CSIRO PUBLISHING

Marine and Freshwater Research
http://dx.doi.org/10.1071/MF16322

Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event

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Abstract. This study records and documents the most severe and notable instance ever reported of sudden and widespread dieback of mangrove vegetation. Between late 2015 and early 2016, extensive areas of mangrove tidal wetland vegetation died back along 1000 km of the shoreline of Australia's remote Gulf of Carpentaria. The cause is not fully explained, but the timing was coincident with an extreme weather event; notably one of high temperatures and low precipitation lacking storm winds. The dieback was severe and widespread, affecting more than 7400 ha or 6% of mangrove vegetation in the affected area from Roper River estuary in the Northern Territory, east to Karumba in Queensland. At the time, there was an unusually lengthy period of severe drought conditions, unprecedented high temperatures and a temporary drop in sea level. Although consequential moisture stress appears to have contributed to the cause, this occurrence was further coincidental with heat-stressed coral bleaching. This article describes the effect and diagnostic features of this severe dieback event in the Gulf, and considers potential causal factors.

Additional keywords: mangrove forests, plant–climate interactions, tidal wetlands.

Received 19 September 2016, accepted 19 December 2016, published online 14 March 2017

Introduction

During the summer of 2015–16, mangroves in the sparsely populated Gulf of Carpentaria (the Gulf) area of northern Australia suffered a particularly severe occurrence of dieback. News of the incident was, at first, slow to emerge from this remote, largely unmonitored region. A small number of reports and images (e.g. Fig. 1) from concerned community members along the Gulf coast were followed up by *ad hoc* scientific surveys during 2016 (Fig. 2) to better define the affected area. The total area affected extended from Roper River in the Northern Territory to Karumba in Queensland, a distance of more than 1000 km of shoreline.

At the time, there were no coincidental anthropogenic or natural stochastic events likely to cause severe or large-scale stresses on mangrove forests in the Gulf, such as a large oil spill (Duke 2016), a severe storm event, a tropical cyclone (e.g. Cahoon *et al.* 2003; Paling *et al.* 2008; Feller *et al.* 2015), river flooding (Erftemeijer and Hamerlynck 2005), frost effects (Ross *et al.* 2009), locust plagues or other severe herbivory (Reef *et al.* 2012).

In this first report, it was useful to briefly document key circumstances surrounding the incident, along with the range of factors associated with conditions before and during its occurrence. Observations presented are based on available evidence, including photographic images, maps, location data and field survey observations showing areas of severe loss in tidal wetlands along the southern shoreline of the Gulf.

These initial observations of the dieback included its extent, severity, affected habitat type, the species involved, patterns of dieback, geophysical settings, prevailing hydrological settings, recent weather conditions and timing of the incident. Such considerations have been, and will be, used in the development of hypotheses that will target more rigorous inquiries and assist

Fig. 1. Photograph of mangrove dieback taken during an early aerial survey just east of Limmen Bight estuary mouth, Northern Territory on 29 February 2016 by Paul Barden (location: 15°8′51.54″S, 135°47′16.94″E).

in identifying the cause. Based on current findings, an initial hypothesis has been proposed concerning prevailing weather conditions as well as other notable coincident factors.

Materials and methods

For these initial environmental surveys, a four-step rapid, forensic assessment strategy was used, including: (1) an overview of the study area, with a general description, shoreline features and notable biota; (2) validation of mapping methods, linking satellite imagery and spatial views from available oblique photographs; (3) mapping of affected areas, linking satellite imagery and spatial views from available oblique photographs; and (4) brief (*ad hoc*) aerial and field surveys with continuous image capture using the shoreline video assessment method (S-VAM; Duke *et al.* 2010; Mackenzie *et al.* 2016), further

