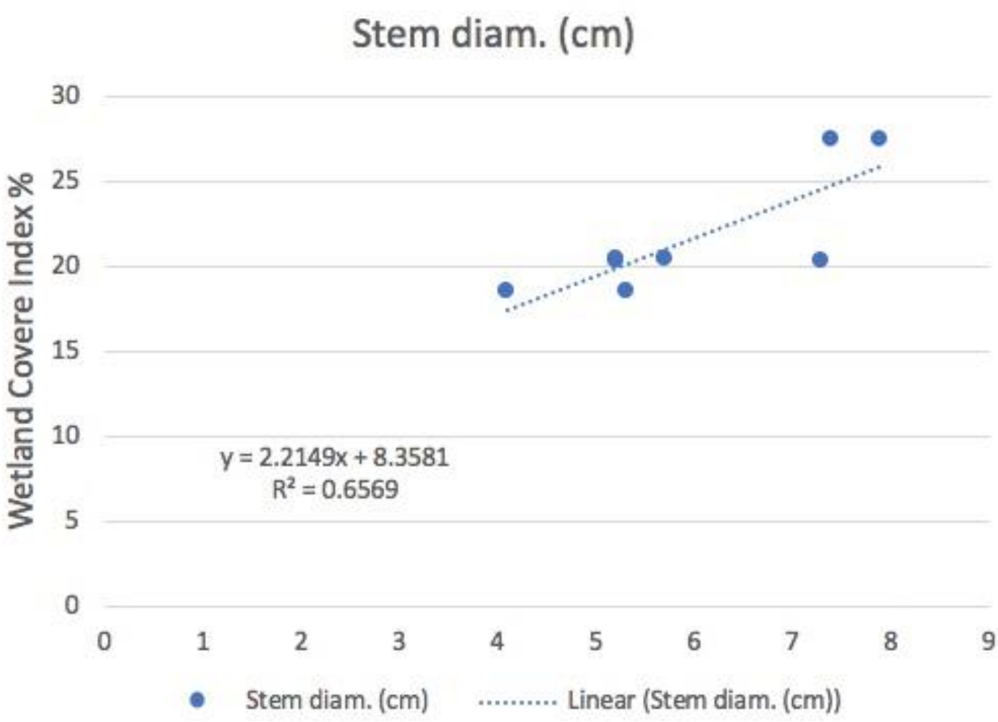


Figure 3.3. Mean stem diameter of mangrove canopy trees compared to the Wetland Cover Index for the eight Gulf transect locations. The index is the ratio of mangrove area proportional to the total tidal wetland area, and this is directly dependent on longer-term annual rainfall (Duke et al., 2019a).

Overall, stem diameters of Gulf *Avicennia marina* trees were much smaller than those found in other sites around Australia. The Gulf stems ranged in mean size around 4.1–7.9 cm in diameter, with maximal mean sizes around 18.1–33.4 cm between transect sites. While a relationship with age is discussed in the next section, the small stem sizes of these mangrove trees were notably common to all eight transects.

There is also a general relationship with age where larger stem sizes depict older trees as relative proxies for age. This key structural character for *Avicennia marina* trees has never been quantified as a determinant of tree age, but there is value in recognising relative trends in these data. Note that it is a planned additional outcome from these studies, outlined in the next section, to possibly validate and quantify a relationship between stem diameter and tree age for this species. Meanwhile, we review the following observations.

Another notable observation concerned the distribution of relative stem sizes across the tidal profile of most transects. A significant relationship occurred between stem diameter and tidal elevation level in three widely located transects (1A, 2A and 4B; Figure 3.4), where larger and older trees were found towards the sea edge, and conversely, smaller stems of younger trees occurred higher up the tidal zone.

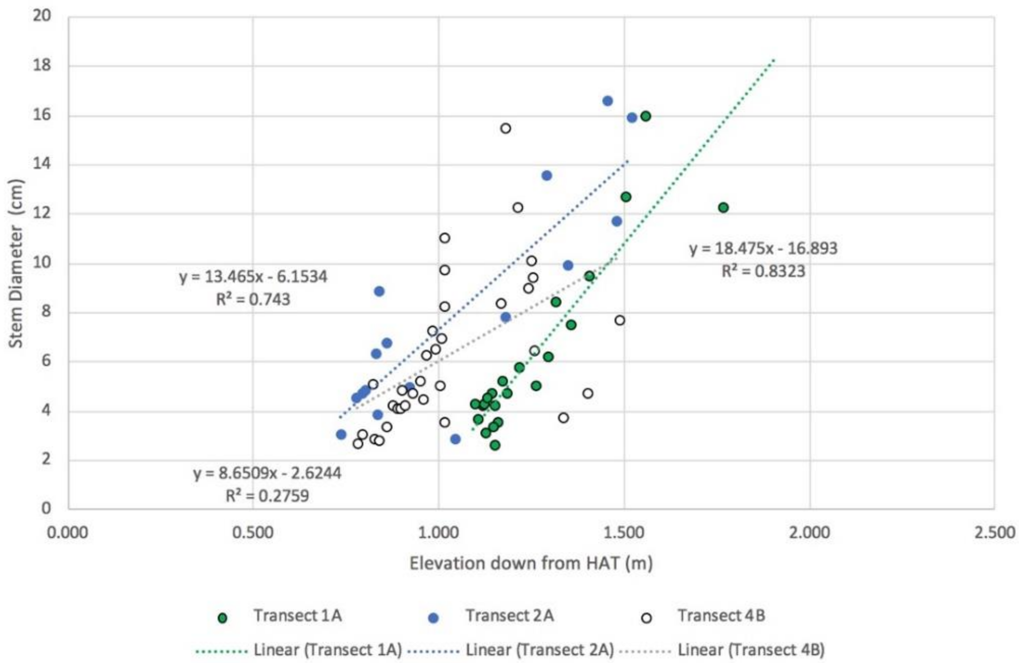


Figure 3.4. Mean size of canopy trees along Transects 1A, 2A and 4B compared to elevation height. These data show the condition of the mangrove fringe as it was before the 2015–2016 dieback. There were significant positive relationships with elevation measured down from ~HAT. These show a relationship where smaller younger trees were found higher up the tidal zone of sites on either side of the Gulf.

This relationship meant that mangrove fringe trees had progressively relocated up the tidal profile. This view of a shift in the mangrove zone was consistent with the loss of older trees at lower elevation sea edges marked by the frequent presence of degraded, dead stumps amongst the mangroves of seaward edge stands (Figure 3.5).

Figure 3.5. Old, degraded stumps were seen along the seaward edge at Transect 5D.

While independent studies showed that sea levels had risen rapidly in the Gulf, this process was also consistent with the observed ecological response. These progressive rises in sea level have been described and quantified by Church and others (Church et al., et al., 2009; Hobday & Lough, 2011). And, as noted above, this was confirmed further in tide gauge records of the three Gulf ports. There is little doubt that sea levels had been rising steadily over many decades.

As mangroves are highly dependent on sea level where they exist more-or-less entirely between mean sea level and highest tidal levels, it must be no surprise that when sea level shift then mangroves must relocate to survive (Duke et al., in press). This primary influence on mangroves was recognisable in these data by their ordered demographic pattern across the tidal zone. The situation has no doubt been made more evident by the remarkably low topographic slopes that characterise these Gulf shorelines. The eight transects had slopes of 185–486 m per 1 m elevation, and the slope was also correlated with tree size (Figure 3.6). There was a significant (<0.001) positive relationship between tree age and slope where smaller younger trees were found on shallower slopes of these Gulf shorelines.

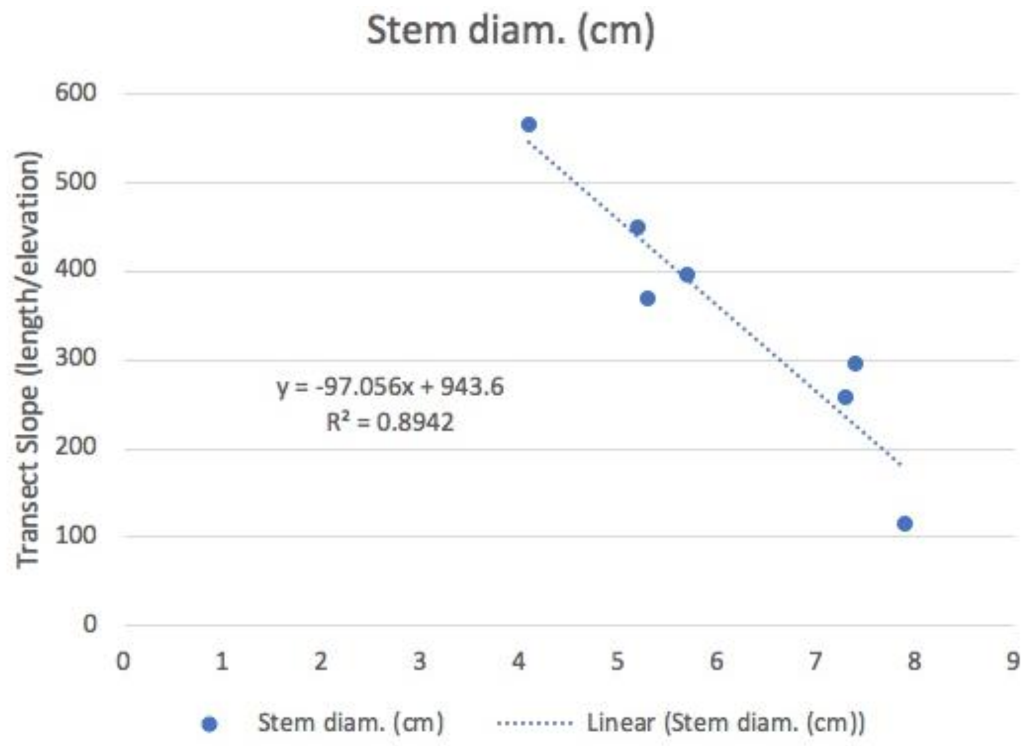


Figure 3.6. Mean stem diameter of canopy trees of seven transects (except 2A) compared to transect slope.

In these circumstances, small changes in sea level are expected to have an exaggerated upward expression of habitat shift. These observations do not exclude additional influences of other localised factors like sediment deposition rates and erosion, or shallow subsidence. But, the overall and common influence of rising sea levels was notably evident across the broad Gulf region. This was largely depicted in a negative trend between tree size and estimated levels of sea level rise (Figure 3.7). This equates roughly to there being smaller trees in sites with greater rates of sea level rise.

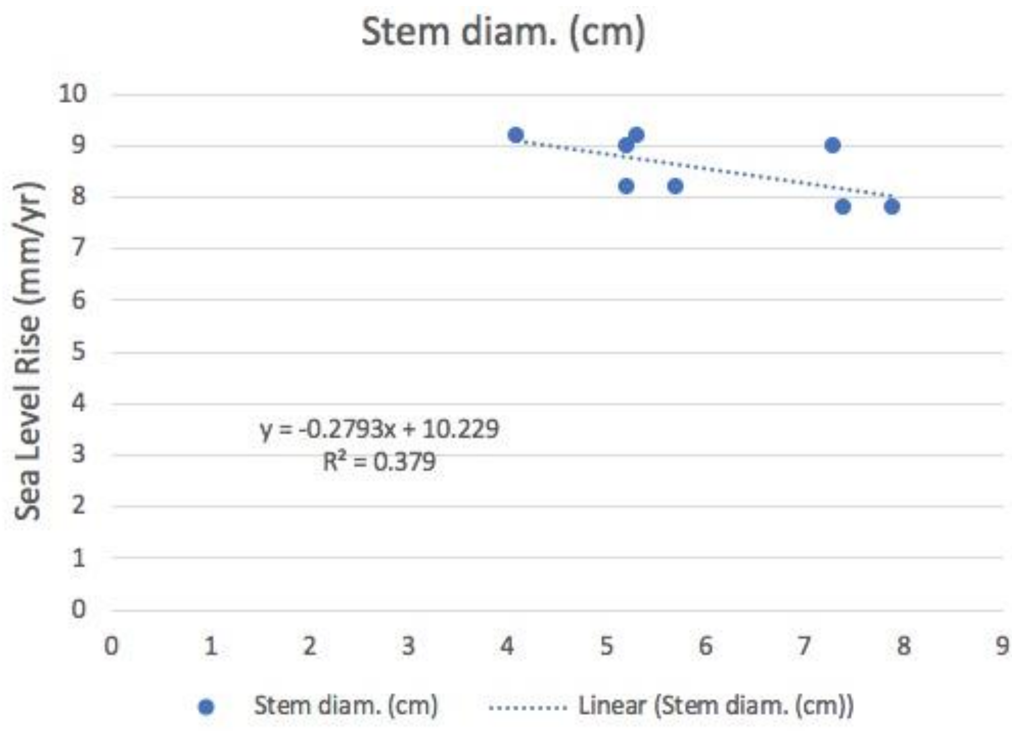


Figure 3.7. Mean stem diameter of canopy trees of eight transects compared to estimated levels of sea level rise. There was a trend where smaller younger trees were found in sites of greater rates of sea level rise along these Gulf shorelines.

In summary, while rising sea levels did not directly influence the 2015–2016 dieback, these changes do, however, indirectly influence mangrove stands by weakening these already vulnerable habitats and lowering their resilience for further adaptation and recovery. Weakened stands become increasingly damaged by the addition of accumulative impacts from the range of drivers of change, especially including the possible re-occurrence of extreme events like the 2015–2016 drop in sea level.

3.4 Assessment of tree rings – an ongoing study with ANSTO

As an extension to our investigation into the sudden mass dieback of mangroves in the Gulf of Carpentaria in late 2015, we considered it highly beneficial to expand these studies to include the additional assessment of tree rings and wood samples of the locally common Grey Mangrove, *Avicennia marina* var. *eucalyptifolia* (Figure 3.8). A project proposal was prepared, and this has received the necessary funding for detailed analyses by the Australian Nuclear Science and Technology Organisation (ANSTO).

Figure 3.8. Stem wood cross-section of an Avicennia marina *tree killed during the 2015–2016 dieback in the Gulf of Carpentaria. Our research is attempting to read the chronological record bound up in this wood to better understand the factors influencing the growth and survival of these mangrove stands.*

2019-2 ANSTO Research Portal Proposal **AP12216***: Can radiocarbon techniques combined with X-ray densitometry of wood samples of the mangrove A. marina from northern Australia's Gulf of Carpentaria help to better understand why mangroves experienced mass dieback in late 2015?*

The analyses could not be completed in time for this final report. However, the plan is to include these results and conclusions as soon as possible in future research publications afterwards.

The purpose of the additional analyses was to greatly extend upon the advances made with the current NESP findings by including a validated assessment of tree rings and wood samples for accurately aging trees of *Avicennia marina*. As this is the dominant mangrove tree species in the Gulf, the wider ramifications extend to gaining a better understanding of its growth and development, and its vulnerabilities to changing climatic conditions.

A key goal was to age sampled trees and to use these data to develop a beneficial allometric relationship from which to determine stand demographic profiles and time series. There is currently no recognised way to achieve this without having the allometric relationship. Having the ability to age these mangrove trees would greatly benefit the assessment of stand-specific structural characters, notably stem diameter, sampled during these NESP field surveys. The data could then be used in combination with other project components like aerial shoreline surveys, historical satellite imagery, plus gaining comparable time series data from regional weather stations and port records. The combination of these data sources could then be used to develop and validate chronological sequences of events over the previous 30–50 years.

A second goal was to evaluate and identify distinct markings in wood sections for use as possible identifiers or markers of specific events like the mass dieback incident (affecting an estimated 300 million trees) along approximately 2,000 km of Gulf shorelines. It is also significant that while many trees died, many others would have survived the conditions that killed their neighbours. In other words, the period of stressful conditions might be expected to be recorded in surviving living trees. The question is whether there is a record of stressful events in these surviving trees? And, the most likely place for finding such a record in trees are the growth layers laid down in their woody stems. Unfortunately, the stem wood of the common mangrove *Avicennia marina* does not have traditionally useful growth layers like annular or seasonal growth rings that encircle the stem core. Instead, these mangroves have a series of overlapping woody lamina segments each incompletely encircling the stem. This anatomy has long defied those looking ways to age these trees (Gull, 1971; Tomlinson & Longman, 1981). However, because the combined effect appears to be the same where bigger trees have more layers as they get older, we used the opportunity with this investigation to re-evaluate wood sections of *A. marina* from these impacted Gulf sites. As noted above, there would be immense benefits and outcomes in finding a sequential record in wood layers linked to changing environmental conditions.

To cover a range of potential outcomes, we have undertaken a multi-pronged approach with these investigations of wood sections of *Avicennia marina* trees, including: 1) an evaluation of lamina layers in wood sections; 2) an assessment of layered dark staining of wood sections of larger older trees (Figure 2.8) which may signify ‘event scars’; 3) carbon dating of the full-size range of Gulf stems; and 4) the sequential scanning of wood sections with density and elemental analyses.

Only the first component is reported on in this report. The remaining studies are not yet completed as they include additional analytical work being done with the ANSTO project. This is an extension to the NESP investigations.

In total, we sampled 41 trees with 3–4 replicates in the sampling design for two severity conditions (moderate and severe) x two tree categories (dead and living trees) x four study sites – a total of 16 treatments. The mean stem diameter sampled was 12.2 cm – a relatively small size range compared to trees growing in wetter east coast locations. Tree ages were estimated for these Gulf trees using an unpublished allometric relationship developed for *A. marina* trees on the Queensland east coast (Figure 3.9). Assuming these trees might have similar growth characteristics, these estimates indicate that Gulf trees had a mean stand age of around 10 years with older trees up to 20–30 years.

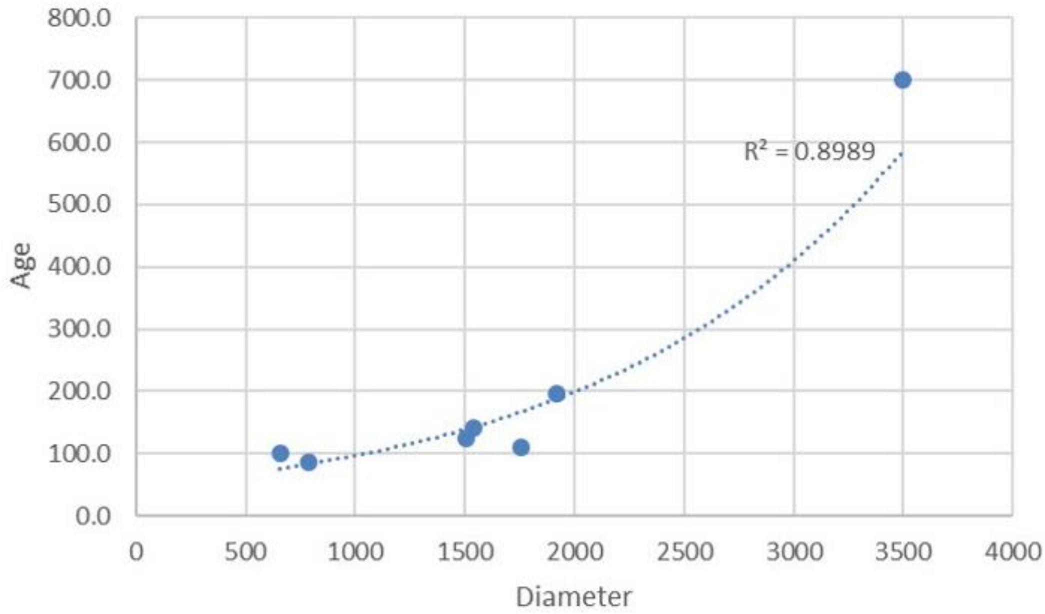


Figure 3.9. A working allometric relationship derived from unpublished radiocarbon dating of Avicennia marina *trees growing in central and southern Queensland. Not that smaller sized trees like those in the Gulf transects are not adequately represented.*

Despite the absence of age determinations so far for Gulf trees, our first investigation of stem sections has revealed an unexpectedly encouraging result. There was a significant linear relationship between the average number of laminae 'rings' and stem diameters (Figure 3.10). This shows that larger trees have a predictable number of averaged lamina rings. So, while the lamina were not useful for normal aging studies, this significant linear relationship implies there might be a relationship with age after all. The plan is to resolve this question with the ANSTO carbon dating of wood samples. These data can then be used to amend a developing allometric relationship (Figure 3.9) to account for the smaller and younger age trees found in the Gulf. The aim is to use the updated allometric relationship in an evaluation of demography amongst Gulf populations represented by the ~1,800 trees of *A. marina* (live and dead) we measured in the eight Gulf transects. This is likely to provide important additional insights into the mass dieback of mangroves in 2015–2016.

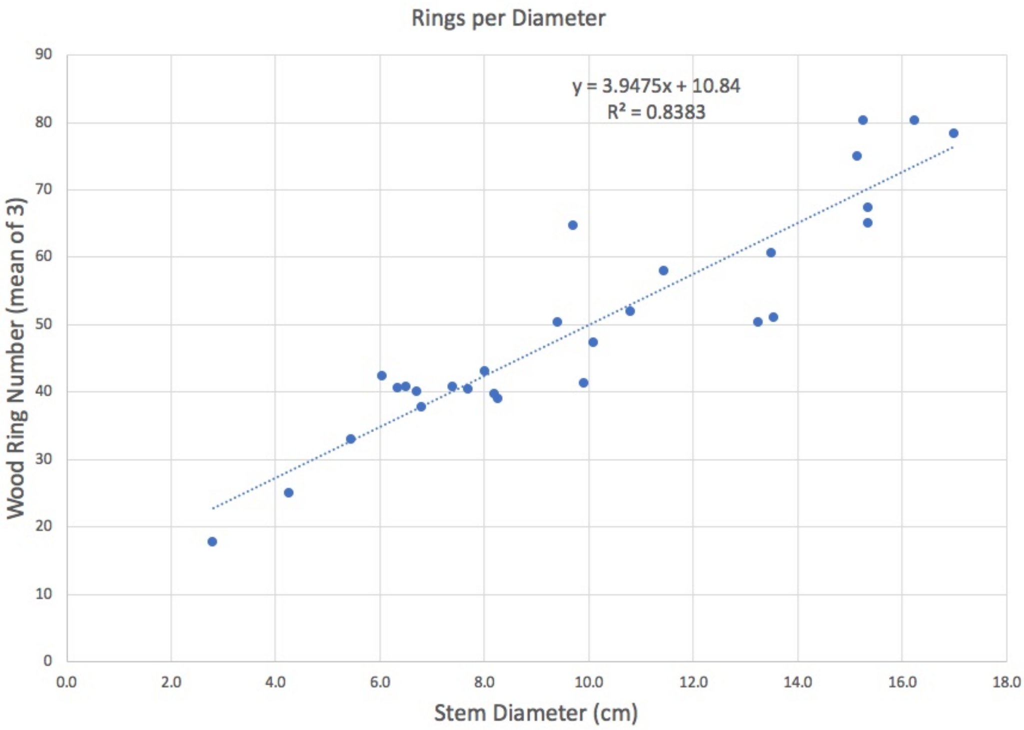


Figure 3.10. The allometric relationship comparing averaged tree laminae 'ring' numbers with stem diameter for trees of Avicennia marina *sampled from the eight Gulf transects. Unfortunately, the relationships between either ring number or stem diameter with age were not quantified for this species, especially for this small size range of stems (Figure 3.9).*

The 28 samples for analysis by ANSTO are listed in Table 3.5. These included four samples ('FG' series) as wood fragments from older degraded stumps in an attempt to identify whether these trees died at more or less the same earlier time. The results for these analyses will be published in a future scientific research publication reporting to complete these investigations.

Table 3.5. Mangrove wood samples (28) collected and prepared for ANSTO analyses. The results were not available for the completion of this final report for the project. Specimens in bold italics are being carbon-dated to determine age. AM = Avicennia marina.

#	Label code	Collection date	AU	Stem diam.	Growth end	Spp	Sample L (cm)	Sample Type
1	G-1A-2Y	13-Oct-18	NT	10.3	31-Dec-15	AM	10.4	Slice Y
2	G-1A-3Y	13-Oct-18	NT	11.2	31-Dec-15	AM	9.8	Slice Y
3	G-1A-4Y	13-Oct-18	NT	8.7	31-Dec-15	AM	8.2	Slice Y
4	G-1B-3Y	12-Oct-18	NT	10.2	31-Dec-15	AM	6.6	Slice Y
5	***G-1B-6XD***	***12-Oct-18***	***NT***	***9.7***	***12-Oct-18***	***AM***	***9.0***	***Core X***
6	***G-1B-7XD***	***12-Oct-18***	***NT***	***13.2***	***12-Oct-18***	***AM***	***13.0***	***Core X***
7	G-2A-1X	17-Oct-18	NT	14.9	17-Oct-18	AM	13.5	Core X
8	G-2A-2X	17-Oct-18	NT	15.5	17-Oct-18	AM	15.2	Core X
9	G-2A-6Y	17-Oct-18	NT	15.2	31-Dec-15	AM	14.8	Slice Y
10	***G-2B-1YD***	***16-Oct-18***	***NT***	***16.1***	***31-Dec-15***	***AM***	***16.0***	***Slice Y***
11	G-2B-3Y	16-Oct-18	NT	15.6	31-Dec-15	AM	14.2	Slice Y
12	G-2B-4Y	16-Oct-18	NT	10.2	31-Dec-15	AM	9.8	Slice Y
13	G-4A-1X	7-Aug-18	Qld	13.9	07-Aug-18	AM	13.5	Core X
14	G-4A-3Y	7-Aug-18	Qld	18.8	31-Dec-15	AM	7.0	Slice Y
15	***G-4B-1YD***	***7-Aug-18***	***Qld***	***7.1***	***31-Dec-15***	***AM***	***6.8***	***Slice Y***
16	G-4B-2Y	7-Aug-18	Qld	7.5	31-Dec-15	AM	8.0	Slice Y
17	G-4B-3Y	7-Aug-18	Qld	15.6	31-Dec-15	AM	15.2	Slice Y
18	G-4B-4X	7-Aug-18	Qld	19.4	07-Aug-18	AM	7.4	Core X
19	G-5A-1Y	10-Aug-18	Qld	16.9	31-Dec-15	AM	16.2	Slice Y
20	G-5A-2Y	10-Aug-18	Qld	10.8	31-Dec-15	AM	10.4	Slice Y
21	***G-5D-1XD***	***11-Aug-18***	***Qld***	***23.2***	***11-Aug-18***	***AM***	***23.1***	***Core X***
22	G-5D-2Y	11-Aug-18	Qld	15.1	31-Dec-15	AM	14.2	Slice Y
23	G-5D-6Y	11-Aug-18	Qld	13.4	31-Dec-15	AM	12.7	Slice Y
24	***G-5C-1XD***	***10-Aug-18***	***Qld***	***18.4***	***10-Aug-18***	***AM***	***17.6***	***Core X***
25	***FG01-1A-D***	***20-Sep-19***	***NT***	***-***	***?***	***AM***	***-***	***fragment***
26	***FG10-2B-D***	***18-Sep-19***	***NT***	***-***	***?***	***AM***	***-***	***fragment***
27	***FG14-4A-D***	***14-Sep-19***	***Qld***	***-***	***?***	***AM***	***-***	***fragment***
28	***FG20-5A-D***	***13-Sep-19***	***Qld***	***-***	***?***	***AM***	***-***	***fragment***

3.5 Sampling and assessment of molluscan fauna

Mollusc community composition was evaluated from samples collected during field studies in 2018 (Figure 3.11). All transects in dieback impacted sites in the Gulf of Carpentaria were sampled for molluscan fauna present during 2018 field surveys in August for Transects 4A, 4B, 5A and 5D, and September for Transects 1A, 1B, 2A and 2B (Figure 2.1; Table 3.6).

Figure 3.11. Collection of mollusc faunal records in a severely impacted site with only a few sprouting seedling recruits. The ground was often parched and firm with high temperatures.

While these surveys do not represent a complete taxonomic survey of Gulf sites, they do provide a useful snapshot in time showing differences between levels of dieback severity and providing a baseline for future reference. These records provide a comprehensive baseline dataset of the species present at particular sites. The shell lengths of the potamidid snails further provide a valuable indicator of what these snails might do in regards to future recolonisation of each site.

Overall in 2018, a total of 32 species were recorded representing 17 families. Sites in Queensland (4A, 4B, 5A and 5D) at the time had 21 species from 14 families while sites in the Northern Territory (1A, 1B, 2A and 2B) had 24 species from 12 families. All sites shared 13 species and nine families.

Table 3.6. List of molluscs recorded along the Gulf mangrove transects in 2018 (Figure 2.1). Shading indicates severely impacted transects, while the non-shaded transects were moderately impacted.

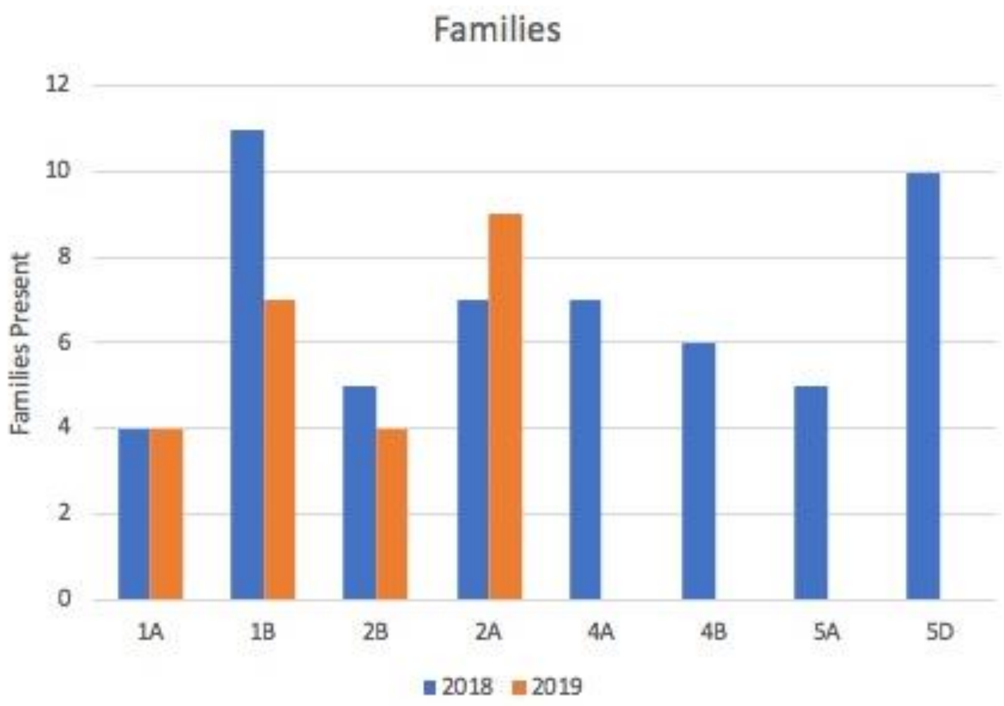
	1A	1B	2B	2A	4A	4B	5A	5D
No. of mollusc species	14	19	11	16	12	9	5	13
No. of mollusc families	4	10	5	8	7	6	5	10
Grand total (of 3 x 1m^2 quadrats)	612	580	227	696	350	73	20	950
Mean count per 1m^2	204.0	193.3	75.7	232.0	116.7	24.3	6.7	316.7
±SD	109.3	82.0	16.0	96.4	29.0	6.4	5.9	229.2
Min count/1m^2	0	0	0	0	0	0	0	0
Max count/1m^2	112	45	31	161	87	16	8	350

Family	Species	1A	1B	2B	2A	4A	4B	5A	5D
Potamididae	*Terebralia semistriata*	X	X	X	X	X	X		X
Potamididae	*Terebralia sulcata*	X	X	X	X				
Potamididae	*Telescopium telescopium*	X				X	X		X
Potamididae	*Terebralia palustris*	X							
Potamididae	*Pirenella delicatula*	X	X	X	X	X			
Potamididae	*Pirenella austrocingulata*	X	X						
Potamididae	*Cerithideopsis australiensis*	X	X	X	X		X		X
Potamididae	*Cerithidea anticipata*	X	X		X				
Neritidae	*Neripteron violaceum*	X	X	X	X	X	X		X
Neritidae	*Clithon oualaniense*	X	X	X	X				
Littorinidae	*Littoraria articulata*	X	X	X	X	X	X	X	X
Littorinidae	*Littoraria intermedia*	X	X	X	X				
Littorinidae	*Littoraria filosa*	X	X			X	X		X
Littorinidae	*Peasiella lutulenta*	X	X	X	X				
Assimineidae	*Rugapedia* sp.		X	X	X			X	X
Ellobiidae	*Ophicardelus* sp.							X	
Pyramidellidae	*Turbonilla* sp.		X				X		
Undetermined	Micro sp.				X				
Retusidae	*Retusa* sp.								
Calopiidae	*Calopia* cf. *imitata*								
Amphibolidae	*Lactiforis tropicalis*					X			
Amphibolidae	*Salinator rosacea*					X	X		X
Iravadiidae	*Fluviocingula resima*					X			X

Family	Species	1A	1B	2B	2A	4A	4B	5A	5D
Iravadiidae	*Iravadia quadrina*		X			X			
Limapontiidae	*Ercolania* sp.								X
Lottidae	*Patelloida* cf. *cryptalirata*				X				
Cerithiidae	*Clypeomorus bifasciata*		X						
Stenothyridae	*Stenothyra australis*		X						X
Stenothyridae	*Stenothyra gelasinosa phrixa*								X
Mytilidae	*Modiolus* cf. *flavida*		X	X	X	X		X	
Mytilidae	*Arcuatula* sp.				X				
Ostreidae	*Saccostrea cucullata*	X	X		X	X	X	X	X

3.5.1 *Mollusc community composition in Northern Territory sites re-measured in 2019*

Sites in the Northern Territory (1A, 1B, 2A and 2B) were resampled in December 2019 (Table 3.7). Twenty-four mollusc species belonging to twelve families were recorded in these Northern Territory sites between 2018 and 2019 (Figure 3.12).



