



Processes and Factors Driving Change in Mangrove Forests: An Evaluation Based on the Mass Dieback Event in Australia's Gulf of Carpentaria

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Abstract

A vast area of more than 80 km² (6–10% of total) of mangrove forests bordering Australia's Gulf of Carpentaria died *en masse* in late 2015 and early 2016. The dieback occurred over a number of months in synchrony across more than 1500 km of exposed Gulf shorelines. There are serious concerns about the implications of such an event given the important ecological and economic services provided by mangrove ecosystems, and the challenges to policy and management of such an abrupt loss of natural resources at both local and regional scales. In this chapter, we begin by structuring and quantifying the distinct and complex mix of processes involved in the natural establishment, growth, and development of mangrove stands in the context of enhanced environmental variability. Based on these findings, we develop a new evaluation framework to explain the severe response observed in late 2015 in mangroves of the Gulf of Carpentaria. We explore in detail the multiple drivers involved in the event and address the complex question of the role of climate change. These analyses and other observations about this unique event are brought together to assist the ongoing development and implementation of effective management policy, starting with monitoring programs at national and local scales. While this is a work in progress, these findings already provide unequivocal evidence that

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mangroves are vulnerable and acutely sensitive to extreme variations in sea level and climate change.

9.1 Introduction

Mangrove vegetation, along with saltmarsh and saltpans, make up tidal wetlands which together exist almost exclusively within the upper intertidal zone of temperate and tropical shorelines (Tomlinson 2016). These habitats are largely recognised as environmentally resilient. This observation is reinforced in part in the literature, where the broad distributional ranges of mangrove habitats extend across extremely different climatic zones, from arid desert regions to the wet humid tropics. Furthermore, across this range, the habitat maintains similar structural characteristics with often closed canopies sharing common aspects of functionality, faunal communities and ecosystem benefits. For more than 50 million years, tidal wetland habitats are believed to have persisted (Duke 2017) maintaining their adherence to the tidal zone throughout time—despite sometimes dramatic circumstances, such as changes in sea level of tens of metres. The mere presence today of this relatively small group of plants in the intertidal zone clearly demonstrates the success of their survival and life history strategies. But, this tightly constrained existence, coupled with their narrow genetic diversity, further implies there must be tightly defined environmental limits beyond which the habitat cannot survive. These plants, like all others, are defined by their essential and unique characteristics: salt tolerance and their viviparous propagules, allowing them to occupy this particularly specialised niche across space and time.

Overall, mangrove habitat is limited by sea level and temperature at a global scale (Duke et al. 1998). Plants of the tidal wetland niche are primarily limited to the upper tidal zone, determined by species-specific survival limits often displayed in their distinct zonation patterns. Mangroves and saltmarsh plants flourish within relatively narrow zones determined by the ecological limits of each species where each has conformed to the defining environmental factors present. Beyond these limits the plants cannot exist; importantly, they must also be responsive and adaptable to change.

As environmental factors rapidly change, so the mangroves must relocate if they are to survive and persist. This relocation is limited further by the growth conditions of each species along with their reproductive, dispersal and establishment capabilities. This involves either the relocation of habitat into newly created unoccupied space, or its retreat once the current space becomes inhospitable. For mangrove habitats, relocation equates to instances of either expansion via seedling recruitment, or retreat with dieback. In this way, we aim to further define and quantify the distinct and unusual processes involved in the establishment, growth and development of tidal wetlands. Such an extended understanding of the processes involved will then be used to explain the responses observed when the habitat comes under stress.

With this chapter, we examine key factors influencing tidal wetlands along with the responses of the ecosystem as environmental conditions alter. Our aim has been to link observed processes of change to the key responsible drivers. We specifically draw on the recent instance of severe environmental change associated with the unprecedented mass dieback of mangroves in Australia's remote Gulf of Carpentaria in 2015–2016 (Duke et al. 2017). This event affected a vast region of coastal tidal wetlands and warranted considerable attention. Detailed additional investigations are currently underway by various groups including that by the James Cook University TropWATER Centre funded by the National Environmental Science Program (Fig. 9.1a, b). The current situation is evaluated, but first, we review the factors that define the habitat of mangroves and tidal wetlands.

9.2 Dynamic Processes Influencing Tidal Wetlands and Mangroves

The tidal wetland habitat comprises mangroves, tidal saltmarsh and salt pans (Duke et al. 2019). Key features of this habitat are defined and characterised in a series of four conceptual models (Figs. 9.2, 9.3, 9.4, and 9.5) each describing different levels of a nested framework that provides a ranking of environmental drivers and connections needed to understand and explain observed relationships and the responses of tidal wetlands and mangroves when specific environmental factors change. Using this framework, we describe the drivers that operate at different spatial and temporal scales (Table 9.1).

9.2.1 Level 1: Global Setting of Tidal Wetlands: Site Geomorphology, Sea Level and Climate

The primary determining physical factors for tidal wetland habitat are dominated by sea level, tidal range, slope, and sediment type (Fig. 9.2). Factors influencing mangrove plant diversity, structure and cover are otherwise described in Level 2 (Fig. 9.3). In general, habitat features depend on the extent of soft, unconsolidated sediments between mean sea level and high water levels in order to define the presence, zonation and overall areas of the tidal wetland ecosystem along shoreline and estuarine reaches (Duke 2006; Duke et al. 1998). Accordingly, changes to any of these factors will have profound impacts on the habitat, forcing the affected vegetation to either expand or retreat, depending on the direction, trend and rate of change of these factors, and specifically sea level.

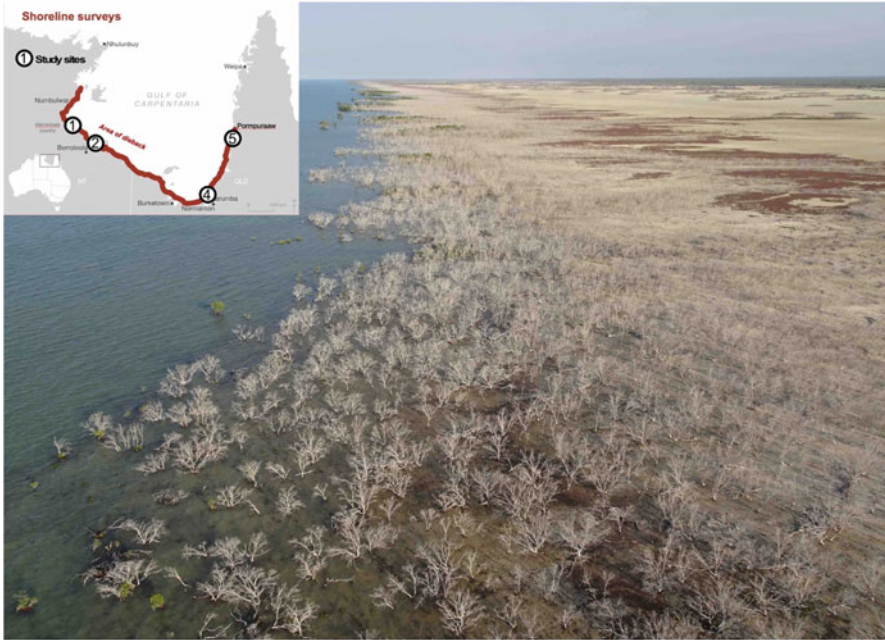


Fig. 9.1 (a) Around 8000 ha of shoreline fringing mangroves were killed between late 2015 and early 2016 along ~1500 km around the Gulf of Carpentaria. This picture shows some of the dead shoreline 3 years after (Limmen Bight shoreline at location 1, Northern Territory, 2018). These trees are believed to have died when normally flooding tides were temporarily lowered with a 20 cm drop in sea level associated with the particularly severe El Niño event. The inset shows the extent of the impacted shoreline along with four study site locations (1 and 2 in the Northern Territory, 4 and 5 in Queensland) where detailed investigations focused on vegetation, fauna and topography. Credit: Norman Duke. (b) Paired views of seaward fringe mangrove areas in Australia’s Gulf of Carpentaria in non-impacted (left images) and impacted (right images) areas following the mass dieback event in late 2015 exemplified in shorelines between Limmen Bight River and McArthur River, Northern Territory, as: **A** and **B** represented in vegetation cover indices pre- and post-impact from satellite imagery (source: National Map)—note, yellow squares mark the location of the green fraction timeline for site 1A (Fig. 9.15); **C** and **D** in aerial surveys of the seaward mangrove fringe observed in June 2016; and **E** and **F** in field studies in 2016 and 2018, respectively (Credit: NC Duke)

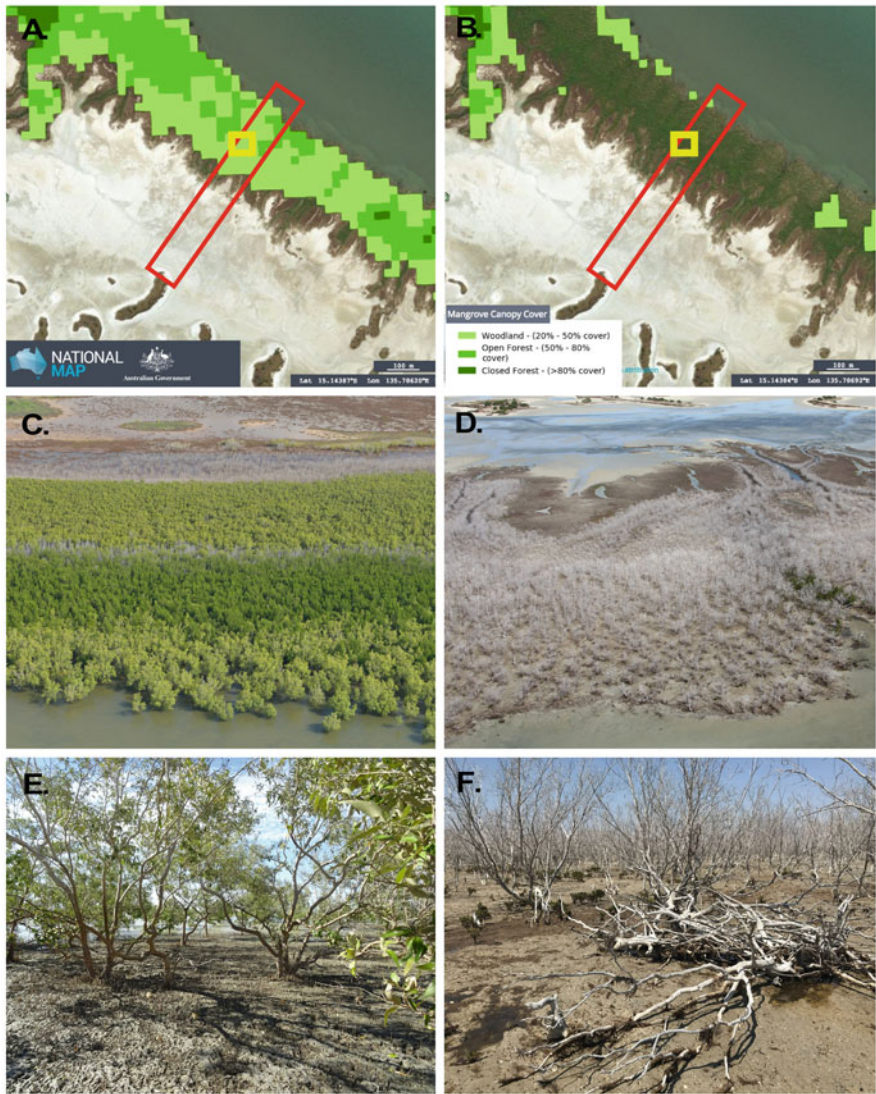


Fig. 9.1 (continued)

9.2.2 Level 2: Composition of Dominant Vegetation Types of Tidal Wetlands: Regional Influences of Temperature and Rainfall