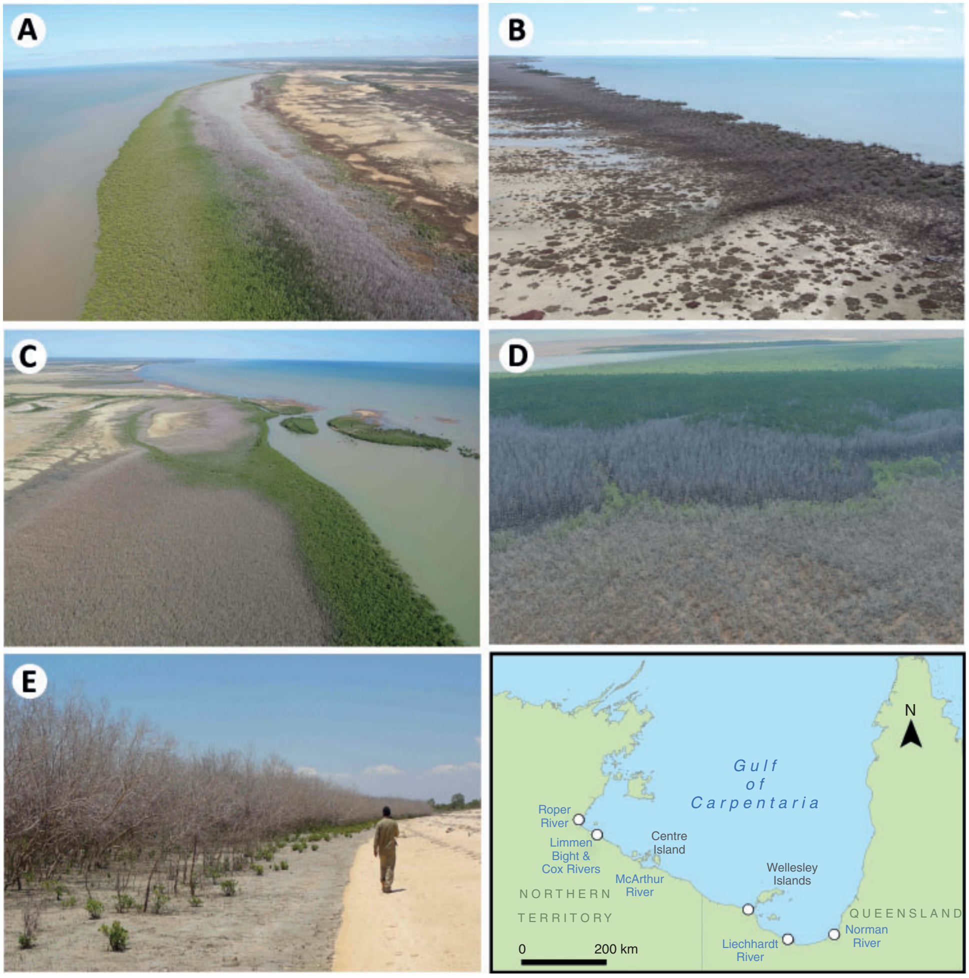


Fig. 2. Photographs of mangrove dieback in five example locations (A–E) across the southern Gulf of Carpentaria from the Northern Territory to Queensland. Locations shown in the map at the bottom right-hand corner. Location A is the Roper River shoreline (14°45′26.77″S, 135°23′23.55″E); Location B is the Limmen Bight River shoreline (15°8′50.47″S, 135°47′37.59″E; images taken by Tony Griffiths, 9 June 2016. Location C shows the Gangalidda shoreline (16°52′40.57″S, 138°55′39.19″E; image taken by Roger Jaensch, 13–14 April 2016). Location D is at the Leichhardt River mouth on 17 November 2016 (17°34′35.55″S, 139°48′56.78″E) and Location E is at Karumba, Queensland, Norman River shoreline (17°26′2.13″S, 140°50′39.18″E) on 27 October 2016 (images from surveys reported in this article).

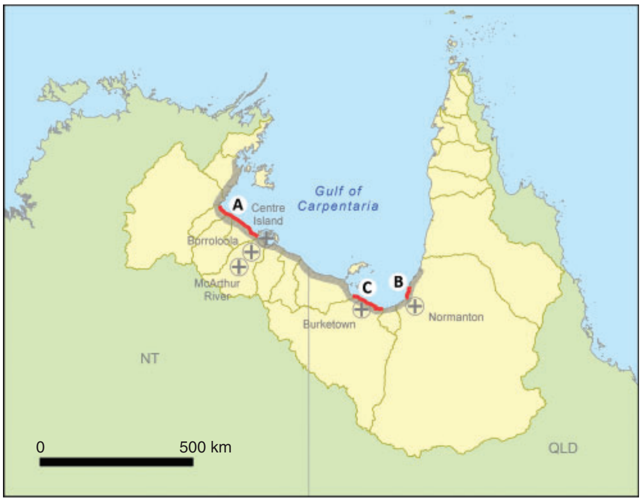


Fig. 3. Catchment areas of the Gulf of Carpentaria (yellow shading) between the Northern Territory and Queensland, Australia, where ~1000 km of the southern shoreline (grey shading) was affected by severe dieback of mangroves in late 2015. Crosses mark the locations of five local Australian Bureau of Meteorology Stations (http://www.bom.gov.au/) referred to in the present study. Note also the locations of *ad hoc* aerial surveys (red lines) conducted during 2016, including the western shoreline from Roper River to Borroloola on 9 June (A), the eastern shoreline north of the Norman River mouth and Karratha on 27 October (B) and the eastern shoreline east and west of the Albert and Leichhardt Rivers near Burketown on 17 November (C).

validation of spatial data with specific on-ground measurements of conditions.