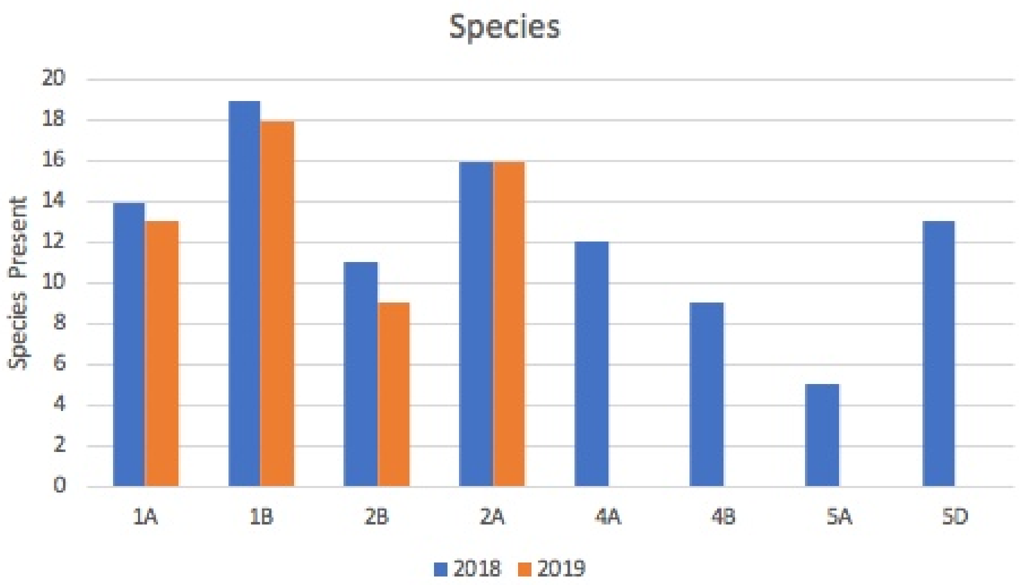


Figure 3.12. Numbers of mollusc families (top) and species (bottom) recorded in the eight transects in the Gulf of Carpentaria in 2018 and 2019. There was some deterioration between years.

The numbers of molluscan families represented were relatively uniform although numbers tended to be lower in severely impacted sites (1A, 2B, 4A, and 5A), and generally lower in 2019. One exception was Transect 2A suggesting there were localised influences on these measures of faunal diversity. For example, the numbers of families represented correlated strongly (2018: r^2= 0.8384; n=8; P<0.001; 2019: r^2= 0.7634; n=4; P<0.05) with the density of under-canopy vegetation (Figure 3.13).

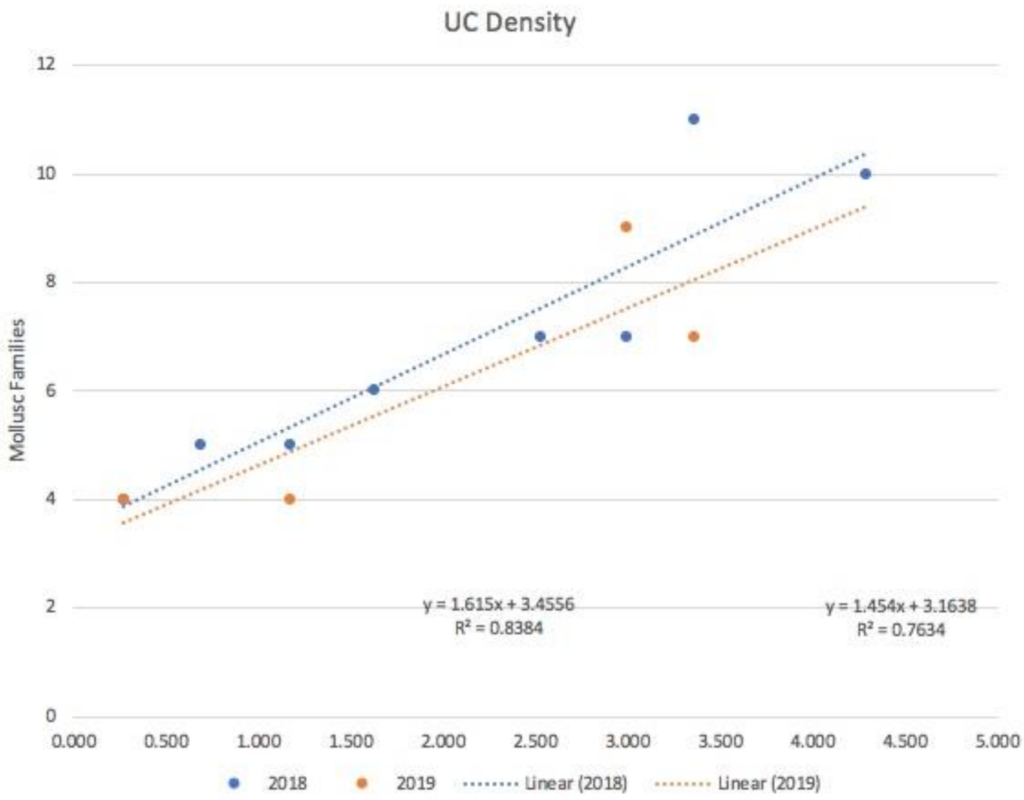


Figure 3.13. Graph showing relationships between the density of under-canopy vegetation in 2018 and mollusc families found in the eight mangrove transects in the Gulf of Carpentaria in 2018 and 2019. Both relationships were highly significant (see text).

This latter observation was notable because the amounts of under-canopy were negatively correlated (r^2= -0.7014; n=8; P<0.01) with the percentage of canopy dieback in 2015–2016.

The most diverse families recorded were Potamididae (eight species), Littorinidae (four species), Neritidae (two species), and Mytilidae (two species). While the numbers of families represented in Northern Territory transects were related to post-impact recovery of the under-canopy and sapling plants, this did not appear to have influenced each family in the same way. For example (Figure 3.14), note that Littorinids in 2018 had a significant negative correlation with under-canopy density (r^2= -0.7711; n=4; P<0.05), while Potamids appeared unaffected by under-canopy vegetation and Neritids showed a generally positive trend.

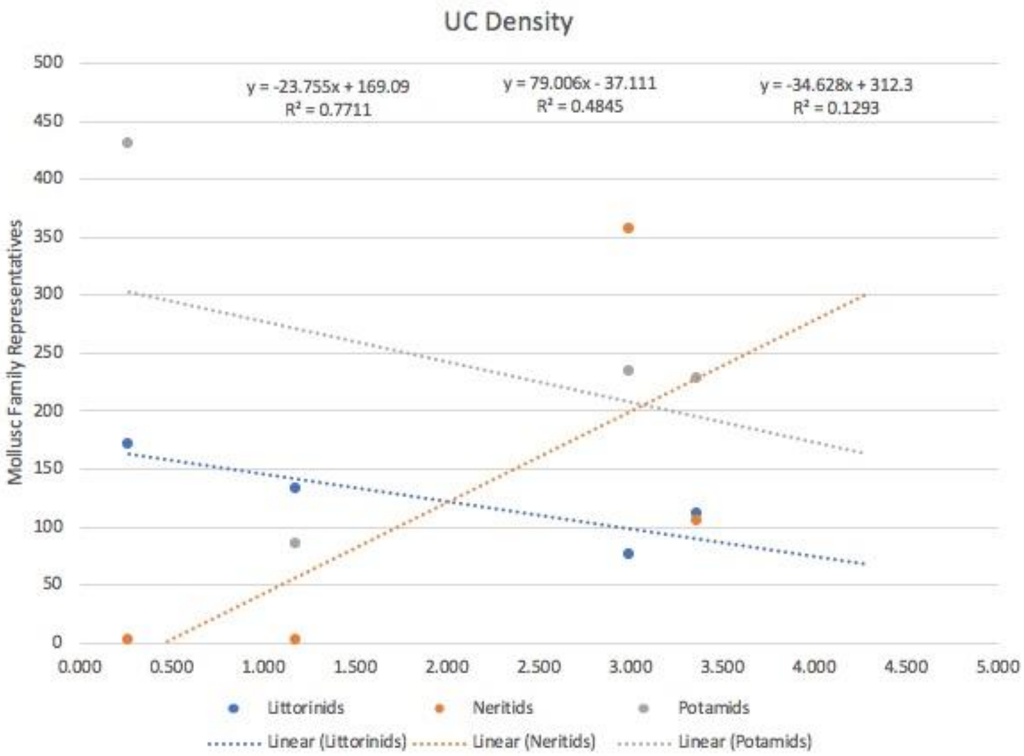


Figure 3.14. Comparison of relationships between the density of under-canopy vegetation and three mollusc families, Littorinids (blue), Neritids (orange), and Potamids (grey), found in mangrove transects in the Northern Territory in 2018. There was only one significant relationship with Littorinids.

A more detailed assessment is likely to better reveal the range of responses by molluscan fauna, where some might thrive in disturbed conditions while others do better in less disturbed recovering mangrove stands (Figure 3.14).

Overall, Transect 1B had the greatest species diversity, recording 21 species in 2018 and 18 species in 2019. The greatest mollusc diversity was recorded in 2018, while the greatest densities of molluscs were recorded in 2019. In 2019 mollusc diversity decreased at all sites except 2A, and mollusc abundance increased at all sites except 2A.

A PERMANOVA test showed there were significant differences in mollusc density amongst sites (p= 0.001), and abundance differed between the 2018 and 2019 surveys (p= 0.01) while changes in density recorded in each site varied between the two the surveys (p= 0.005). A further assessment using Principal Coordinate Analysis of sites 1A and 1B compared with sites 2A and 2B showed distinct regional differences between two Northern Territory locations (Figure 3.15).

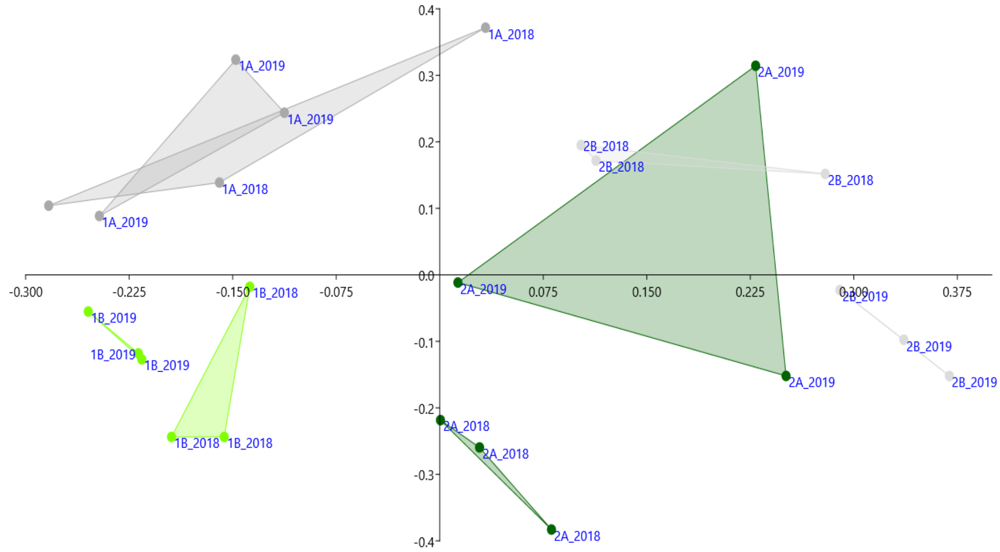


Figure 3.15. Principle coordinate analysis of mollusc abundance recorded from the Northern Territory Gulf mangrove sites in 2018 and 2019.

3.5.2 Mud-creeping Potamid snails

Of the four large Potamid snails *Telescopium telescopium, Terebralia palustris, T. semistriara,* and *T. sulcata* recorded at Northern Territory Gulf sites, the two former species showed remarkably low densities. At sites 2A and 2B, *Telescopium telescopium* was rare, with only a single adult specimen (85.4 mm SL) recorded in 2019. No *Terebralia palustris* snails were recorded at either of the sites 2A and 2B, suggesting the species may now be locally extinct. Interestingly, more *Terebralia palustris* snails were recorded in the severely impacted Limmen Site 1A rather than 1B. Shell measurements of potamidid snails revealed valuable information on the current population dynamics of the four species. These records indicate that some populations were stable while others were emigrating, or unbalance and lacking recruitment of juvenile snails.

Densities of the small, mudflat potamidid *Pirenella delicatula* greatly increased at all sites in 2019. Increased abundances of this species possibly indicated subtle changes in microtopography along the seaward mangrove fringe.

Table 3.7. List of molluscs recorded along Northern Territory Gulf mangrove transects sampled in 2018 and 2019. Shading indicates severely impacted mangrove transects while the others were moderately impacted.

	1A		1B		2B		2A	
	2018	2019	2018	2019	2018	2019	2018	2019
Species	15	13	21	18	11	9	15	16
Families	4	4	11	7	5	4	7	9
Grand total	611	770	578	1090	227	544	695	455
Mean count (m^{-2})	203.7	256.7	192.7	363.3	75.7	181.3	231.7	151.7
Mean no. spp. (m^{-2})	10.3	9.7	16.3	14.3	8.3	5.7	11.3	9
Shannon Diversity (H')	1.91	1.85	2.52	2.16	1.85	1	1.61	1.36
Pielou Eveness (J')	0.71	0.72	0.83	0.75	0.77	0.46	0.59	0.49
Family: Potamididae								
*Terebralia semistriata**	164	152	5	66	33	7	18	36
*Terebralia sulcata**	161	39	90	255	29	6	29	35
*Telescopium telescopium**	4	36		19				1
*Terebralia palustris**	25	8	1	1				
*Pirenella delicatula**	42	74	67	215	22	374	181	296
*Pirenella austrocingulata**	26	29	51	121				
*Cerithideopsis australiensis**	7	4	11	17	2	1	5	
*Cerithidea anticipata**	2		3	1			1	
Family: Neritidae								
*Neripteron violaceum**	2	17	61	41	1	1	30	10
Clithon oualaniense	1	1	44	177	2		327	2
Family: Littorinidae								
*Littoraria articulata**	118	212	74	81	76	49	44	31
*Littoraria intermedia**	10	3	24	10	34	94	27	19
*Littoraria filosa**	1		8	10				2
*Peasiella lutulenta**	42	194	5	61	23	10	5	10
Family: Trochidae								
Austrocochlea diminuta			1					
Family: Assimineidae								
Rugapedia sp.*			15	3	1		1	1
Family: Pyramidellidae								
Turbonilla sp.*			2	3				1
Family: Iravadiidae								
*Iravadia quadrina**			15					
Family: Lottidae								
Patelloida cryptalirata							2	1

	1A		1B		2B		2A	
	2018	2019	2018	2019	2018	2019	2018	2019
Family: Cerithiidae								
Clypeomorus bifasciata			3					
Family: Stenothyridae								
*Stenothyra australis**		1	54					1
Family: Mytilidae								
Modiolus cf. *flavida*			2	7	4	2	7	8
Arcuatula sp.							1	
Family: Ostreidae								
*Saccostrea cucullata**	6		42	2			17	1

*Predominantly mangrove-associated species

3.5.3 Tree-dwelling Littorinid snails

These collections revealed a significant difference in the density of tree-dwelling *Littoraria* snails (p=0.043) amongst the four Northern Territory Gulf sites. Interestingly, more *Littoraria articulata* snails were recorded on trees in severely impacted forests than in moderately affected mangrove forests. In 2019, Severely impacted mangrove sites in sites 1A and 2B displayed increased regional variation in species composition.

Figure 3.16. Measurement of mollusc fauna amongst mangrove roots within sites with surviving mangroves of moderately impacted sites.

3.5.4 Tree-dwelling bivalves

In general, both the mangrove oyster, *Saccostrea cucullata* and the two Mytild mussels *Modiolus* cf. *flavida* and *Arcuatula* sp. were most abundant in moderately impacted mangrove sites. In 2019, densities of *Saccostrea cucullata* significantly decreased in all sites.

3.5.5 The predatory snail, Thais trigonus

As of 2019, no individuals of the predatory Murcid *Thais trigonus* were observed at either the Limmen (1A and 1B) sites or the Borroloola (2A and 2B) sites. Notably, dead shells of this species were recorded at both locations, indicating the snails were present before the 2015 mangrove dieback event.

3.6 Community engagement and training sessions with Indigenous rangers

3.6.1 Ranger consultation and training programs

This section lists the various ranger training programs by Dr Duke and Mr Mackenzie for training Indigenous rangers of groups across the Gulf region (Figure 3.17). The opportunity was taken to identify and discuss local issues, including the 2015–2016 mass mangrove dieback incident (Figure 3.18, Figure 3.19, Figure 3.20, and Figure 3.21).

Figure 3.17. Practical training in MangroveWatch shoreline monitoring was given by NESP researchers for rangers in locations across the Gulf. This training session was for Il-Anthawirrayarra rangers with the Mabunji Aboriginal Corporation from Borroloola in September 2017.

The aim was to build a dialogue with local Indigenous peoples, to inform them of the research being undertaken, to update them on the results and findings, to incorporate their views and knowledge of climate processes influencing their local natural marine and tidal wetland ecosystems, and to engage, equip and train locally based rangers in the monitoring of environmental condition using systematic, simple and robust scientific techniques. The training program included the compilation and publication of a dedicated training manual (MangroveWatch, 2020).

Training involved formal instruction in the use of monitoring equipment supplied and the acquisition of useful geo-tagged image data using the shoreline video assessment method (S-VAM; Mackenzie et al., 2016).

Figure 3.18. Discussions about the 2015–2016 dieback were combined in training sessions for monitoring mangrove country – on this occasion with Normanton-based rangers with the CLCAC.

Figure 3.19. Discussions about mangrove country in dieback areas during NESP field studies like this one with Borroloola-based rangers of the Mabunji Aboriginal Corporation.

Figure 3.20. Rangers with Borroloola-based rangers with the Mabunji Aboriginal Corporation assisted with the NESP field studies in October 2018.

Figure 3.21. Normanton-based senior ranger Hayden Tyrrell with the CLCAC assisted the NESP project fieldwork at Karumba sites in 2018.

Figure 3.22. Information sharing sessions were an on-going exercise like this one in Burketown with Senior Ranger Brenton Yanner with CLCAC during NESP aerial surveys in September 2019.

Figure 3.23. MangroveWatch training sessions were conducted with ranger groups around the Gulf like this one in Borroloola with rangers with the Mabunji Aboriginal Corporation during NESP aerial surveys in September 2019.

Training in each session involved an initial discussion around a computer screen projection to explain the reasons for monitoring and to introduce the equipment to be used. This was followed by a field visit to a nearby estuary using one or two small vessels depending on the numbers of rangers attending. There were generally up to 10 rangers at each session.

Cairns

26 March 2019 – MangroveWatch co-presentation with Phillip George and Brenton Yanner Carpentaria Land Council Aboriginal Corporation (CLCAC) rangers from Normanton and Burketown at the Queensland Indigenous Ranger Workshop.

Normanton

14–15 March 2019 – MangroveWatch training for CLCAC rangers based in Normanton (Figure 3.18 and Figure 3.24).

Figure 3.24. Training sessions for monitoring saltmarsh country were conducted with ranger groups around the Gulf like this one with Normanton-based rangers with the CLCAC.

Burketown

16 September 2019 – MangroveWatch training for CLCAC rangers based in Burketown (Figure 3.22).

Borroloola

19–20 September 2017 – MangroveWatch training for the Il-Anthawirrayarra rangers of the Mabunji Aboriginal Corporation supported by the Territory NRM group. Assisted by Des Purcell, a senior ranger with the Gidarjil Development Corporation in the Bundaberg region (Figure 3.17).

19 September 2019 – MangroveWatch training for Il-Anthawirrayarra rangers of the Mabunji Aboriginal Corporation (Figure 3.19, Figure 3.20 and Figure 3.23).

Numbulwar

7–8 November 2017 – MangroveWatch training for Yugul Mangi and Numburrindi Aboriginal rangers supported by the Territory NRM group. Assisted by Shaun Evans, a senior ranger with the Il-Anthawirrayarra rangers of the Mabunji Aboriginal Corporation based in Borroloola.

3.6.2 Community public meetings in the Gulf region

This section lists the various community public meeting attended by Dr Duke to brief the local community on the status of the NESP mangrove dieback project (Figure 3.25). This usually sparked vigorous discussions and many questions. All was explained, and the questions were each answered. Those attending included local elders and other community stakeholders. The numbers attending on each occasion was around 10–15 people.

Figure 3.25. Community meeting in Normanton and Borroloola talking about mangroves, the dieback, and the work by local rangers. This is the meeting in Normanton in 2019.

Normanton

14–15 August 2019 – a two-hour community public meeting organised with the CLCAC rangers based in Normanton (Figure 3.25).

Borroloola

19 September 2019 – a two-hour community public meeting organised with the Mabunji Aboriginal Corporation.

Darwin

13 November 2018 – TNRM Sea Country Workshop with rangers and associates from the Gulf region and other parts of the NT.

3.7 Communication outcomes

This section includes communication products related to this project about the 2015–2016 mass dieback of mangroves in the Gulf of Carpentaria.

3.7.1 Published peer-reviewed research articles

Albert, S., Saunders, M. I., Roelfsema, C. M., Leon, J. X., Johnstone, E., Mackenzie, J. R., Hoegh-Guldberg, O., Grinham, A. R., Phinn, S. R., Duke, N. C., Mumby, P. J., Kovacs, E., and Woodroffe, C. D. (2017). Winners and losers as mangrove, coral and seagrass ecosystems respond to sea level rise in Solomon Islands. *Environmental Research Letters*, *12*(9). pp. 1–11. https://doi.org/10.1088/1748-9326/aa7e68

Amir, A. A., & Duke, N. C. (2019). Distinct characteristics of canopy gaps in the subtropical mangroves of Moreton Bay, Australia. *Estuarine Coast Shelf Science 222*, 66–80. https://doi.org/10.1016/j.ecss.2019.04.007

Duke, N.C. (2017a). Climate calamity along Australia's gulf coast. Landscape Architecture Australia 153: 66–71.

Duke, N.C. (2017b). Mangrove floristics and biogeography revisited: further deductions from biodiversity hot spots, ancestral discontinuities and common evolutionary processes. In: Rivera-Monroy V., Lee S., Kristensen E., Twilley R. (Eds.) *Mangrove Ecosystems: A Global Biogeographic Perspective.* (2nd ed., 17–53) Springer. https://doi.org/10.1007/978-3-319-62206-4_2

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

Duke, N.C., & Kudo, H. (2018). *Bruguiera* × *dungarra*, a new hybrid between mangrove species *B. exaristata* and *B. gymnorhiza* (Rhizophoraceae) recently discovered in north-east Australia. *Blumea 63*, 279–285. https://doi.org/10.3767/blumea.2018.63.03.03

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Duke, N. C., & Mackenzie, J. R. (2020). *Indigenous Ranger field guide to the MangroveWatch Shoreline Video Assessment Method.* TropWATER, James Cook University.

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

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

Duke, N. C., Hutley, L. B., Mackenzie, J. R., Burrows. D., (in press). Processes and factors driving change in mangrove forests – an evaluation based on the mass dieback event in Australia's Gulf of Carpentaria. In: Canadell, J. G. & Jackson, R. B. (eds.), *Ecosystem Collapse – and Climate Change*, Springer.

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

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Salmo III, S., Tibbetts I., & Duke, N. C. ((2018). Nekton communities as indicators of habitat functionality in Philippine mangrove plantations. *Marine and Freshwater Research 69*(3), 477–486. https://doi.org/10.1071/MF17116

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

Van Oosterzee, P., & Duke, N. (2017, March 14). Extreme weather likely behind worst recorded mangrove dieback in northern Australia. *The Conversation*. http://theconversation.com/extreme-weather-likely-behind-worst-recorded-mangrove-dieback-in-northern-australia-71880

3.7.2 Technical reports

Duke N. C., & Mackenzie, J. (2018). *Project ISP018: Development of mangrove indicators for the Gladstone Harbour Report Card. Report to Gladstone Healthy Harbour Partnership by TropWATER Centre* (Publication 18/38). James Cook University.

Duke N. C., & Mackenzie, J. (2018). *East Cape York Report 2017. Final Report: East Cape York Shoreline Environmental Surveys. Report to the Commonwealth of Australia* (Publication 17/67). TropWATER, James Cook University.

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

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

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

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

Harris, T., Hope, P., Oliver, E., Smalley, R., Arblaster, J., Holbrook, N., Duke, N., Pearce, K., Braganza, K., & Bindoff., N. (2017). *Climate drivers of the 2015 Gulf of Carpentaria mangrove dieback. Australia* (JCU TropWATER Report #17/57) NESP Earth Systems and Climate Change Hub.

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Schultz, M., Hansler, M., Logan, M., Carter, A., Chartrand, K. M., Wells, J., Rasheed, M. A., Costello, P., Thompson, A. A., Davidson, J., Duke, N. C., Mackenzie, J. R., Flint, N., Irving, A., Anastasi, A., Jackson, E. L., Sawynok, S., Sawynok, B. Dunlop, A., … Star, M. (2020). *Gladstone Harbour Report Card 2019 – Technical Report.* GHHP, Fitzroy Basin Association.

3.7.3 Presentations at conferences, community symposia and workshops

This section includes key presentations related to this project about the 2015–16 mass dieback of mangroves in the Gulf of Carpentaria.

(1) Presentation title. Application of MangroveWatch for broad-scale assessment of mangrove condition and dynamics in the Torres Strait Islands the northern-most Australian islands.

Authors. Damien Burrows, Norman C. Duke and Jock Mackenzie

July 2016 – MMM4 Conference, St. Augustine, Florida USA

***Abstract*.** The Torres Strait islands lay between northern Australia and southern New Guinea. These islands are of particular interest because of their position between Australia and SE Asia, their predominantly Indigenous population and management, and their low elevation which makes them especially vulnerable to sea level rise and increased storm surge. The Torres Strait islanders have a unique seafaring culture and they identify strongly with their marine and coastal resources.

Despite being part of Australia, the coastal habitats of these islands are poorly known and this, combined with the threat of rising sea levels and seawater intrusion, resulted in local communities and regional natural resource managers expressing a desire for further information on the state of these ecosystems in order to improve management. We used the MangroveWatch methodology[2] to survey the diversity, extent and condition of mangrove and shoreline habitats on these islands. This involved boat and helicopter-based video recording of shoreline habitats using GPS-linked still and video cameras, where the footage is analysed using various metrics back in the lab. This work was supplemented by ground-truthing and analysis of historical imagery. Local Indigenous land and rangers were trained in the use of MangroveWatch field protocols, and participated in all aspects of fieldwork. This involvement is critical given their prime role as Traditional Owners and current managers of the resource.

A total of 35 mangrove species were recorded, with 2 of these being new records for Australia. A total of 26,054 ha of mangrove forests are mapped throughout the islands. We assessed mangrove condition along 300km of shoreline across 14 islands. Mean extent of mangrove cover along shorelines was 67%, demonstrating how important mangroves are as coastal habitats on these islands. [Approximately] 59% of shorelines were assessed as being in a healthy state and 18% in poor condition – this being indicative of the dynamic coastal environment in Torres Strait where even natural stands undergo significant change.

Shoreline processes affecting mangroves varied considerably between individual islands, reflecting that management options will also vary. Overall the dominant shoreline process is erosion (21% greater than expansion). Several islands are undergoing significant expansion and loss at different locations. Mangrove cutting is common on the inhabited islands. Sea level rise appears to be directly threatening 13% of Torres Strait mangrove habitat. Evidence of historical mangrove dieback along shorelines appears to coincide with changes in sea level. Historical change was assessed across 11 islands. One island has had a net increase in mangrove area of 13% since 1974 with half of that being regrowth in historically cleared areas.

The MangroveWatch methodology allows for a broad-scale, yet rapid, assessment of mangrove condition, especially in remote locations. In particular, it is suitable for meaningful involvement of Indigenous participants in the gathering of field data.

(2) *Presentation title*. Managing oil spill impacts on mangroves: should we be concerned?

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[2] mangrovewatch.org

***Authors*.** Norman C. Duke

July 2016 – MMM4 Conference, St. Augustine, Florida USA

***Abstract*.** Mangroves are widely acknowledged as highly vulnerable to oil spills, but this is measured mostly in terms of severity of impacts on vegetation rather than their longer-term recovery and the consequences for associated trophic processes. Little is known about key linkages and functional relationships between the plants and animals making up mangrove habitat. This includes not knowing how long it takes for oil-damaged mangrove habitat to recover. While recovery of forest structure appears to occur within three decades, full habitat recovery may take much longer. From the limited data available, it seems that prevention would be the better option, rather than restoring oil-damaged habitat. But when mangrove habitat is oiled then an effective strategy is needed.

When petroleum oil deposits on sensitive plant surfaces, it also affects soils and dependant animal life, causing a range of lethal and sublethal impacts that extend widely throughout associated coastal and estuarine ecosystems. Such disruptions also affect ecosystem services, like fisheries production and shoreline protection. And, all such impacts may persist for decades, as well as occurring at any time and at any place. So, for as long as oil is extracted and transported, there will be an ever-present risk to the health and survival of mangrove habitats worldwide. Therefore, it is essential where possible to be prepared.

Preparedness includes evaluation of risks and vulnerability, developed from baseline shoreline surveys, records of earlier impacts and recovery, and using effective longer-term monitoring. For instance, impact severity on mangroves might easily be quantified by the area of tree death along with other pragmatic descriptors, like the estimated volume of oil lost, the types of oil, the area of oiled habitat, and the area of likely sublethal impacts. The situation would also be much improved by an agreed global assessment strategy using standard criteria for the longer-term, better management and monitoring of mangrove habitat affected by large oil spills. Only in applying such a strategy will it be possible to adequately understand, evaluate and assist longer-term recovery of oil-impacted mangrove ecosystems.

***(3) Presentation title*. Effects of severe flooding on estuarine mangroves – disturbance, resilience, and restoration.**

***Authors*.** Jock Mackenzie

July 2016 – MMM4 Conference, St. Augustine, Florida USA

***Abstract*.** "*I love a sunburnt country, a land of sweeping plains, of ragged mountain ranges of droughts and flooding rains, I love her far horizons, I love her jewel-sea, her beauty and her terror, the wide brown land for me*" (excerpt from Dorethea Mackellar *My Country)*. Australia is a country typified by diverse and iconic landscapes, severe climate, and severe weather events, which are at times terrifying in their power and destruction. Mangroves are highly adapted to extreme environments as demonstrated by their survival at the interface between land and sea, exposing them to short and long-term climate extremes such as cyclones, floods, and droughts. But anthropogenic driven degradation of estuarine mangroves may threaten the capacity of mangroves to withstand extreme climate events. Direct damage leading to mangrove loss and fragmentation and indirect effects such as altered hydrology and eutrophication reduce the capacity of mangroves to withstand climate extremes and limits their resilience capacity. It is expected that extreme weather events will

increase in both severity and frequency in coming years. It is therefore imperative that we understand how anthropogenic degradation of mangroves influences their resistance and resilience to extreme weather events in order to inform better mangrove management. Recently, a series of severe flood events impacted the east coast of Australia, causing extreme flooding in major coastal rivers and estuaries. These flood events caused widespread loss of shoreline mangroves, with an estimated loss of 30% of estuarine mangroves in some coastal estuaries. Some of the estuaries impacted form part of the monitoring network of MangroveWatch, a citizen-science based program designed to monitor long-term changes in the condition of shoreline mangroves using geotagged video. The MangroveWatch monitoring data enabled assessment of mangrove condition before and after flooding. Here we examine the effect of flooding on estuarine mangroves in three different coastal settings with differing levels of human impacts to assess the effects of estuarine and catchment modification on mangrove resilience to severe flood events. Our results show that shoreline mangrove forest fragmentation, eutrophication, and estuarine shoreline modification result in greater risk of estuarine mangrove loss during severe flood events with recovery dependent on pre-existing forest structure, forest continuity, condition, level of anthropogenic disturbance and adjacent land use. This information is used to develop a strategic approach to mangrove rehabilitation investment in the target estuaries and inform future estuarine mangrove management.