Two key factors, temperature and rainfall, strongly influence the diversity, biomass, presence and relative area of mangrove and tidal saltmarsh in any tidal wetland setting (Fig. 9.3; Duke 1992)—as defined in Level 1. At a regional scale, higher

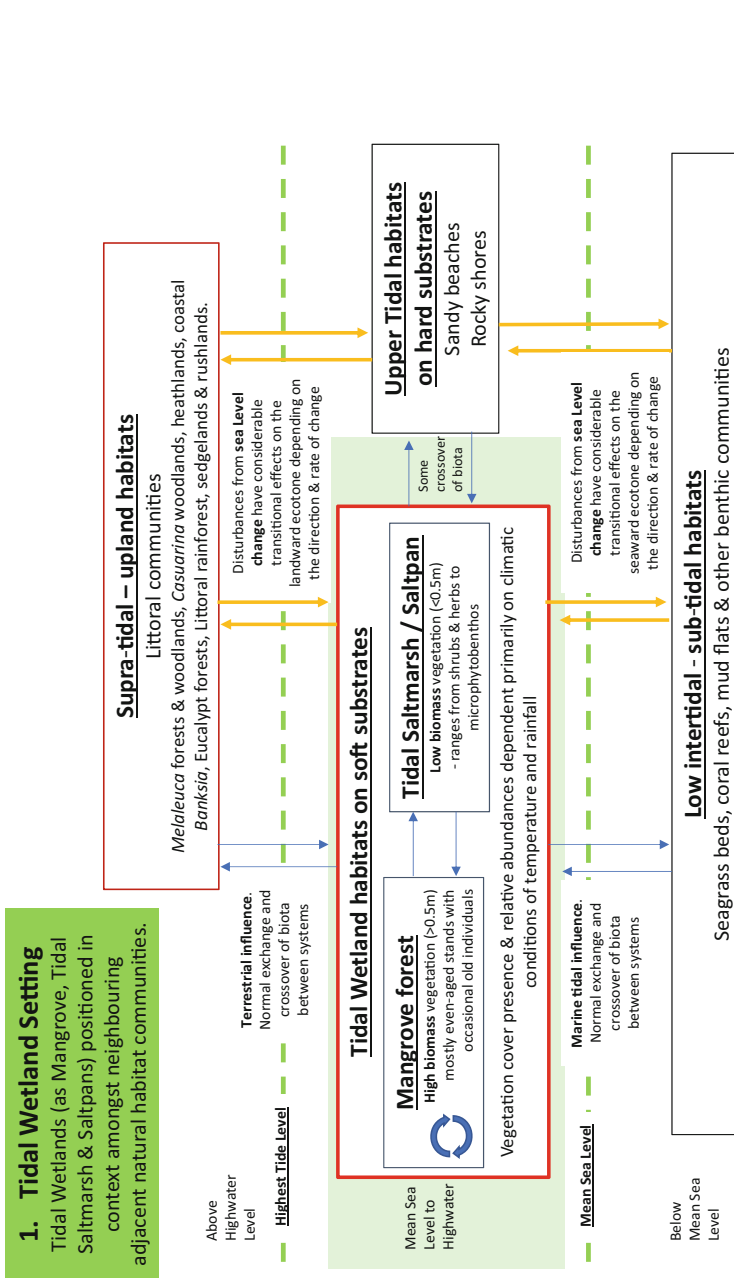


Fig. 9.2 Level 1 schematic conceptual model sets the global physical context for tidal wetlands (red box) amongst neighbouring natural shoreline habitats (Duke et al. 1998; Duke 2006). Blue and yellow arrows respectively signify natural exchanges of biota between habitats and shifts due to disturbances at landward and seaward margins

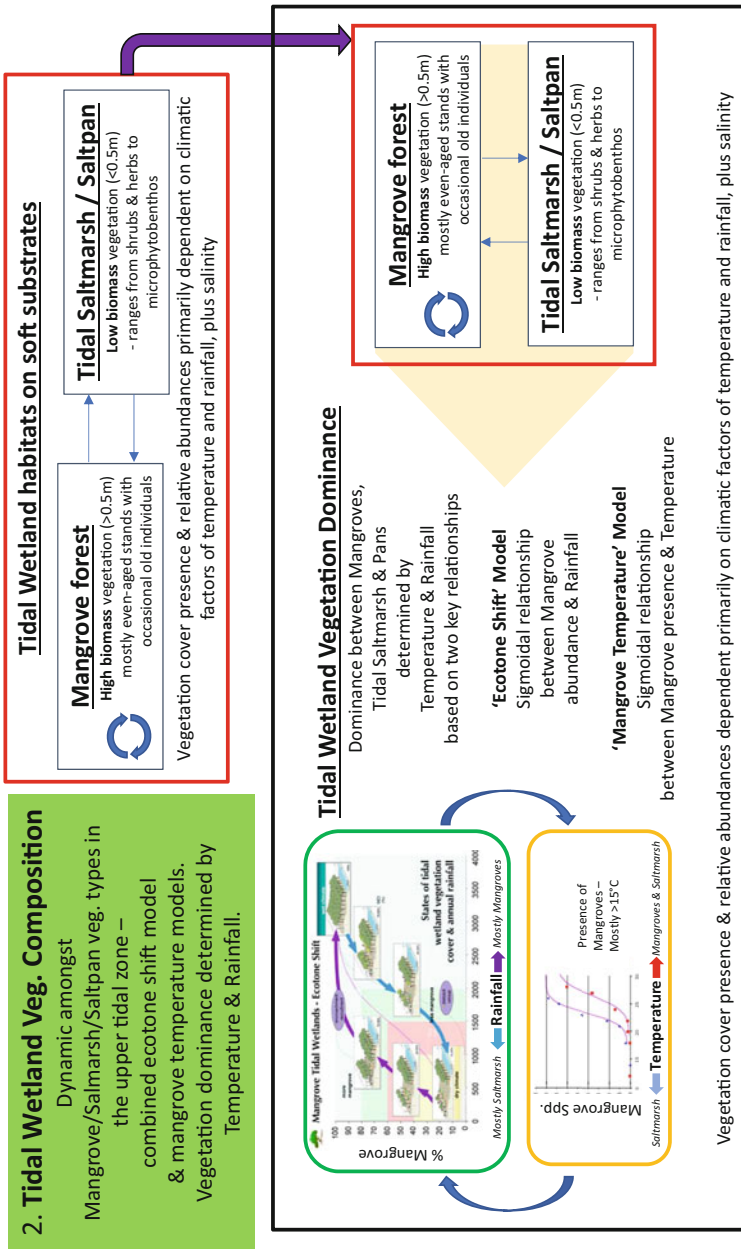


Fig. 9.3 Level 2 schematic conceptual model showing regional climate influences shaping tidal wetlands (red box) with the complex influences of climate variables, particularly temperature (yellow box) and rainfall (green box) (see Duke et al. 2019)

moisture conditions and higher temperatures tend to favour mangrove dominance. The relative abundance of tidal wetland vegetation components (tidal saltmarsh, saltpan and mangroves) is largely determined by local levels of temperature and rainfall—within the constraints defined in the Level 1 schematic (Fig. 9.2). The presence of mangrove species tends to be restricted to sites with higher temperatures while shorter saltmarsh plants, less constrained by temperature, are favoured in temperate settings in the absence of taller mangroves blocking available light. In addition, biomass and biodiversity are also affected, with mangrove and saltmarsh plant types more abundant where temperature and moisture conditions are moderate to maximal (Duke 1992; Duke et al. 2019). There are two distinct relationships for these factors. The models separately define relationships between biodiversity in particular, with either temperature or rainfall. The extent, composition and biomass of tidal wetland vegetation are all primarily influenced by temperature and rainfall. At this time, these influences are best characterised by two separate models for either temperature or rainfall that respectively define each relationship and the relative abundances of mangrove and saltmarsh-saltpan.

A third factor, salinity as the dilution of seawater, is influenced by both temperature and rainfall. This factor can be added to better define and explain the processes involved. While temperature influences relationships with latitude, and rainfall influences distributions across tidal profiles, salinity primarily influences occurrences along estuarine reaches upstream.

9.2.3 Level 3: Sustainable Turnover and Replenishment of Mangrove Forests: Small-Scale, Natural Disturbance Driving Forest Re-establishment, Development and Regeneration

Mangrove habitat is based on the stable structure of living organisms, analogous to coral reefs and forests generally. For this structure to be sustained through time, mangroves must be replaced naturally in an ongoing regenerative process (Fig. 9.4). Mangrove forests have well-developed adaptations and strategies for successfully achieving long-term survival in their specialised niche, including advanced propagule development, buoyant dispersal, enhanced establishment, rapid growth, efficient stand development and turnover. There are tolerances and limits to these capabilities, and once exceeded, the ecosystem and habitat are likely to collapse and become dysfunctional (Duke 2001).

The conceptual model for this third level of tidal wetland processes has been structured around the forest development model—establishment, stand growth, maturity and senescence (Duke 2001; Amir and Duke 2019). The features added relate to those that dominate and influence mangrove forests, like the importance of small gap creation and their restoration. For example, to explain the lack of mangrove forests in senescent conditions, it was proposed these forests were normally replaced before they exceeded advanced maturity. The schematic helps explain the vulnerability of this process by showing the importance of small gap creation events.

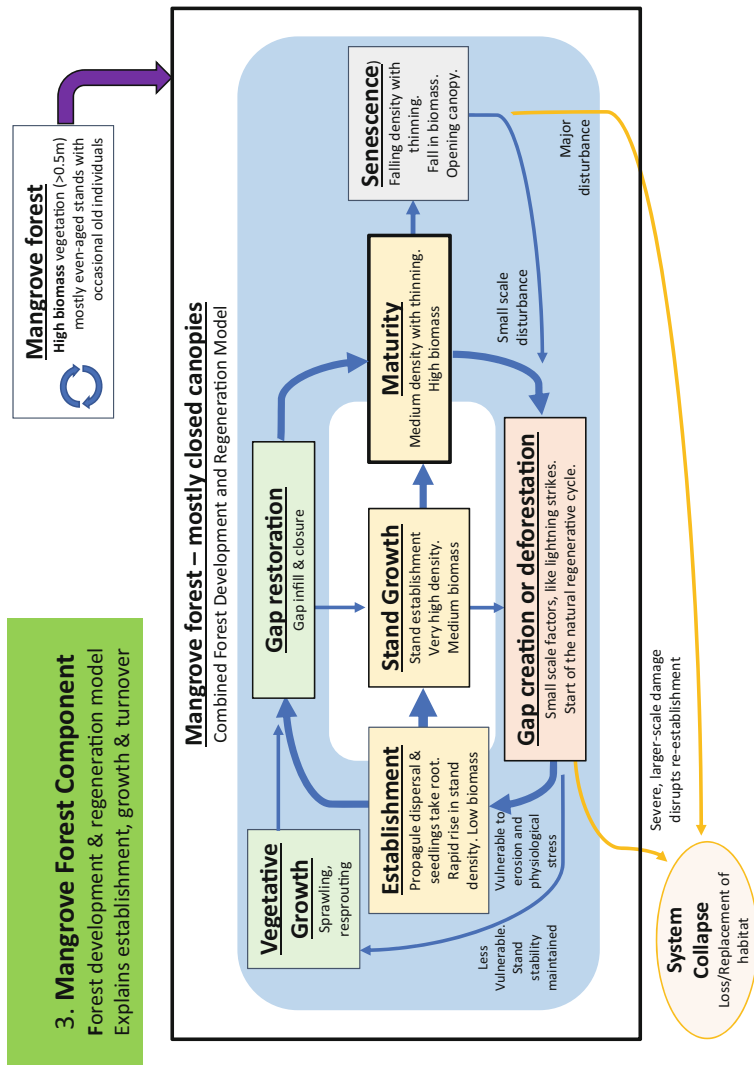


Fig. 9.4 Level 3 schematic conceptual model. The model of sustainable replenishment of mangrove forests has been adapted from a forest development and regeneration model with a notable emphasis on gap creation and restoration (adapted from Duke 2001)

Therefore, while gap creation helps maintain forest vigour and fitness with the maximal presence of healthy mature trees, when the disturbance frequency intensifies this drives higher rates of gap creation leading to the overwhelming of habitat regeneration processors. In this scenario, the mangrove habitat will collapse because there is insufficient time for recovery.