Study area: the Gulf

The Gulf of Carpentaria of tropical northern Australia (Fig. 3) is a large, shallow (<70-m depth) coastal gulf of ~330 000 km^2. It almost equally straddles two political jurisdictions of Australia, the Northern Territory to the west, and the state of Queensland to the east. Industries in the region chiefly include mining, grazing, ecotourism and fisheries.

The Gulf itself is the receiving water body of numerous large and small river systems that drain ~92 000 GL of water into the Gulf each year, mainly during the north-west monsoon between January and March (Burford *et al.* 2009). The coastal areas consist of low-lying swampy, chiefly level ground that is largely inaccessible and comparatively little affected by direct human activity, making it globally exceptional (Halpern *et al.* 2008). However, there are notable effects of livestock trampling and grazing, as well as feral animal damage. In addition, there are several mining operations in the region. Pressures from such activities may have added relevance in this semi-arid region with relatively low annual rainfalls of ~950 mm on average (Bureau of Meteorology, see www.bom.gov.au).

Although mangroves are abundant in the area, the dry climate limits their diversity, height and extent. Owing to the dry climate, large areas of high intertidal saltpans and saltmarsh communities cover at least two- to threefold more area than mangroves. These wide tidal wetland expanses are spread along shorelines and upstream verges for tens of kilometres of meandering estuaries of rivers, creeks and back beach systems throughout the region. The seaward margin forms a low-lying, continuous sweeping coastline often fringed with mangroves along with occasional stretches of sandy beaches, fronted by shallow, broad mud flats and large patches of seagrass meadows (Poiner *et al.* 1987; Roelofs *et al.* 2005). These Gulf habitats support thousands of marine turtles and dugongs (Bayliss and Freeland 1989; Kennett *et al.* 2004), as well as numerous other estuarine species (Long *et al.* 1995).

Preliminary validation of satellite image interpretation

Given the remoteness of the area, the extent and character of mangroves and the recent dieback were mostly described and mapped using satellite imagery. Field investigations were used to validate and confirm interpretations made from satellite imagery. Ten oblique aerial photographs were assessed in specific validation trials (e.g. Fig. 4). Dieback was readily identified using available satellite imagery and all affected areas were mapped.

Mapping of the affected area from satellite imagery

A preliminary scientific visualisation of historical Landsat products (Fig. 5) was conducted for the southern coast of the Gulf to determine whether the die-off of the mangroves was a unique event. All imagery was acquired from the USGS Earth Explorer website (https://earthexplorer.usgs.gov, last accessed 3 August 2016). Because the months of March, April and May were found to have the least amount of cloud cover, a time series based on Landsat 4, 5, 7 and 8 (30-m pixel resolution) scenes collected from these three months were acquired from 1984 onwards for each of the six locations. For two of these areas, namely the Nicholson River (path 100/row 72) and the Limmen Bight (path 102/row 71), older Landsat Multispectral Scanner (MSS) imagery (79-m pixel resolution) was also examined dating back to 1972 and 1978 respectively. The scientific visualisation of these historical records indicated that the recent die-off was a unique event, occurring between 2015 and 2016. Consequently, a monthly series of Landsat 8 imagery was then created between 2015 and 2016 in order to identify as much as possible the timing of the effects on the mangroves.

To determine the extent of mangrove loss between 2015 and 2016, a quantitative binary change detection approach (Kovacs *et al.* 2001) was conducted on recent Landsat 8 Level 1 products (Table 1). Specifically, a near anniversary date comparison was conducted between these years. Of the 12 Landsat 8 scenes used, 10 were acquired in April and, due to cloud cover, 1 each was acquired from late March and early May.