(4) ***Presentation title.*** **Assessing Mangrove Dieback in the Gulf of Carpentaria, a Globally Significant Dieback Event**

***Authors*.** Norman C. Duke, J.M. Kovacs, A.D. Griffiths, J. Mackenzie, and D. Burrows

July 2016 – MMM4 Conference, St. Augustine, Florida USA

***Abstract*.** In October-November 2015, 7,000 hectares of mangroves have suffered dieback along a 1,000 km stretch of coastline in the Gulf of Carpentaria form Karumba in the east to the Roper River in the west. Presentations on this event at recent national and international mangrove conferences confirm that this is a globally unprecedented event. The dieback appears to have started about the same time Oct-Nov 2015, even across these broad areas. The area of impact is too large to be due to chemical contamination or other localised effects. This is suggestive of extreme climate as the cause. Climate data for that period reveal abnormally low rainfall, extreme air, and sea temperatures and even a local drop in sea level. Across the impacted area, the dieback has, at various locations, affected all mangrove species across all tidal zones – it's not just one species or one tidal zone. Of the 1,000 km affected, 200 km of this includes shoreline mangrove communities, whose death now exposes the shoreline to erosion from storms and cyclones for at least the next 15 years till the forests recover. This event has serious implications for biodiversity, commercial and recreational fisheries, local and Indigenous communities, shoreline protection and for government and management agencies.

(5) ***Presentation title.*** **Mangrove Science & Art Show: The Beauty Within'**

***Authors*.** Norman C. Duke and Jock Mackenzie

October 2016 – Reef Blitz Citizen Science Workshops, Cairns.

***Abstract*.** MangroveWatch, The Cairns & Far North Environment Centre and the Djunbunji Land & Sea Rangers are excited to be teaming up to deliver some exciting mangrove related

events to Cairns residents this weekend as a part of the 2016 ReefBlitz. Mangroves nurture 75% of Queensland's fish catch and protect the Reef by filtering catchment runoff and reducing shoreline erosion. Healthy mangroves support healthy corals with clearer, cleaner water – lower in sediments and chemicals. We're inviting the residents of Cairns to learn more about this unique and vital ecosystem by joining in on educational events over the weekend. Everyone is invited to come along on Saturday to the board walk and discover how much carbon our local mangroves are sequestering, attend a mangrove themed art show in the evening, and on Sunday jump aboard and cruise up Trinity Inlet. Attend one event, two or all three!

(6) ***Presentation title.*** **Mangrove monitoring methods and how rangers can get involved.**

***Authors*.** Norman C. Duke and Jock Mackenzie

November 2016 – MangroveWatch training workshop for Indigenous rangers, Normanton & Burketown with the Carpentaria Land Council Aboriginal Corporation.

***Abstract*.** Indigenous rangers are working to evaluate the extent of the massive and mysterious mangrove dieback in the Gulf of Carpentaria. The dieback, involving more than 7,400 hectares of mangroves stretching 1,000 km west of the Gulf town of Karumba, was discovered a year ago, with scientists describing it as "*unprecedented*". The Queensland-based Carpentaria Land Council Aboriginal Corporation, with the help of TropWATER at James Cook University, is now training 19 rangers to monitor the situation for the eastern side. The training began on November 12 for Indigenous ranger teams based in both Normanton and Burketown. The program is being led by TropWATER scientist, Dr Norm Duke. "*TropWATER is giving its full support towards having well-advised, and science-trained local Indigenous rangers across the north of Australia. The rangers are very keen to improve their recording and dissemination of information so the data they collect is relevant to environmental managers in Government, as well as for science researchers*," he said. Dr Duke said the implications of the dieback are likely to be far reaching. "*Locals are justified in their concern for possible impacts on fisheries, coastal productivity, as well as to shoreline stability and more. Losses of shoreline mangroves exposes those shorelines to severe storms and waves that could erode large sections of coastline*." This work has been undertaken and funded at the initiative of the CLCAC as Traditional Owners are extremely concerned about this phenomenon. Through this training, CLCAC Rangers will gain to the skills and knowledge to continue monitoring and evaluating mangrove shorelines across the southern Queensland Gulf. Normanton Senior Head Ranger Paul Richardson is keen to see further investigation into this occurrence and opportunities for Indigenous rangers to undertake monitoring. "*Traditional Owners are concerned about the recent dieback event and the potential widespread environmental impacts it may have. For example, dieback has occurred across important habitat for migratory shorebirds*" Mr Richardson said. Dr Duke said the methods used in MangroveWatch monitoring are readily learnt and applied – requiring participants to simply know how to use a camera and a GPS device. "*This is a remote part of the country, so by using such methods in a standard way provides extremely valuable and useful data.*" Dr Duke said it will be a win-win outcome to support Indigenous rangers as guardians of Australia's shoreline resources - especially in the more remote regions of the country.

***(7) Presentation title.* Update on the largest occurrence of sudden mangrove dieback ever recorded: a lesson in shoreline habitat vulnerability and those who can help!**

***Authors*.** Norman C. Duke, J. M. Kovacs, A. D. Griffiths, J. Mackenzie and D. Burrows

November 2016 – Territory Natural Resource Management Conference, Darwin

***Abstract*.** In October-November 2015, 7,400 ha of mangrove forests died along 1,000 km of the southern shoreline of the Gulf of Carpentaria from Roper River in the Northern Territory to Karumba into Queensland. Presentations about the incident at recent national and international mangrove conferences confirmed that this was globally unprecedented. While the area impacted is too large to have been due to accidental contamination or other localised factors, this does not rule out secondary effects on ecosystems resilience. Current evidence suggests that the overall influences were due to the extreme climatic conditions prevailing at the time, coupled with an unusual but short-lived 20 cm drop in sea level. Climate data during the preceding period revealed abnormally low rainfall, extreme high air and sea temperatures, and an unusually long dry spell. Across the impacted area, the dieback affected all mangroves present in the high tidal zone – so the impact was not restricted to just one species, nor part of the tidal profile. Most worrying furthermore, around 10% of the impacted coastline, ~200 km, suffered more or less complete loss of foreshore mangrove communities. Their death now exposes these coastal sections to likely catastrophic erosion from occasional severe storms and cyclones over at least the next 15–20 years until forests recover – assuming they do. Whatever the cause, this event has serious long term implications for biodiversity, commercial and recreational fisheries, local industries and Indigenous communities, raising this as an urgent and emerging priority for government and management agencies to sure up shoreline protection. There is also a pressing need to support longer-term monitoring by trained and well-advised groups, starting with Indigenous rangers living along these remote northern shorelines.

***(8) Presentation title.* Working with Traditional Owners to better manage northern Australia's coastal and estuarine tidal wetlands.**

***Authors*.** Norman C. Duke, Jock Mackenzie and Damien Burrows

November 2016 – Territory Natural Resource Management Conference, Darwin

***Abstract*.** There are good reasons for protecting Australia's northern coastal and estuarine tidal wetlands. They provide essential ecosystem services of lucrative resources like fisheries productivity, protection of Australia's northern shorelines, buffering erosion, and bolstering coastal water quality. But, these benefits and the habitats themselves are threatened by human development as well as from occasional climate events like the recent extensive dieback in the Gulf. A national strategy is needed for prioritising at-risk and damaged shorelines to help in their protection and rehabilitation, as needed. Scientists at TropWATER Centre James Cook University are working on a number of innovative projects with Traditional Owner rangers and local citizens to meet these national objectives. These partnerships are delivered in a program called MangroveWatch which raises capacity for shoreline assessment amongst individual groups. Key recent projects with Indigenous partners include: the Southern GBR estuaries with Gidarjil Development Corporation, Eastern Princess Charlotte Bay shorelines with Balkanu, Noosa and Maroochy region with

Bunya Bunya Corporation, Torres Strait islands with Torres Strait Regional Authority, and most recently in the south-eastern Gulf region with the Carpentaria Land Council Aboriginal Corporation. In each project, close partnerships are producing beneficial outcomes that deliver detailed assessments of shoreline health, condition, vulnerability, dominant issues, and prioritisation of shoreline sites for rehabilitation. Indigenous Rangers make key contributions as they monitor, assess, manage and rehabilitate estuarine wetlands within their individual cultural landscapes. At the same time, scientists and regional managers obtain first hand observations, data and imagery for better understanding changes taking place in each region. It's a win-win outcome!

Indigenous rangers key to monitoring mangrove dieback. A leading mangrove researcher has called for training of Indigenous rangers to help monitor and prevent mangrove dieback amid fears future cyclones could have serious impacts on the north Australian coastline. The death of more than 7,000 hectares of mangrove forests along 1,000 km of the southern shoreline of the Gulf of Carpentaria from Roper River in the Northern Territory to Karumba in Queensland was globally unprecedented and has left these shorelines exposed to serious threats. James Cook University senior mangrove ecologist and Professional Research Fellow, Dr Norman Duke said he was most concerned about the threat future cyclones would have on the coast. "*The mangrove dieback has made these coastal sections vulnerable to severe storms and cyclones for the next two decades which could cause catastrophic erosion until new seedlings grow*," Dr Duke said. "*Because of the remote location, it is important that we work with Indigenous communities, particular rangers so they can not only work with visiting specialists but also conduct monitoring of the shoreline on their own.*" Dr Duke will present an update on his research at the 2016 Territory Natural Resources Conference will be held from 22–24 November. The conference will bring together people working in natural resource management from across the Northern Territory.

(9) ***Presentation title*.** Update on the training of Traditional Owners for shoreline monitoring and the current status of mangrove dieback in the Gulf.

***Authors*.** Norman C. Duke, Damien Burrows and Jock Mackenzie

March 2017 – Australian Mangrove and Saltmarsh Network (AMSN) Conference, Hobart

***Abstract*.** This talk will provide an update on the status of the extensive mangrove areas impacted in the late 2015 incident of unprecedented severe dieback in the Gulf of Carpentaria. This includes the specific training and monitoring being undertaken by Traditional Owners with JCU's TropWATER Centre that have helped achieve a range of results. Since the issue was first raised at AMSN 2016 in Darwin in May, there have been a number of field and aerial surveys that have significantly raised the levels of knowledge and understanding about the dieback. It is notable that much has been achieved in characterising the incident - despite an initial lack of committed funding. The situation has now changed. With the combination of studies planned and being undertaken, the stage now is set to build on the valuable baseline information gathered about the incident: to look more closely at the potential cause; to make assessments of recovery and/or further loss; along with, detailed evaluations of key likely implications and consequences flowing from such an abnormally severe and widespread impact on tidal wetlands of northern Australia.

(10) ***Presentation title*.** Highlighting the value of MangroveWatch program for mangrove management in Moreton Bay and the challenges facing long-term citizen-science based mangrove monitoring.

***Authors*.** Jock Mackenzie, Norman C. Duke, Damien Burrows, Simon Baltais and Debra Henry

March 2017 – Australian Mangrove and Saltmarsh Network (AMSN) Conference, Hobart

***Abstract*.** There are many opportunities to engage the general public in citizen-science to address the immediate and widespread threats facing mangrove and saltmarsh habitats in Australia. The challenge is to translate citizen-science data to on-ground management action, ensuring long-term sustainability of citizen-science programs, and keeping the 'science' in citizen-science. Here we examine the opportunities and challenges involved in harnessing citizen-science to achieve better outcomes for mangrove management using the example of the Wildlife Preservation Society Queensland (WPSQ) Moreton Bay MangroveWatch program, a long-term mangrove monitoring program in South-East Queensland. WPSQ citizen-scientists have monitored 500 km of shoreline since 2012. The analysed data shows that Moreton Bay mangroves are generally healthy but there are hotspots of degradation that would benefit from proactive management intervention. What appear to be minor issues, like small-scale mangrove removal, localized runoff, and shoreline erosion, at a whole of system scale collectively equate to a substantial threat, putting Moreton Bay mangroves at risk of a 'death by a thousand cuts'. Effective management of mangroves and prioritisation of investment in mangrove rehabilitation and protection requires knowledge of these local issues, identification of high value habitats and degradation hot-spots. The Moreton Bay MangroveWatch program demonstrates that citizen-science can provide this information to managers with low data collection costs and scientifically robust outcomes. But, the future of the Moreton Bay MangroveWatch is uncertain.

(11) ***Presentation title*.** A mangrove management plan for the southern GBR.

***Authors*.** Norman C. Duke, Jock Mackenzie and Gidarjil rangers

April 2017 – Southern Great Barrier Reef CHAMP NESP project workshop, Rockhampton.

***Abstract*.** This talk is about prioritising investment in tidal wetland rehabilitation to improve water quality in the southern Great Barrier Reef waters. Traditional Owner rangers and local citizens of the Port Curtis Coral Coast (PCCC) TUMRA will be engaged in developing a Mangrove Management Plan (MMP) that provides a strategic basis for estuarine repair activity and maximizes water quality outcomes in the southern GBR. Development of this MMP will build capacity within the Gidarjil Development Corporation (GDC) and local community to undertake scientifically rigorous, ecological monitoring and assessment. These management and rehabilitation strategies will protect sea country resources through partnerships between community, scientists and NRM agencies. The MMP will enable rangers and citizen scientists to conduct scientifically valid surveys of estuarine monitoring, management and rehabilitation within the PCCC TUMRA area.

(12) ***Presentation title*****.** New Innovative Tools and Partnerships for an effective National Shoreline Monitoring Program.

Authors**.** Norman C. Duke and Jock Mackenzie

May 2017 – National Estuaries Network workshop, Townsville.

Abstract**.** This talk is about Using Mangroves/Tidal Wetlands for Coastal Monitoring. The aim is to fill knowledge gaps in monitoring of shoreline processes for coasts and estuaries across large areas – adding to existing satellite and aerial image remote sensing, along with on-ground field surveys. An effective assessment framework has been specially developed that is comprehensive, all-encompassing use of selected methodologies for rapid and rigorous quantification of condition and health of coastal habitats. The goal was to use current science, familiar technologies like geo-videographic methods (HD digital video cameras with GPS = S-VAM) for monitoring coastal environmental health, with data acquisition on a publicly accessible archive of imagery and assessments. And, these tools need to be easily familiar with community groups in partnerships with science specialists and managers for their practical and valuable contributions to environmental monitoring - adding invaluable first-hand accounts of habitat condition at sites along coastal shorelines.

(13) ***Presentation title*****.** Golden Beach MangroveWatch shoreline restoration 2014–2017.

Authors**.** Norman C. Duke and Jock Mackenzie

August 2017 – Australian Coastal Restoration symposium, Townsville.

Abstract**.** This talk is about learning how to rehabilitate damaged shorelines based on a successful project at Golden Beach in southern Queensland. The planting and other ground works have involved the local Bunya Bunya Traditional Owners along with some dedicated community volunteers. The works involved reprofiling of the shoreline to accommodate the establishment of mangrove seedlings. Supporting structures installed included burying coir logs laid out in a special 'fish scale' pattern to provide an artificial subterranean root mat. This was protected by a layer of gravel whilst the seedlings become established over the next 10–20 years. The proof of the project's success was recorded when the site was inundated and washed over by flooding waters during a particularly violent local storm. Since that time, the seedlings have continued to grow and develop wider support roots. The project is supported by not only local community members but also the local council, state government and industry.

(14) Presentation title**. MangroveWatch training workshop for Indigenous rangers in Borroloola with Territory Natural Resource Management Group and the Northern Land Council.**

Authors**.** Norman C. Duke and Jock Mackenzie

September 2017 – Territory Natural Resource Management field training workshop, Borroloola.

Abstract**.** Indigenous rangers are working to evaluate the extent of the massive and mysterious mangrove dieback in the Gulf of Carpentaria. The dieback, involving more than 7,400 hectares of mangroves stretching 1,000 km west of the Gulf town of Karumba, was discovered a year ago, with scientists describing it as "*unprecedented*". The TropWATER Centre, James Cook University, is now training 15 more rangers to monitor the situation. The program is being led by TropWATER scientist, Dr Norm Duke. "*TropWATER is giving its full support towards having well-advised, and science-trained local Indigenous rangers across the north of Australia. The rangers are very keen to improve their recording and dissemination of information so the data they collect is relevant to environmental managers in Government, as well as for science researchers*," he said. Dr Duke said the implications of the dieback are likely to be far reaching. "*Locals are justified in their concern for possible impacts on fisheries, coastal productivity, as well as to shoreline stability and more. Losses of shoreline mangroves exposes those shorelines to severe storms and waves that could erode large sections of coastline*." This work has been undertaken and funded at the initiative of the Territory NRM in support of Traditional Owners who are extremely concerned about this phenomenon. Through this training, Borroloola Rangers will gain to the skills and knowledge to continue monitoring and evaluating mangrove shorelines across the western NT Gulf. Dr Duke said the methods used in MangroveWatch monitoring are readily learnt and applied – requiring participants to simply know how to use a camera and a GPS device. "*This is a remote part of the country, so by using such methods in a standard way provides extremely valuable and useful data*." Dr Duke said it will be a win-win outcome to support Indigenous rangers as guardians of Australia's remote shoreline resources.

(15) Presentation title. **Cairns MangroveWatch shoreline monitoring program**

***Authors*.** Norman C Duke, Jock Mackenzie and Geoffrey Redman

October 2017 – Reef Blitz Citizen Science Workshops, Cairns.

***Abstract*.** MangroveWatch, The Cairns & Far North Environment Centre (CAFNEC) and the Djunbunji Land & Sea Rangers are excited to be teaming up to deliver some exciting mangrove related events to Cairns residents as a part of the 2017 ReefBlitz. Mangroves nurture 75% of Queensland's fish catch and protect the Reef by filtering catchment runoff and reducing shoreline erosion. Healthy mangroves support healthy corals with clearer, cleaner water - lower in sediments and chemicals. We're inviting the residents of Cairns to learn more about this unique and vital ecosystem by joining in on educational events over the weekend. Everyone is invited to come along to the workshop and training session to discover how to monitor the health of tidal wetlands, with hands on experience in Trinity Inlet.

***(16) Presentation title*.** **MangroveWatch training workshop for Indigenous rangers in Numbulwar with Territory Natural Resource Management Group and the Northern Land Council.**

***Authors*.** Norman C. Duke and Jock Mackenzie

November 2017 – Territory Natural Resource Management field training workshop, Numbulwar and Ngukuur.

***Abstract*.** Indigenous rangers are working to evaluate the extent of the massive and mysterious mangrove dieback in the Gulf of Carpentaria. The dieback, involving more than 7,400 hectares of mangroves stretching 1,000 km west of the Gulf town of Karumba, was discovered a year ago, with scientists describing it as "*unprecedented*". The TropWATER group at James Cook University, is training 10 more rangers to monitor the situation. The program is being led by TropWATER scientist, Dr Norm Duke. "*TropWATER is giving its full support towards having well-advised, and science-trained local Indigenous rangers across the north of Australia. The rangers are very keen to improve their recording and* *dissemination of information so the data they collect is relevant to environmental managers in Government, as well as for science researchers*," he said. Dr Duke said the implications of the dieback are likely to be far reaching. "*Locals are justified in their concern for possible impacts on fisheries, coastal productivity, as well as to shoreline stability and more. Losses of shoreline mangroves exposes those shorelines to severe storms and waves that could erode large sections of coastline*." This work has been undertaken and funded at the initiative of the Territory NRM in support of Traditional Owners who are extremely concerned about this phenomenon. Through this training, Numbulwar and Ngukuur Rangers will gain to the skills and knowledge to continue monitoring and evaluating mangrove shorelines across the western NT Gulf. Dr Duke said the methods used in MangroveWatch monitoring are readily learnt and applied – requiring participants to simply know how to use a camera and a GPS device. "*This is a remote part of the country, so by using such methods in a standard way provides extremely valuable and useful data*." Dr Duke said it will be a win-win outcome to support Indigenous rangers as guardians of Australia's remote shoreline resources.

(17) *Presentation title.* Healthy Habitat equals healthy fish - the MangroveWatch shoreline monitoring program

***Authors*.** Norman C. Duke and Jock Mackenzie

February 2018 – Fishers for Fish Habitat Forum, Logan.

***Abstract*.** MangroveWatch, Healthy Land and Water and OzFish Unlimited teamed up to deliver an exciting Mangrovewatch event for Logan residents. Mangroves nurture 75% of Queensland's fish catch and protect the Reef by filtering catchment runoff and reducing shoreline erosion. Healthy mangroves support healthy corals with clearer, cleaner water - lower in sediments and chemicals. We're inviting the residents of Logan to learn more about this unique and vital ecosystem by joining in on educational events over the weekend. Everyone is invited to come along to the workshop and training session to discover how to monitor the health of tidal wetlands, with hands on experience in Logan River estuary.

(18) *Presentation title.* Healthy Mangrove Habitat equals healthy fish - the MangroveWatch shoreline monitoring program

***Authors*.** Norman C. Duke and Jock Mackenzie

March 2018 – MangroveWatch workshop, Ballina, NSW.

***Abstract*.** MangroveWatch, Ballina City Council and NSW Fisheries teamed up to deliver an exciting Mangrovewatch event for Ballina residents. Mangroves nurture 75% of Queensland's fish catch and protect coastal waters by filtering catchment runoff and reducing shoreline erosion. Healthy mangroves support healthy shorelines with clearer, cleaner water - lower in sediments and chemicals. We're inviting the residents of Ballina to learn more about this unique and vital ecosystem by coming to this special event. Everyone is invited to come along to discover how to monitor the health of their local tidal wetlands.

(19) *Presentation title*. Mass mangrove dieback in the Gulf – 2 years on!

***Authors*.** Norman C. Duke, Jock Mackenzie and Damien Burrows

April 2018 – Australian Mangrove and Saltmarsh Network (AMSN) Conference, Sydney

Abstract**.** It was a surprise to everyone when normally resilient mangroves were observed dying *en masse* in the Gulf of Carpentaria in early 2016 – being concurrent more or less with severe coral bleaching and a particularly severe El Niño event at the time. What has happened since for mangroves and tidal wetlands? There are many questions – some to do with impact and whether the situation has gotten worse? To questions about added and consequential impacts on associated marine habitats like seagrass beds, and on turtles and local fisheries.

Has there been detectable recovery either as sprouting trees, or recruitment of damaged mangrove forest habitat? Have intervening severe weather events had any effect, like cyclonic winds and flooding in the region. And, of course, there remain questions about the cause. While scientists involved have a short-list of considered hypotheses, the specific cause remains unconfirmed. In this talk, I will update on such key questions, while sharing a number of recent insights from research and monitoring studies undertaken over the last year. One objective in this is to update and prepare the way for a targeted workshop to address concerns about what is being done, plans in affect, and what to do next.

(20) Presentation title**. Understanding the effects of consecutive severe flood events on estuarine mangroves – the role of citizen-science mangrove monitoring in informing effective mangrove management in a changing climate.**

Authors**.** Jock Mackenzie and Norman C. Duke

April 2018 – Australian Mangrove and Saltmarsh Network (AMSN) Conference, Sydney

Abstract**.** Recent consecutive severe flood events in south-east Queensland dramatically impacted local communities. Less well recognised has been the impact of these flood events on estuarine ecology, including mangrove habitats. Here we present a study on the effects of consecutive extreme flood events on shoreline estuarine mangrove habitats along 30 km of the Logan River estuary, SEQ. Using detailed analysis of continuous, georeferenced shoreline video data collected by local MangroveWatch citizen-scientists and school students between 2014 and 2017 we answer three questions; 1) Are Logan River estuarine mangroves resilient to consecutive severe flood events? 2) what are the factors that increased shoreline mangrove vulnerability to severe flooding in the Logan River? 3) What are the longer-term implications of more frequent and severe flooding in the Logan River anticipated under current climate change projections? Based on this assessment we conclude that increased extreme flood frequency will dramatically alter the extent and habitat structure of estuarine shoreline mangrove habitats along the Logan River. Of particular note is the likely long-term loss of the upper-estuary *Aegiceras corniculatum* dominated mangrove fringe, prime breeding habitat for commercially valuable prawn species. Maintaining estuarine shoreline mangrove habitat and the continued provision of the ecosystem services they provide under changing climate conditions will require effective ecosystem management and direct management intervention, including limiting shoreline habitat fragmentation and disturbance, weed management and ‘living shoreline’ habitat creation and shoreline stabilisation. Effective mangrove management can only occur if there is sound scientific understanding of the likely ecological response of mangroves to changing climate, knowledge of existing threats and vulnerabilities that will reduce mangrove ecosystem resilience to climate change and community awareness and support for management intervention. This study demonstrates that citizen-science driven long-term mangrove

monitoring programs, like MangroveWatch, provide opportunities to improve understanding of mangrove ecological response to climate change impacts, identify local threats and vulnerabilities and directly engage local communities in local mangrove stewardship likely to increase public support for investment in mangrove resource protection.

(21) *Presentation title.* Mangroves. Why are they important? - the MangroveWatch shoreline monitoring program

***Authors*.** Norman C. Duke and Jock Mackenzie

April 2018 – MangroveWatch workshop, Mackay.

***Abstract*.** MangroveWatch with Mackay Christian College teamed up to deliver an exciting Mangrovewatch event for Mackay residents. Mangroves nurture 75% of Queensland's fish catch and protect coastal waters by filtering catchment runoff and reducing shoreline erosion. Healthy mangroves support healthy shorelines with clearer, cleaner water - lower in sediments and chemicals. We're inviting the residents of Mackay to learn more about this unique and vital ecosystem by coming to this special event. Everyone is invited to come along to discover how to monitor the health of their local tidal wetlands.

(22) *Presentation title.* Mass dieoff of mangroves in Australia's remote north – 2 years on!

***Authors*.** Norman C. Duke, Jock Mackenzie & Damien Burrows

May 2018 – Boden Conference, Canberra, ACT.

***Abstract*.** It was a surprise to everyone when mangroves, believed to be quite resilient, were observed dying en masse in the Gulf of Carpentaria in early 2016. This incident was especially cogent as it was co-incident with severe coral bleaching on the GBR, and a severe El Niño event. The landscape-scale statistics surrounding the dieback of mangroves, where 7,400 ha of forest trees died in 2–3 months along a 1,000 km shoreline, demonstrated clearly that these ecosystems were indeed, highly vulnerable to sudden changes in climate and environmental conditions. It was further remarkable that this incident was not only slow to be reported, but also because of its remoteness on Australia's northern coast, there was little chance of the usual direct human suspects being involved. In this talk, I will share recent insights, observations and concerns for better informing enlightened, effective management actions – like an effective national shoreline environmental monitoring capability.

(23) *Presentation title*. MangroveWatch for assessment of mangrove condition and dynamics in the Torres Strait Islands.

***Authors*.** Norman C. Duke, Damien Burrows and Jock Mackenzie

June 2018 – Torres Strait Terrestrial Island Ecosystems Workshop, Cairns

***Abstract*.** The Torres Strait islands lay between northern Australia and southern New Guinea. These islands are of particular interest because of their position between Australia and SE Asia, their predominantly Indigenous population and management, and their low elevation which makes them especially vulnerable to sea level rise and increased storm surge. The Torres Strait islanders have a unique seafaring culture and they identify strongly with their marine and coastal resources.

Despite being part of Australia, the coastal habitats of these islands are poorly known and this, combined with the threat of rising sea levels and seawater intrusion, resulted in local communities and regional natural resource managers expressing a desire for further information on the state of these ecosystems in order to improve management. We used the MangroveWatch methodology (www.mangrovewatch.org) to survey the diversity, extent and condition of mangrove and shoreline habitats on these islands. This involved boat and helicopter-based video recording of shoreline habitats using GPS-linked still and video cameras, where the footage is analysed using various metrics back in the lab. This work was supplemented by ground-truthing and analysis of historical imagery. Local Indigenous land and rangers were trained in the use of MangroveWatch field protocols, and participated in all aspects of fieldwork. This involvement is critical given their prime role as Traditional Owners and current managers of the resource.

A total of 35 mangrove species were recorded, with 2 of these being new records for Australia. A total of 26,054 ha of mangrove forests are mapped throughout the islands. We assessed mangrove condition along 300km of shoreline across 14 islands. Mean extent of mangrove cover along shorelines was 67%, demonstrating how important mangroves are as coastal habitats on these islands. [Approximately] 59% of shorelines were assessed as being in a healthy state and 18% in poor condition – this being indicative of the dynamic coastal environment in Torres Strait where even natural stands undergo significant change.

Shoreline processes affecting mangroves varied considerably between individual islands, reflecting that management options will also vary. Overall the dominant shoreline process is erosion (21% greater than expansion). Several islands are undergoing significant expansion and loss at different locations. Mangrove cutting is common on the inhabited islands. Sea level rise appears to be directly threatening 13% of Torres Strait mangrove habitat. Evidence of historical mangrove dieback along shorelines appears to coincide with changes in sea level. Historical change was assessed across 11 islands. One island has had a net increase in mangrove area of 13% since 1974 with half of that being regrowth in historically cleared areas.

The MangroveWatch methodology allows for a broad-scale, yet rapid, assessment of mangrove condition, especially in remote locations. In particular, it is suitable for meaningful involvement of Indigenous participants in the gathering of field data.

(24) *Presentation title*. Mass dieoff of mangroves in Australia's remote north – 3 years on!

***Authors*.** Norman C. Duke and Jock Mackenzie

August 2018 – NESP Northern Australia Hub Workshop, Brisbane

***Abstract*.** It was a surprise to everyone when mangroves, believed to be quite resilient, were observed dying en masse in the Gulf of Carpentaria in early 2016. This incident was especially cogent as it was co-incident with severe coral bleaching on the GBR, and a severe El Niño event. The landscape-scale statistics surrounding the dieback of mangroves, where 7,400 ha of forest trees died in 2–3 months along a 1,000 km shoreline, demonstrated clearly that these ecosystems were indeed, highly vulnerable to sudden changes in climate and environmental conditions. It was further remarkable that this incident was not only slow to be reported, but also because of its remoteness on Australia's northern coast, there was little chance of the usual direct human suspects being involved. In this talk, I will share recent

insights, observations and concerns for better informing enlightened, effective management actions – like an effective national shoreline environmental monitoring capability.

(25) *Presentation title*. We are losing mangrove tidal wetlands - so what is being done about it?

***Author*.** Norman C. Duke

September 2018 – 3rd International Symposium on the Conservation and Management of Wetlands, Sabah, Malaysia.

***Abstract*.** It is now well-documented that mangrove and tidal wetlands are in decline, with many accounts describing ongoing losses and deterioration of wetland habitats worldwide. In addition, recent dramatic and unexpected losses to mangrove habitats are further challenging the view that mangrove and tidal wetlands were tough habitats, resilient and able to rebound from all sorts of damage. It was further worrying when recent observations showed that more isolated areas were also at great risk. For instance, it was a surprise to everyone when mangroves were observed dying en masse in Australia's remote Gulf of Carpentaria in early 2016. This incident was especially cogent as it was co-incident with severe coral bleaching on the GBR and a severe El Niño event at the time. The scale of damage was staggering considering no direct human agent was to blame. The statistics surrounding the mass dieback record more than 7,400 ha of mangrove trees died in 2–3 months along approximately 1,500 km of shoreline. It seems hardly necessary to say, but this incident demonstrated that these tidal wetland ecosystems were indeed, highly vulnerable to the recent extreme changes in climate, sea level and other environmental variables. A key question arising from this occurrence was that if this could happen in such a remote wetland environment, then what must be happening in other, more populated places? In this presentation, I want to share recent insights and observations in support of local and regional efforts to better understand the status of tidal wetlands. And, how these places might be managed better. I would also like to promote enlightened, more effective management actions that build on important conservation initiatives, by enhancing the capacity of local people to assist in regional and national environmental monitoring strategies focusing on vulnerable tidal wetlands along with other shoreline natural environments. The growing consensus amongst stakeholders is that a science-based strategy is highly desirable if we are to effectively deal with the changes taking place in tidal wetlands locally and worldwide.

(26) *Presentation title*. Mass dieoff of mangroves in Australia's remote north – 3 years on!

***Authors*.** Norman C. Duke and Jock Mackenzie

November 2018 – NESP Northern Australia Hub Workshop, Darwin

***Abstract*.** The latest data are presented from aerial surveys and extensive field studies. It was a surprise to everyone when mangroves, believed to be quite resilient, were observed dying en masse in the Gulf of Carpentaria in early 2016. This incident was especially cogent as it was co-incident with severe coral bleaching on the GBR, and a severe El Niño event. The landscape-scale statistics surrounding the dieback of mangroves, where 7,400 ha of forest trees died in 2–3 months along a 1,000 km shoreline, demonstrated clearly that these ecosystems were indeed, highly vulnerable to sudden changes in climate and environmental

conditions. It was further remarkable that this incident was not only slow to be reported, but also because of its remoteness on Australia's northern coast, there was little chance of the usual direct human suspects being involved. In this talk, I will share recent insights, observations and concerns for better informing enlightened, effective management actions – like an effective national shoreline environmental monitoring capability.

(27) ***Presentation title*. Assessing mangrove dieback in the Gulf**

***Authors*.** Norman C. Duke and Jock Mackenzie

February 2019 – NESP Northern Australia Hub Research Forum, Canberra.