Figure 9.4 also describes a difference in recovery trajectories based on the severity of damage. While gap creation often involves tree death, there are occasions when a gap might be filled and recover by the ingrowth-expansion of surrounding surviving trees. In this case, recovery might be relatively rapid, occurring within a number of years. However, small gap recovery involves the establishment of seedlings and the growth of saplings where gap closure is often much slower, taking one or two decades.

The cause of light gaps in mangrove forests appears mostly to be due to lightning strikes (Amir and Duke 2019), although this remains to be proven. Other causes include herbivore or pathogen attacks, microbursts (small scale, intense downdrafts of wind), root burial from deposited sediments leading to tree death, timber harvesting and large oil spill contamination (Duke 2016).

9.2.4 Level 4: Severe Drivers of Change and Replacement of Tidal Wetland Habitat: Large-Scale Disturbance-Recovery Dynamics Influenced by Human and Natural Drivers

Locally, tidal wetland habitats have highly developed strategies and adaptations supporting their ability to regenerate (Fig. 9.5). When the habitat is disturbed by more extreme conditions exceeding ambient levels, as with catastrophic storms, human cutting, or large oil spills (Duke 2016; Duke et al. 1998), then there is an innate habitat response towards either recovery and re-establishment, or collapse with habitat loss when it fails. This dynamic response is initiated by a larger-scale disturbance event, and the subsequent processes in response incorporate the innate recovery processes of mangrove forests and tidal saltmarsh vegetation.

Severe damage to these tidal wetland components results in both sexual and asexual recovery processes being activated. Both can occur, but there are significant differences as asexual recovery (resprouts) can result in a rapid return to pre-damaged conditions and this pathway is the least disruptive. By contrast, the much slower sexual recovery is essentially the default strategy (depending on the dominant species present) should asexual recovery not be feasible, or the habitat setting has been transformed limiting germination.

Regeneration via sexual recovery takes an order of magnitude longer than asexual pathways (Duke 2016). This is because there is a reliance on the full reproductive development cycle of the affected vegetation, including floral development, fertilisation, seedling production, dispersal, plant establishment, and growth to maturity. During this process, possibly taking decades, the habitat remains vulnerable and at great risk from further disturbance affecting immature plants less able to resist and buffer the exposed conditions following disturbance. Stands undergoing

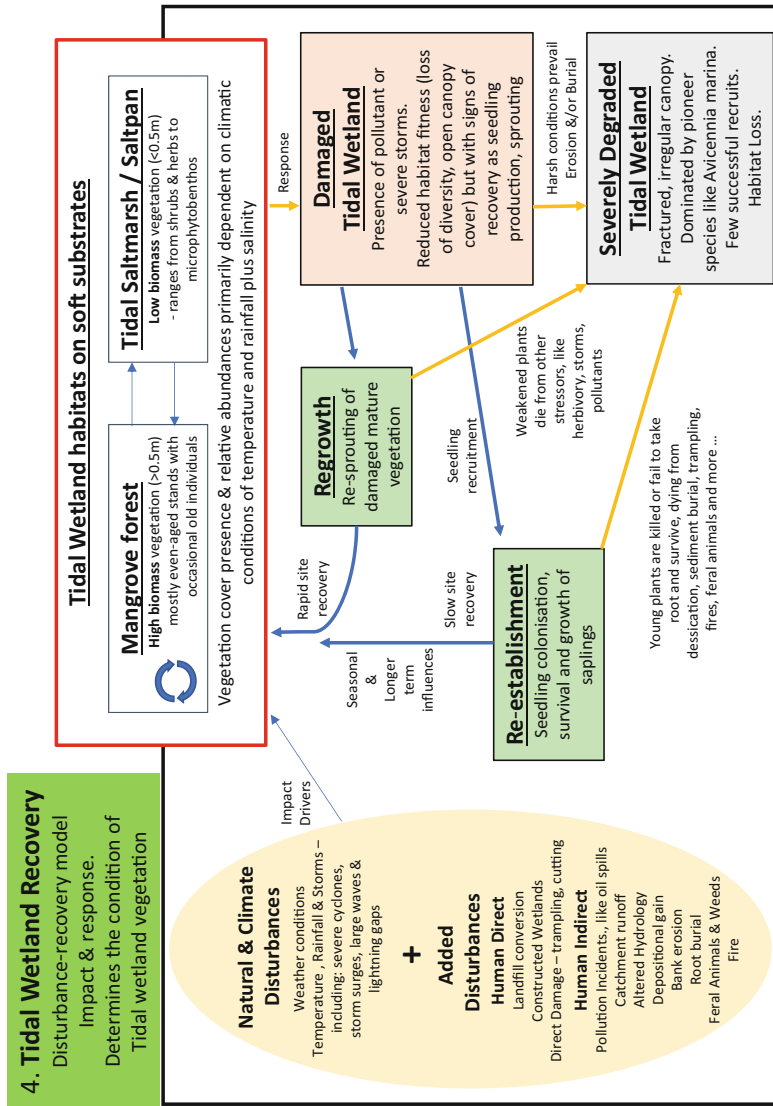


Fig. 9.5 Level 4 schematic conceptual model showing largely localised influences on tidal wetlands (red box) and their recovery processes initiated by various types of severe disturbances due to natural and human impacts. Blue arrows depict regenerative steps while yellow arrows describe initial impacts and degenerative processes (adapted from Duke 2016)

Table 9.1 Four levels of the factors driving key processes that define the occurrence, extent and character of vegetation types inhabiting tidal wetlands, including mangroves, tidal saltmarsh and saltpans. Blank spaces indicate overall influences from other process levels

	Regional drivers, Local impacts			
	Level 1	Level 2	Level 3	Level 4
Physical factors	Shoreline topographic setting plus sea level	Climate variability—spatially & temporally	Regional mangrove forest replenishment with small-scale disturbances	Larger-scale, localised disturbances exceeding ambient range
Sea-level ambient range	Defined between MSL to HAT, mostly	Prevailing influences	Progressive plus fluctuating	Inundation, exposure, loss and gains due to flooding &/or encroachment
Slope	Various from gentle to steep	Prevailing influences	Slow spatial change	High rates of spatial change
Soil condition	Unconsolidated, occasionally coarse & hard	Prevailing influences	Soil stability influences	Loss or gain due to erosion scouring & burial deposition
Temperature		Latitude-related climatic zones	Extremes in evapotranspiration reduce habitat resilience	High- or low-temperature stress reduces biodiversity
Rainfall		Along tidal profile as groundwater, tidal inundation & direct rainfall	Incremental shift towards high or low biomass vegetation	Wet or dry conditions reduce biodiversity with dramatic impacts on
Salinity		Upstream estuarine flows & tides	Incremental shift towards high or low biomass vegetation	Hypersaline to hyposaline extremes reduce biodiversity
Storm severity			Cyclone—high winds, large waves cause plant damage & death in small patch areas	Cyclone—high winds, large waves cause plant damage & death across broad areas
Flooding events			Inundation, erosion, burial cause plant damage & death in small patch areas	Inundation, erosion, burial cause plant damage & death across broad areas
Pollutant incident			Toxic/smothering oil spill, chemical, nutrients cause plant damage & death in small patch areas	Toxic/smothering oil spill, chemical, nutrients cause plant damage & death across broad areas

Direct damage			Harvest, trampling, landfill of broad areas	Harvest, trampling, landfill of broad areas
Lightning strike			Tree death and recovery in small mangrove canopy patch gaps	Tree death and recovery in compounded Level 3 areas.
Herbivore damage			Plant death and recovery in small patch gaps	Plant death and recovery of broad areas.
Pathogen attack			Plant death and recovery in small patch gaps	Plant death and recovery of broad areas
Temporal circumstances— timing, frequency	Ambient	Ambient	Regular or episodic	Episodic
Vegetation most affected	Tidal wetlands generally (L1 Model), but knowledge of influences on mangroves are better established	Tidal wetlands generally (L2 Model), but knowledge of influences on saltmarsh species are less known	Mangroves primarily (L3 Model)—small-scale saltmarsh turnover likely impacted by comparable disturbances	Tidal wetlands generally (L4 Model), broad-scale impacts largely dominated by mangrove vegetation as the higher biomass structural component

such recovery are continually vulnerable to large waves, strong winds, severe flooding, erosive currents, extreme desiccation, and these factors are often now combined with direct human pressures from pollutants, disrupted drainage, boat wash, cutting and access damage.

As with most tropical forests, mangrove stands comprise a canopy mosaic of different recovery phases from establishment to near maturity with stands distinguished by damaged and dead individuals along with varying growth stages to maturity. Figure 9.6 shows these two contrasting pathways and their respective periods of vulnerability leading to either habitat recovery or collapse. The distinction between recovery trajectories highlights the great importance of maintaining stand stability, if at all possible. Measures of damage severity and extent can support informative modelling of likely habitat recovery.

The type of drivers causing damage effect the rate and pathway to recovery. While all have distinguishable impacts, recovery processes differ when drivers include persistent detrimental effects of harmful pollutants like oil spillage (Duke 2016), agricultural pesticides (Duke et al. 2005) and excess nutrients (Lovelock et al. 2015). By contrast, physical damage from storms and large waves has no persistent detrimental factors limiting their recovery (cs. Duke et al. 2017).

9.3 Climate and Natural Drivers of Key Environmental Changes Along Mangrove Shorelines

The state, condition and health of shorelines can be classified and quantified according to a series of indicators as potential drivers of change (Fig. 9.6). Their consideration provides an improved ability to monitor change affecting tidal wetlands on a broad scale. These data can be used to monitor habitat conditions associated with identified drivers, as well as providing an assessment benchmark for local and national management priorities.

An assessment protocol quantifying these processes compliments pre-existing mapping of coastal environment and tidal wetland habitats using remote sensing of oblique and vertical imagery. In the following section and in reference to Fig. 9.6, a selection of major drivers of change are described. In consideration of our case study evaluation of the cause of mangrove dieback in the Gulf of Carpentaria, we focus particularly on drivers related largely to climate and natural processes affecting tidal wetlands and shorelines (Duke 2014), acknowledging that each are indirectly affected by anthropogenic greenhouse gas emissions.

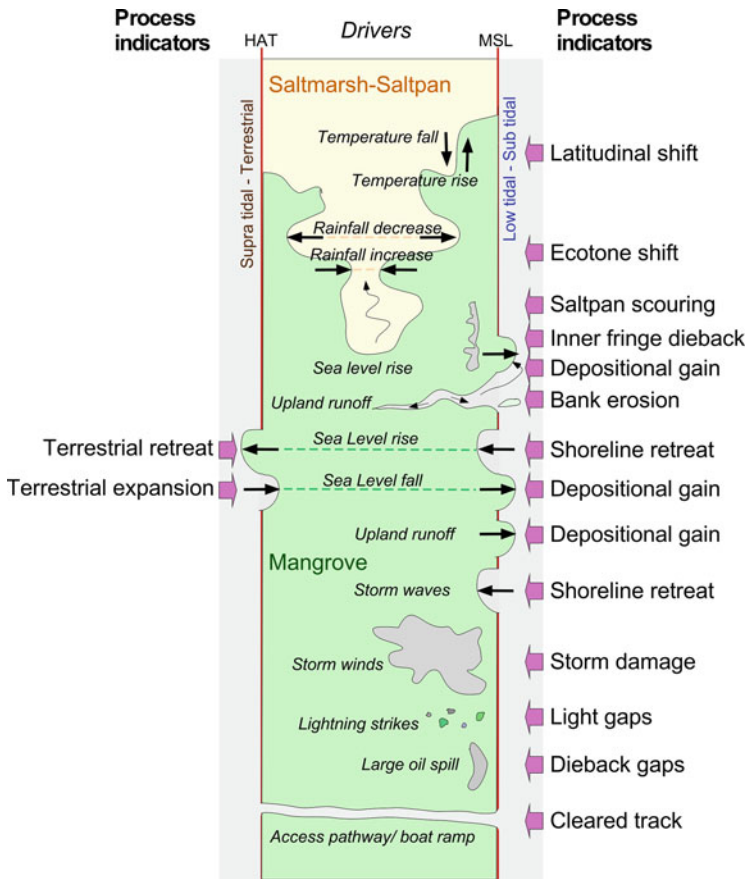


Fig. 9.6 An illustrative schematic showing process response indicators associated with respective drivers acting at the more obvious ecotone locations across the tidal profile

9.3.1 Shoreline Erosion and Seafront Retreat: Severe Storms, Sea Level Rise

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

Indicator Loss of foreshore and shoreline mangrove vegetation marked by fallen and eroded dead trees and exposed stumps, eroded peat mat, and uprooted mobilised stem wood. Instances often also have a lack of seedlings and regrowth recovery, along with the close proximity of depositional sediment banks and berm ridges (see Fig. 9.7).

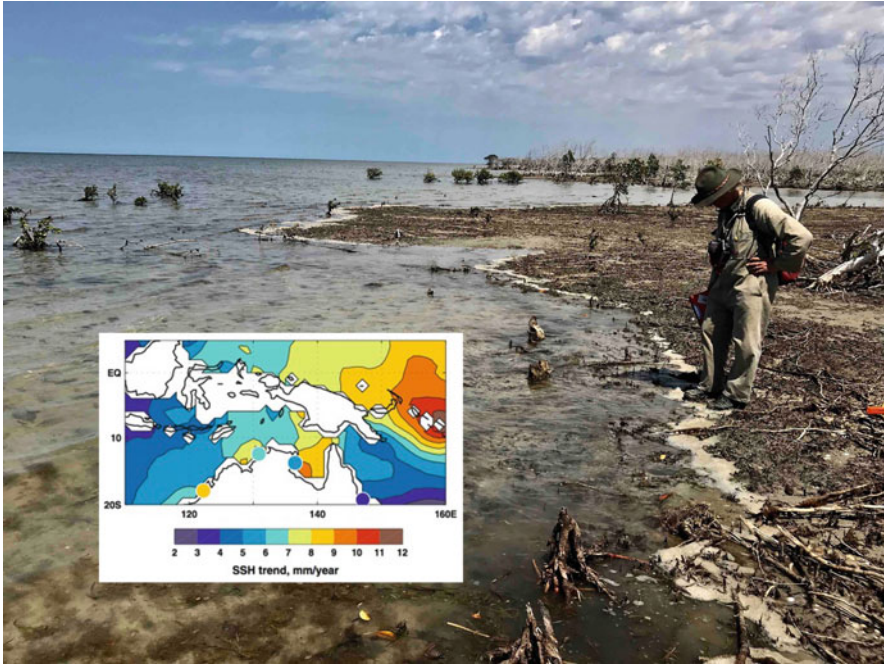


Fig. 9.7 Shoreline erosion occurs when sea edge trees are lost, as seen in the Gulf of Carpentaria (Limmen Bight shoreline at location 1 (Fig. 9.1), Northern Territory, in 2018). Surviving plants are unable to resist strong winds and waves that regularly buffet exposed shorelines. Seedling re-establishment is seemingly too slow and unable to keep up. This can be due to a change in Level 1 processes associated with rising sea levels, but at a local scale similar impacts may be due to Level 4 processes, like cyclones. INSET. Sea level trends estimated from satellite altimeter data from January 1993 to December 2007 in the region. Comparable sea level data from tide gauge data from the National Tidal Centre are indicated by the coloured circles (Image credit: NC Duke)

Impact A loss of shoreline mangrove vegetation not only represents the loss of habitat and ecosystem benefits, but also identifies locations currently experiencing unsustainable rates of change. Such eroded shorelines are highly vulnerable to further imminent disruptive events because they lack the normal protection of exposure-adapted, frontal tree species. Mangrove tree structural types differ in growth form depending on their position along the tidal profile and where they are established. Once matured, these trees are unable to change and adapt further. Exposed seafront positioned trees develop sturdy support structures extending the complex tangle of prop roots of *Rhizophora* species (also see Fig. 9.8). When the same species grow in the middle of a forest, they have significantly fewer prop roots and support structures. In these circumstances, inner trees redirect their growth and structure into gaining maximal crown height in response to light competition. When exposed to shoreline erosion, the inner trees offer little or no benefit in terms of protection for shorelines, or themselves. The only way shoreline mangroves can be re-established is with new recruits growing in exposed conditions. In regions experiencing high rates of sea level rise, this may not be possible! Such shorelines are highly vulnerable.

Process Level This factor relates to the Level 4 (Fig. 9.5) disturbance processes combined with an unusual change in a Level 1 (Fig. 9.2) setting driver, namely sea level. The impacts of rising sea levels are likely to be more severe when combined with severe storms, and any other factors causing damage to protective shoreline vegetation.

9.3.2 Estuarine Bank Erosion: Flood Events, Sea Level Rise

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

Indicator Eroded banks are steep slopes, showing bare and crumbling earth faces, slumped bank sections with intact vegetation, along with general remnants of collapsed and undermined vegetation like fallen trees, uprooted and inundated plants as seen in many Gulf estuaries (Fig. 9.8).



Fig. 9.8 Bank erosion is normal where it occurs as the alternate response to depositional gain (Fig. 9.11). The two responses account for the slow but natural shift of riverine channels as they meander and migrate across lower estuarine tidal flood plains (Limmen River lower estuary, Northern Territory, in 2017). However, when one exceeds the net effect of the other, this imbalance indicates Level 4 process changes associated with factors like rising sea levels causing increases in tidal volume of estuarine systems (Image credit: NC Duke)

Impact Lost mangrove habitat represents a loss of ecosystem benefits. Also significant is the loss of bank stability much as mentioned with Shoreline Erosion. Such estuarine banks are highly vulnerable.

Process Level This factor mostly relates to a Level 4 process. However, because of rising sea levels, a Level 1 process, there is a greater level of impact delivered by the increased frequency of flooding from the catchment.

9.3.3 Terrestrial Retreat: Upland Erosion, Sea Level Rise

Cause When sea levels rise progressively over time, there is continual pressure on high intertidal shorelines behind tidal wetland habitat and bordering the verge of supratidal vegetation. This upward pressure is caused by saltwater encroachment and higher tidal inundation levels during seasonal and daily highwater tidal peaks.

Indicator There are two notable effects that represent these types of changes: (1) erosion along the upper intertidal edge as a shallow eroded ledge (Fig. 9.9), and as scouring of small runoff tributaries; and (2) death of established supratidal vegetation, like dead *Melaleuca*, *Casuarina* and *Eucalyptus* trees. These effects are



Fig. 9.9 Terrestrial retreat, coupled with saline intrusion, is marked by erosion and dieback of supratidal terrestrial vegetation, and encroachment of mangrove seedlings (Mule Creek area, Northern Territory in 2017). This impact is considered an indicator of changes to Level 1 processes, notably rising sea levels. Impacted sites are likely greatest in areas of flatter terrain (Image credit: NC Duke)

combined with mangrove encroachment which may be scored separately, but dead mature terrestrial trees are more visible than newly established mangrove seedlings, as seen in upper tidal shorelines throughout the southern Gulf (Fig. 9.9).

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

Process Level This factor mostly relates to a Level 4 process with an unusual change in a Level 1 character. This is driven by rising sea levels.

9.3.4 Saltpan Scouring: Pan Erosion, Sea Level Rise

Cause When unusual and progressively higher levels of tidal waters flood across tidal saltpans, sediments can be sheet eroded, scoured and transported into tidal channels. An associated driver with this one might be Terrestrial Retreat Erosion.

Indicator Scoured saltpan surfaces marked with drainage lines coupled with a lack of saltmarsh vegetation across the saltpan surface, as seen in the Gulf (Fig. 9.10).



Fig. 9.10 Surface sheet erosion is a consequence of additional water in an estuary (Limmen River upstream, Northern Territory in 2017). As with terrestrial retreat, saline intrusion, and mangrove encroachment, this impact is associated with rising sea levels as a Level 1 process (Image credit: NC Duke)

Impact The loss of saltmarsh habitat is significant. There is also a further supply of fine sediments finding their way into the estuary and likely further contributing to depositional gain. In extreme instances, saltmarsh vegetation including natural layers of microphytobenthos has been unable to re-establish so the whole inundated area is actively scoured leaving bare sediments and pools of residual tidal waters.

Process Level This factor mostly relates to a Level 4 process with an unusual change in a Level 1 character. This is driven by rising sea levels coupled with wide gentle sloping profiles.

9.3.5 Depositional Gain: Flood Events, Sea Level Rise

Cause Depositional gain is particularly evident along estuarine channels where seedlings colonise accreting banks. When sediments are flushed downstream from catchment areas disturbed by flooding erosion, they are usually deposited towards the river mouth and along lower estuarine channel margins. The depositional materials often emerge as large mudbanks and form mangrove ‘islands’ when colonised naturally by mangrove vegetation. Mangroves appear to colonise these banks after mud banks exceed mean sea level elevations—the mangrove ‘sweet spot’ zone.

Indicator Newly recruited mangrove seedling and sapling stands growing on shallow muddy banks generally towards the lower estuarine reaches towards the mouth of riverine estuaries (Fig. 9.11). Various key mangrove genera are involved including mostly: *Avicennia*, *Rhizophora*, *Aegialitis*, *Aegiceras* and *Sonneratia*. In general, depositional gain is indicative of the combination of sediment transport processes including catchment runoff and the reworking of deltaic sediments, as seen in the Gulf (Fig. 9.11).

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

Process Level This factor mostly relates to Level 4 with an unusual change in a Level 1 character. It occurs mainly because of increased flooding across areas of largely unconsolidated sediments, coupled with rising sea levels.



Fig. 9.11 Depositional gain occurs when mangrove seedlings and saplings occupy accreting mudbanks exceeding elevations above mean sea level. Because this additional sediment deposition can be associated with periodic flood events, the expanding vegetation canopy is often stepped and incremental (near Leichardt River mouth, QLD. In 2017. This feature is indicative of a Level 4 process related to larger flood events (Image credit: NC Duke)

9.3.6 Severe Storm Damage: Mangrove Dieback, Cyclonic Winds, Large Waves

Cause Storm conditions bring heavy seas, strong winds and scouring currents that often cause significant and extensive damage to tidal wetland and mangrove habitat. A key agent of such destructive weather conditions is tropical cyclones (Fig. 9.12). The resulting impacts are usually localised in timing and severity, as recorded by the tracks over the last 20 years in the Gulf of Carpentaria (Fig. 9.13).

Indicator Loss of saltmarsh vegetation and loss of mangroves as defoliated uprooted broken trees as well as the loss of canopy cover (Fig. 9.12). For mangroves, both the re-established younger plants and the degradation state of dead trees are indicative of when the damage occurred.

Impact Habitat damage and losses reduce the fitness of tidal wetlands. As a consequence, the ecosystem services are also lost. It is important to quantify such indirect consequences. One key example the likely effects on local fisheries, or any loss of shoreline protection with erosion.