***Abstract*.** Current results and assessment findings are presented from the 2017 aerial surveys and extensive field studies conducted in late 2018. The plan was to discuss the works in progress, identify the planned outputs and list the achievements to date. The research project was on track and significant conclusions about the cause of dieback and the management options were discussed.

(28) ***Presentation title*. Mangrove dieback – does it matter?**

***Authors*.** Norman C. Duke

March 2019 – Torres Strait Environmental Management Committee (EMC27), Thursday Island.

***Abstract*.** A review of the current findings gained from the NESP mangrove dieback project to emphasise the importance of mangroves and the environmental benefits lost when large areas of mangrove die. The scope of the talk also include reference to the extensive studies conducted as part of the NERP project in Torres Strait during 2012–2014.

(29) ***Presentation title*. Mangrove monitoring – why & how to do it!**

***Authors*.** Phillip George, Brenton Yanner and Norman C. Duke

March 2019 – Queensland Indigenous Ranger Workshop, Cairns.

***Abstract*.** A talk by rangers with Dr Duke about the MangroveWatch monitoring program and the importance of coastal monitoring. The importance of mangroves to the Gangalidda and Garawa peoples was also discussed along with a review of the monitoring projects currently being undertaken by Indigenous rangers with the Carpentaria Land Council Aboriginal Corporation. The mass dieback of mangroves in the Gulf was also reviewed.

(30) ***Presentation title*. Assessing mangrove dieback in the Gulf**

***Authors*.** Norman C. Duke and Jock Mackenzie

April 2019 – NESP Northern Australia Hub Research Forum, Brisbane.

***Abstract*.** A presentation to stakeholders in the Brisbane region to review current results and assessment findings for the 2017 aerial surveys and extensive field studies conducted in late 2018. We discussed the works in progress, identified planned outputs and listed achievements to date. The research project was on track with significant conclusions being developed about the cause of dieback and the best considered management options.

(31) ***Presentation title*. Mangroves. Why they are important!**

***Authors*.** Norman C. Duke

April 2019 – Community meeting, Mackay.

***Abstract*.** A presentation to local educators in a public community meeting in the Mackey region to brief those attending about the benefits of mangroves and the threats they face.

This included a review of current findings for the aerial surveys and field studies concerning the mass mangrove dieback event in the Gulf. The discussion included a definition of mangroves as well as a review of key drivers of change like rainfall, storms, rainfall, sea level and significant pollution incidents. The discussion lead to a further review of the best considered management options.

(32) ***Presentation title*. Changes in mangrove tidal wetland habitat.**

***Authors*.** Norman C. Duke and Jock Mackenzie

June 2019 – Wet Tropics Stakeholder workshop, Cairns.

***Abstract*.** A presentation to local educators in a stakeholder workshop in the Cairns region to brief those attending about the benefits of mangroves and the threats they face.

This included a review of current findings for the aerial surveys and field studies concerning the mass mangrove dieback event in the Gulf. The discussion included a definition of mangroves as well as a review of key drivers of change like rainfall, storms, rainfall, sea level and significant pollution incidents. The discussion lead to a further review of the best considered management options.

(33) ***Presentation title*. Ongoing threats, damaging processes and longer-term consequences associated with the 2015 dieback of mangroves in northern Australia's Gulf of Carpentaria.**

***Authors*.** Norman C. Duke, Jock Mackenzie and Lindsay Hutley

June 2019 – Australian Mangrove & Saltmarsh Conference, Melbourne.

***Abstract*.** How are mangroves in the Gulf of Carpentaria coping four years after the mass dieback event in late 2015? With this presentation, we re-evaluate the broad environmental conditions and constraints that define this instance of severe impact on mangrove tidal wetland habitat. Our objective has been to structure and quantify the distinct and unusual mix of processes involved in the natural establishment, growth and development of these stands in the context of the environmental changes taking place. Based on our findings, a new evaluation framework has been developed to better explain the severe response observed in late 2015, and what has happened since. These and other observations about this unique event are assisting with the ongoing development and implementation of effective management policy, starting with monitoring programs at national and local scales.

(34) ***Presentation title*. Coastal and estuarine mangrove ecosystems are feeling the pinch – what do we know about the threats, the processes affected, and the prognosis for not coping?**

***Authors*.** Norman C. Duke and Jock Mackenzie

July 2019 – MMM5 : Mangrove Macrobenthos & Management Conference, Singapore.

***Abstract*.** For more than 50 million years, mangrove habitats have flourished along shifting intertidal shorelines, seemingly in deference to changes in continental margins, sea levels fluctuating tens to hundreds of metres, combined with their direct exposure to coastal waves and winds. This small group of specialised plants clearly have highly successful strategies to cope and survive in this tightly constrained, mostly tropical niche worldwide. Currently however there is an unprecedented accumulation of pressures, their increasingly rapid delivery, and wide global influence. Never before has there been such a combination of ever-expanding human development pressures coupled with extreme alterations in climates and rising sea levels. This combination of pressures along with the growing evidence of habitat deterioration worldwide has given cause for widespread concern. A common question is how will these ecosystems cope.

With this presentation, we outline and review the broad environmental conditions and constraints that define the mangrove tidal wetland habitat. In so doing, our objective has been to structure and quantify the distinct and unusual mix of processes involved in their establishment, growth and development. The framework created helps explain a number of larger ecosystem responses by tidal wetlands, including one notable incident in Australia's Gulf of Carpentaria involving the mass dieback of mangroves on a regional scale. Observations and deductions made from such case studies are essential to the development and implementation of effective management policy. The framework applied supports well-advised strategies for managing recovery while minimising socio-economic and environmental impacts.

(35) ***Presentation title*. Assessing mangrove dieback in the Gulf.**

***Authors*.** Norman C. Duke

August 2019 – NESP Northern Australia Hub Field Trip workshop, North Queensland.

***Abstract*.** Discussions with stakeholders along with Hub Steering Committee members. The field trip involved flying over the mangrove dieback field site at Karumba and making a ground visit afterwards. The impact and extent of the mangrove dieback was clearly displayed. Progress with the project was discussed.

(36) ***Presentation title*. Assessing mangrove dieback in the Gulf.**

***Authors*.** Norman C. Duke and Jock Mackenzie

December 2019 – NESP Northern Australia Hub Research Forum, Darwin.

***Abstract*.** A presentation to stakeholders in the Darwin region to review current results and assessment findings for the 2017 and 2019 aerial surveys and field studies conducted in late 2018. We discussed the works in progress, identified planned outputs and listed achievements to date. The research project was on track with significant conclusions being developed about the cause of dieback and the best considered management options.

(37) ***Presentation title*. Assessing mangrove dieback in the Gulf.**

***Authors*.** Norman C. Duke and Jock Mackenzie

February 2020 – NESP Northern Australia Hub workshop, Brisbane.

***Abstract*.** A workshop for project leaders in the Brisbane region to review current results and assessment findings. We discussed the works in progress, identified planned outputs and listed achievements to date. The research project was on track with significant conclusions being developed about the cause of dieback and the best considered management options.

(38) ***Presentation title*. Assessing mangrove dieback in the Gulf.**

***Authors*.** Norman C. Duke and Jock Mackenzie

March 2020 – NESP Tropical Water Quality Hub workshop, Townsville.

***Abstract*.** A workshop for project leaders to review current results and assessment findings. We discussed finalisation of works in progress, identified planned outputs and listed achievements to date. The research project was on track with significant conclusions being developed about the cause of dieback and the best considered management options.

4. Discussion of overall project findings

The key findings from field studies described in this volume provide validation of aerial survey observations presented in Volume 1. The 2015–2016 dieback of mangroves occurred down from the upper ecotone edge of the seaward fringing mangrove zone (Figure 2.2). We describe the detailed characteristics of the dieback, especially in the relationship to its occurrence within the tidal wetland zonation and for its elevation levels relative to common highwater reference levels. These observations will be expanded upon in popular articles and research publications for better dissemination amongst the broader group of interested stakeholders and end users. For instance, observations new to science like the temporary drop in sea level and its consequences for tidal wetlands has considerable interest amongst the scientific community. Furthermore, information relevant to improving management outcomes like the damage caused and the accumulative factors repressing recovery, have great relevance and interest amongst a wider audience, including environmental managers. This, Volume 2, outlines and summarises these and other significant findings from our investigations.

Figure 4.1. Much of these NESP studies have been about reading the signs and making deductions from them about the processes taking place. For example, these degraded dead stumps often observed at the seaward edge of the field sites like this one at Transect 4B, were indicative of shoreline retreat.

The project studies making up these NESP investigations are listed in Table 4.1. Each of these component investigations provides additional insights and observations that contribute to our current knowledge of the 2015–2016 mass dieback event. The breadth of efforts to disseminate these findings is represented in the number of communication outcomes listed with our summary of technical, training sessions, meetings, and public presentations, as well as in the professional research publications. Our communication and interaction with Indigenous ranger groups across the Gulf have been most extensive, productive, and very successful. All these project outcomes have guaranteed and made effective, the dissemination of emerging knowledge and understanding of the 2015–2016 mangrove dieback. These efforts have further ensured the interested stakeholders and end-users have both developed and maintained their strong interest in these NESP investigations and their outcomes.

Table 4.1. A listing of overall project outcomes derived from the range of studies undertaken with this NESP investigation into the 2015–2016 mass mangrove dieback in the Gulf of Carpentaria.

Study finding	Project studies							
	1	2	3	4	5	6	7	8
Dieback features								
Regional extent	X		X					
Timing	X	X						
Area	X							
Location character	X			X		X		
Impact severity	X		X	X		X		
Profile zone					X	X		
Elevation position					X			
Fringe presence and recovery			X		X	X		
Wrack accumulations				X		X		
Aging and tree demography		X					X	
Event scars in wood		X					X	
Molluscan fauna								X
Prior occurrence		X					X	
Associated factors								
Rainfall	X			X				
Sea level rise			X	X				
Sea level drop		X			X	X	X	
Cyclones			X	X			X	
Flooding			X					

Note: Study findings are grouped under features of ecosystem responses and factors of associated climate-environment.

Project study components listed in the table include:

1. Vol. 1: Mapping changes to vegetation 2015–2016.
2. Vol. 1: Mapping historical changes to vegetation.
3. Vol. 1: Aerial assessment of shorelines in 2017 and 2019.
4. Vol. 1: Aerial assessment of estuary mouths in 2017 and 2019.
5. Vol. 2: Field assessment of transect profiles in 2018 and 2019.
6. Vol. 2: Field assessment of transect vegetation in 2018.
7. Vol. 2: Field assessment of transect tree wood in 2018.
8. Vol. 2: Field assessment of transect molluscan fauna in 2018 and 2019.

4.1 Changes in sea level and mangrove dieback

Sea level and regular tidal inundation are primary controlling factors of mangrove distributions, particularly across the intertidal zone (Duke et al., 1998). The inundation extent across tidal foreshores depends on the tidal amplitude and its range. And, as becomes evident when studying tides, mean sea levels vary across space and time (Church & White, 2011). When assessing the influences of changing sea level on mangroves, all these variables must be recognised and considered.

Coincident with the 2015–2016 mass dieback of mangroves in the Gulf, sea levels reportedly dropped in the region by at least 20 cm (Duke et al., et al., 2017). It was, however, considered useful to further explore this occurrence to better understand its implications and the likely consequences on parameters measured in the field study. The aim was to isolate the factors that might be recorded in measurements and observations of profile elevations linked to the condition of vegetation present.

A key assumption was that where sea levels varied significantly beyond a normal ambient range, then mangrove plants would become stressed and die where they no longer had sustainable levels of inundation and moisture retention. This view recognises that mangrove intertidal distributions are normally distinguished by distributional limits in distinct and often abrupt elevation gradients. These limits are species-dependent. This further coincides with the characteristic feature of mangroves in having distinct species zonation across tidal profiles. These zones tend to follow tidal elevation levels where mangrove species assemblages have been broadly classified into zones which at their extremes include lower seaward and upper landward tidal positions. And, where these zones occur along shorelines with relatively shallow slope, then the width of each zone will be wider – but so also will be the response (like dieback) when inundation levels change.

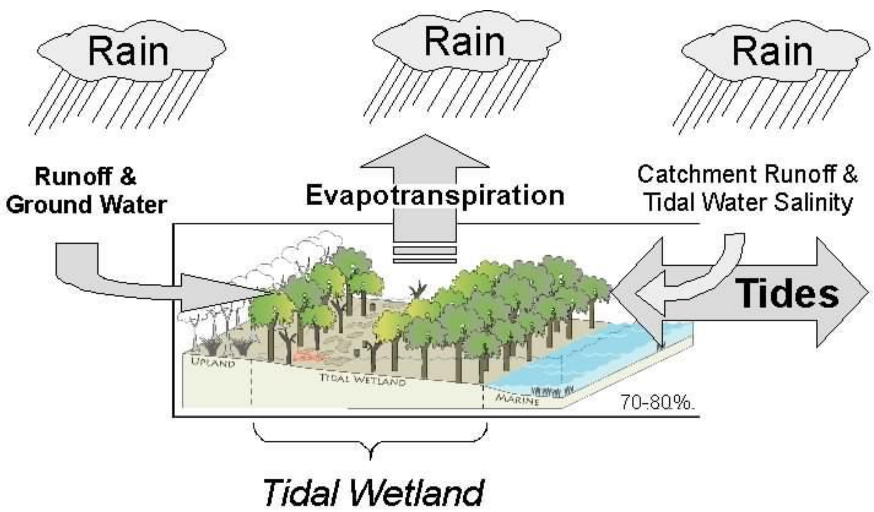

Figure 4.2. The schematic diagram describes the role of tides, rainfall, and other climatic factors in controlling mangrove distributions across the tidal profile in the absence of changes in sea level (Duke et al., in press).

Mangrove zonation across the tidal profile is known to be influenced and partly defined by rainfall and temperature as well as tidal inundation (Figure 4.2). A recent account of such influences described the role of one major factor, rainfall, and how its effects were entirely predictable (Duke et al., 2019a). But that analysis did not include changes in sea level. Such sudden and abrupt changes would be expected to have profound and dramatic consequences for sea level-dependent tidal wetlands (Duke et al., in press).

A useful observation regards the influence of tidal inundation is that mangroves along with tidal saltmarsh (collectively termed tidal wetlands), often occur just above mean sea level (MSL) and up to the highest astronomical tide (HAT) level. These levels provide practical reference points used in the field investigation. In the following assessment of sea level changes in the Gulf, these reference levels further identify and define a mechanism for projected influences on mangroves in situations when sea levels change in both the short (months) and longer (years to decades) term.

4.2 Assessment of sea level data from three Gulf ports – a stress index

The likely importance of sea level changes was assessed further from tide gauge records from three ports in the Gulf region including Milner Bay (Groote Island) in the Northern Territory, and Karumba (Figure 4.3) and Weipa in Queensland. The time period covered by these records varied with significant gaps, but the period from 1993 to 2018 was commonly represented for each port.

Figure 4.3. The port with tide gauge at Karumba is situated near the mouth of the Norman River in close proximity to the severely impacted shoreline of 2015–2016 mangrove dieback just north of the mouth (Figure 5.34).

The time series plot of monthly records (Figure 4.4) show correspondence between annual seasonal cycles and amplitude that varied between locations. The site with the most extreme variation was Karumba at the south-eastern corner of the Gulf. Note that Karumba was also the only port location where severe mangrove dieback was observed in 2015–2016 (Vol. 1: Section 5.3.4 ‘Norman River lower estuary‘).

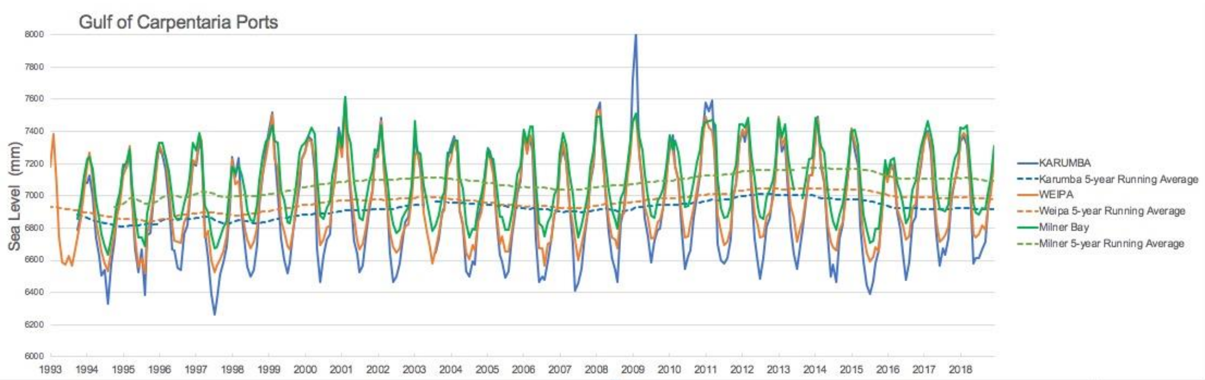

Figure 4.4. The time series of monthly sea levels for three Gulf of Carpentaria port tide gauges for Milner Bay (Groote Island) in the Northern Territory, and Karumba and Weipa in Queensland from 1993–2018. Note the minimum level for Karumba in 2015–2016 and the lower minimum periods in the 1990s. The most extreme lower levels did not appear to correspond with mangrove dieback occurring only in late 2015. However, there was a question regards the progressive sea level rise over this period and how this might have influenced the severity of the 2015–2016 extreme low event.

By contrast, there was little of no severe dieback in the Weipa area or around Groote Island. This raises an important question as to whether there might be differences between the three port records that might explain differences likely to be linked with the 2015–2016 mass dieback event. The focus in this treatment was on seasonally (monthly) extreme low sea levels rather than high peaks. In the short term, excessive inundation equated to occasional flooding while the lack of inundation might have resulted in more harmful impacts associated with desiccation.

Based on this plot, the lowest levels recorded were most extreme in 1994–1995 and 1997–1998. Clearly, these extreme lower levels did not correspond with unusual mangrove dieback that occurred only during 2015–2016. However, there remains a question as to whether progressive sea level rise might have skewed the relative severity of these extreme low tide events.

By fitting a linear curve to the sea level data, the rates of sea level rise could be estimated from the slope of the curve – recorded for each location over the same time period from 1998 to 2018. Accordingly, the estimated rates of sea level rise were 3.03 mm/year for Karumba, 3.54 mm/year for Weipa, and 4.60 mm/year for Milner Bay. These rates were less than those listed by Church et al. (2009) and used in Vol. 1.

These rate values were then used to normalise the data in a re-evaluation of the relative importance of monthly and annual variations in sea level. Differences were estimated between monthly sea levels and the 5-year running averages for each of the three Gulf of Carpentaria port tide gauge records. The time series plot of monthly records (Figure 4.5) displays a normalised data set with sea level rise trends removed. In this graph, there were two comparably extreme low events (near minus 0.6) in the most widely variable Karumba record with low troughs in 1997–1998 and 2015–2016. These data show the relative differences in maximal severity of each extreme event, but there is one unaccounted factor. As mangroves only died *en masse* in the latter event, an important consideration was whether the duration of these severe instances might also have differed and would these stresses have impacted mangrove vegetation. For this reason, we explore the notion of whether a combination of stress severity and duration might explain whether the event in 2015–2016 was in any way unusual.

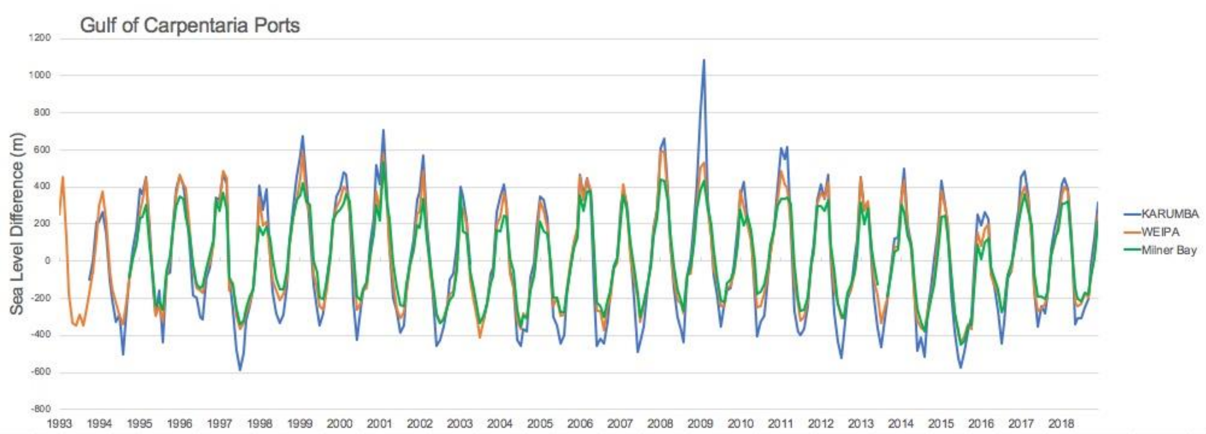

Figure 4.5. The time series of the difference between monthly sea levels and their 5-year running averages for three Gulf of Carpentaria port tide gauges for Milner Bay (Groote Island) in the Northern Territory, and Karumba and Weipa in Queensland from 1993 to 2018. These differences tend to normalise the data (Figure 4.4), 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 4.2. Time series data and derivation of the stress index (combining severity and duration) estimated from the three Gulf of Carpentaria port tide gauge records for Milner Bay (Groote Island) in the Northern Territory, and Karumba and Weipa in Queensland for 1995–2018. The index was calculated using the multiple of months when sea levels were less than minus 300 mm of the 5-year running average (as duration) times the average of monthly difference values less than minus 300 mm (as severity, see Figure 4.5). Note extreme low sea level events varied between ports, years, and months. Seasonal extreme lows occurred mostly between the months of May and September. In Karumba 2015–2016 the extreme low occurred over a 5-month period of minus 469 mm averaged sea levels.

	Months <-300 mm			Sea level difference			Stress Index			
	Milner Bay	Weipa	Karumba	Milner Bay	Weipa	Karumba	Milner Bay	Weipa	Karumba	*
1995	0	1	1	0	324	435	0	0.324	0.435	
1996	0	0	2	0	0	307	0	0	0.614	
1997	2	2	4	329	348	470	0.658	0.696	1.88	1
1998	0	0	1	0	0	336	0	0	0.336	
1999	0	0	1	0	0	345	0	0	0.345	
2000	0	0	1	0	0	424	0	0	0.424	
2001	0	1	2	0	304	365	0	0.304	0.73	
2002	2	2	3	325	320	411	0.65	0.64	1.233	
2003	1	3		332	350		0.332	1.05		
2004	3	4	4	319	319	405	0.957	1.276	1.62	2
2005	0	0	4	0	0	373	0	0	1.492	3
2006	1	1	4	302	370	410	0.302	0.37	1.64	4
2007	1	1	3	300	328	428	0.3	0.328	1.284	
2008	0	0	3	0	0	369	0	0	1.107	
2009	0	0	1	0	0	353	0	0	0.353	
2010	0	0	2	0	0	366	0	0	0.732	
2011	0	2	3	0	310	379	0	0.62	1.137	
2012	1	2	3	305	303	450	0.305	0.606	1.35	
2013		1	3		330	379		0.33	1.137	
2014	2	3	3	355	351	469	0.71	1.053	1.407	
2015	5	5	5	388	388	469	1.94	1.94	2.345	5
2016	0	0	2	0	0	390	0	0	0.78	
2017	0	0	1	0	0	353	0	0	0.353	
2018	0	0	3	0	0	318	0	0	0.954	

The combination of severity and duration represents a potentially useful stress index (Figure 4.6). In this case, the severity was quantified as periods of extremely low sea levels like those shown in the time series plots (Figure 4.5). The duration would be the period when extreme values were recorded (Table 4.2). Using the three port records, indices (Box 4.1) were calculated as the multiple of months (duration) when sea levels were less than minus 300 mm for difference values from 5-year running averages multiplied by the average of these monthly differences (severity). Firstly, note that extreme low sea level events varied between ports, years, and months. However, the seasonal extreme lows occurred mostly between the months May and September.

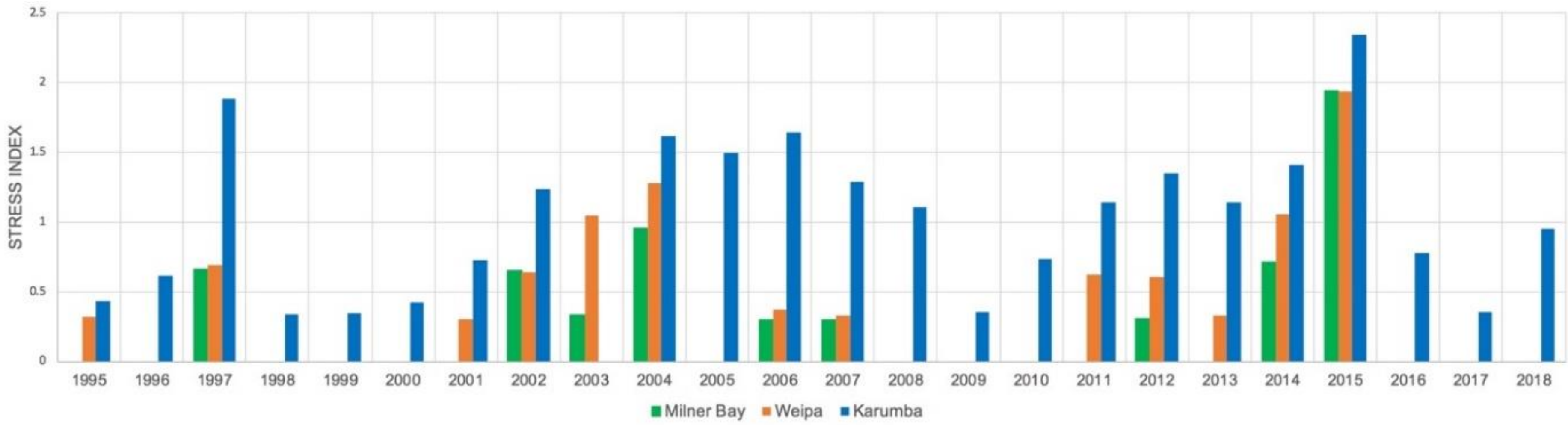

Figure 4.6. The time series of the nominal stress index (combining severity and duration) estimated from the three Gulf of Carpentaria port tide gauge records for Milner Bay (Groote Island) in the Northern Territory, and Karumba and Weipa in Queensland for 1995 to 2018. Calculation of the index used the multiple of months when sea levels were less than -300 mm of the 5-year running average (as duration, see Table 4.2) times the average of monthly difference values less than -300 mm (as severity, see Figure 4.5). In this way, the 2015–2016 event was notably most severe in the Karumba area (>2 on the stress index) – noting this was the only port of the three to be in close proximity to an area of severe or moderate mangrove dieback in 2015–2016.

Box 4.1. Derived index from sea level records concurrent with high levels of mangrove dieback.

STRESS INDEX – for sea level drop influences on mangroves

Based on monthly sea level records and calculation of differences between sea level and the 5-year running average.

Equation: *Stress Index = Duration* X *Severity*

Where…

Duration = number of consecutive months < -300 mm of the difference between sea level (mm) and the 5-year running average.

Severity = averaged sea levels of consecutive months < -300 mm of the difference between sea level (mm) and the 5-year running average.

Note…

Values in excess of 2.0 correspond to dieback of mangroves in 2015–2016 (Table 4.2).

In Karumba 2015–2016, the extreme trough occurred over a 5-month period when averaged sea levels were minus 469 mm – with a stress index value greater than 2. While the same duration was experienced at that time in the other two ports, these locations the situations were not as severe – stress indices less than 2. Of further note, the slightly more severe levels experienced in 1997–1998 however were sustained over fewer months, so stress indices were lower in each port location – less than two. Based on these examples, index values appear to depict a threshold level of stress. As such, low moisture levels may have caused mangroves to dieback and retreat from upper intertidal zone margins with the reduced tidal flooding associated with the sea level drop event. This point will be considered further in the following assessment of patterns of mangrove dieback observed and measured in field studies of transect elevation profiles and corresponding vegetation condition.

4.3 Overview of the current findings

As noted, the assessment of aerial survey and mapping data identified a number of distinguishing characteristics of the 2015–2016 mass dieback of mangroves in the Gulf of Carpentaria – most notably its broad extent and its synchronicity. These aspects were introduced and discussed in Vol. 1 with interim deductions made from satellite imagery for mapping, and survey imagery for shoreline condition assessments. In this, Volume 2, we continue our investigations to further enhance and extend upon those initial findings. A first addition was the description and assessment of the losses in vegetation measured from upper ecotones positions linked to a quantifiable decrease in elevation across the tidal profile. This approach had an immediate benefit in providing a measure comparable between the mass dieback of mangroves in late 2015 and the decrease in sea levels correlated with the severe El Niño event.

Overall, the combination of field and aerial observations largely confirm the likely primary cause of the 2015–2016 mangrove dieback as the temporary drop in sea level. And, the severity of the corresponding El Niño event shows how this dieback event was the result of a change in the climate. Further to this conclusion, we also discovered that there appeared to have been a similar mass mangrove dieback event 33 years earlier in 1982–1983. But these conclusions were more challenging to reach because records of the event are limited. While there was a comparable and severe El Niño at the time causing a comparable drop in sea level, no observations of mangrove dieback had been made, nor has there been readily available aerial imagery. Our attempts were also made difficult by the regions' remoteness. Nevertheless, sufficient records have been gathered with these investigations from which to arrive at a reasonably certain conclusion. It may not be as succinct as we would like, we do however believe the evidence for an earlier occurrence is conclusive. This means there has been a repeated event delivering a dramatic and severe environmental impact of widespread mass dieback of mangroves in the Gulf region on at least two occasions around three decades apart.

The findings from these NESP project investigations are summarised as follows:

1. Mangrove forests fringing shorelines areas around the Gulf were characterised by the concurrent occurrence of wide areas of dieback with sometimes complete loss of fringing mangrove stands. Dieback appeared to align with upper tidal elevation contours (Figure Figure 2.2 and Vol. 1: Figures 2.2 and 2.25). The nature of this impact was observed in aerial surveys and later confirmed in field studies.
2. Impacted areas occurred along approximately 2,000 km of the Gulf shoreline from just north of the North Mitchell River mouth and along the southern Gulf coast of Queensland to Blue Mud Bay in the Northern Territory (Vol. 1: Table 3.1; Vol. 1: Figure 3.13). While field studies focused on eight transects at four sites across the impacted area, the wider conditions were confirmed during the 2019 aerial surveys by landing at specific locations to validate aerial observations made, including for each of the relevant response indicators.
3. The occurrence of this unusual event of severe mangrove dieback was synchronous along Gulf shorelines depicted in time series plots of green fraction indices (NDVI) at selected sites around the Gulf (Vol. 1: Figure 3.4). Furthermore, the timing of the event in late 2015 was co-incident with the severe 2015–2016 El Niño event that was also responsible for the exceptionally high seawater temperatures and coral bleaching recorded in north-eastern Australia (Hughes et al., 2017).
4. The mass mangrove dieback was specifically distinguished by its occurrence along tidal zone saltpan–saltmarsh margins at the rear of seaward fringing mangrove stands (Figure 2.2). The proportional loss of mangrove fringe and its reduction in width was further used to rank the severity of impact ranging mostly from 10% – 100% loss (Vol. 1: Figure 2.2). Transect sites used in field studies were selected to include sites with and without surviving trees at the seaward fringe. This allowed a preliminary comparison of consequential differences in recovery after three years (Figure 2.2). These observations were updated further following the 2019 aerial surveys because two severe cyclones delivered significant additional impacts reducing recovery of affected areas.
5. Field measurements showed that dieback zones were wider where the slope of the intertidal zone was flatter (Table 3.1; Figure 3.6). In addition, the tidal zone slope tended to be steeper in areas with greater numbers of cyclones.
6. The chief species of mangrove impacted was the locally dominant species the Grey Mangrove, *Avicennia marina* var. *eucalyptifolia*. Other mangroves affected included *Rhizophora stylosa* and *Ceriops australis*. By contrast, a notable survivor was the Club Mangrove, *Aegialitis annulata*. This latter species may have been less impacted than

Avicennia marina because of its short shrubby stature similar to saltmarsh plants which also survived the dieback event (Table 3.3).