Fig. 9.12 Cyclones often cause severe damage to mangrove forests. Note that where more resilient, exposure-adapted, edge trees remained intact, damaged areas may recover but only after several decades after seedling re-establish amongst the dead and damaged trees (Rose River lower estuary, Northern Territory in Dec 2017; damaged possibly by TC Winsome in Feb 2001, a 981 hPa storm). This impact is a Level 4 natural process (Image credit: NC Duke)

Process Level This factor mostly relates to Level 4 and it occurs mainly because of occasional extreme sea level lows and severe storms coupled with a shoreline weakened by rising sea levels.

9.3.7 Light Gaps: Lightning Strikes, Herbivore Attacks, Mini Tornadoes

Cause When severe storm weather includes lightning strikes, it causes notable and distinctive damage to mangrove forests in the form of discrete, circular light gaps (Fig. 9.14). These gaps are typically 50–100 m² in area. The impacts are unlike other storm damage where trees die standing and unbroken. As gaps mature, the dead trees deteriorate, seedlings establish and grow, and eventually after about 2–3 decades, the gap fills. This process may explain how mangrove forests naturally regenerate and sustain their existence in such a wide selection of locations.

Indicator These relatively small circular light gaps are observed in mangrove forest canopies worldwide. It is important to recognise that gaps will be at a particular stage towards recovery and closure depending on when they were created (Fig. 9.14). Only for 1–8-year-old gaps will the original trees be recognisable as the ones that started the process. While the number of gaps is considered an indicator of storm

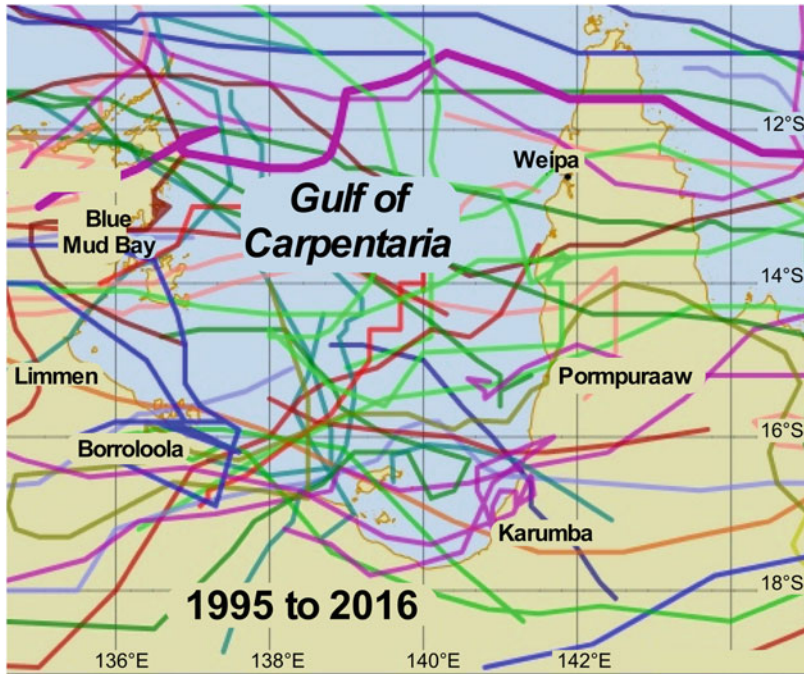


Fig. 9.13 Cyclones are a common feature in the Gulf of Carpentaria. This figure shows tracks of cyclones in the region during the last 20 years, roughly 1–2 each year. Overall, there is a regional net influence, but the impacts delivered by these events are mostly localised as Level 4 damaging processes. This is exemplified further where some shorelines have been notably less affected during this time (BOM 2020)

frequency, the net effect appears to influence the stand age of mangrove forests which curiously lack old senescent stands (Duke 2001).

Impact Light gaps are considered fundamental to forest replacement and turnover. It is notable that the frequency of gap creation is likely dependent on storm severity. As such, as this might increase in any particular area then this will have a profound effect on forest turnover rates. At higher levels of impact, these forests are predicted to be unable to sustain the natural processes involved in their replacement. At this point, mangrove forests would enter a state of ecosystem collapse as the stand becomes fragmented and dysfunctional.

Process Level This factor mostly relates to Level 3 (Fig. 9.4) and it occurs because gap creation is coupled with the increased severity of damaging factors like storms.



Fig. 9.14 Light gaps are caused by lightning strikes killing small patches (~50 m²) of mangrove trees in amongst otherwise undamaged surrounding mangrove forests. The creation of such gaps is believed to be the chief driver of Level 3 processes responsible for their natural turnover and replacement (Duke 2001; Image credit NC Duke)

9.3.8 Zonal Retreat: Local-Scale Patterns of Single, Dual and Triple Zones of Concurrent Upper Zone Dieback

Cause Zonal retreat describes the relocation of the vegetative habitat of the intertidal zone to higher or lower elevations with respect to the change in water level. For example, tidal wetlands affected by rising sea levels involve concurrent recruitment and expansion into upland habitat with corresponding dieback and loss of mature mangroves at the low water's edge. By contrast, a temporary drop in sea level was experienced in the Gulf of Carpentaria (Duke et al. 2017; Harris et al. 2018) forcing a severe stress response in plants left stranded at higher elevations.

Indicator When a band of mangrove vegetation dies suddenly at the upper ecotone fringe with saltmarsh vegetation, this may be indicative of a sudden drop in sea level. This might be caused by tectonic uplift, severe ENSO events, or it might be due to subsidence, or simply changes in barometric pressure.

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

Process Level This factor mostly relates to Level 4 where it concerns the unusual and sudden change in a Level 1 character.

9.4 The Synchronous, Large-Scale Mass Dieback of Mangroves in Australia's Remote Gulf of Carpentaria

Observations of driving factors mentioned above describe a range of processes likely to be responsible for the occurrence and condition of tidal wetland habitats, including mangroves in the Gulf of Carpentaria (Fig. 9.1a, b; Table 9.2). Key questions include how severely has the Gulf coastline been impacted and what factors had contributed to such a sudden event? Was this instance of large-scale dieback influenced or caused by climate change, and what is the expectation of its re-occurrence?

Laurance et al. (2011) suggested salt marshes and mangroves were in Australia's top ten most vulnerable ecosystems, with sea level rise, extreme weather events and changes to water balance and hydrology ranked as the three most likely threats. These predictions appear to be broadly accurate as in late 2015 and early 2016, the vast area of more than 80 km² of mangrove forests bordering Australia's Gulf of Carpentaria died *en masse* with no known precedent for such a simultaneous and widespread occurrence (Duke et al. 2017). The dieback was extensive and it occurred in synchrony across more than 1500 km of exposed shorelines from Queensland to the Northern Territory (see Fig. 9.15). Canopy vegetation condition expressed as a fractional green cover derived from Landsat and Sentinel-2 data for each of eight sites at four locations spread across the Gulf (Fig. 9.1; see insert). Each time series shows localised changes in cover between 1987 and 2018, highlighting the event in late 2015 when the synchronous mass dieback occurred. This shows unequivocal evidence of a singular, regional-scale impact that defines this mass dieback event.

Table 9.2 A brief summary of environmental observations associated with the 2015 mass mangrove dieback event in Australia's Gulf of Carpentaria (Duke et al. 2017), updated in 2018

General observations	Observed impact	Likely cause	Recovery or degradation	Consequences
Mangrove condition—extent	Dieback of 8000 ha widespread over 1500 km	Regional applied factors	3 years post event, degradation appears to outweigh recovery	Likely to influence fisheries catches, enhanced sediment mobilisation
Mangrove condition—timing	Dieback occurrence synchronous	Single unusual event	Negative localised influences of severe storms and flooding	Shorelines habitats at risk where they share threats
Mangrove condition—biodiversity	Dieback of multiple mangrove species	Setting factor like species zonation	Recovery and degradation rates of wood and roots vary for each species	Some species are at risk of local extinction
Mangrove condition—tidal elevation	Dieback at higher elevation zones and of taller plants	Factor related to tidal elevation	Because taller trees affected most, there is reduced erosion and exposure resilience of surviving stands	The loss of entire foreshore fringing stands, likely to take many decades to recover, if at all
Extreme events—natural variability	No widespread severe storms, cyclones, tsunamis, flooding, etc.	Not applicable	Subsequent cyclones and flooding are likely to cause severe damage to natural recovery	Disturbances likely to alter ecosystem replacement and turnover processes
Extreme events—anthropogenic	No widespread oil spills or other pollutant or sediment discharges	Not applicable	Not applicable	Reduced resilience of shoreline habitats
Extreme events—temperature climate and weather	Likely to be related but limited direct evidence	Extreme high temperatures	No subsequent events of comparably high temperatures	Vulnerable to future extreme high-temperature events
Extreme events—rainfall climate and weather	Likely to be related but limited direct evidence	Prolonged drought and extreme low rainfall	No subsequent events of comparably low rainfall	Vulnerable to future periods of low rainfall
Extreme events—sea level rise	Likely to be related but limited direct evidence	Rising sea levels up to 3×'s the global average	Rising sea levels are likely to affect recovery trajectories	Saline inundation, erosion of terrestrial edge habitats plus scouring of saltmarsh-saltpan
	Very likely related	Temporary sea level	No subsequent events	Damage to shoreline integrity

(continued)

Table 9.2 (continued)

General observations	Observed impact	Likely cause	Recovery or degradation	Consequences
Extreme events—sea level drop		drop of 20 cm Sept–Dec 2015		and exposure resilience

Supplemental source: Hope et al. (2016)

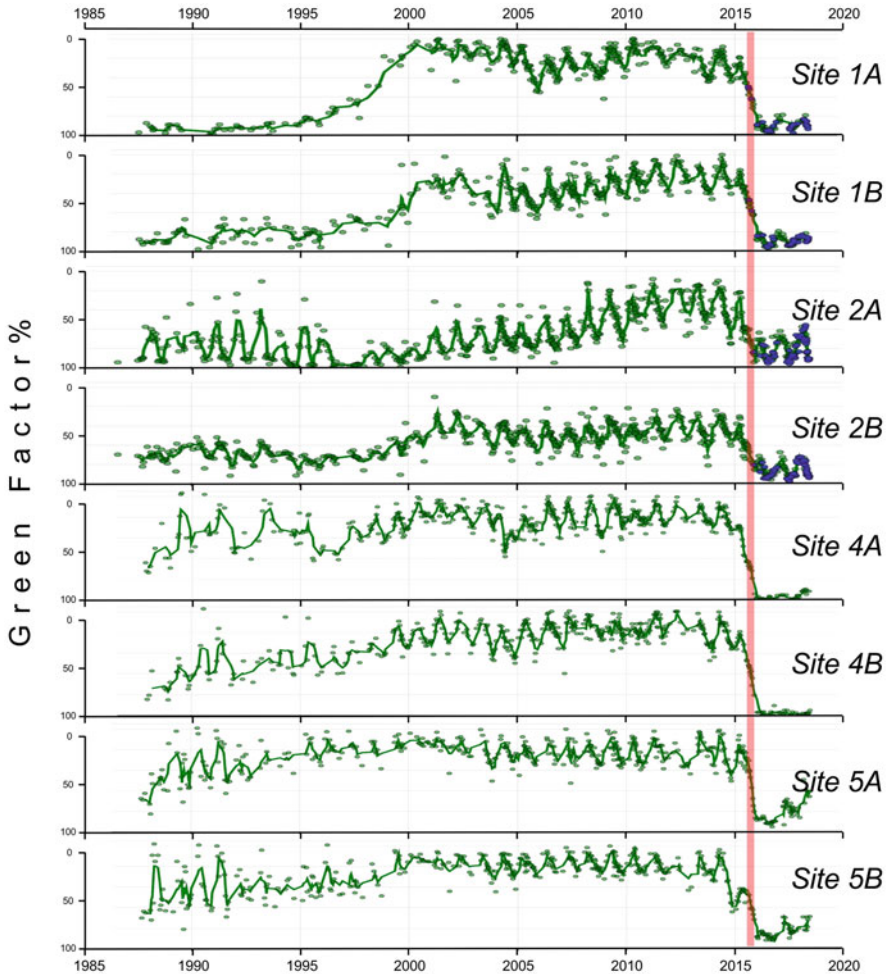


Fig. 9.15 Time series plots of green fractional (Bokeh) cover estimates from Landsat and Sentinel-2 for the four field locations in the Northern Territory (site locations 1 and 2, Fig. 9.1a) and Queensland (site locations 4 and 5, Fig. 9.1) during 1987–2017. The red line indicates the synchronous timing of the late 2015 mass dieback event. The widespread impact was indicative of a dramatic change in a Level 1 factor (see Fig. 9.2)