7. Consistent with these general observations, the dominant species in field sites were *Avicennia marina* var. *eucalyptifolia* forming the canopy (often dead) and *Aegialitis annulata* (mostly surviving) often making up the under-canopy (Table 3.3). The under-canopy, including saplings and seedlings of *Avicennia marina*, was proportionally more dense in transects with wider surviving seaward fringing canopy trees (Figure 3.1). This was interpreted as evidence of the benefits of exposure buffering by living trees along seaward margins. These findings were often matched by a proportional lack of erosion and exposed below ground roots in more sheltered areas. However, one important caveat was that these field observations were made before the two severe cyclones impacted sites in the Northern Territory several months later.
8. In some locations, there were multiple dieback 'fronts' at adjoining species zone edges (Vol. 1: Figures 1.1 inset and 2.25). This included dieback zones with survivors within alternate zones across the tidal profile. The normal ranking of species was *A. marina* (lower elevation zone fringing the sea edge)*, R. stylosa*, *C. australis,* and *A. marina* (also at the upper elevation zone fringing the saltpan–saltmarsh edge).
9. A number of longer-term drivers associated with climate change were considered active throughout the Gulf region, and these had recognisable influences as recorded in our assessments of tidal wetlands in estuary mouths and along shoreline stands. These drivers included cyclones, sea level rise, flooding during winter months in late 2015, and the temporary 20 cm drop in sea level event.
10. Cyclones regularly impacted the Gulf with at least one notable cyclone every two years (Vol. 1: Figure 2.14). The more infrequent, higher strength cyclones (> Category 3) have caused severe damage to mangrove forests (Vol. 1: Figures 0.6, 0.7, 2.13, 4.6, 5.86, 5.89, 5.92, and 5.112), with shoreline erosion, uprooted trees, large areas of canopy stripped bare of leaves, piles of wood wrack dumped inshore, and sediment deposition with root burial dieback. During this study, there were at least two severe tropical cyclones in the 2018–2019 season. They were Trevor and Owen (Category 4 and 3 cyclones) that impacted at least 600 km of shorelines in the Northern Territory. These cyclones especially, severely scoured areas damaged earlier during 2015–2016. Dead wood from the earlier dieback event was swept into stacks and mounds and dumped onto nearby surviving stands causing significant additional damage. This damage included the scouring loss of seedling recruits and severe damage to re-sprouting trees throughout the dieback zone. These impacts were recognised as significant accumulative impacts severely compromising progress towards recovery made until that time.
11. Rising sea levels recognised in port tide gauge records were consistent with observations of 20–30-year-old dead stumps along the seaward edges of many sections of Gulf shorelines (Figure 0.14, Figure 3.10, Figure 4.4, Figure 4.6, Figure 5.11, Figure 5.12, Figure 5.46, Figure 5.47, Figure 5.60, and Figure 5.61), as well as severe levels of saltpan scouring (Vol. 1: Figure 2.22) coupled with terrestrial retreat (Vol. 1: Figure 2.16) and bank erosion (Vol. 1: Figures 2.21 and 2.23). This driver was readily quantified in this assessment from the number of notable impact responses seen in mangroves throughout the study region. Field observations further found that mangrove fringe stands were often characterised by the progressive ordering of stem sizes with larger older trees at the front and smaller younger trees up the tidal profile (Figure 3.9). This was consistent with the

demographic profile expected with progressively rising sea levels as stand populations migrate upland.

12. Flooding impacts were notable in several estuarine systems and shoreline sections. The most notable was the Flinders River estuary, where saltpan–saltmarsh scouring was severe and accompanied by deep gullying and erosion across saltpan–saltmarsh areas (Vol. 1: Figures 2.23 and 5.48). These impacts were concurrent with bank erosion and depositional gain. The latter was distinguished by the accumulation of sediment where this exceeds mean sea level to form sediment banks that rapidly become colonised by mangrove seedlings (Vol. 1: Figures 2.20 and 5.124). Lengthy sections of seaward shorelines around the Flinders and Bynoe River estuaries were distinguished by such wide banks of depositional gain resulting from the extraordinary flood event in February 2019.
13. The unusual temporary drop in sea level in late 2015 was identified early as a likely influence on the 2015–2016 mass dieback of mangroves (Duke et al., 2017). This likelihood was investigated further in this study. In conclusion, it was confirmed as the most likely cause. This was based on a number of observations, including the detailed assessment of tide gauge records from three ports in the Gulf (Table 4.2; Figure 4.6). These findings showed there was a significant, but temporary, drop in sea level. The impact of this event was likely to cause extreme moisture stress on mangroves along higher intertidal elevation zones (Box 4.1) – consistent with our field observations of the locations of dieback across the tidal profile (Table 3.1 and Table 3.2). Measurements taken in the eight transects had a significant positive relationship (P<0.01) between estimated levels of sea level drop and the elevation range of lost mangroves (Table 3.2).
14. Field measures of molluscan fauna helped characterise the habitat role of mangroves and how this was affected by the mass dieback. Key features of the habitat were shown in significant relationships comparing the density of vegetation and the number of mollusc families (Figure 3.13). This was further relevant considering the relationship between under-canopy and the surviving fringe width. Conversely, there was also a negative relationship between mollusc families and the percentage of dead trees and the loss of biomass from the dieback. But not all was straight forward when looking at individual families. There were clearly some faunal groups that prospered with greater canopy density like the Littorinids, while others like some Potamids thrived on disturbance (Figure 3.14). The responses by these fauna demonstrated the complex and dynamic state of these highly disturbed mangrove systems.
15. Field observations on the vegetation demography of Gulf mangroves further show they were relatively young and highly disturbed ecosystems (Table 3.3; Figure 3.9). Firstly, the dominance of *Avicennia marina* in the Gulf was comparable with observations in other tropical latitudes where this mangrove species was recognised as more resilient to physical disturbance than other mangroves (e.g., Duke, 2013; Mackenzie & Duke, 2011). Secondly, in the Gulf, while size classes of canopy trees of *A. marina* were similar in all transects, their small stem size was exceptional and comparable with regrowth stands in other places. Since stem diameter is recognised as a proxy for age (specific studies are ongoing for these Gulf trees), such a finding was indicative of the relatively young age of seaward fringing mangroves across the Gulf. These structural features were indicative of repeated occurrences of severe damage to Gulf seaward fringing stands over the last three decades. This was consistent with our observations of the accumulative impacts of severe cyclones and there being an earlier instance of mass dieback with the 1982–1983 El Niño event.

4.4 Evidence of an earlier dieback event

There were several pieces of evidence suggesting that the 2015–2016 mass dieback event was not unprecedented and that there was an earlier occurrence. There is considerable interest in this point since an additional occurrence would provide further confirmation of the cause and it would allow prediction of future occurrences.

In brief, the evidence for an earlier incident of mass mangrove dieback in the Gulf includes:

4.4.1 Vegetative condition and the mangrove response

1. Historical satellite imagery show substantive and comparable loss of mangroves between 1979 and 1989 (Vol. 1: Figure 3.5; Vol. 1: Section 4.5 'Evidence from mapping').
2. Green fraction plots across the Gulf region (Vol. 1: Figure 3.4) showing depleted shorelines in 1987 that recover afterwards up until 2015. The demonstrated recovery trajectory shows these severely damaged fringing mangrove forests had recovered naturally over that time period.
3. Aerial and field observations of degraded dead stumps fronting and amongst mangrove shorelines across the region (Figure 0.14, Figure 3.5, Figure 3.11, and Figure 4.1). It is important that we determine whether there was a common event responsible for the death of these trees. As this represents an unanticipated objective, the approach taken with this project has been to get additional funding for carbon dating analyses of selected wood samples – noted with the field study results. This action represents an important extended project outcome.
4. Field observations of the demography of mangrove fringe forest stands (dominated by *Avicennia marina* var. *eucalyptifolia*) show that the mean estimated age of trees was around 10–20 years with maximal tree ages around 33 years (Table 3.3, Figure 3.9). These measures suggest that Gulf fringing mangroves exist in an unusually disturbed state. They also appear unable to achieve the more mature stand structures observed in nearby regions (Duke, 2013; Mackenzie & Duke, 2011). As noted for the degraded stumps, it is planned to have a representative selection of trees aged using carbon dating, since the laminae 'rings' in the common mangrove tree there, are not growth rings normally suitable for dendrochronological assessment. This action represents a significant future project outcome.

4.4.2 Associated occurrences of the likely driver and its impacts

5. The condition of vegetation made in the field studies was such that recovery had been taking place three years after the 2015–2016 event in all sites. This was most evident in under-canopy vegetation (Table 3.3; Figure 3.1), as well as there being a growth of surviving *Aegialitis annulata* shrubs, there was notable recruitment of canopy seedlings especially in damaged zones behind wider stands of surviving trees at seaward edges. This was evidence that the factor causing the impact was temporary and that conditions that caused the dieback had been restored.
6. Our investigation of tide gauge data records for three ports in the Gulf shows there was a period in mid-late 2015 when sea levels were unusually low (Table 4.2; Figure 4.6). This period was coincident with observations of the occurrence of mangrove dieback (Duke et al., 2017). While port records were available only back to 1987, they did provide detailed

information from that time showing that the 2015–2016 event was unique in both severity and duration. This was shown in a possible mangrove stress index developed with this investigation. During this time series, while another significant El Niño event in 1997–1998 was severe, its impact was relatively short-lived.

7. Further to these field investigations, measurement of elevation levels at the eight widely placed sites across the Gulf gave a uniform range of levels defining a common impacted elevation zone across these tidal profiles of around 0.4–0.5 m (Table 3.1 and Table 3.2). This elevation range, effectively lost with this impact, was furthermore comparable to the anomalous low sea levels measured in the Gulf port tide gauge at Karumba (Norman River estuary). This was the only port sea level record in close proximity to an area of severe mangrove dieback in 2015–2016. Away from the impacted areas, low levels in other Gulf ports were not as low at the time. This evidence was entirely consistent with the primary role of the temporary drop in sea level in causing this incidence of mass mangrove dieback.
8. 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. And, as noted, there were observations of a corresponding severe loss of mangroves recorded between 1978 and 1987 with this NESP investigation (Vol. 1: Figure 3.5).
9. According to Wyrtki (1985), the 1982–1983 El Niño event started in July 1982 during the southern hemispheric winter, unlike earlier events which had mostly started during southern summers. These circumstances are now recognized as comparable with the 2015–2016 event. At the time, the 1982–1983 event was the largest El Niño in recorded history based on the size and intensity of the collapse of the tropical wind field and by the reaction of the southern oscillation associated with high-temperature anomalies in the equatorial and eastern Pacific.

These observations were consistent with the cause of mangrove dieback in late 2015 being the temporary drop in sea level associated with the 2015–2016 El Niño. They also identify for the first time the likely earlier occurrence of mass mangrove dieback with the 1982–1983 EL Niño. In each case, the dramatic dieback of mangroves appeared to have been caused by the temporary collapse of the tropical wind field associated with commonly severe El Niño conditions. These atmospheric conditions caused a shift in the southern oscillation whereby seawaters flowed eastward across the Pacific Ocean to cause a dramatic but temporary drop in sea level of at least 20 cm on the western side. This situation was apparently exaggerated in the Gulf of Carpentaria because of its broad and shallow topography at this south-western limit of the Pacific Ocean.

The impact on mangroves in the Gulf appears to have been caused by a lack of normal highwater flooding and inundation with daily high tides. Mangrove trees at the upper edge of the desiccation ecotone with saltpan–saltmarsh died due to a lack of essential tidal wetting over 4–5 months, causing acute moisture stress. The situation would undoubtedly have been worsened by the extremely hot and dry conditions at the time (Harris et al., 2017), but it appears most likely the trees may not have died *en masse* had there not been the extreme low sea levels at the time.

4.5 Management implications

Environmental managers are understandably concerned about the consequences of losing significant beneficial natural resources. More informed and targeted strategies are required to minimise future impacts affecting the social and economic well-being of human communities living in these remote coastal areas generally. We outline key deductions and lessons learned in reviewing these deductions regards the mass dieback event in the context of other large-scale disturbances.

For each area, management options will vary, but broadly speaking, only direct human-related drivers may be addressed effectively at the local scale. For climate-natural drivers, local management options mostly concern making on-going evaluations of status and ensuring local human-related pressures are minimised. The aim in each case is to increase the resilience of existing natural habitats.

The manifestations of climate-natural impacts are driven by changes in climate extent and the rate of change. The recommended management options for such climate-related pressures are best considered as part of a National Strategy for on-going monitoring and evaluation across the entire catchment and regional areas.

Locally delivered management actions needed to address the impacts observed include:

- Restrict vehicle access generally onto and bordering tidal wetland areas – mangroves and saltpans;
- Reduce the heat of fires where possible. In addition, limit controlled fires near tidal wetlands to periods of spring tides;
- Increased feral pig control measures;
- Restrict access by cattle and other stock into tidal wetland areas;
- Step up weed eradication measures;
- Limit runoff loads of nutrient, agricultural chemicals, and sediments;
- Discourage any human-assisted planting of mangrove seedlings;
- Only allow well-considered shoreline stabilisation and rehabilitation projects in particularly damaged areas; and
- Monitor shoreline condition and key drivers on a regular basis and map/quantify shoreline change.

4.5.1 A national mitigation and monitoring strategy

The key management opportunity identified from these NESP investigations surrounds the identification of specific shoreline processes, their severity, the location of impacted areas, and the lasting value of such data as baseline measures from which future changes may be quantified. Each of these factors is best framed as fundamental contributions towards an updated National Strategy for the monitoring and mitigation of Australian shoreline environments.

With the current investigations, it is now possible to identify and document the more severe impacts on shoreline communities and tidal wetlands. Such a knowledge base is essential for the best management of shoreline habitats facing rapid changes in climate, increased storm impacts, and rising sea levels.

It is recommended that a national strategy be implemented using such newly acquired information of shoreline imagery and scored observations using standard and pragmatic descriptors of habitat condition linked to the likely drivers of change. It is also essential to develop a comprehensive shoreline monitoring program that uses the key indicators of status and condition of tidal wetlands and associated shoreline habitats.

Such a National Strategy would also benefit from mutual partnerships developed between dedicated Aboriginal Ranger groups and experienced environmental specialists. In more populated areas, community involvement might also include local community environmental groups, as is done in the community environmental monitoring program called MangroveWatch (mangrovewatch.org.au). Scientists with the program partner with local groups to survey shorelines using methods comparable to the current survey.

The core role of monitoring concerns recording the occurrence and extent of vulnerable shoreline habitats, as well as quantification of their condition and the changes affecting them. Such a strategy concerns both remote and more populated areas. There is a need to avoid confusion about the differences in direct Human influences and Climate-Natural factors, so as to maximise the application and benefits of local management decisions.

4.5.2 Further assessment of estuarine and shoreline data sets

The identification of impacts and drivers identified in this survey provide important steps towards an updated National Shoreline Monitoring Strategy. The assessment framework has been applied earlier to prioritise cost-effective mitigation works within individual catchment areas (Duke et al., 2010, 2015, 2019b; Duke & Mackenzie, 2018a, 2018b). An example of an advanced case study is the shoreline monitoring program being undertaken since 2009 in the southern GBR catchment area between Port Curtis and Bundaberg in separate projects with the Gladstone Ports Corporation and Australia's National Environmental Science Program (Duke et al., 2019b). A further case study example of the management outcomes to be derived from the current NESP surveys is given for the Albert River estuary (Appendix 9 and Appendix 10).

4.5.3 This report complements tidal wetland mapping

The findings of these NESP studies compliment prior regional ecosystem mapping of tidal wetland areas by the Queensland Herbarium and the Wetlands Mapping Group with the Department of Environment and Heritage Protection (Queensland Government, 2020a, 2020b). The NT government is also focused on better understanding and documenting shoreline habitats. These State and Territory groups have detailed maps of wetland areas as valuable information on the type and location of tidal wetlands in the Gulf of Carpentaria study area. However, such accurate observations of the type and location of wetland areas are only part of the information needed by State and Federal environmental managers to act decisively and effectively regards the state and condition of mangrove wetland environments. Information about the condition and health of tidal wetlands especially needs to be better-informed and current if it is to be useful.

Our recent survey addresses this gap by providing enhanced and complementary expert information about the condition of these previously mapped wetlands along the Gulf coast. For all 37 major estuarine systems, we gathered extensive oblique imagery (a permanent baseline database), individual condition assessments, identification and quantification of key changes taking place (responses and impacts), and the dominant drivers of change associated with each location. In addition, we also produced for the first time, a detailed evaluation of current condition for the entire shoreline (specifically at every 100-metre point over ~2,000 km), to complement individual assessments for the major estuarine systems.

There are more than 25,000 high-resolution images of the shoreline as a continuous baseline record of the entire shoreline of the study area on two occasions in 2017 and 2019. Accompanying these images, a spreadsheet provides a metadata listing as the head resource for a database compilation that includes location coordinates and location names. It is our intention to present these data and imagery for public viewing as soon as possible. In the first instance, all images have been submitted with this report.

4.5.4 Long-term success and on-going benefits of management

We classified the likely causes and drivers into two broad categories – namely human relatively direct factors, and natural with climate factors. The discrimination of these key factors influencing habitat responses consequently defines our recommendations for potentially successful interventions to be most effective. These groupings range from local to regional and national levels. However, since all levels of intervention are expected to influence each other, none of the intervention outcomes should be considered in isolation.

To gain positive outcomes efforts need to focus on building the resilience of shoreline habitats to improve survival prospects (in growth, reproduction, recruitment, and ecological conditions) coupled with efforts to curb factors driving harmful change (like land use disruption, excessive erosion, pollution, climate change, and sea level rise). The optimal management intervention is a two-pronged approach to slow down change while enhancing the fitness of shoreline ecosystems allowing them to respond and adapt by maintaining their living structure and functionality more effectively.

4.5.5 Ongoing benefits resulting from management interventions

The benefits derived from successful management intervention equate directly to the maintenance of ecosystem services derived from natural shoreline ecosystems. A key living component of shoreline tidal wetlands is mangrove vegetation. Where this intertidal ecosystem is healthy, it provides valuable structure, shelter, carbon stocks, shoreline protection, nursery habitat, and food for estuarine, coastal, and reef fisheries. Furthermore, there is notable connectivity amongst coastal habitats, especially for estuarine and marine biota for a range of life-history stages in fishes, crustaceans, and other marine life. So, a key benefit is the maintenance of coastal marine life, especially benefitting recreational and commercial fisheries.

These benefits extend to the maintenance of shoreline stability with the buffering of exposed shorelines from erosion and retreat inland. These shoreline protection benefits are much needed where sea levels are rising, and storm severity is increasing, as predicted with global climate change. Healthy living mangrove habitats are also known to hold considerable carbon reserves both in their woody structure and below ground in peaty sediments. These underground reserves only survive intact while the living vegetation on top remains intact and protected. The 2015–2016 dieback has caused the release of large amounts of carbon into the atmosphere (Table 3.3).

Note this single event caused 76.5 km^2 of mangroves to die in the Gulf (Vol. 1: Table 3.1), where 100% dieback areas averaged ~5,152 dead stems/ha (Table 3.3), equating to ~39.4

million trees having a total carbon content for average sized trees of 20.8 kg (Table 3.3), equates to 820,895 tC. Prevention of the release of such a carbon reserve to the atmosphere is a critical and practical benefit of preserving tidal wetlands at national and global scales – but this can only happen if the living vegetation is kept healthy, biodiverse and intact.

There is also benefit from the natural cleansing and filtration services provided by mangrove forests – a functional role that terms mangroves as 'kidneys of the coast'. Where mangrove vegetation is lost, then this results in a reduction in the buffering and filtering of runoff from land catchment in the capture of harmful agents like excess sediments, nutrients, and agricultural chemicals. These and other benefits provided by these shoreline ecosystems can only be maintained where these natural habitats remain intact and functional. And, it is becoming increasingly apparent that the survival of beneficial mangrove habitat greatly depends on the well-intentioned and best-advised management intervention backed-up with updated knowledge of habitat condition gained from regular monitoring.

Figure 4.7. During surveys in September 2019, significant piles of woody wrack were observed along Gulf shorelines, like these near Karumba and the Norman River. The woody stems of mangrove trees killed by the 2015–2016 dieback had fallen and joined the tidal ebb to wash across shorelines breaking additional stems as well as shearing and smothering seedlings and surviving plants. Unfortunately, there appears to be little that can be done to alleviate this situation.

4.5.6 Specific recommended actions

It is firstly critical to note that rehabilitation based on planting mangrove propagules by any means is highly unlikely to succeed and is not recommended. By our best estimates, such interventions would be a waste of valuable human and financial resources, and possibly a lot worse! The on-ground works are likely to cause further damage to these already damaged natural systems. This conclusion is soundly supported in this investigation by 1) our observations of adequate natural recruitment coupled with 2) other observations of cumulative impacts by factors like severe cyclones, flooding and rising sea levels. These points are discussed in this report in some detail. But, it suffices to say that assistance with recruitment (as planting) is fully unnecessary because this outcome has been adequately achieved by the notable (up to 90%) survivorship of mature trees across the impacted region of the Gulf. These trees delivered abundant natural recruitment throughout the impacted area.

There was a problem, however, with the survival and establishment of this recruitment, post-planting. This had been exacerbated by both episodic and continuous events of strong storms, fires, weeds, and feral pigs coupled with constantly rising sea levels. Such cumulative impacts have damaged areas disrupting recovery, reducing normal growth and establishment of young mangrove plants.

In consideration of these circumstances and our recent findings, our recommended response concerns actions focused on the minimisation of future impacts while actively implementing locally based management practices that maximise habitat resilience so these living shoreline ecosystems can better adapt and deal with the unavoidable consequences of climate change. The optimal plan is to support survivorship of mature trees plus the normally efficient recovery processes of mangroves. Once mangrove-vegetated habitats are lethally damaged it becomes extremely difficult for these shoreline stands to re-establish especially with increasing pressures of climate change, more severe storms and rapidly rising sea levels. The key message is that *damage prevention is better than rehabilitation*.

The recommended 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.

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 for this component 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 then a response team would be deployed as required to implement the next level response component action.

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 during our current 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 each 10-year period. This component would also include an evaluation and review process after each deployment to refine successful practices and improve future responses.

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 land owners and regional NRM groups while on-ground works could be lead and assisted by Indigenous rangers.

5. Transect summary data

Field sites and transect locations in the Gulf of Carpentaria are shown in Figure 4.7 – Figure 5.8.

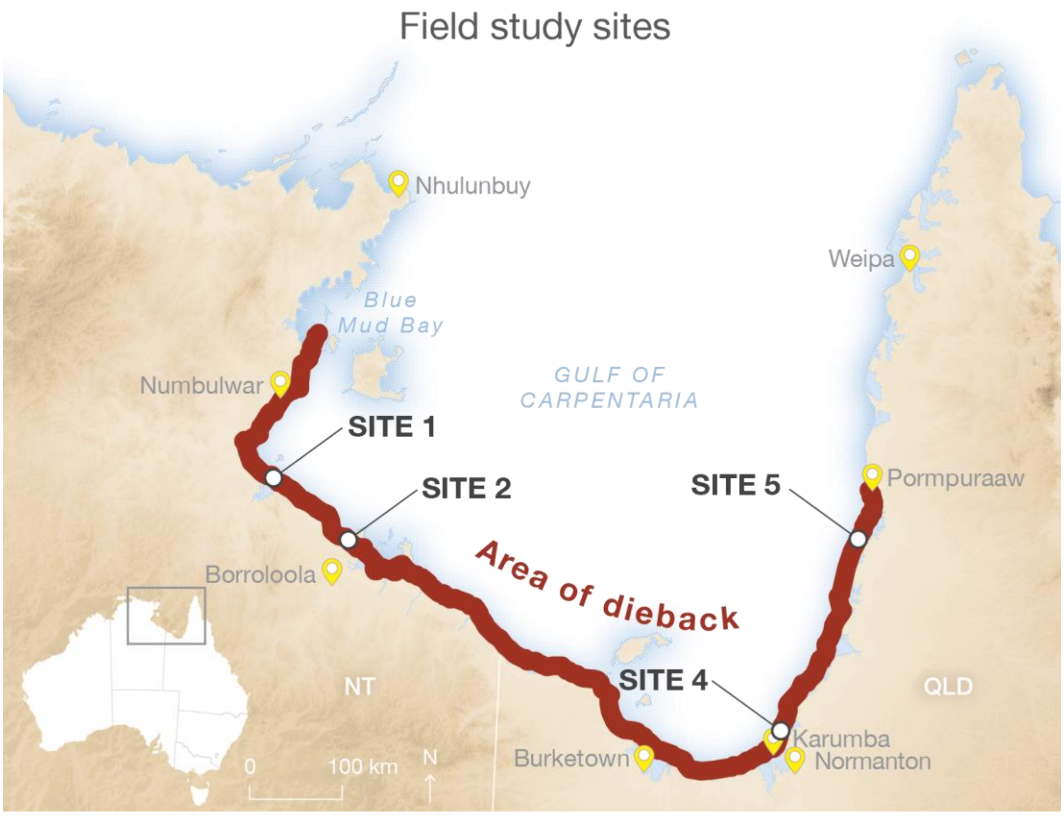

Figure 5.1. Distribution of the four field study sites in the mangrove dieback area of the Gulf of Carpentaria.

Figure 5.2. Locations of Transects 1A and 1B in the Limmen shoreline area. See Figure 5.1.

Figure 5.3. Locations of Transects 2A and 2B in the Mule shoreline area. See Figure 5.1.

Figure 5.4. Locations of Transects 4A and 4B in the Norman shoreline area. See Figure 5.1.

Figure 5.5. Locations of Transects 5A and 5D in the Mitchell shoreline area. See Figure 5.1.

5.1 Transect 1A – NT Limmen: 90%–100% dieback impacted

Transect 1A was on the Northern Territory side of the Gulf of Carpentaria.

Site information (Figure 5.6 and Figure 5.7, Table 5.1):

- General site location: -15.146215°; 135.788778°
- Length of the map transect: ~637 m
- Tidal range: ~2.0 m
- Sea level rise: ~9.2 mm/yr
- Close by cyclones since 1975: minimal
- General impact condition: 90%–100% loss of mangrove fringe between 2015 and 2016.

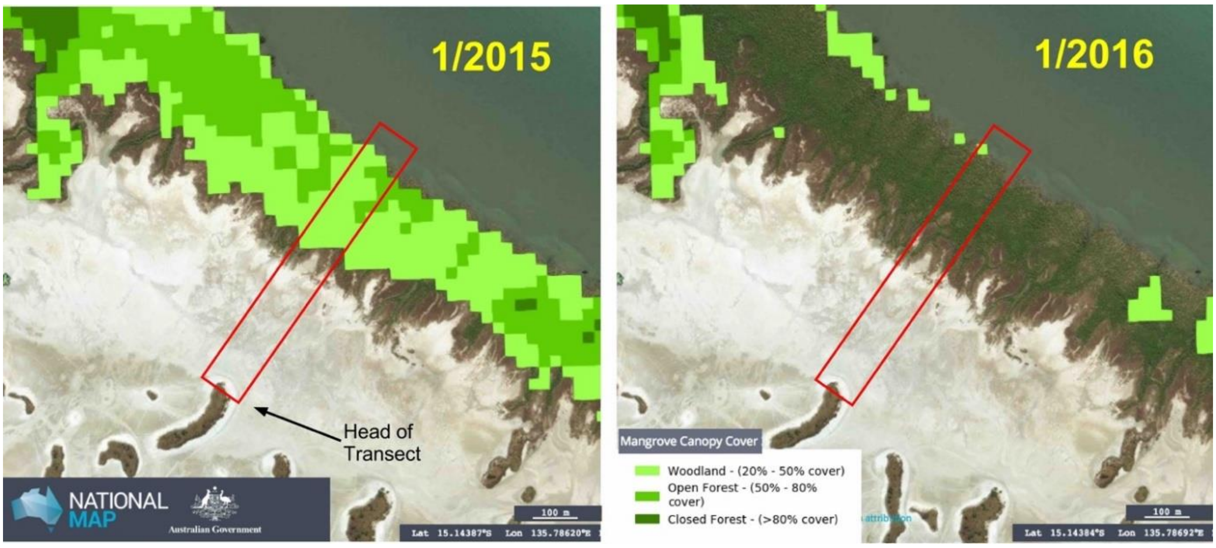

Figure 5.6. Location of Transect 1A (red box) visited in October 2018. Note the loss of mangrove canopy cover (green shaded) between 2015 and 2016.

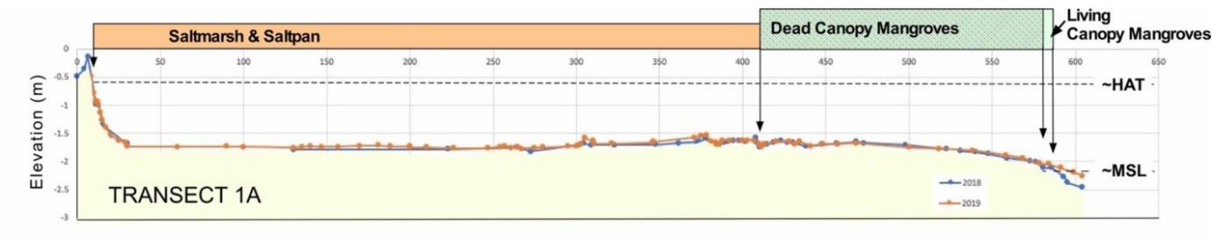

Figure 5.7. Profile of Transect 1A showing elevations measured in Oct 2018 and Sept 2019 and tidal wetland vegetation zones including canopy mangroves that died in late 2015.

Table 5.1. Summary information for Transect 1A measured during 11–13 October 2018.

Head: -15.149808° S; 135.785448° E	Seaward: -15.145018° S; 135.788876° E
Length – land (HAT) to sea edge (~MSL): 572 m	Mangrove fringe width: 170 m
Total area of measured mangroves: 332 m^2	Mean width of transect plot: 1.47 m
Estimated tidal wetland MSL range: 1.55 m	Wetland cover index: 29.8%
Upper mangrove fringe – pre-impact: -1.19 m	Upper mangrove fringe – post-impact: -1.50 m
Fringe mangrove elevation range: 0.36 m	Impacted mangrove elevation range: 0.31 m
Dead portion of fringe: 98.7%	2015 mangrove dieback impact severity: **High**

Note: HAT = highest astronomical tide; MSL = mean sea level.

Note that detailed observations were scored and measured from 332 m^2 of vegetation or remnant vegetation along this transect. Data are summarised in Table 5.2 and listed in Appendix 1. The following figures (Figure 5.8–Figure 5.10) show characteristics of vegetation along this transect, particularly the location and elevation of 2015–2016 dieback plus age-related features based on stem diameter of canopy trees, *Avicennia marina*.

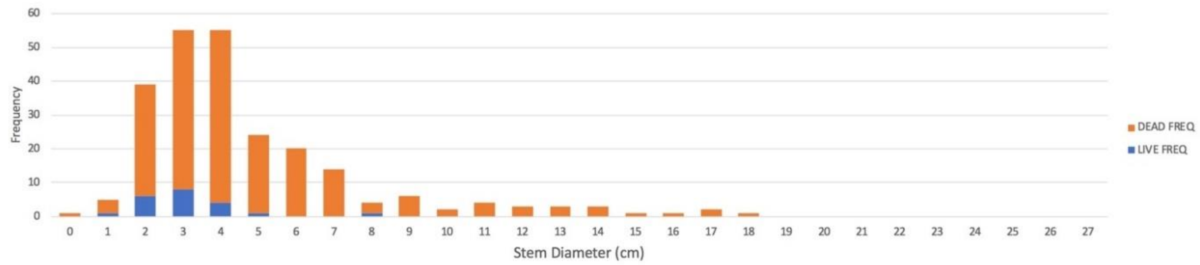

Figure 5.8. Size frequency of vegetation along Transect 1A, showing live and dead plants in October 2018. Trees died mostly in late 2015. Notably, the smaller (younger) individuals had the greatest survivorship.

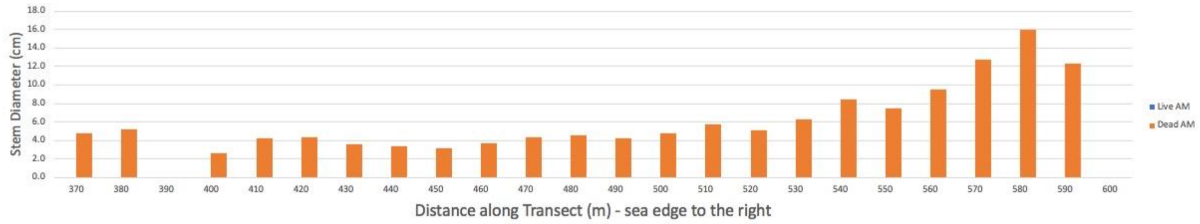

Figure 5.9. Mean size of live and dead canopy trees along Transect 1A for each 10-metre section. There were no surviving canopy trees. Distances were taken from the transect head (left side) at around highest astronomical tide (~HAT) towards the landward shoreline.

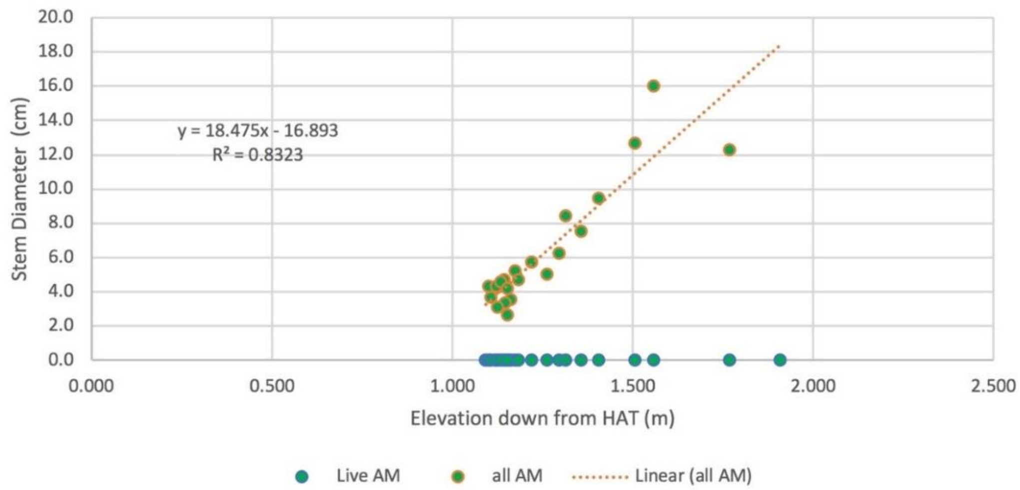

Figure 5.10. Mean size of canopy trees along Transect 1A compared to their elevation position. Although all trees were dead, there was a significant (<0.001) positive relationship with elevation. This defines a distinct relationship where younger trees were found higher up the tidal zone.

Table 5.2. Vegetation along Transect 1A recorded during 11–13 October 2018.

Heavily impacted in late 2015	Canopy	Under-canopy
Total trees and shrubs measured	213	59
Total density	0.68 stems/m^2	0.27 stems/m^2
Height mean (max.)	1.5 (4.3) m	0.4 m
Trees and shrubs dead – 2015 dieback	93.3%	55.6%
Total standing carbon	77.8 tC/ha	
Dead standing carbon – 2015 dieback	75.8 tC/ha	
Dominant species	*Avicennia marina*	*Aegialitis annulata*
Proportion of dominant	63.5%	72.2%
Proportion of dead – 2015 dieback	63.2%	38.9%
Stem diameter (max.)	5.3 (18.1) cm	

See Appendix 1.

Comparisons between 2018 and 2019 aerial surveys (Figure 5.11 and Figure 5.12)

Figure 5.11. Views of Transect 1A visited in October 2018 showing the high tide edge (left) and seaward margin (right).

Figure 5.12. Views of Transect 1A visited in September 2019 showing the high tide edge (left) and seaward margin (right).

Note a lack of driftwood wrack at the highwater margin in 2018 and 2019. A number of high intertidal vegetation had eroded leaving notably exposed margins along the high intertidal margin. At the seaward edge, there were fewer standing *Avicennia* dead stems with branches. There was sediment erosion generally under dead *Avicennia* trees in dieback areas up to the front edge.

5.2 Transect 1B – NT Limmen: 60%–80% dieback impacted

Transect 1B was on the Northern Territory side of the Gulf of Carpentaria.

Background site information (Figure 5.13 and Figure 5.14; Table 5.3):

- General site location: -15.171145°; 135.836993°
- Length of the map transect: ~905 m
- Tidal range: ~2.0 m
- Sea level rise: ~9.2 mm/yr
- Close by cyclones since 1975: minimal
- General impact condition: 60%–80% loss of mangrove fringe between 2015 and 2016.

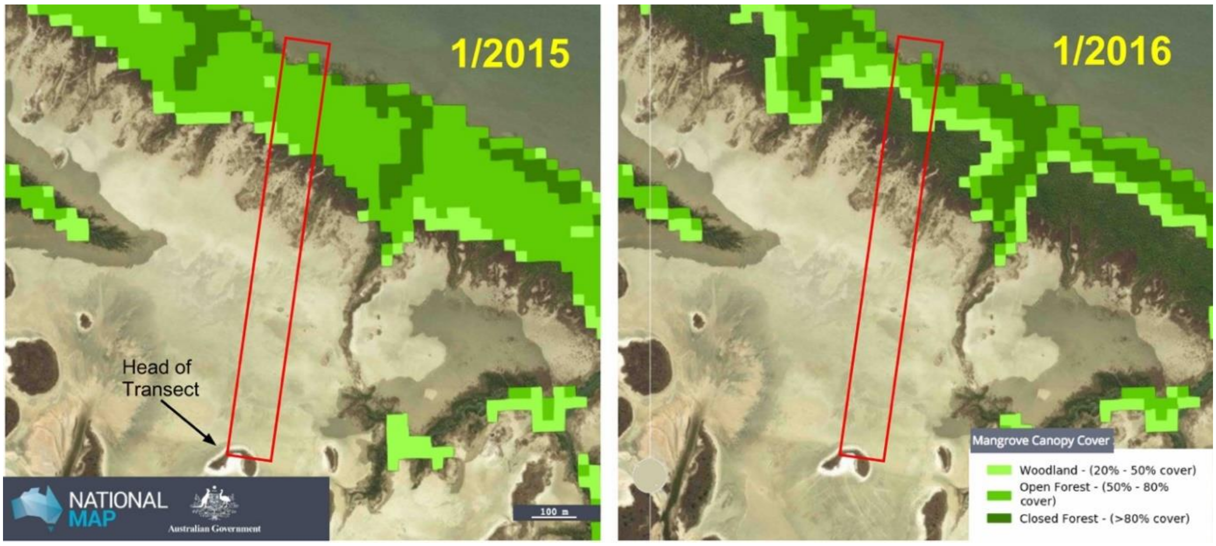

Figure 5.13. Location of Transect 1B (red box) visited in October 2018. Note the loss of mangrove canopy cover (green shaded) between 2015 and 2016.

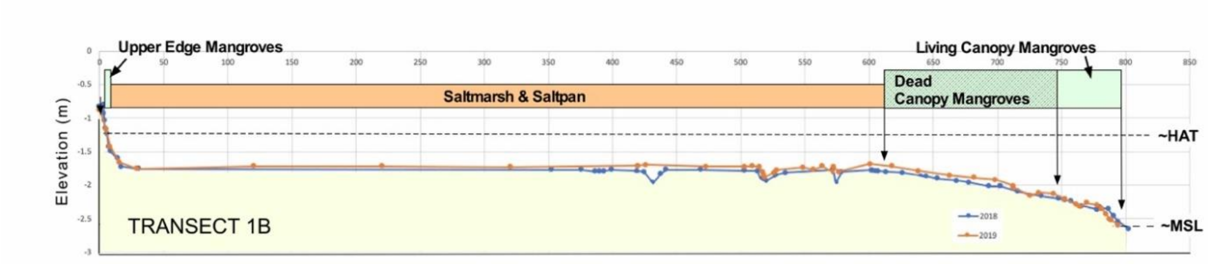

Figure 5.14. Profile of Transect 1B showing elevations measured in Oct 2018 and Sept 2019 and tidal wetland vegetation zones including canopy mangroves that died in late 2015.

Table 5.3. Survey information for Transect 1B measured during 11–13 October 2018.

Head: -15.178126° S; 135.835897° E	Seaward: -15.169922° S; 135.837137° E
Length – land (HAT) to sea edge (~MSL): 790 m	Mangrove fringe width: 181 m
Total area of measured mangroves: 343 m^2	Mean width of transect plot: 1.86 m
Estimated tidal wetland MSL range: -1.40 m	Wetland cover index: 23.0%
Upper mangrove fringe – pre-impact: -1.05 m	Upper mangrove fringe – post-impact: -1.06 m
Fringe mangrove elevation range: 0.75 m	Impacted mangrove elevation range: 0.41 m
Dead portion of fringe: 75.6%	2015 mangrove dieback impact severity: **Moderate**

Note: HAT = highest astronomical tide; MSL = mean sea level.

Note that detailed observations were scored and measured from 343 m^2 of vegetation or remnant vegetation along this transect. Data are summarised in Table 5.4 and listed in Appendix 2. The following figures (Figure 5.15–Figure 5.17) show characteristics of vegetation along this transect, particularly the location and elevation of 2015–2016 dieback plus age-related features based on stem diameter of canopy trees, *Avicennia marina*.

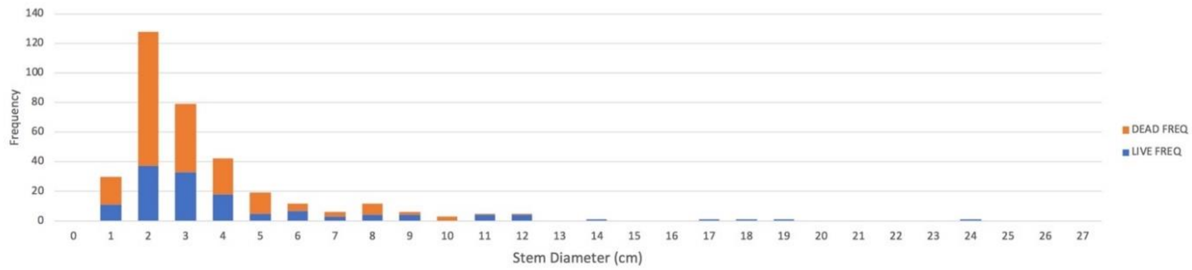

Figure 5.15. Size frequency of vegetation along Transect 1B showing live and dead plants in October 2018. Trees died mostly in late 2015.

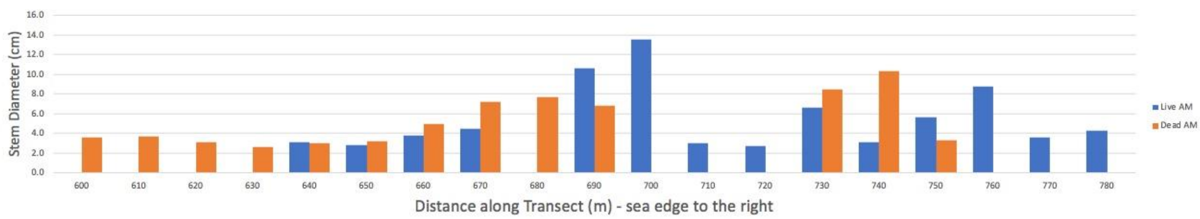

Figure 5.16. Mean size of live and dead canopy trees along Transect 1B for each 10-metre section. There was a disruption in the canopy between 710–720 m. Distances were taken from the transect head (left side) at around highest astronomical tide (~HAT) towards the landward shoreline.

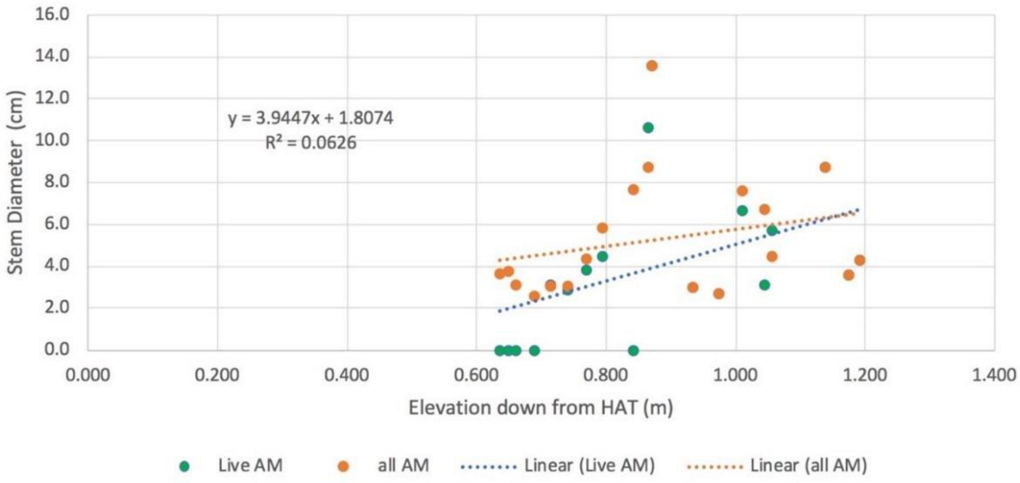

Figure 5.17. Mean size of canopy trees along Transect 1B compared to their elevation position. There was an apparent trend with elevation where younger trees were found higher up the tidal zone, although this relationship was confounded by the disruption in lower fringing trees.

Table 5.4. Vegetation along Transect 1B recorded during 11–13 October 2018.

Heavily impacted in late 2015	Canopy	Under-canopy
Total trees and shrubs measured	311	672
Total density	0.94 stems/m^2	3.4 stems/m^2
Height mean (max.)	1.5 (3.6) m	0.3 m
Trees and shrubs dead – 2015 dieback	68.5%	6.8%
Total standing carbon	92.6 tC/ha	
Dead standing carbon – 2015 dieback	37.3 tC/ha	
Dominant species	*Avicennia marina*	*Avicennia marina*
Proportion of dominant	86.0%	64.4%
Proportion of dead – 2015 dieback	59.8%	1.3%
Stem diameter (max.)	4.1 (20.5) cm	

See Appendix 2

Comparisons between 2018 and 2019 aerial surveys (Figure 5.18 and Figure 5.19)

Figure 5.18. Views of Transect 1B visited in October 2018 showing the high tide edge (left) and seaward margin (right).

Figure 5.19. Views of Transect 1B visited in September 2019 showing the high tide edge (left) and seaward margin (right).

Note a lack of driftwood wrack at the highwater margin in 2018 and 2019. A significant number of high intertidal vegetation had eroded leaving notably exposed margins along the high intertidal margin. At the seaward edge, there were fewer standing *Avicennia* dead stems with branches. There was sediment erosion generally under dead *Avicennia* trees in dieback areas behind the front edge.

5.3 Transect 2A – NT Mule: 60%–80% dieback impacted

Transect 2A was on the Northern Territory side of the Gulf of Carpentaria.

Background site information (Figure 5.20 and Figure 5.21; Table 5.5):

- General site location: -15.647369°; 136.434148°
- Length of the map transect: ~239 m
- Tidal range: ~2.2 m
- Sea level rise: ~9.0 mm/yr
- Close by cyclones since 1975: at least 2
- General impact condition: 60%–80% loss of mangrove fringe between 2015 and 2016.

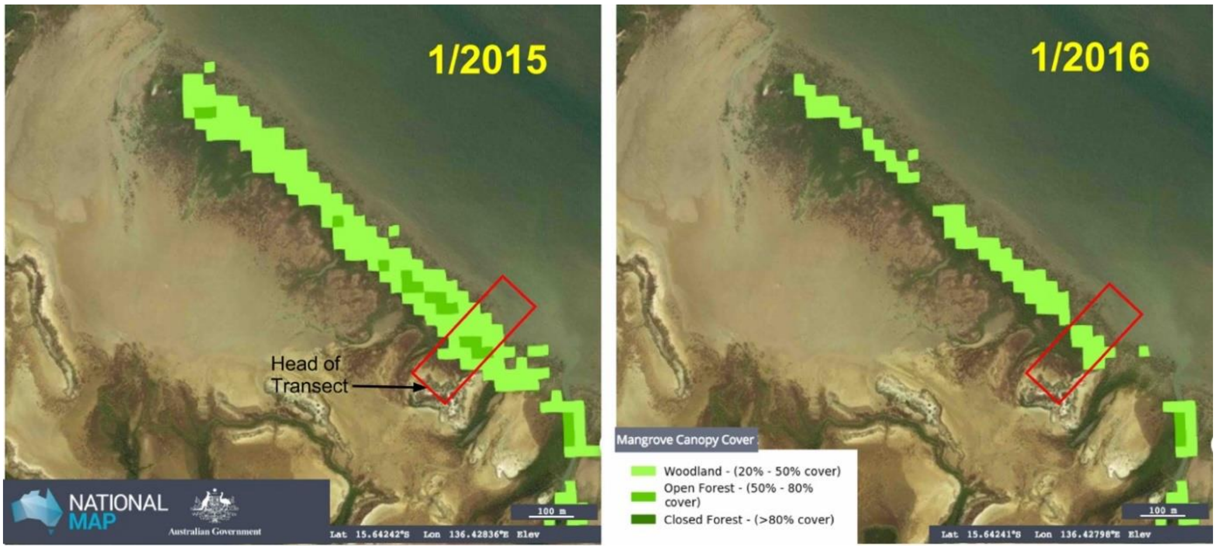

Figure 5.20. Location of Transect 2A (red box) visited in October 2018. Note the loss of mangrove canopy cover (green shaded) between 2015 and 2016.

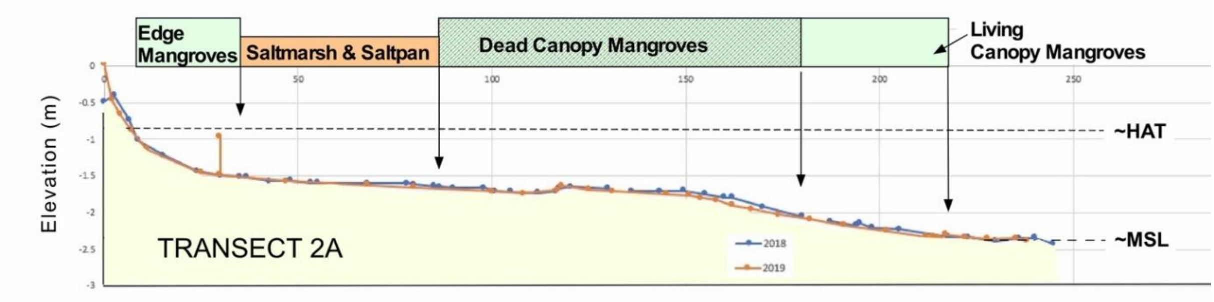

Figure 5.21. Profile of Transect 2A showing elevations measured in Oct 2018 and Sept 2019 and tidal wetland vegetation zones including canopy mangroves that died in late 2015.

Table 5.5. Survey information for Transect 2A measured during 15–17 October 2018.

Head: -15.648503° S; 136.433860° E	Seaward: -15.646469° S; 136.434803° E
Length – land (HAT) to sea edge (~MSL): 210 m	Mangrove fringe width: 131 m
Total area of measured mangroves: 238 m^2	Mean width of transect plot: 1.43 m
Estimated tidal wetland MSL range: -1.46 m	Wetland cover index: 62.4%
Upper mangrove fringe – pre-impact: -0.78 m	Upper mangrove fringe – post-impact: -1.15 m
Fringe mangrove elevation range: 0.68 m	Impacted mangrove elevation range: 0.37 m
Dead portion of fringe: 70.2%	2015 dieback impact severity: **Moderate**

Note: HAT = highest astronomical tide; MSL = mean sea level.

Note that detailed observations were scored and measured from 238 m^2 of vegetation or remnant vegetation along this transect. Data are summarised in Table 5.6 and listed in Appendix 3. The following figures (Figure 5.22–Figure 5.24) show characteristics of vegetation along this transect, particularly the location and elevation of 2015–2016 dieback plus age-related features based on stem diameter of canopy trees, *Avicennia marina*.

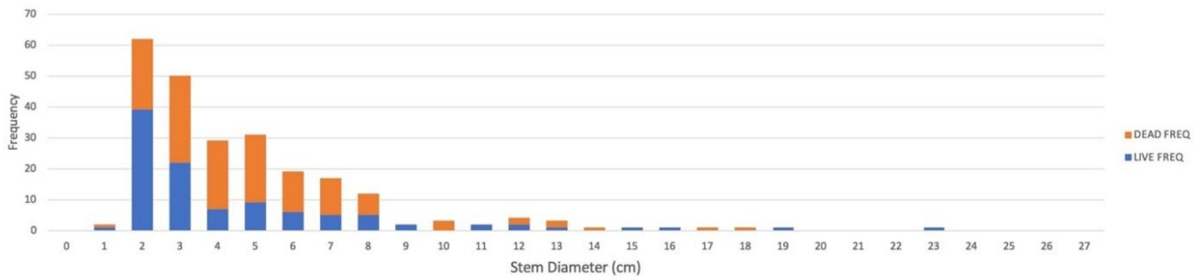

Figure 5.22. Size frequency of vegetation along Transect 2A showing live and dead plants in October 2018. Trees died mostly in late 2015. Notably, the smaller (younger) individuals had the greatest survivorship.

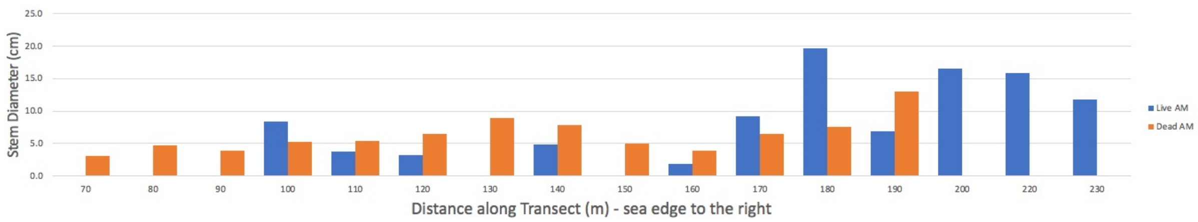

Figure 5.23. Mean size of live and dead canopy trees along Transect 2A for each 10-metre section. Distances were taken from the transect head (left side) at around highest astronomical tide (~HAT) towards the landward shoreline.

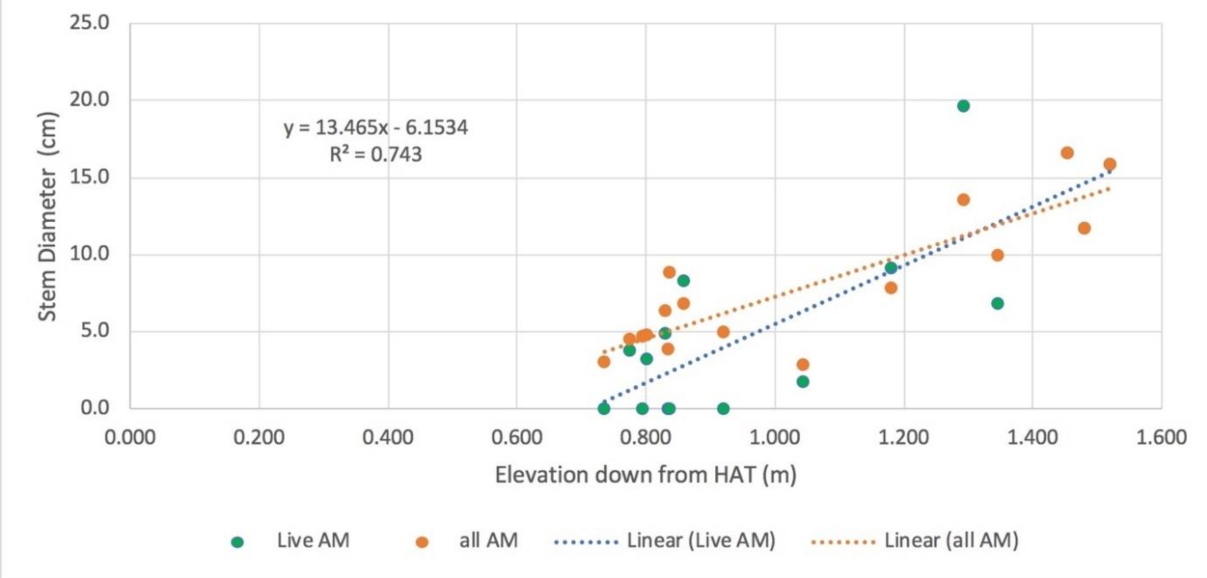

Figure 5.24. Mean size of canopy trees along Transect 2A compared to their elevation position. There was a significant (<0.001) positive relationship with elevation, notably with all trees. This defines a distinct relationship where younger trees were found higher up the tidal zone.

Table 5.6. Vegetation along Transect 2A recorded during 15–17 October 2018.

Heavily impacted in late 2015	Canopy	Under-canopy
Total trees and shrubs measured	173	259
Total density	0.62 stems/m^2	1.18 stems/m^2
Height mean (max.)	1.9 (6.0) m	0.2 m
Trees and shrubs dead – 2015 dieback	94.9%	83.4%
Total standing carbon	139.2 tC/ha	
Dead standing carbon – 2015 dieback	70.0 tC/ha	
Dominant species	*Avicennia marina*	*Aegialitis annulata*
Proportion of dominant	98.5%	85.7%
Proportion of dead – 2015 dieback	94.9%	72.6%
Stem diameter (max.)	7.3 (33.4) cm	

See Appendix 3.

Comparisons between 2018 and 2019 surveys (Figure 5.25 and Figure 5.26)

Figure 5.25. Views of Transect 2A visited in October 2018 showing the high tide edge (left) and seaward margin (right).

Figure 5.26. Views of Transect 2A visited in September 2019 showing the high tide edge (left) and seaward margin (right).

Note a lack of driftwood wrack at the highwater margin in 2018 and 2019. A significant number of high intertidal vegetation had eroded leaving notably exposed margins along the high intertidal edge. At the seaward edge, there were fewer standing *Avicennia* dead stems with branches. There was sediment erosion generally under dead *Avicennia* trees.

5.4 Transect 2B – NT Mule: 90%–100% dieback impacted

Transect 2B was on the Northern Territory side of the Gulf of Carpentaria.

Background site information (Figure 5.27 and Figure 5.28; Table 5.7):

- General site location: -15.650919°; 136.441971°
- Length of the map transect: ~370 m
- Tidal range: ~2.2 m
- Sea level rise: ~9.0 mm/yr
- Close by cyclones since 1975: at least 2
- General impact condition: 90%–100% loss of mangrove fringe between 2015 and 2016.

Figure 5.27. Location of Transect 2B (red box) visited in October 2018. Note the loss of mangrove canopy cover (green shaded) between 2015 and 2016.

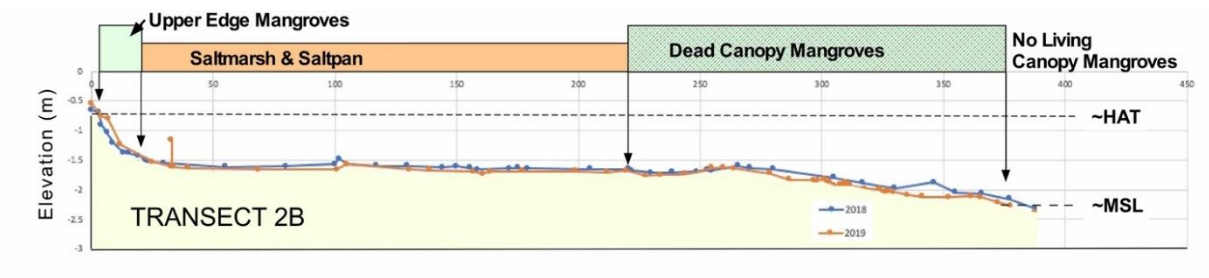

Figure 5.28. Profile of Transect 2B showing elevations measured in Oct 2018 and Sept 2019 and tidal wetland vegetation zones including canopy mangroves that died in late 2015.

Table 5.7. Survey information for Transect 2B measured during 15–17 October 2018.

Head: -15. 652837° S; 136.440879° E	Seaward: -15.649622° S; 136.441739° E
Length – land (HAT) to sea edge (~MSL): 374 m	Mangrove fringe width: 155 m
Total area of measured mangroves: 266 m^2	Mean width of transect plot: 1.73 m
Estimated tidal wetland MSL range: -1.46 m	Wetland cover index: 41.5%
Upper mangrove fringe – pre-impact: -0.98 m	Upper mangrove fringe – post-impact: -1.46 m
Fringe mangrove elevation range: 0.48 m	Impacted mangrove elevation range: 0.48 m
Dead portion of fringe: 100%	2015 dieback impact severity: **High**

Note: HAT = highest astronomical tide; MSL = mean sea level.

Note that detailed observations were scored and measured from 266 m^2 of vegetation or remnant vegetation along this transect. Data are summarised in Table 5.8 and listed in Appendix 4. The following figures (Figure 5.29–Figure 5.31) show characteristics of vegetation along this transect, particularly showing the location and elevation of 2015–2016 dieback showing age-related features based on stem diameter of canopy trees, *Avicennia marina*.

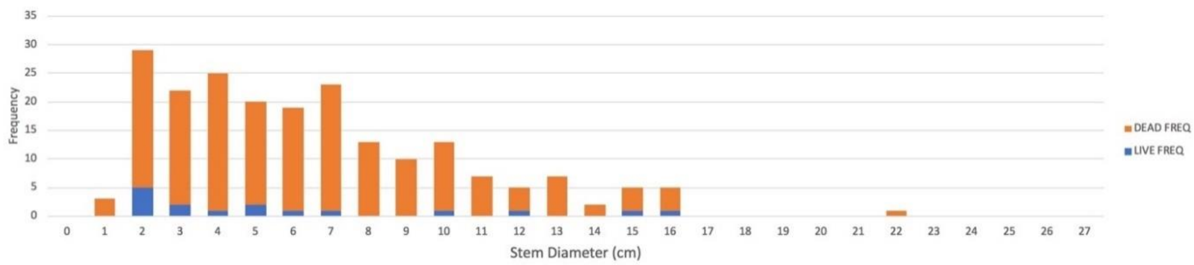

Figure 5.29. Size frequency of vegetation along Transect 2B showing live and dead plants in October 2018. Trees died mostly in late 2015. Notably, the smaller (younger) individuals had the greatest survivorship.

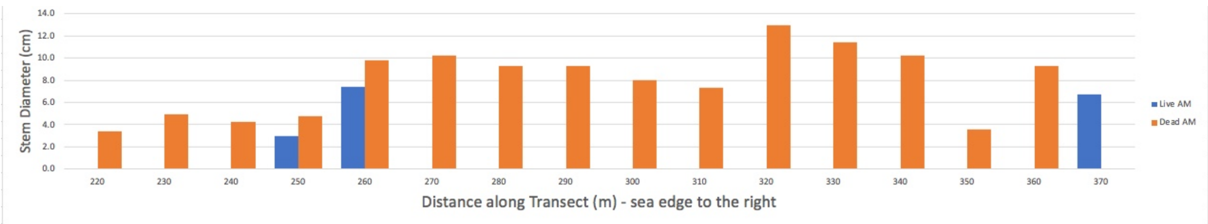

Figure 5.30. Mean size of live and dead canopy trees along Transect 2B for each 10-metre section. Distances were taken from the transect head (left side) at around highest astronomical tide (~HAT) towards the landward shoreline.

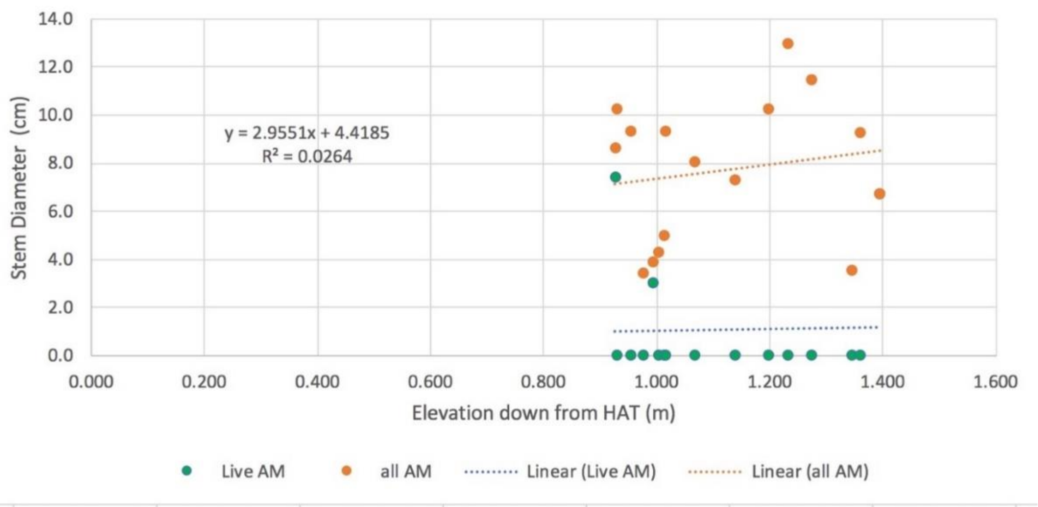

Figure 5.31. Mean size of canopy trees along Transect 2B compared to their elevation position. Although most trees were dead, there no relationship with elevation.

Table 5.8. Vegetation along Transect 2B recorded during 15–17 October 2018.

Heavily impacted in late 2015	Canopy	Under-canopy
Total trees and shrubs measured	209	632
Total density	0.97 stems/m^2	3.00 stems/m^2
Height mean (max.)	1.4 (4.2) m	0.3 m
Trees and shrubs dead – 2015 dieback	52.4%	20.5%
Total standing carbon	153.9 tC/ha	
Dead standing carbon – 2015 dieback	148.6 tC/ha	
Dominant species	*Avicennia marina*	*Aegialitis annulata*
Proportion of dominant	70.6%	70.0%
Proportion of dead – 2015 dieback	49.8%	7.9%
Stem diameter (max.)	5.2 (23.5) cm	

See Appendix 4.

Comparisons between 2018 and 2019 surveys (Figure 5.32 and Figure 5.33)

Figure 5.32. Views of Transect 2B visited in October 2018 showing the high tide edge (left) and seaward margin (right).

Figure 5.33. Views of Transect 2B visited in September 2019 showing the high tide edge (left) and seaward margin (right).