Box. Mangrove Diversity in the Area of Mass Dieback of Mangroves

Mangrove plant species diversity is relatively low compared to other tropical forest habitats because of the harsh environmental limitations imposed by regular saline inundation. There are around 80 species and hybrids known worldwide (Duke 2017); 46 of these occur in Australia and 25–28 in Australia's Gulf of Carpentaria (Duke 2006). These numbers are further reduced in the southern Gulf with just 12–16 species in this semi-arid (mean annual rainfall ~700 mm) area where the mass dieback of mangroves occurred (Duke et al. 2017). Each of these variations in diversity is directly attributed to levels of rainfall with fewer species in drier regions (Tomlinson 2016). These depressed levels of diversity exemplify that this Gulf area is normally under considerable environmental stress. As such, it is perhaps not surprising therefore that such an area was the first known for a mass impact on mangroves caused by a particularly extreme fluctuation in mean sea level.

With the death of so many mangroves, erosion of the shoreline was expected to follow. But, by how much, and how long before this might be observed? Would there be any recovery? The occurrence of such a large-scale disturbance to shoreline mangroves has raised serious concerns about the consequences for shoreline mangroves and the growing risks these habitats face as the threatening pressures escalate (Harris et al. 2018; Bergstrom et al. 2021). This places a growing urgency towards gaining a better understanding of the key drivers of such a major disturbance event and to ask how had these pressures impacted this mangrove ecosystem to such an extent.

Having established that the mass dieback event was very likely in response to an extreme climate event (Duke et al. 2017), questions were focused on verification as well as the likely implications for policy and management. Local managers facing the consequence of losing significant beneficial natural resources were considered justified in their concern. More informed and targeted strategies would appear to be required to minimise future impacts affecting the social and economic well-being of human communities living in coastal areas generally, and especially along the remote Gulf shoreline. We outline key deductions and lessons learned in reviewing these deductions regards the mass dieback event in the context of other large-scale disturbances.

Our deductions must be prefaced by the manifest realisation that tidal wetland ecosystems are vulnerable and sensitive to both moderate and extreme fluctuations in climate and weather (cs., Duke et al. 2019). Our goal therefore at this time has been to better define the disturbances and risks faced by these unique ecosystems, and to do this by referring to the four process levels involved (Figs. 9.2, 9.3, 9.4, and 9.5) to qualify and possibly quantify the factors identified (Table 9.2). This evaluation is helped also by considering some of the major stochastic processes associated with this event, as recorded in imagery collected during field and aerial surveys of the impacted areas of the Gulf (Fig. 9.16). The image shows the often-complex overlap



Fig. 9.16 An extreme instance of compounded ‘classes/types’ of temporal and spatial processes observed along shorelines of the Gulf of Carpentaria in December 2017. Note that among other things, foreshore erosion and retreat have left remnants of earlier foreshore mangrove stands marked by short dead stumps, sediments mobilised in various ways, a chenier ridge of drift sands, along with the extensive 2015 dieback of the uniform stand of dead mangroves behind the ridge (Image credit: NC Duke)

of temporal and spatial processes present along this broad shoreline. In the case shown, the processes included:

1. Earlier dieback 20–30 years prior to 2017—visible as dead stumps towards the seaward margin
2. Shoreline sediment mobilisation and shoreline retreat
3. Chenier ridge development with sediment trapped by remnant dead trunks
4. Development of mangroves behind the chenier ridge
5. Channel formation behind the mangrove fringe with root development and sediment trapping raising the mangrove topographical profile
6. Channels prevent further upland migration of mangroves.
7. Shoreline retreat and mangrove regrowth determined by ambient sea level conditions
8. The zone of 2015 mangrove dieback

These and other processes need to be reasonably defined and where possible accounted for. While the circumstances do not necessarily follow standard geomorphological description, they do show the influence of exposure and sediment

condition. With such matters in mind, a systematic compilation is being undertaken to more fully describe the location and frequency of at least the more common and widespread factors, especially for the 2015 dieback damage. At this time, it is possible to broadly focus on the key factors involved.

9.4.1 Likely Causal Factors Observed Along the Impacted Shoreline

The dieback event was strongly linked to the severe El Niño of 2015–2016, the third most severe event in Australia’s instrumental climate record (Hope et al. 2016; Harris et al. 2017). Arguably the key factor responsible for the mass dieback appears to have been a temporary 20 cm drop in sea level that reduced levels of tidal inundation (Duke et al. 2017). The drop in sea level was also co-incident with above-average air temperatures and drought conditions with over 4 years of below-average monsoonal rains (see Fig. 9.17).

The impacts of these short term ‘pulse’ events (rapid drop in sea level, elevated temperatures, monsoonal failure) were amplified by a longer-term climatic ‘press’ driven by decades of air and ocean warming (Harris et al. 2018; Bergstrom et al. 2021). Weather data gathered from eight meteorological stations spread across the Gulf south coast region (Numbulwar, Ngukurr, Borrooloola, Centre Island, Macarthur River Mine, Mornington Island, Burketown, Normanton) showed mean temperatures rose by around 0.9 °C over the previous 50 years, and that temperatures during late 2015 exceeded all previous records—as shown in the plot (Fig. 9.17a). While concurrent rainfall levels were mostly below average over the 4 years previous to 2015, over the last 50 years there was no distinguishable trend in mean rainfall (Fig. 9.17b).

There was, however, a significant long-term rise in sea level recorded across three monitoring stations (Milner Bay on Groote Island, Karumba and Weipa; see Fig. 9.17c). This trend had a mean 3.65 mm/year rise in sea level over the previous 25 years (9.1 cm over the period). These data were detrended based on this rise to further emphasise the unusually low sea levels at the time of the mass dieback in 2015. The reduced sea levels were a notable consequence of the particularly severe El Niño event depicted in Southern Oscillation Index measures (Fig. 9.17d).

Sea levels are particularly sensitive to changes in climatic conditions, including atmospheric wind forcing (Wyrтки 1984, 1985). When a severe El Niño event occurs, such as the 2015–2016 event, the prevailing wind field collapses (Freund et al. 2019). In southern tropical latitudes, this results in prevailing south-easterly trade winds being reversed by strong westerly winds. These unusual atmospheric conditions force warm surface waters from the western to the eastern side of the Pacific Ocean for as long as the El Niño conditions last. The resulting sea levels in the western Pacific can be notably lower (up to 20 cm), and in the eastern Pacific, they will be correspondingly higher and warmer. During these times also, there are often an unusually large number of tropical cyclones.

Severe El Niño conditions bring large changes to sea level and extreme climatic conditions like drought and heatwave. Together, they have a strong influence on

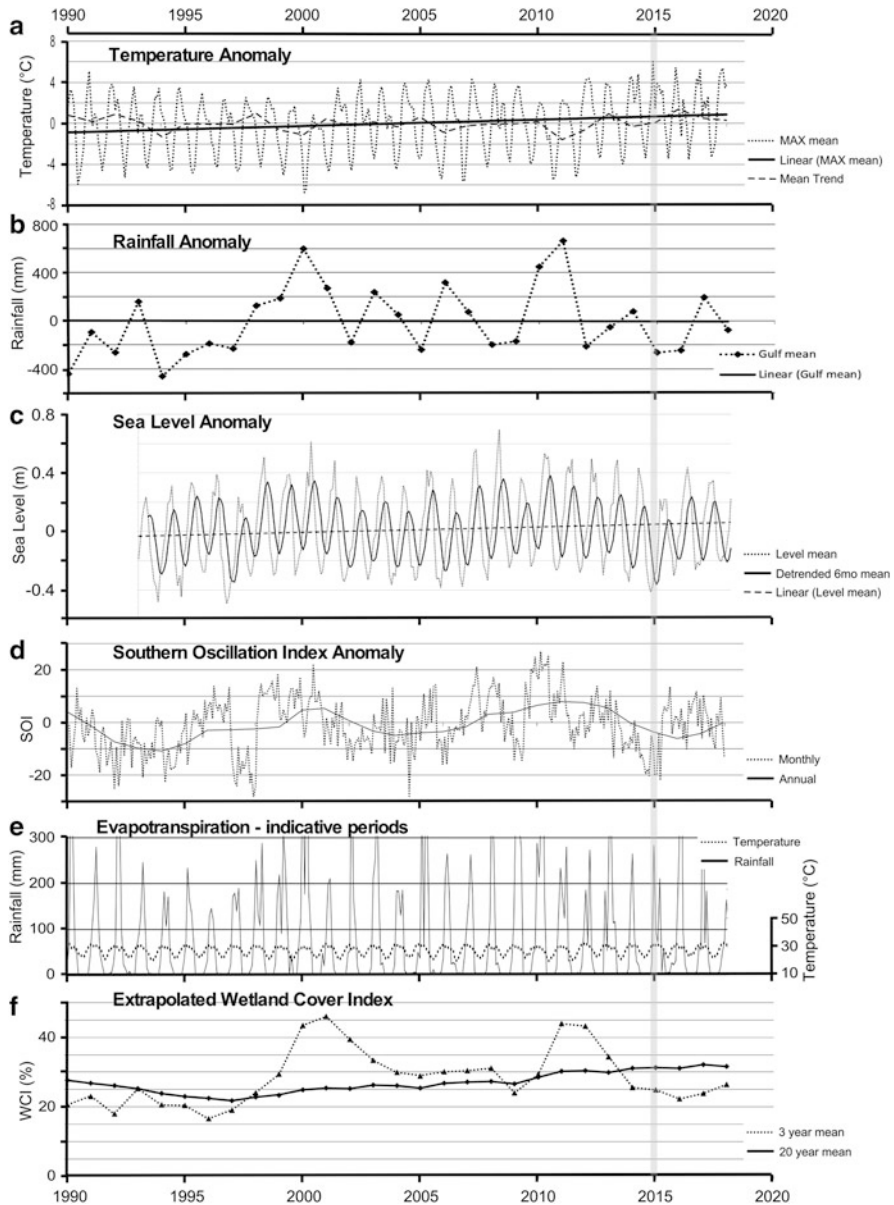


Fig. 9.17 The condition of climate and environmental factors up to and after the 2015 mangrove dieback event (grey vertical line) in the Gulf of Carpentaria. Data were sourced online mostly from the Australian Bureau of Meteorology (BOM 2020). Factors showing anomalies were calculated using the 1990–2019 reference period, including (top to bottom): (a) temperature monthly and annual mean maxima plus the overall trend; (b) rainfall annual means plus the overall trend; (c) sea level monthly means, the overall trend, and the detrended six-monthly means; (d) the Southern Oscillation Index monthly and annual means; (e) indicative levels of evapotranspiration shown as periods when the temperature exceeded rainfall at respective scales; and (f) wetland cover index levels deduced from its rainfall correlate (see Duke et al. 2019) using 3- and 20-year running means

mangrove forests. These tidal habitats are already under extreme pressure from steadily rising sea levels. The 2015–2016 mass dieback of mangroves has therefore been considered a classic ‘press-pulse’ response as described by Harris et al. (2018) for this and other ecosystems across Australia, both marine and terrestrial. Available moisture, vapour pressure, temperature and sea level across the Gulf of Carpentaria up to and during the dieback period were all consistent with a failure in the monsoon’s normal arrival that year (Harris et al. 2018). These were likely to have influenced the widespread occurrence of hypersaline sediment porewater, resulting in severe mortality of mangroves as conditions exceeded plant tolerances. These conditions are likely to have resulted in the rapid decline seen in mangrove cover during November–December 2015 (Fig. 9.15) which persisted into the dry season of 2016. Apparently, similar circumstances were reported by Lovelock et al. (2017) for mangrove stands on the semi-arid Western Australian coastline, except that the drop in sea levels was not as large as that experienced along the Gulf. Nevertheless, low sea levels had corresponded with the 2015–2016 ENSO event, resulting in enhanced soil salinity, some loss of mangrove cover and slow recovery. In this instance, the impacted area was two orders of magnitude smaller than the event in the Gulf of Carpentaria.