Note a lack of driftwood wrack at the highwater margin in 2018 and 2019. A significant number of high intertidal vegetation had eroded leaving notably exposed margins along the high intertidal edge. At the seaward edge, there were fewer standing *Avicennia* dead stems with branches. There was sediment erosion generally under dead *Avicennia* trees.

5.5 Transect 4A – Qld Karumba: 90%–100% dieback impacted

Transect 4A was on the Queensland side of the Gulf of Carpentaria.

Background site information (Figure 5.34 and Figure 5.35; Table 5.9):

- General site location: -17.422561°; 140.853576°
- Length of the map transect: ~604 m
- Tidal range: ~3.3 m
- Sea level rise: ~8.2 mm/yr
- Close by cyclones since 1975: minimal
- General impact condition: 90%–100% loss of mangrove fringe between 2015 and 2016.

Figure 5.34. Location of Transect 4A (red box) visited in August 2018. Note the loss of mangrove canopy cover (green shaded) between 2015 and 2016.

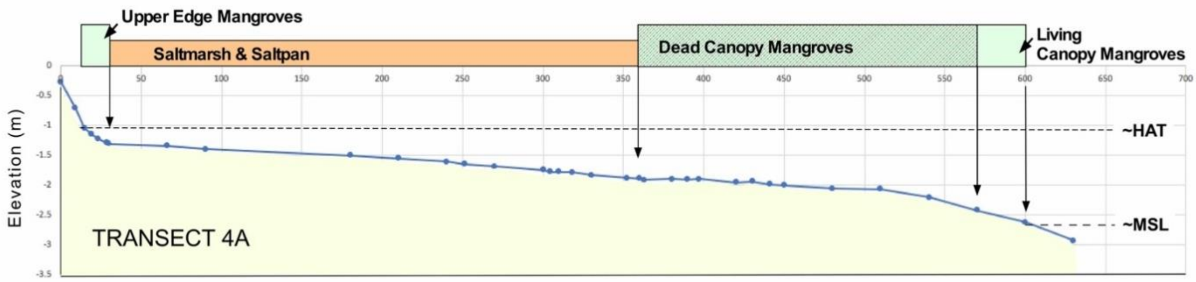

Figure 5.35. Profile of Transect 4A showing elevations measured in Oct 2018 and tidal wetland vegetation zones including canopy mangroves that died in late 2015.

Table 5.9. Survey information for Transect 4A measured during 4–6 August 2018.

Head: -17.424518° S; 140.856458° E	Seaward: -17.421622° S; 140.851288° E
Length – land (HAT) to sea edge (~MSL): 581 m	Mangrove fringe width: 240 m
Total area of measured mangroves: 741 m^2	Mean width of transect plot: 2.14 m
Estimated tidal wetland MSL range: -1.47 m	Wetland cover index: 41.3%
Upper mangrove fringe – pre-impact: -0.74 m	Upper mangrove fringe – post-impact: -1.37 m
Fringe mangrove elevation range: 0.73 m	Impacted mangrove elevation range: 0.63 m
Dead portion of fringe: 93.8%	2015 dieback impact severity: **High**

Note: HAT = highest astronomical tide; MSL = mean sea level.

Note that detailed observations were scored and measured from 741 m^2 of vegetation or remnant vegetation along this transect. Data are summarised in Table 5.10 and listed in Appendix 5. The following figures (Figure 5.36–Figure 5.38) show characteristics of vegetation along this transect, particularly the location and elevation of 2015–2016 dieback plus age-related features based on stem diameter of canopy trees, *Avicennia marina*.

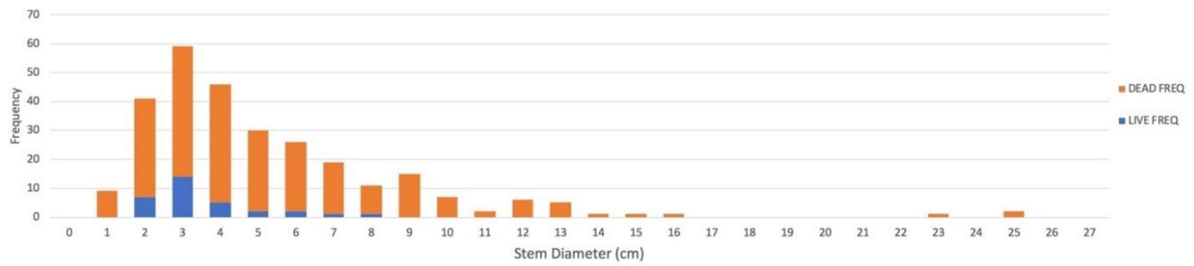

Figure 5.36. Size frequency of vegetation along Transect 4A showing live and dead plants in August 2018. Trees died mostly in late 2015. Notably, the smaller (younger) individuals had the greatest survivorship.

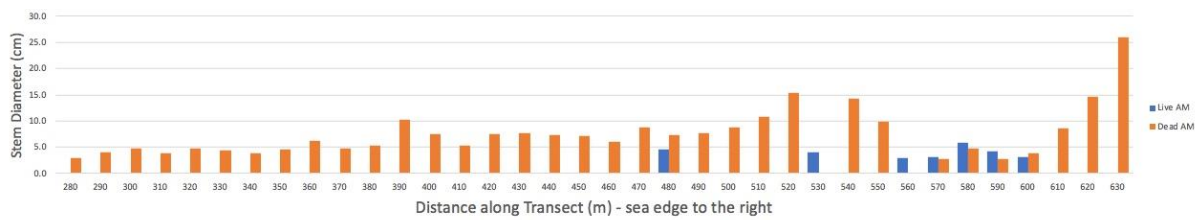

Figure 5.37. Mean size of live and dead canopy trees along Transect 4A for each 10-metre section. Younger surviving canopy trees occurred mostly towards the seaward fringe. Distances were taken from the transect head (left side) at around highest astronomical tide (~HAT) towards the landward shoreline.

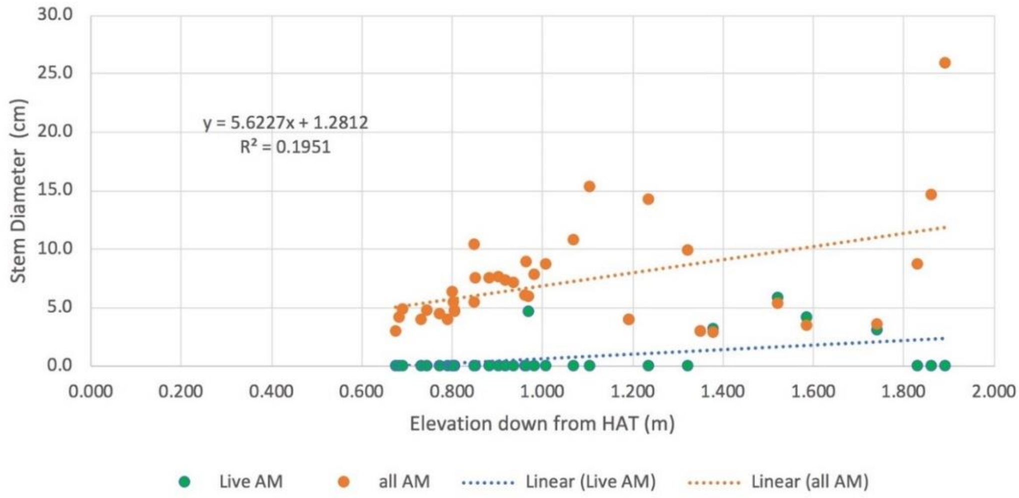

Figure 5.38. Mean size of canopy trees along Transect 4A compared to their elevation position. Although many trees were dead, there was an apparent positive trend with elevation. This is consistent with a positive relationship where older trees were generally found in lower parts of the tidal zone.

Table 5.10. Vegetation along Transect 4A recorded during 4–6 August 2018.

Heavily impacted in late 2015	Canopy	Under-canopy
Total trees and shrubs measured	281	693
Total density	0.49 stems/m^2	2.53 stems/m^2
Height mean (max.)	2.3 (8.8) m	0.5 m
Trees and shrubs dead – 2015 dieback	83.9%	0.1%
Total standing carbon	75.1 tC/ha	
Dead standing carbon – 2015 dieback	70.8 tC/ha	
Dominant species	*Avicennia marina*	*Aegialitis annulata*
Proportion of dominant	96.2%	71.3%
Proportion of dead – 2015 dieback	83.9%	0.0%
Stem diameter (max.)	5.7 (25.9) cm	

See Appendix 5.

Comparisons between 2018 and 2019 surveys (Figure 5.39 and Figure 5.40)

Figure 5.39. Views of Transect 4A visited in August 2018 showing the high tide edge (left) and seaward margin (right).

Figure 5.40. Views of Transect 4A visited in September 2019 showing the high tide edge (left) and seaward margin (right).

Note driftwood wrack was piled up along the highwater margin in 2018 and 2019. A significant number of high intertidal plants had died because of the driftwood scouring. At the seaward edge, there were fewer standing *Avicennia* dead stems with branches, and fewer surviving shrubby *Aegialitis* mangroves presumably because of sediment burial and erosion as the root matt of the dead *Avicennia* forests degrades and releases sediments.

5.6 Transect 4B – Qld Karumba: 60%–80% dieback impacted

Transect 4B was on the Queensland side of the Gulf of Carpentaria.

Background site information (Figure 5.41 and Figure 5.42; Table 5.11):

- General site location: -17.340024°; 140.896250°
- Length of the map transect: ~690 m
- Tidal range: ~3.3 m
- Sea level rise: ~8.2 mm/yr
- Close by cyclones since 1975: minimal
- General impact condition: 60%–80% loss of mangrove fringe between 2015 and 2016.

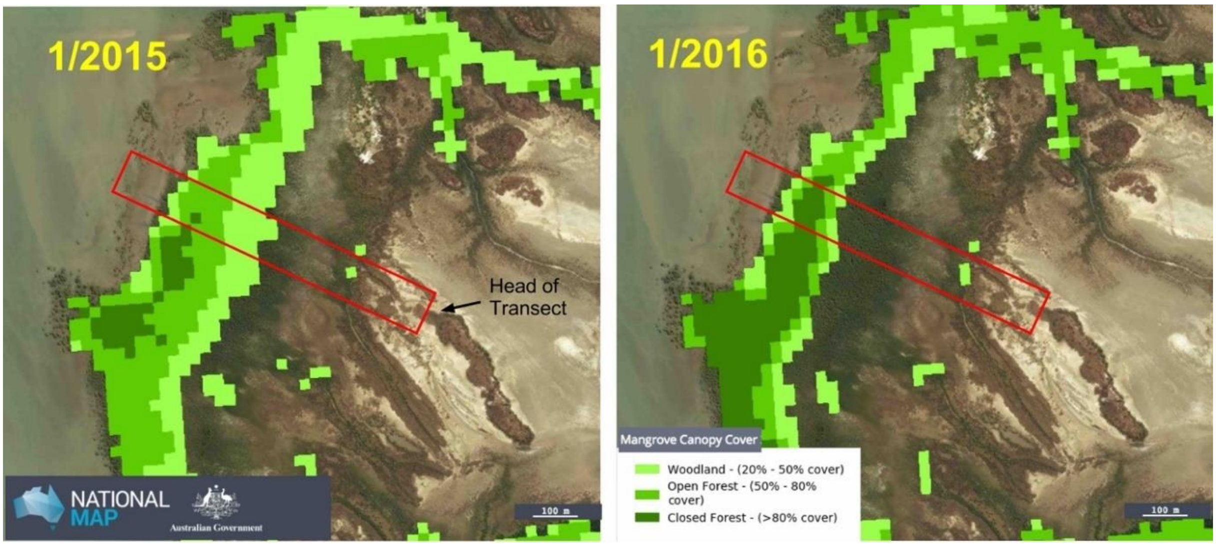

Figure 5.41. Location of Transect 4B (red box) visited in August 2018. Note the loss of mangrove canopy cover (green shaded) between 2015 and 2016.

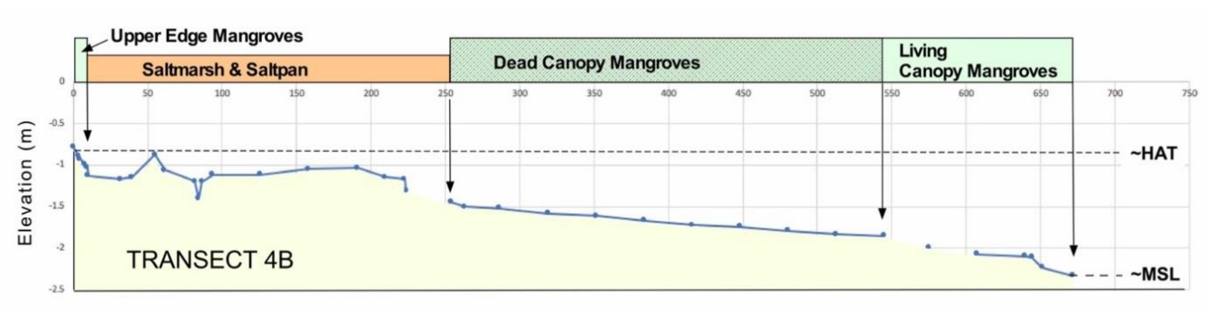

Figure 5.42. Profile of Transect 4B showing elevations measured in Oct 2018 and tidal wetland vegetation zones including canopy mangroves that died in late 2015.

Table 5.11. Survey information for Transect 4B measured during 4–6 August 2018.

Head: -17.341598° S; 140.900541° E	Seaward: -17. 338715° S; 140.894919° E
Length – land (HAT) to sea edge (~MSL): 651 m	Mangrove fringe width: 397 m
Total area of measured mangroves: 621 m^2	Mean width of transect plot: 1.92 m
Estimated tidal wetland MSL range: -1.45 m	Wetland cover index: 61.0%
Upper mangrove fringe – pre-impact: -0.67 m	Upper mangrove fringe – post-impact: -1.14 m
Fringe mangrove elevation range: 0.78 m	Impacted mangrove elevation range: 0.47 m
Dead portion of fringe: 72.9%	2015 dieback impact severity: **Moderate**

Note: HAT = highest astronomical tide; MSL = mean sea level.

Note that detailed observations were scored and measured from 621 m^2 of vegetation or remnant vegetation along this transect. Data are summarised in Table 5.12 and listed in Appendix 6. The following figures (Figure 5.43–Figure 5.45) show characteristics of vegetation along this transect, particularly the location and elevation of 2015–2016 dieback plus age-related features based on stem diameter of canopy trees, *Avicennia marina*.

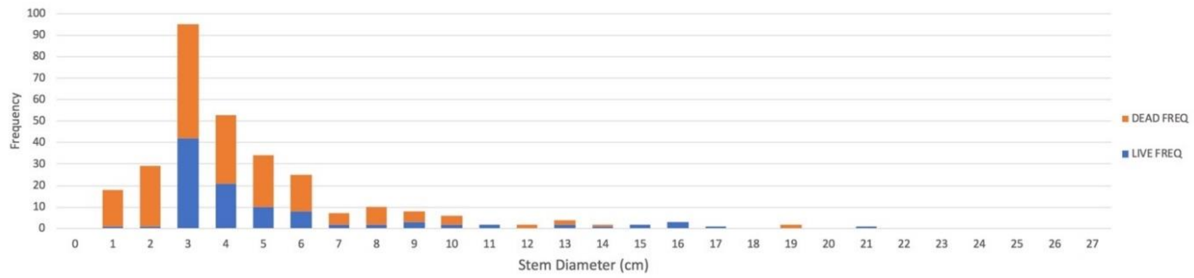

Figure 5.43. Size frequency of vegetation along Transect 4B showing live and dead plants in August 2018. Trees died mostly in late 2015.

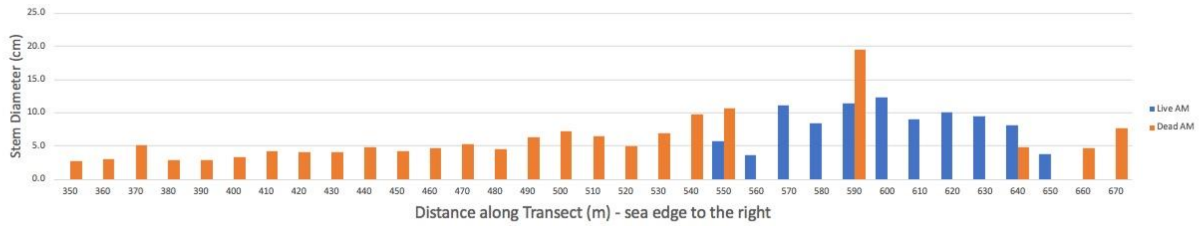

Figure 5.44. Mean size of live and dead canopy trees along Transect 4B for each 10-metre section. There were notable surviving canopy trees towards the seaward edge. Distances were taken from the transect head (left side) at around highest astronomical tide (~HAT) towards the landward shoreline.

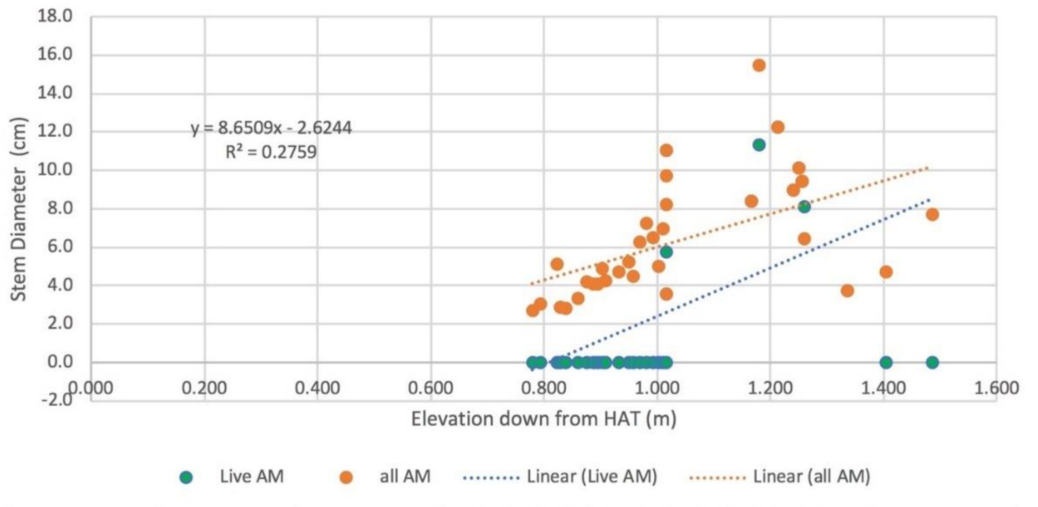

Figure 5.45. Mean size of canopy trees along Transect 4B compared to their elevation position. Although many trees were dead, there was a significant (<0.01) positive relationship with elevation prior to 2015. This defines a distinct relationship where younger trees were found higher up the tidal zone.

Table 5.12. Vegetation along Transect 4B recorded during 4–6 August 2018.

Heavily impacted in late 2015	Canopy	Under-canopy
Total trees and shrubs measured	304	3698
Total density	0.66 stems/m^2	1.63 stems/m^2
Height mean (max.)	2.1 (8.5) m	0.5 m
Trees and shrubs dead – 2015 dieback	76.6%	0.3%
Total standing carbon	86.6 tC/ha	
Dead standing carbon – 2015 dieback	53.8 tC/ha	
Dominant species	*Avicennia marina*	*Avicennia marina*
Proportion of dominant	75.2%	90.1%
Proportion of dead – 2015 dieback	66.2%	0.0%
Stem diameter (max.)	5.2 (21.7) cm	

See Appendix 6.

Comparisons between 2018 and 2019 surveys (Figure 5.46 and Figure 5.47)

Figure 5.46. Views of Transect 4B visited in August 2018 showing the high tide edge (left) and seaward margin (right).

Figure 5.47. Views of Transect 4B visited in September 2019 showing the high tide edge (left) and seaward margin (right).

Note few driftwood wracks at the higher tidal edge due to its location. At the seaward edge, there was notable erosion with numerous exposed old dead stumps indicating the earlier loss of sea edge trees.

5.7 Transect 5A – Qld North Mitchell: 90%–100% dieback impacted

Transect 5A was on the Queensland side of the Gulf of Carpentaria.

Background site information (Figure 5.48 and Figure 5.49; Table 5.13):

- General site location: -15.027324°; 141.665424°
- Length of the map transect: ~208 m
- Tidal range: ~2.2 m
- Sea level rise: ~7.8 mm/yr
- Close by cyclones since 1975: at least 4
- General impact condition: 90%–100% loss of mangrove fringe between 2015 and 2016.

Figure 5.48. Location of Transect 5A (red box) visited in August 2018. Note the loss of mangrove canopy cover (green shaded) between 2015 and 2016.

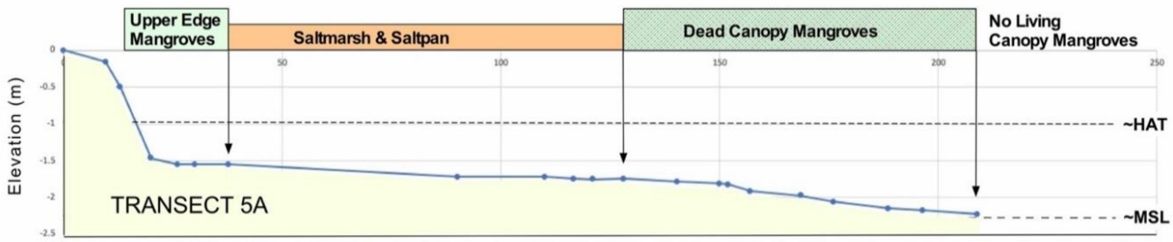

Figure 5.49. Profile of Transect 5A showing elevations measured in Oct 2018 and tidal wetland vegetation zones including canopy mangroves that died in late 2015.

Table 5.13. Survey information for Transect 5A measured during 8–10 August 2018.

Head: -15.026952° S; 141.667017° E	Seaward: -15.026736° S; 141.665095° E
Length – land (HAT) to sea edge (~MSL): 196 m	Mangrove fringe width: 81 m
Total area of measured mangroves: 318 m^2	Mean width of transect plot: 4.00 m
Estimated tidal wetland MSL range: -1.73 m	Wetland cover index: 41.3%
Upper mangrove fringe – pre-impact: -1.24 m	Upper mangrove fringe – post-impact: -1.73 m
Fringe mangrove elevation range: 0.49 m	Impacted mangrove elevation range: 0.49 m
Dead portion of fringe: 100%	2015 dieback impact severity: **High**

Note: HAT = highest astronomical tide; MSL = mean sea level.

Note that detailed observations were scored and measured from 318 m^2 of vegetation or remnant vegetation along this transect. Data are summarised in Table 5.14 and listed in Appendix 7. The following figures (Figure 5.50–Figure 5.52) show characteristics of vegetation along this transect, particularly the location and elevation of 2015–2016 dieback plus age-related features based on stem diameter of canopy trees, *Avicennia marina*.

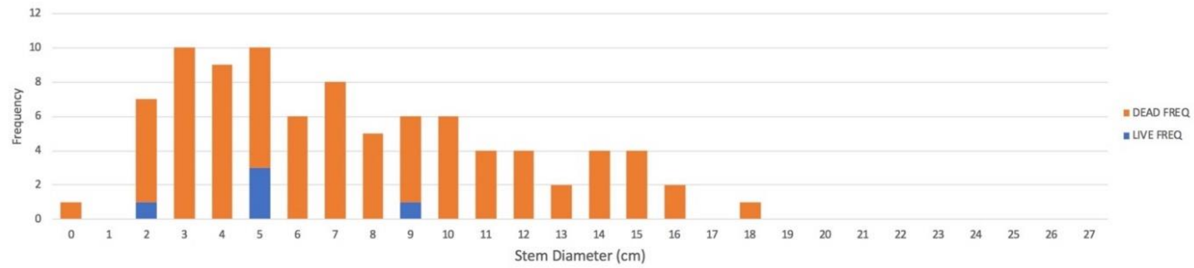

Figure 5.50. Size frequency of vegetation along Transect 5A showing live and dead plants in August 2018. Trees died mostly in late 2015. Notably, the smaller individuals had the greatest survivorship.

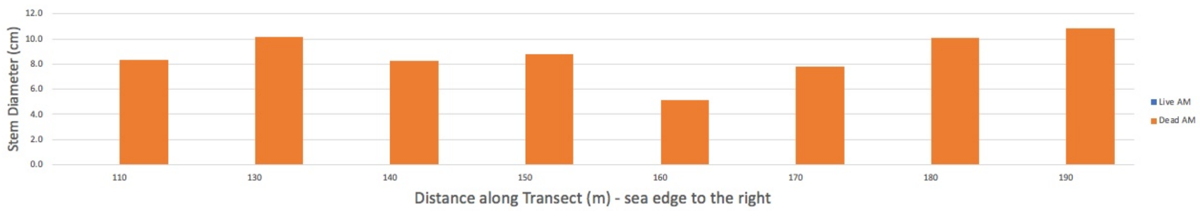

Figure 5.51. Mean size of live and dead canopy trees along Transect 5A for each 10-metre section. There were no surviving canopy trees. Distances were taken from the transect head (left side) at around highest astronomical tide (~HAT) towards the landward shoreline.

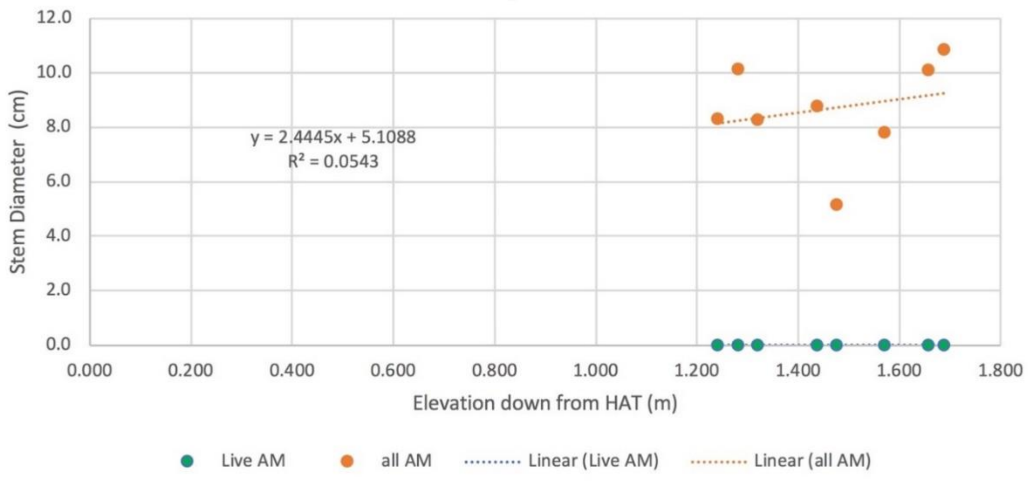

Figure 5.52. Mean size of canopy trees along Transect 5A compared to their elevation position. There was no apparent relationship with elevation.

Table 5.14. Vegetation along Transect 5A recorded during 8–10 August 2018.

Heavily impacted in late 2015	Canopy	Under-canopy
Total trees and shrubs measured	89	62
Total density	0.28 stems/m^2	0.69 stems/m^2
Height mean (max.)	1.6 (7.8) m	0.5 m
Trees and shrubs dead – 2015 dieback	95.5%	0.0%
Total standing carbon	95.0 tC/ha	
Dead standing carbon – 2015 dieback	93.4 tC/ha	
Dominant species	*Avicennia marina*	*Avicennia marina*
Proportion of dominant	90.9%	98.4%
Proportion of dead – 2015 dieback	90.9%	0.0%
Stem diameter (max.)	7.9 (18.6) cm	

See Appendix 7.

Comparisons between 2018 and 2019 surveys (Figure 5.53 and Figure 5.54)

Figure 5.53. Views of Transect 5A visited in August 2018 showing the high tide edge (left) and seaward margin (right).

Figure 5.54. Views of Transect 5A visited in September 2019 showing the high tide edge (left) and seaward margin (right).

Note driftwood wrack in 2018 was scattered across the higher tidal flat, while a year later it was piled up along the highwater margin. A significant number of high intertidal plants had died because of the driftwood scouring. At the seaward edge, there were fewer standing dead stems and fewer surviving shrubby *Aegialitis* mangroves presumably because of sediment burial and erosion as the dead forests root matt degrades and releases sediments.

5.8 Transect 5D – Qld North Mitchell: 60%–80% dieback impacted

Transect 5D was on the Queensland side of the Gulf of Carpentaria.

Background site information (Figure 5.55 and Figure 5.56; Table 5.15):

- General site location: -14.996538°; 141.660919°
- Length of the map transect: ~533 m
- Tidal range: ~2.2 m
- Sea level rise: ~7.8 mm/yr
- Close by cyclones since 1975: at least 4
- General impact condition: 60%–80% loss of mangrove fringe between 2015 and 2016.

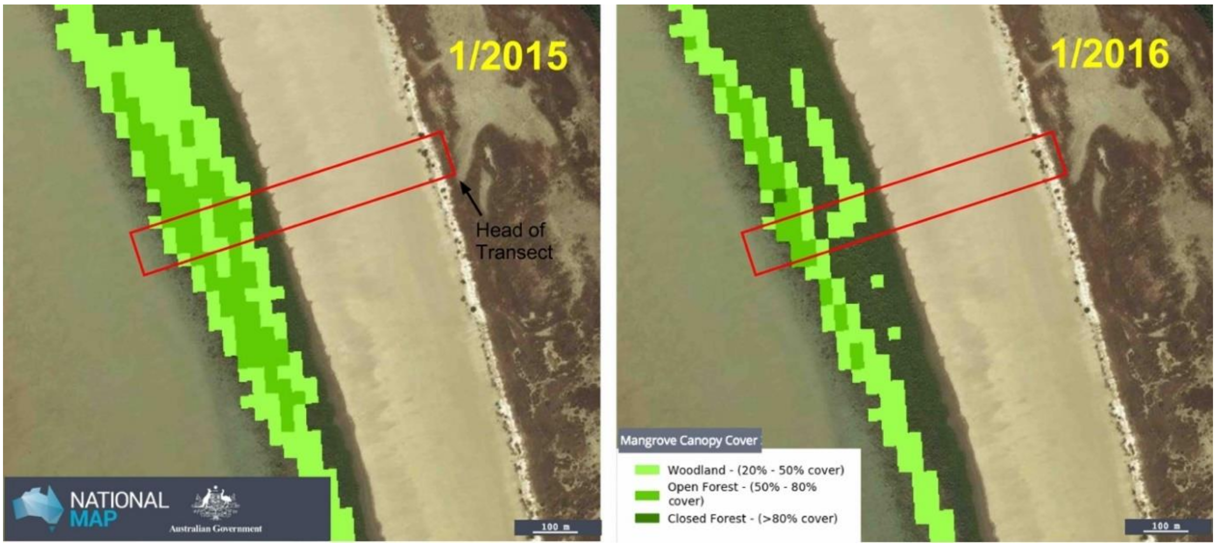

Figure 5.55. Location of Transect 5D (red box) visited in August 2018. Note the loss of mangrove canopy cover (green shaded) between 2015 and 2016.

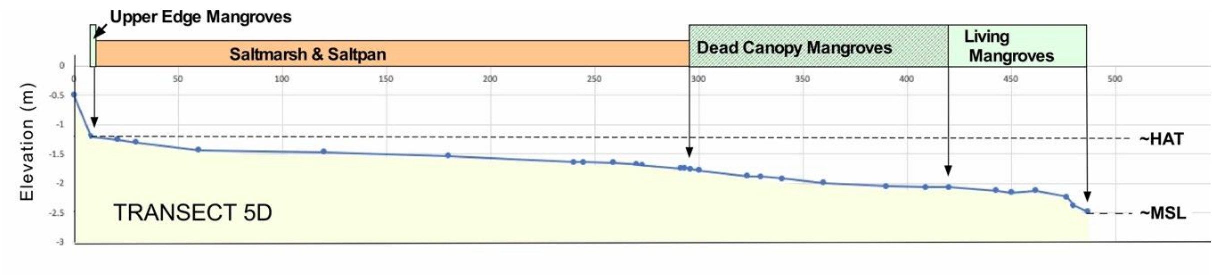

Figure 5.56. Profile of Transect 5D showing elevations measured in Oct 2018 and tidal wetland vegetation zones including canopy mangroves that died in late 2015.

Table 5.15. Survey information for Transect 5D measured during 8–10 August 2018.

Head: -14.995454° S; 141.664741° E	Seaward: -14.996881° S; 141.660014° E
Length – land (~HAT) to sea edge (~MSL): 483 m	Mangrove fringe width: 191 m
Total area of measured mangroves: 777 m2	Mean width of transect plot: 4.00 m
Estimated tidal wetland MSL range: -1.64 m	Wetland cover index: 39.5%
Upper mangrove fringe – pre-impact: -0.90 m	Upper mangrove fringe – post-impact: -1.25 m
Fringe mangrove elevation range: 0.74 m	Impacted mangrove elevation range: 0.35 m
Dead portion of fringe: 68.1%	2015 dieback impact severity: **Moderate**

Note: HAT = highest astronomical tide; MSL = mean sea level.

Note that detailed observations were scored and measured from 777 m² of vegetation or remnant vegetation along this transect. Data are summarised in Table 5.16 and listed in Appendix 8. The following figures (Figure 5.57–Figure 5.59) show characteristics of vegetation along this transect, particularly the location and elevation of 2015–2016 dieback plus age-related features based on stem diameter of canopy trees, *Avicennia marina*.

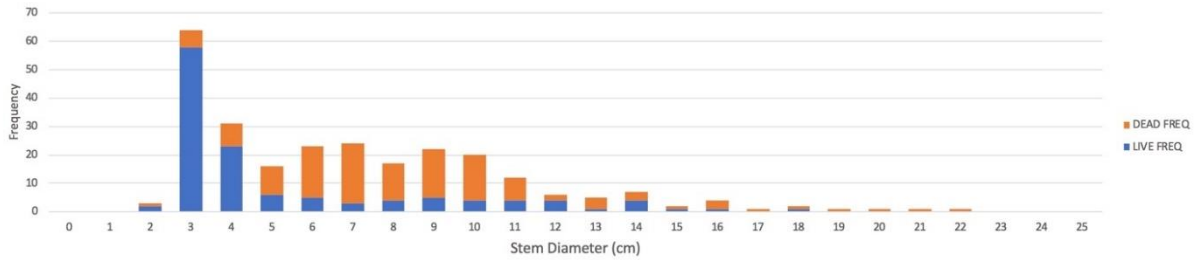

Figure 5.57. Size frequency of vegetation along Transect 5D showing live and dead plants in August 2018. Trees died mostly in late 2015. Notably, the smaller (younger) individuals had the greatest survivorship.

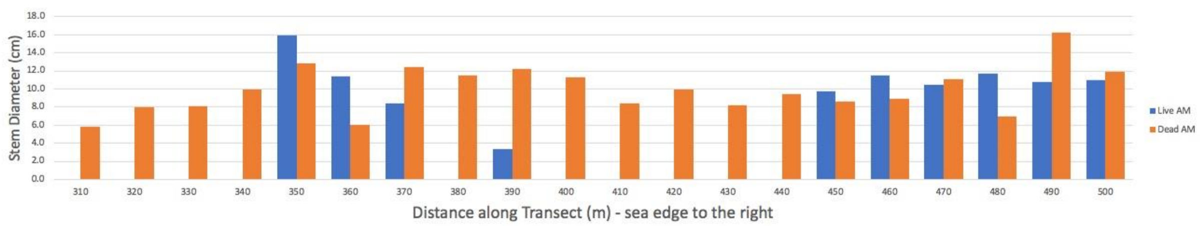

Figure 5.58. Mean size of live and dead canopy trees along Transect 5D for each 10-metre section. Surviving canopy trees were notably both within an inner fringe stand and towards the seaward edge. Distances were taken from the transect head (left side) at around highest astronomical tide (~HAT) towards the landward shoreline.

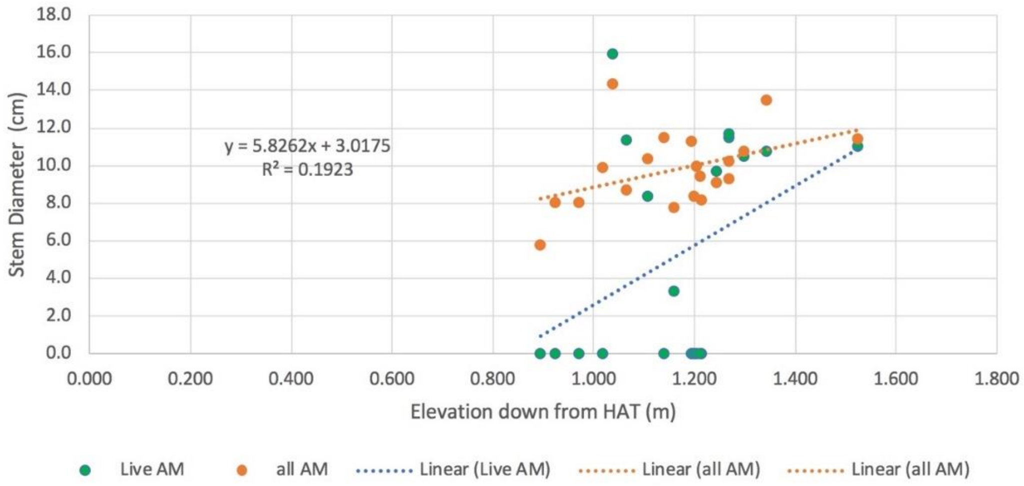

Figure 5.59. Mean size of canopy trees along Transect 5D compared to their elevation position. Although many trees were dead, there was an apparent trend with elevation. This was consistent with a relationship where younger trees were found higher up the tidal zone.

Table 5.16. Vegetation along Transect 5D recorded during 8–10 August 2018.

Heavily impacted in late 2015	Canopy	Under-canopy
Total trees and shrubs measured	230	855
Total density	0.33 stems/m^2	4.29 stems/m^2
Height mean (max.)	2.9 (9.6) m	0.6 m
Trees and shrubs dead – 2015 dieback	51.5%	2.7%
Total standing carbon	92.2 tC/ha	
Dead standing carbon – 2015 dieback	62.9 tC/ha	
Dominant species	*Avicennia marina*	*Avicennia marina*
Proportion of dominant	63.1%	70.4%
Proportion of dead – 2015 dieback	49.6%	1.2%
Stem diameter (max.)	7.4 (22.0) cm	

See Appendix 8.

Comparisons between 2018 and 2019 surveys (Figure 5.60 and Figure 5.61)

Figure 5.60. Views of Transect 5D visited in August 2018 showing the high tide edge (left) and seaward margin (right).

Figure 5.61. Views of Transect 5D visited in September 2019 showing the high tide edge (left) and seaward margin (right).

Note driftwood wrack in 2018 was scattered across the higher tidal flat, while a year later it was piled up along the highwater margin. At the seaward edge eroding edges had been filled with soft mud presumably from sheet erosion across higher intertidal dieback areas. There were also numerous old, degraded dead stumps indicating the earlier loss of sea edge trees.

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Appendix 1: Details of *Avicennia marina* (AM) canopy trees along the Limmen shoreline Transect 1A in October 2018

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
1		370	1.037	1	0	3	0.000	0.300	0.00	0.72	0.0	4.7
2		380	1.217	1	0	3	0.000	0.300	0.00	1.37	0.0	5.2
3		390	1.092	1	0	0	0.000	0.000	0.00	0.00	0.0	0.0
4	*M2 Up*	*400*	*1.017*	*1*	*0*	*6*	*0.000*	*0.600*	*0.00*	*1.22*	*0.0*	*2.7*
5		410	1.156	1	0	7	0.000	0.700	0.00	1.02	0.0	4.2
6		420	1.077	1	0	7	0.000	0.700	0.00	0.56	0.0	4.3
7		430	1.140	1	0	5	0.000	0.500	0.00	0.77	0.0	3.5
8		440	1.167	1	0	3	0.000	0.300	0.00	1.03	0.0	3.4
9		450	1.129	1	0	5	0.000	0.500	0.00	0.81	0.0	3.1
10		460	1.115	1	0	8	0.000	0.800	0.00	1.08	0.0	3.7
11		470	1.119	1	0	4	0.000	0.400	0.00	1.70	0.0	4.3
12		480	1.127	1	0	6	0.000	0.600	0.00	0.93	0.0	4.6
13		490	1.140	1	0	11	0.000	1.100	0.00	1.78	0.0	4.2
14		500	1.168	2	0	13	0.000	0.650	0.00	1.63	0.0	4.7
15		510	1.200	2	0	8	0.000	0.400	0.00	1.67	0.0	5.8
16		520	1.237	2	1	12	0.050	0.600	0.45	0.97	0.0	5.1
17		530	1.287	2	0	9	0.000	0.450	0.00	0.94	0.0	6.2
18		540	1.305	2	0	4	0.000	0.200	0.00	3.18	0.0	8.5
19		550	1.337	2	0	5	0.000	0.250	0.00	2.18	0.0	7.5
20		560	1.383	2	0	8	0.000	0.400	0.00	2.77	0.0	9.5

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
21		570	1.432	2	0	8	0.000	0.400	0.00	2.71	0.0	12.7
22		580	1.557	2	0	1	0.000	0.050	0.00	3.30	0.0	16.0
23	*~MSL M2 dead*	*590*	*1.712*	*2*	*0*	*2*	*0.000*	*0.100*	*0.00*	*0.10*	*0.0*	*12.3*
24		600	1.907	2	0	0	0.000	0.000	0.00	0.00	0.0	0.0

Note: Values are means for stems within 10-metre sections of the transect measured from the head at ~HAT (Figure 2.2). See Methods for codes used for transect ecotones. Note: length, elevation and height measures in metres, density in stems per m2, and stem diameter in centimetres.

Appendix 2: Details of *Avicennia marina* (AM) canopy trees along the Limmen shoreline Transect 1B in October 2018

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
1	M2 Up	*600*	*0.635*	*1*	*0*	*6*	*0.000*	*0.600*	*0.00*	*1.22*	*0.0*	*3.6*
2		610	0.650	1	0	16	0.000	1.600	0.00	1.68	0.0	3.7
3		620	0.661	1	0	30	0.000	3.000	0.00	1.49	0.0	3.1
4		630	0.689	2	0	35	0.000	1.750	0.00	1.37	0.0	2.6
5		640	0.715	2	1	17	0.050	0.850	1.00	1.34	3.1	3.0
6		650	0.741	2	3	20	0.150	1.000	1.03	1.38	2.9	3.2
7		660	0.770	2	3	12	0.150	0.600	1.12	2.15	3.8	5.0
8		670	0.794	2	5	13	0.250	0.650	1.30	2.09	4.5	7.2
9		680	0.842	2	0	4	0.000	0.200	0.00	1.45	0.0	7.7
10	M2 dead	*690*	*0.865*	*2*	*2*	*4*	*0.100*	*0.200*	*1.43*	*0.70*	*10.7*	*6.8*
11		700	0.870	2	5	0	0.250	0.000	2.06	0.00	13.6	0.0
12		710	0.934	2	3	0	0.150	0.000	0.63	0.00	3.0	0.0
13		720	0.973	2	4	0	0.200	0.000	0.78	0.00	2.7	0.0
14		730	1.010	2	3	1	0.150	0.050	1.58	0.10	6.7	8.5
15		740	1.045	2	1	1	0.050	0.050	0.50	0.05	3.1	10.3
16	M2 live	*750*	*1.057*	*2*	*28*	*2*	*1.400*	*0.100*	*1.54*	*0.48*	*5.7*	*3.3*
17		760	1.138	2	4	0	0.200	0.000	1.65	0.00	8.8	0.0
18		770	1.175	2	14	0	0.700	0.000	1.78	0.00	3.6	0.0
19	~MSL	*780*	*1.193*	*2*	*17*	*0*	*0.850*	*0.000*	*1.94*	*0.00*	*4.3*	*0.0*

Note: Values are means for stems within 10-metre sections of the transect measured from the head at ~HAT (Figure 2.2). See Methods for codes used for transect ecotones. Note: length, elevation and height measures in metres, density in stems per m2, and stem diameter in centimetres.

Appendix 3: Details of *Avicennia marina* (AM) canopy trees along the Mule shoreline Transect 2A in October 2018

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
1	M2 Up	70	0.735	1	0	4	0.000	0.400	0.00	0.89	0.0	3.1
2		80	0.795	1	0	6	0.000	0.600	0.00	1.16	0.0	4.7
3		90	0.835	1	0	3	0.000	0.300	0.00	1.70	0.0	3.9
4		100	0.860	1	6	10	0.600	1.000	2.60	2.01	8.3	5.3
5		110	0.776	1	3	6	0.300	0.600	1.68	3.11	3.8	5.4
6		120	0.802	1	9	4	0.900	0.400	1.52	2.54	3.2	6.4
7		130	0.838	1	0	2	0.000	0.200	0.00	2.19	0.0	8.9
8		140	0.830	1	7	13	0.700	1.300	2.21	2.68	4.9	7.8
9		150	0.921	2	0	28	0.000	1.400	0.00	0.50	0.0	5.0
10	M2 dead	160	1.045	2	1	24	0.050	1.200	0.35	0.37	1.8	3.9
11	M2 live	170	1.180	2	7	4	0.350	0.200	1.15	1.81	9.2	6.5
12		180	1.293	2	1	1	0.050	0.050	3.50	0.50	19.7	7.5
13		190	1.348	2	2	1	0.100	0.050	1.43	0.01	6.9	13.0
14	~MSL	200	1.455	2	1	0	0.050	0.000	1.50	0.00	16.6	0.0
15		210	1.520	2	0	0	0.000	0.000	2.60	0.00	15.9	0.0
16		230	1.480	2	2	0	0.100	0.000	1.15	0.00	11.8	0.0

Note: Values are means for stems within 10-metre sections of the transect measured from the head at ~HAT (Figure 2.2). See Methods for codes used for transect ecotones. Note: length, elevation and height measures in metres, density in stems per m^2, and stem diameter in centimetres.

Appendix 4: Details of *Avicennia marina* (AM) canopy trees along the Mule shoreline Transect 2B in October 2018

	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
1	M2 Up	220	0.975	1	0	11	0.000	1.100	0.00	1.27	0.0	3.4
2		230	1.014	1	0	10	0.000	1.000	0.00	1.84	0.0	5.0
3		240	1.004	2	0	18	0.000	0.900	0.00	1.84	0.0	4.3
4		250	0.993	1	1	17	0.100	1.700	1.00	3.22	3.0	4.8
5		260	0.926	2	2	10	0.100	0.500	0.75	4.16	7.4	9.8
6		270	0.930	2	0	9	0.000	0.450	0.00	3.74	0.0	10.3
7		280	0.955	2	0	16	0.000	0.800	0.00	3.06	0.0	9.3
8		290	1.015	2	0	14	0.000	0.700	0.00	0.79	0.0	9.3
9		300	1.067	2	0	14	0.000	0.700	0.00	1.00	0.0	8.0
10		310	1.139	2	0	12	0.000	0.600	0.00	0.72	0.0	7.3
11		320	1.231	2	0	4	0.000	0.200	0.00	1.69	0.0	12.9
12		330	1.273	2	0	4	0.000	0.200	0.00	0.06	0.0	11.4
13		340	1.198	2	0	6	0.000	0.300	0.00	0.51	0.0	10.2
14		350	1.345	2	0	3	0.000	0.150	0.00	0.37	0.0	3.5
15	M2 dead	360	1.360	2	0	2	0.000	0.100	0.00	1.49	0.0	9.3
16	~MSL M2 live	370	1.395	2	3	0	0.150	0.000	1.40	0.00	6.7	0.0

Note: Values are means for stems within 10-metre sections of the transect measured from the head at ~HAT (Figure 2.2). See Methods for codes used for transect ecotones. Note: length, elevation and height measures in metres, density in stems per m^2, and stem diameter in centimetres.

Appendix 5. Details of *Avicennia marina* (AM) canopy trees along the Karumba shoreline Transect 4A in August 2018

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
1	M2 Up	280	0.675	1	0	10	0.000	1.000	0.00	0.63	0.0	3.0
2		290	0.681	1	0	5	0.000	0.500	0.00	1.03	0.0	4.1
3		300	0.690	1	0	8	0.000	0.800	0.00	1.14	0.0	4.8
4		310	0.730	1	0	5	0.000	0.500	0.00	1.74	0.0	3.9
5		320	0.743	1	0	12	0.000	1.200	0.00	1.76	0.0	4.8
6		330	0.772	2	0	24	0.000	1.200	0.00	1.88	0.0	4.5
7		340	0.790	2	0	19	0.000	0.950	0.00	1.76	0.0	3.9
8		350	0.805	2	0	13	0.000	0.650	0.00	1.44	0.0	4.6
9		360	0.800	2	0	6	0.000	0.300	0.00	3.33	0.0	6.3
10		370	0.805	2	0	3	0.000	0.150	0.00	2.10	0.0	4.8
11		380	0.803	2	0	16	0.000	0.800	0.00	1.61	0.0	5.4
12		390	0.847	2	0	1	0.000	0.050	0.00	5.80	0.0	10.3
13		400	0.850	2	0	7	0.000	0.350	0.00	3.18	0.0	7.5
14		410	0.848	2	0	3	0.000	0.150	0.00	2.47	0.0	5.4
15		420	0.882	2	0	5	0.000	0.250	0.00	2.42	0.0	7.5
16		430	0.902	4	0	9	0.000	0.225	0.00	3.17	0.0	7.7
17		440	0.918	4	0	9	0.000	0.225	0.00	3.04	0.0	7.3
18		450	0.935	4	0	14	0.000	0.350	0.00	2.28	0.0	7.1
19		460	0.960	4	0	6	0.000	0.150	0.00	3.45	0.0	6.0
20		470	0.963	4	0	11	0.000	0.275	0.00	4.44	0.0	8.9

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
21		480	0.967	4	1	7	0.025	0.175	3.20	3.87	4.6	7.3
22		490	0.982	4	0	2	0.000	0.050	0.00	3.75	0.0	7.8
23		500	1.007	4	0	5	0.000	0.125	0.00	2.96	0.0	8.8
24		510	1.068	4	0	3	0.000	0.075	0.00	5.37	0.0	10.8
25		520	1.105	4	0	2	0.000	0.050	0.00	4.35	0.0	15.4
26		530	1.191	4	1	0	0.025	0.000	1.90	0.00	4.0	0.0
27		540	1.234	4	0	2	0.000	0.050	0.00	4.80	0.0	14.2
28	M2 dead	550	1.320	4	0	2	0.000	0.050	0.00	5.20	0.0	9.9
29	M2 live	560	1.349	1	2	0	0.200	0.000	1.33	0.00	2.9	0.0
30		570	1.377	1	4	1	0.400	0.100	1.58	0.30	3.1	2.7
31	~MSL	580	1.520	1	4	5	0.400	0.500	2.84	4.25	5.8	4.8
32		590	1.583	1	9	16	0.900	1.600	2.25	1.11	4.2	2.8
33		600	1.741	1	2	12	0.200	1.200	1.23	2.03	3.1	4.0
34		610	1.830	1	0	3	0.000	0.300	0.00	5.47	0.0	8.7
35		620	1.860	1	0	3	0.000	0.300	0.00	4.14	0.0	14.6
36		630	1.890	1	0	1	0.000	0.100	0.00	5.29	0.0	25.9

Note: Values are means for stems within 10-metre sections of the transect measured from the head at ~HAT (Figure 2.2). See Methods for codes used for transect ecotones. Note: length, elevation and height measures in metres, density in stems per m^2, and stem diameter in centimetres.

Appendix 6: Details of *Avicennia marina* (AM) canopy trees along the Karumba shoreline Transect 4B in August 2018

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
1	M2 Up	350	0.780	1	0	7	0.000	0.700	0.00	0.42	0.0	2.7
2		360	0.793	1	0	16	0.000	1.600	0.00	0.40	0.0	3.1
3		370	0.823	1	0	3	0.000	0.300	0.00	1.78	0.0	5.1
4		380	0.828	1	0	6	0.000	0.600	0.00	1.22	0.0	2.9
5		390	0.839	1	0	11	0.000	1.100	0.00	0.67	0.0	2.8
6		400	0.860	1	0	8	0.000	0.800	0.00	1.02	0.0	3.3
7		410	0.876	1	0	7	0.000	0.700	0.00	1.53	0.0	4.2
8		420	0.888	1	0	6	0.000	0.600	0.00	0.21	0.0	4.1
9		430	0.896	1	0	5	0.000	0.500	0.00	1.41	0.0	4.1
10		440	0.902	1	0	3	0.000	0.300	0.00	0.32	0.0	4.9
11		450	0.908	1	0	8	0.000	0.800	0.00	1.67	0.0	4.3
12		460	0.931	1	0	6	0.000	0.600	0.00	2.15	0.0	4.7
13		470	0.949	1	0	3	0.000	0.300	0.00	2.37	0.0	5.3
14		480	0.957	1	0	7	0.000	0.700	0.00	1.22	0.0	4.5
15		490	0.968	1	0	8	0.000	0.800	0.00	1.40	0.0	6.3
16		500	0.982	1	0	7	0.000	0.700	0.00	2.21	0.0	7.3
17		510	0.993	1	0	5	0.000	0.500	0.00	3.19	0.0	6.5
18		520	1.002	1	0	4	0.000	0.400	0.00	2.09	0.0	5.0
19		530	1.010	1	0	3	0.000	0.300	0.00	4.00	0.0	6.9
20	M2 dead	540	1.015	1	0	6	0.000	0.600	0.00	5.37	0.0	9.7

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
21	M2 live	550	1.015	4	4	7	0.100	0.175	2.83	4.37	5.7	10.7
22		560	1.015	4	2	0	0.050	0.000	1.78	0.00	3.6	0.0
23		570	1.015	4	4	0	0.100	0.000	4.95	0.00	11.1	0.0
24		580	1.167	2	4	0	0.200	0.000	4.60	0.00	8.4	0.0
25		590	1.179	2	3	1	0.150	0.050	6.43	5.70	11.4	19.6
26		600	1.213	2	4	0	0.200	0.000	5.64	0.00	12.3	0.0
27		610	1.241	2	2	0	0.100	0.000	5.35	0.00	9.0	0.0
28		620	1.251	2	5	0	0.250	0.000	4.96	0.00	10.1	0.0
29		630	1.255	1	4	0	0.400	0.000	4.68	0.00	9.4	0.0
30		640	1.260	4	4	1	0.100	0.025	3.40	1.50	8.1	4.8
31		650	1.335	1	3	0	0.300	0.000	3.67	0.00	3.8	0.0
32		660	1.403	1	0	10	0.000	1.000	0.00	0.22	0.0	4.7
33	~MSL	670	1.487	1	0	2	0.000	0.200	0.00	3.65	0.0	7.7

Note: Values are means for stems within 10-metre sections of the transect measured from the head at ~HAT (Figure 2.2). See Methods for codes used for transect ecotones. Note: length, elevation and height measures in metres, density in stems per m^2, and stem diameter in centimetres.

Appendix 7: Details of *Avicennia marina* (AM) canopy trees along the North Mitchell shoreline Transect 5A in August 2018

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
1	M2 Up	110	1.240	4	0	9	0.000	0.225	0.00	1.87	0.0	8.3
2		120	1.280	4	0	8	0.000	0.200	0.00	3.43	0.0	10.1
3		140	1.320	4	0	13	0.000	0.325	0.00	2.01	0.0	8.3
4		150	1.437	4	0	3	0.000	0.075	0.00	0.95	0.0	8.8
5		160	1.477	4	0	11	0.000	0.275	0.00	0.84	0.0	5.2
6		170	1.570	4	0	23	0.000	0.575	0.00	0.89	0.0	7.8
7		180	1.656	4	0	8	0.000	0.200	0.00	1.93	0.0	10.1
8	~MSL M2 dead	190	1.688	4	0	5	0.000	0.125	0.00	2.51	0.0	10.9

Note: Values are means for stems within 10-metre sections of the transect measured from the head at ~HAT (Figure 2.2). See Methods for codes used for transect ecotones. Note: length, elevation and height measures in metres, density in stems per m^2, and stem diameter in centimetres.

Appendix 8: Details of *Avicennia marina* (AM) canopy trees along the North Mitchell shoreline Transect 5D in August 2018

#	Transect ecotone	Dist. ex ~HAT	Elev. (m)	Width (m)	AM live count	AM dead count	AM live density	AM dead density	AM live height	AM dead height	AM live stem diameter	AM dead stem diameter
1	*M2 Up*	310	0.895	4	0	9	0.000	0.225	0.00	1.00	0.0	5.8
2		320	0.925	4	0	16	0.000	0.400	0.00	2.03	0.0	8.0
3		330	0.972	4	0	16	0.000	0.400	0.00	1.95	0.0	8.0
4		340	1.019	4	0	6	0.000	0.150	0.00	3.70	0.0	9.9
5		350	1.039	4	1	5	0.025	0.125	7.80	5.35	15.9	12.8
6		360	1.065	4	3	6	0.075	0.150	8.00	0.38	11.4	6.0
7		370	1.107	4	2	2	0.050	0.050	7.55	2.65	8.4	12.4
8		380	1.141	4	0	4	0.000	0.100	0.00	3.96	0.0	11.5
9		390	1.159	4	1	1	0.025	0.025	2.00	6.10	3.3	12.3
10		400	1.196	4	0	2	0.000	0.050	0.00	3.33	0.0	11.3
11		410	1.200	4	0	3	0.000	0.075	0.00	3.15	0.0	8.4
12		420	1.204	4	0	11	0.000	0.275	0.00	0.94	0.0	9.9
13		430	1.214	4	0	11	0.000	0.275	0.00	1.68	0.0	8.2
14	*M2 dead*	440	1.213	4	0	13	0.000	0.325	0.00	0.95	0.0	9.4
15	*M2 live*	450	1.245	4	1	10	0.025	0.250	0.95	1.35	9.7	8.6
16		460	1.268	4	3	6	0.075	0.150	5.05	2.35	11.5	8.9
17		470	1.300	4	8	2	0.200	0.050	7.40	2.85	10.5	11.1
18		480	1.270	4	6	2	0.150	0.050	8.42	1.85	11.7	6.9
19		490	1.343	4	5	1	0.125	0.025	6.20	0.15	10.8	16.2
20	*~MSL*	500	1.525	4	5	3	0.125	0.075	3.64	1.97	11.0	11.9

Note: Values are means for stems within 10-metre sections of the transect measured from the head at ~HAT (Figure 2.2). See Methods for codes used for transect ecotones. Note: length, elevation and height measures in metres, density in stems per m^2, and stem diameter in centimetres.

Appendix 9: Report on the lower estuarine condition for the Albert River (Vol. 1: 'Albert River lower estuary'). An example of the detail in imagery and data collected.

Gulf of Carpentaria
Tidal Wetland Surveys 2017

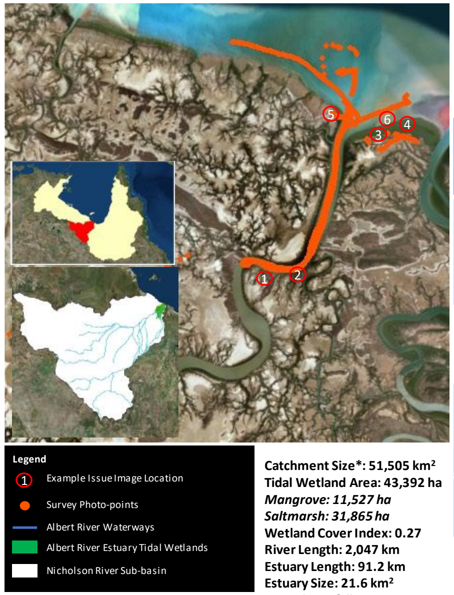
15. Albert River

17°34'0.59"S , 139°45'37.02"E

Tidal Wetland Threat Ranking: **11**

Cumulative Threat Score: **10.1**

Threat to tidal wetlands: Severe



Catchment Size*: 51,505 km²
Tidal Wetland Area: 43,392 ha
Mangrove: 11,527 ha
Saltmarsh: 31,865 ha
Wetland Cover Index: 0.27
River Length: 2,047 km
Estuary Length: 91.2 km
Estuary Size: 21.6 km²
Annual Rainfall: 800 mm
Catchment Landuse*
Grazing, Managed Resource Protection, Nature Conservation, Wetlands
***Nicholson River sub-catchment**

Issue	Local Threat Score	Action Priority		Observations	Time Frame	Management Response		
		Estuary	Gulf of Carpentaria			Local	Regional	National
Saltpan Scouring	**2.1**	**1**	**1**	**Eroded edges and escarpments in upper saltpan areas indicating erosion**	**1 to 3**	**Fencing & watering points to prevent cattle access. Local education to prevent vehicle access**		**Climate change strategy to limit sea level rise.**
Bank Erosion	**1.8**	**2**	**2**	**Widespread erosion on banks of the lower estuary**	**2 to 3**	**Establish buffer zones along tidal wetland margins.**		**Climate change strategy to limit sea level rise and severe flooding**
Weeds	1.2	3	7	Rubber vine on beach ridge vegetation & mangrove upper edges	1 to 3	Local weed management.	Regional Rubber Vine management strategy to limit coastal impacts	
2015 Dieback	**1.2**	**3**	**4**	**Dead mangroves on saltpan edges**	**2**	**Ensure all local impacts are managed during recovery phase**		**National Climate Change strategy**
Ecotone Shift	1.2	3	5	Notable zonation (Am, Rs, Ca). Older & recent dead mangroves at saltpan edges impacting Am & Ca	1 to 3			National Climate Change strategy
Depositional Gain	1.2	3	6	Shoreward mangrove expansion, most notable at estuary mouth.	1 to 3		Implement catchment wide erosion management to reduce estuary fine sediment loads.	

Other Issues Observed: Fire, Pigs, Vehicle Tracks

1. Saltpan Scouring

2. Bank Erosion

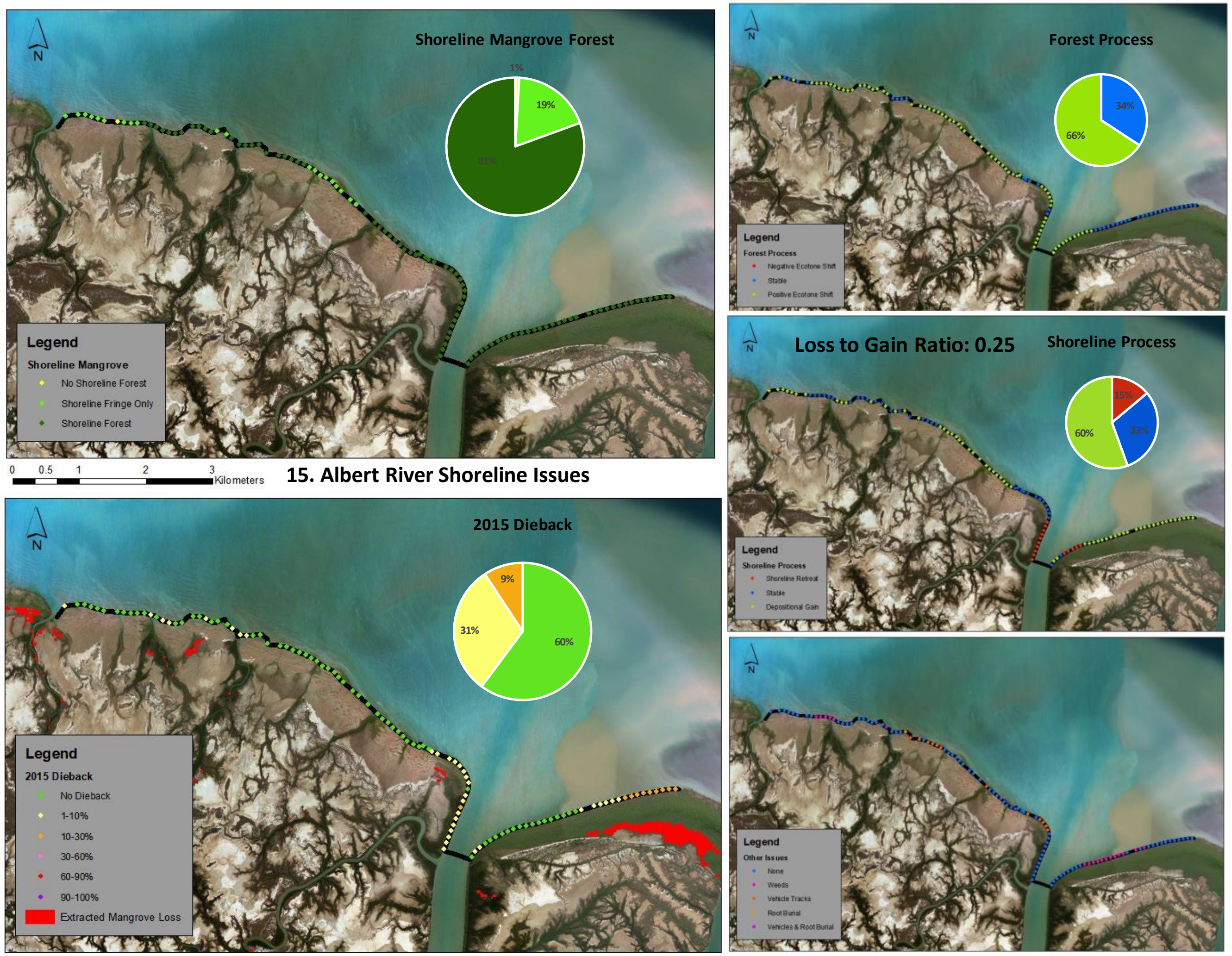
3. Weeds

4. 2015 Dieback

5. Ecotone Shift

6. Depositional Gain

Appendix 10: Maps of lower estuarine condition for the Albert River (Vol. 1: ‘Albert River lower estuary’). An example of the detail in imagery and data collected.



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