The observations from the Gulf of Carpentaria reveal a complex interplay of at least four environmental factors, (namely a sea level drop, a lengthy drought, low rainfall and a heatwave), which are associated with the severe El Niño event. The combination of drivers forced a severe short-term response while under the longer-term influence of prevailing climatic conditions (namely, rising sea levels caused by rising temperatures). In this way, the climatic press was amplified by an extreme pulse event (Harris et al. 2018), notably where it forced exceedance of the physiological and ecological tolerance of these plants driving the vulnerable habitat they make up, into a significantly degraded state—perhaps irreversibly.

Mangroves of the semi-arid, wet-dry tropical Gulf of Carpentaria coastline exist at or near the upper limit of their zonal distribution positions in terms of tolerance of seasonal aridity, air and sea surface temperatures, and porewater salinity. They were therefore highly susceptible to this particular climate press. At the time of the mass dieback, spatially averaged, mean air temperatures and sea surface temperatures had increased by 1.64 and 1.56 °C, respectively since 1910.

At a local stand scale, mangrove species distributions were notably coupled to their periods of regular tidal flooding. Tidal inundation levels were reduced by abnormally low sea levels for the Gulf of Carpentaria during the latter months of 2015 (Fig. 9.17c), a consequence of the extreme El Niño conditions at the time, with its derived effect of high barometric pressures and prevailing winds (Harris et al. 2017).

These climatic conditions can be compared to a previous instance of a short-term (less than 5 month) drop in sea level as notably observed with the very severe 1982–1983 El Niño event (Lukas et al. 1984; Wyrski 1984, 1985; Oliver and Thompson 2011). On that occasion, however, no record of mangrove condition was reported, so we do not know if they were impacted or not. What we do know is that the 1982–1983 pulse event did not appear to have coincided with equivalent

amplified temperatures as observed with the 2015–2016 event, nor was it accompanied by monsoonal rainfall failure.

In order to understand the cause of such mass dieback of mangroves, it is important to know if there have been any earlier similar events. There is compelling evidence to suggest there have been.

If we refer again to Fig. 9.15 with its Green Fraction plots from sites across the Gulf of Carpentaria for the period from 1987 to 2017, note that there were synchronously depressed levels of canopy cover during the late 1980s and early 1990s, and these levels gradually increased to more or less maximal levels by 2000. After that time, canopy cover remained at relatively high levels until the abrupt drop in 2015–2016. Notably, during this period, there were no comparably severe El Niño events since 1997–1998 (BOM 2020). What is apparent in these plots is that there was a steady increase in canopy cover from very low levels starting in 1987. The question is why were the levels generally low during that time? While there are a number of factors to consider, this feature is consistent with there being a similarly significant event of synchronous, mass mangrove dieback across the Gulf with the very severe El Niño event in 1982–1983. The likely impact of the intervening 1997–1998 event might also be depicted in these plots where there was a notable, but less pronounced drop in canopy cover at that time. This implies that the 1997–1998 event may have had a lesser impact.

These findings are of great relevance and importance, warranting further detailed investigations. There is a great need to gain a more complete understanding of the ecosystem processes involved, as well as delivering effective management guidelines and models to predict the likelihood and timing of future events. Should there have been similar past dieback events with different associated factors, then it makes it possible to develop and refine predictive models by focusing on the specific climate variables responsible in each case. For example, was a drop in sea level the primary factor causing mass dieback, or was it a combination of factors? Further studies are needed to establish the historic variability in climate in relation to mangrove cover across the Gulf. This relies in part on matching remote sensing data (satellite, historic airborne photography) with climatic conditions during each instance of mass mangrove dieback should that be the case.

Another important climate variable is rainfall. Mangroves require freshwater input from rainfall delivered directly, or as catchment runoff, tidal flooding, or groundwater flows. However, since the southern hemisphere wet season anomaly of 2010–2011, the Gulf of Carpentaria coastline had experienced significantly below average mean annual rainfalls (Fig. 9.17b). The wet seasons of 2014–2015 and 2015–2016 yielded rainfall anomalies of –586 and –295 mm in the Borroloola area of the southern Gulf coastline. In this ‘pulse period’, monsoons were of short duration, inducing low cloud cover, high radiation levels, elevated air temperatures (Fig. 9.17a), vapour pressure deficits and high evaporation rates (Hope et al. 2016). Had these stressors become particularly acute leading into the late dry season of 2015 (Oct to Nov)—the period when the mass dieback event became prominent? The evidence is inconclusive.

Firstly, note that low rainfall levels (Fig. 9.17b) had not resulted in mangrove dieback on previous occasions when rainfall conditions were similarly low, like during the mid-1990s. Furthermore, note the indicative evapotranspiration periods (Fig. 9.17e) also had no specific correlative links to the mass dieback event. Secondly, this observation was supported further by estimates derived using the equation for estimating wetland cover index, as the percentage of mangrove cover versus the total area of tidal wetlands (Duke et al. 2019). During the past 25 years, while the proportion of mangrove extent had risen overall from ~20% to just more than 30% (Fig. 9.17f), then the downward pressure of recent drier weather conditions could be placed in a larger context, where it is considered unlikely to have had a strong influence on the mass dieback of mangroves in 2015–2016.

9.4.2 Linking Specific Factors with the Dieback Event

In view of the evidence available, we evaluated the processes and factors likely to cause the 2015 mass dieback of mangroves in Australia's Gulf of Carpentaria. The key points in our approach are summarised in Table 9.3, based mostly on the information and data listed in Table 9.1. These observations describe features of the dieback event with its impact and dramatic environmental response. The key primary features were: the occurrence of dieback over a broad geographic area; its synchronous occurrence; and, its involvement with multiple mangrove species (Table 9.3). These observations were used to justify ruling out a number of key processes, including those in Levels 3 and 4 as replenishment and localised factors, supported by the lack of evidence for large-scale, human-related extreme events. The investigation into the cause was thus directed towards the two other level influences.

It was considered feasible that Level 1 and 2 processes might have been jointly responsible for the mass dieback event. Both had substantive evidence to justify their further serious consideration (Table 9.3) based on changes in climate as well as sea level. But, there was at least one of the Level 2 climate variables that warranted further critical consideration. As mentioned, an equation describing the significant relationship between mangrove cover and observed annual rainfalls over the previous 20–30 years (Duke et al. 2019) could be applied in this case to estimate areas for comparison with observed areas (Fig. 9.17f). For the Gulf dieback event in 2015, the derived annual estimates of wetland cover index varied between 28.14 and 28.86% during the 2013–2016 period. By comparison, those measured from available mapping data at the time (Duke et al. 2017) were around 27.1%. This meant that the observed extremes in rainfall did not appear to account for the overall losses observed, of around 6% of the regions' mangrove cover. Therefore, the dieback response did not appear to be caused primarily by the short-term low rainfall levels recorded preceding the mass dieback event in late 2015. It appears that moisture levels due to rainfall had been maintained within the normal range for these generally resilient trees.

Accordingly, Level 2 processes were excluded as the most likely primary causes since the unusual climatic variables surrounding the dieback event had not have been

Table 9.3 Deductions from the environmental forensic evaluation of the 2015 mass mangrove dieback event in Australia's Gulf of Carpentaria (Duke et al. 2017), based on the four levels of influencing processes that define the occurrence, extent and character of tidal wetlands

	Regional drivers, local impacts		Disturbance and responses	
	Level 1	Level 2	Level 3	Level 4
Evidence observed	Shoreline topographic setting plus sea level	Climate variability	Regional mangrove forest replenishment with small-scale disturbances	Localised disturbances exceeding ambient range
Mass dieback widespread—synchronous occurrence, not species specific	Likely	Likely	Small-scale human & natural factors excluded	Local human & natural factors excluded—no severe weather event, no large oil spill, etc.
Highest records of air temperature	Likely	Period of high moisture stress. Unlikely primary factor, as temperatures not beyond survival range & not specifically synchronous with mass dieback.	Excluded	Excluded
Prolonged drought period	Likely	Period of high moisture stress. Unlikely primary factor, as deduced Wetland Cover Index from longer-term rainfall data indicated no dieback & event not specifically synchronous with dieback	Excluded	Excluded
Higher elevation zones—dieback of taller vegetation mostly	Severe moisture stress at higher tidal inundation zones	Co-factor moisture stress—primary influence unlikely	Excluded	Excluded
Temporary drop of 20 cm in sea level	Apparent severe moisture stress associated with	Co-factor moisture stress—excluded as the	Excluded	Excluded

(continued)

Table 9.3 (continued)

	Regional drivers, local impacts		Disturbance and responses	
	Level 1	Level 2	Level 3	Level 4
Evidence observed	Shoreline topographic setting plus sea level	Climate variability	Regional mangrove forest replenishment with small-scale disturbances	Localised disturbances exceeding ambient range
correlated with synchronous mass dieback	lack of tidal flooding into higher elevation zones	likely primary factor		

sufficient to explain the severe response. As such, it was considered unlikely therefore that the mass dieback would have occurred had it not been for the temporary 20 cm drop in sea level. This left at least one significant remaining question regarding the cause. Was the drop in sea level alone sufficient to have triggered the event? Or, had the impact of the temporary drop in sea level been enhanced by the extreme climatic conditions at the time? In either case, the co-occurrence of Level 1 and 2 influences was certainly notable for the 2015 mass dieback event—so at this time, such a likelihood cannot be ruled out.

9.4.3 Did Human-Induced Climate Change Play a Role in the 2015–2016 Dieback of Mangroves?

Whether this instance of a climate-related impact is related to human-induced climate change is not yet fully clear. This is because the mass dieback has so far only been reported as a one-off event. This means that the relationship with any particular factors remains inconclusive. As such, the dieback event could simply be a unique and unusual combination of detrimental factors—a situation rarely, if ever, to be repeated. However, as stated above, there are tantalising new observations and evidence suggesting there might be at least one other past occurrence. This possibly is extremely important for several reasons, like better understanding the cause, and it is now being fully investigated.

What is clear at this time is that the ‘press’ component of the multiple drivers identified so far are associated with the general thrust of anthropogenic climate change, specifically warming and its derivative driver, sea level rise. And, we can be reasonably confident that the warming trend will continue for the foreseeable future. So, human-induced climate change is implicated.

The ‘pulse’ component was driven by a drop in sea level, resulting from the severe 2015–2016 El Niño event. And, while it had been established that climate change had intensified ENSO periods in recent decades, with stronger El Niño and

La Niña events with their lower frequency, we have recently become aware that there are different types of ENSO periods, with Central Pacific events becoming more common with climate change, and Eastern Pacific events becoming fewer but more intense (see Cai et al. 2018). In a more recent account (Freund et al. 2019), the authors described some of these complexities in their statement ‘in 2014/2015, the “failed” El Niño was categorized by our classification scheme as a Central Pacific event, whereas the following year, 2015/2016, another event closely resembled a canonical Eastern Pacific event that resulted in one of the strongest in the past 400 years’.

So, are El Niño events influenced by global climate change? The evidence at hand leaves some lingering doubts, but climate records over the past century confirm that the three most severe El Niños occurred during the last 30 years (BOM 2020). This is consistent with the idea that global warming in recent decades (see IPCC 2018) has led to more severe El Niño events. And, with more severe events, there is a strong likelihood of respectively larger sudden drops in sea level, and more damage to mangrove forests.

Having focused on the damage to mangrove forests, it is appropriate now to consider the recovery processes necessary for these forests to survive. And, where damaging events are more frequent or more severe, these habitats still need time to recover to preserve their beneficial ecosystem services like carbon sequestration, shoreline protection and fishery habitat. These recovery processes mostly involve: flowering and germination; production of mature propagules; dispersal to suitable sites; establishment despite tidal flushing, waves and predators; and, growth into mature individuals in preferably closed forest stands. There are quite a few vulnerable steps, but most of all, it takes time for the new stand to gain functionality and sustainability. And, judging by the apparent canopy recovery curve depicted in Fig. 9.15 (1987–2000 for the Gulf sites)—supported in other field studies (e.g. Duke et al. 1997; Duke 2001)—such recovery takes upward of two decades. Should there be accumulative impacts—this includes impacts from additional factors like more intense tropical cyclones (at 2 per year on average for 1975–2015 in the Gulf; also see: BOM 2020) and the growing pressures of sea level rise (notably 8–9 mm/year for 1993–2007 in the southern Gulf, being 2–3 times the global average; see Church et al. 2009)—these combined pressures further inhibit habitat recovery. The scenarios are illustrated in the Level 4 schematic (Fig. 9.5) where the longer-term trajectory for repeated, large-scale disturbances to mangroves inevitably leads to their severely degraded state (marked by low diversity, fragmented structure and poor functionality)—a state of effective ecosystem collapse (described by Duke et al. 2007).

9.5 Current Recommendations for Management Strategies

In this section, we discuss the appropriate and most effective management strategies to best deal with incidents like the mass dieback of Gulf mangroves. There are three chief considerations to bring focus to such actions: (a) to reduce the risk of such

events happening again; (b) to facilitate recovery of damaged stands; and (c) to facilitate the transition of damaged habitat to an alternate environmental state, if recovery to the past state is not possible.

Our recommendations for addressing these requirements regards mangrove and saltmarsh-saltpan habitat, referred to here as tidal wetland habitat, is to follow a carefully considered series of interlinking tasks outlined in the following points:

1. Apply local risk minimisation by reducing localised pressures on threatened tidal wetland habitat: by removing feral animals like wild pigs (*Sus scrofa*), especially where they dig up young mangrove seedlings along the supratidal ecotone edge; by controlling grazing livestock (like cattle, horses, goats, camels, deer) near tidal wetlands; by preventing severe rangeland fires especially those close to tidal wetlands; by eradicating invasive weeds like rubber vine (*Cryptostegia grandiflora*); by preventing spillage or release of toxic chemicals or other pollutants as either airborne or with the water, likely to reach tidal wetlands.
2. Apply regional risk minimisation by reducing national and global pressures where they threaten tidal wetland habitat: by reducing levels of atmospheric carbon to stop rising temperatures, sea level and detrimental changes in rainfall; by finding ways to reduce carbon emissions; by rewarding those who show leadership in this endeavour.
3. Make accurate area maps to describe the extent of impacted and non-impacted tidal wetland habitat: by mapping healthy and damaged areas using satellite data and imagery of mangrove, dead mangroves, saltmarsh and salt pans, biomass and tree height; by mapping elevation levels using data like LIDAR to define habitat relevant contours of mean sea level (MSL) and highwater (HAT) levels; by historical mapping to identify and quantify past areas of each vegetation type and specifically defining ecotone edges.
4. Make accurate area maps to describe the changes taking place to areas of impacted and non-impacted tidal wetland habitat using each of the methods listed in (3).
5. Conduct condition monitoring to learn more about the ongoing health of tidal wetland habitat: by supporting indigenous ranger groups, community groups and researchers to conduct regular surveys measuring current status and comparing with the past condition; by using aerial surveys and boat-based surveys to complement satellite mapping; by scoring the severity and extent of a broad range of habitat responses to the various drivers of change including obviously human-influenced factors like altered hydrology, vegetation clearing, pollution, landfill, rock walls, along with more natural factors, like drought dieback, shoreline erosion, storm damage, saltpan scouring, terrestrial retreat and light gaps.
6. Develop models for the prediction of future events likely to impact tidal wetland habitat, using various types of data sources: by using accurate vegetation data on diversity, tree loss and seedling establishment for development of forest growth and recovery models; by mapping sediment elevation to describe changes in displacement and mobilisation of sediments—sites of erosion and deposition;

climate data for identification of climate factors known to influence forest development, growth and replacement processes, like temperature, rainfall, period length of drought conditions, sea level, southern oscillation index, evapotranspiration.

7. Facilitation of recovery: by careful consideration and evaluation of a range of mitigation intervention methods, like the removal of dead timber, planting seedlings, channelling to improve drainage, alterations to slope and topography, addition of nutrients and other chemical agents. In general, the rule is that no intervention should be applied unless some advantage can be demonstrated. If mitigation works, like planting, are instigated then it is essential that scientifically robust monitoring continues for 3 or more years afterwards and the results published (as per Duke 1996).
8. Develop and implement a strategy for mitigation and monitoring of tidal wetlands at State and National levels: by applying the above recommendations.

9.6 A Regional Mitigation and Monitoring Strategy for Tidal Wetlands

There is a demonstrable need for a regional shoreline resource inventory where the presence and condition of the many natural assets and resources spread along national shorelines can be displayed and quantified. Furthermore, there is a compelling case also for a companion product for registering the many notable environmental impacts occurring along these shorelines caused by damaging events at specific dates and locations.

Our evidence shows that a number of appreciable events, like the mass dieback of mangroves in Australia's Gulf of Carpentaria, had gone undetected for months or years after they occurred. And, there are likely to be many more unreported incidents. For example, during a 2017 survey of the northern sector of the Great Barrier Reef shoreline, it was discovered that two cyclones, 2 and 3 years earlier, had severely damaged and killed up to 600 ha of dense shoreline fringing mangroves near the Starcke River in far north-eastern Queensland (Duke and Mackenzie 2018). There are important questions about how such a large impact had gone undetected for so many years. This is highly relevant given the great level of concern for coral reefs where their condition in the region had noticeably worsened in recent years. The consequences of such a devastating impact on shoreline mangroves are expected to have broad and significant longer-term detrimental influences on reefal environments when sediments become mobilised as mangrove benefits of buffering and shoreline protection deteriorate.

In summary, such observations demonstrate notable inadequacies in current State and National shoreline monitoring efforts. And, it is of great concern that essential awareness of such damaging incidents along the Australian shoreline generally may be lost, or at best delayed from public acknowledgement. What is needed is an effective strategy with a standard and robust methodology for gathering detailed shoreline data for public display.

So, there is one overall lesson to be taken from our assessment presented in this chapter. This is a strong case for developing and implementing a national shoreline monitoring strategy. This can be seen as a fundamental environmental management opportunity. It would be an important outcome also for the identification and quantification of specific prioritisation issues regards future damaging events affecting shorelines around the country. The strategy could be usefully developed around the identification of indicative environmental responses to specific drivers of change. Each indicator can be scored, quantified, located and assessed for its severity and extent based on its multiple occurrences along the vast Australian shoreline.

The lasting value of such a resource would be in its quantification of habitat conditions as well as its identification of emerging environmental issues like the often-notable shoreline damage caused by severe cyclones, large oil spills, sea level rise or extreme fluctuations in mean sea level. This might then be compared systematically against the baseline status of habitat conditions established on a regional scale at the commencement of such a program. Report card scores might also be derived covering specific shoreline sections.

A targeted use of the monitoring strategy might also be to track longer-term change as either recovery takes place, or deterioration continues. In either case, the knowledge gained would be essential for developing national priorities for shoreline mitigation intervention projects. In any case, such knowledge would be used in the development of strategies for the protection and conservation of shoreline resources for each State and around the country.

These arguments and observations support the need for an effective national shoreline monitoring strategy. State and Federal environmental managers of national coastal resources and assets in Australia could use more comprehensive knowledge about the extent and condition of shoreline habitats, as well as the threats, drivers and risks faced by these natural resources. Such a knowledge base is considered essential for best management practice for the protection of shoreline habitats facing escalating changes in climate, higher temperatures, more severe storm impacts and rising sea levels.

9.7 Vulnerability of Impacted Shorelines with Key Risks and Consequences

Our evaluation of the 2015 mass dieback of Gulf mangroves was made in the context of the fundamental processes influencing the drivers of key environmental components. This approach delivered a relatively robust understanding of not only why there was such a dramatic environmental response in the Gulf event, but also whether it might be possible to predict future occurrences. The evidence presented and particularly the processes responsible for environmental changes provide the basis for developing reliable indicators of likely responses. As one example, the wetland cover index could be applied more in the prediction of risks and changes due to longer-term changes in at least one key factor, namely rainfall (Duke et al. 2019). It is expected that relationships with other climate as well as physical factors, plus

disturbance factors, might also contribute to a future predictive capability for better management of vulnerable shoreline ecosystems.

What is clear is the conclusion that the Gulf mass dieback event was seemingly unprecedented. No earlier instances of comparable dieback have been documented elsewhere, nor in the Gulf during the assessment period of 1987–2019. However, this observation has one notable caveat where we have new untested evidence, implying there may have been an earlier event in the region. This potentially significant earlier event may have taken place during the prior severe El Niño of 1982–1983 when a comparable drop in sea level was reported for the Gulf (Wyrski 1984, 1985). While no observations were made at the time regarding the impact on mangrove forests, some historical imagery appears to support this hypothesis (Duke et al. 2021a, b). If this is proven true, an assessment of the associated climatic conditions along with the other variables would greatly enhance the development of a robust and reliable predictor of possible future occurrences.

Such a well-informed understanding of natural ecosystem responses of tidal wetlands is needed for more effective mitigation actions likely to deliver reliable, effective and lasting outcomes. In any case, we have usefully identified a unique and unusual vulnerability of tidal wetlands habitats with their likely extreme responses to future environmental changes.

Our deliberations have also shed further light on the growing number of implications for associated coastal marine habitats like corals and seagrasses as well as mangroves. There are also related questions to be asked regards vulnerable mobile marine fauna, including commercial fishery species like mud crabs, barramundi and prawns (Plaganyi et al. 2020). In addition, coastal water quality is recognised as a significant environmental management issue where severe runoff through estuarine ecosystems like mangroves might contribute to the unusually large amounts of sediments, nutrients and harmful agricultural chemicals moving into coastal waters and amongst other sensitive nearshore habitats, like seagrass beds and the Great Barrier Reef.

The buffering role of coastal mangroves and tidal wetlands is essential knowledge for the minimisation of risks to nearshore habitats. There is increasing awareness also of the benefits of mangrove and tidal wetland estuarine ecosystems, their condition and status. This supports the growing urgency in developing a better understanding of the key drivers of disturbance events, and to better understand how these detrimental pressures might combine to take these ecosystems down a trajectory towards collapse. While there is precedent for the recovery of shoreline ecosystems (Duke and Khan 1999), recent events demonstrate that disturbances are likely to re-occur too frequently for existing recovery processes (cs. Duke et al. 2007).

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