The affected area occurs across two Universal Transverse Mercator (UTM) zones. Therefore, the imagery covering Queensland was left projected in UTM Zone 54, whereas the Northern Territory imagery was left projected to UTM Zone 53. Each image was first radiometrically corrected to surface reflectance using PCI Geomatica's (PCI Geomatics, Richmond Hill, ON, Canada) atmospheric and terrain correction (ATCOR) module. The surface reflectance images were then mosaicked for each year and UTM zone, resulting in four separate mosaic images.

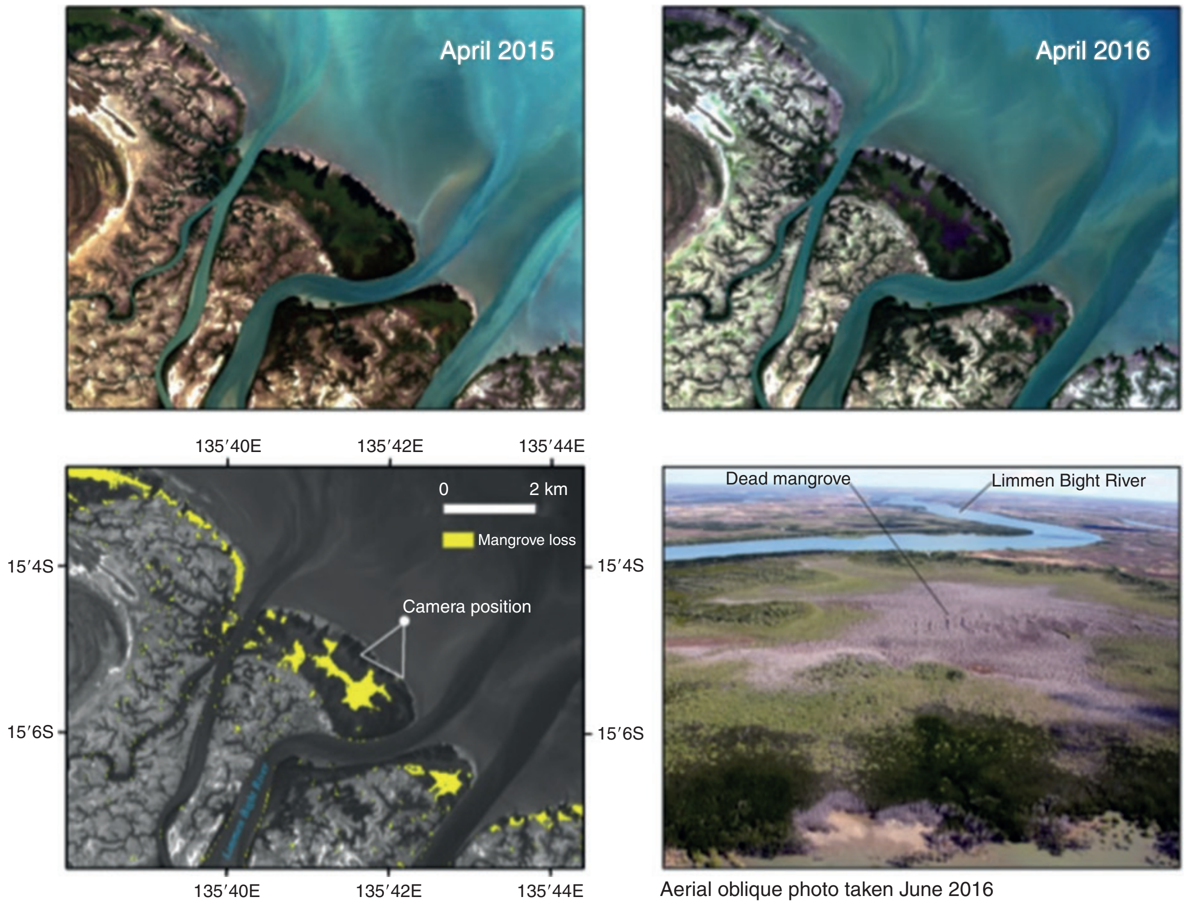


Fig. 4. An example of the current mangrove dieback recorded in satellite imagery of the Limmen Bight (Cox) River estuary mouth and shorelines in the Northern Territory. The camera view (15°4′59.63″S, 135°42′12.70″E) was compared with change detection imagery comparing Landsat 8 April scenes for 2015 and 2016 (top panel) showing healthy vegetation in natural green colours and areas of dieback as dark purple–brown colours. The bottom two images show yellow patches for the dieback (left), whereas the oblique aerial view shows the location with dieback patches in June 2016 (right).

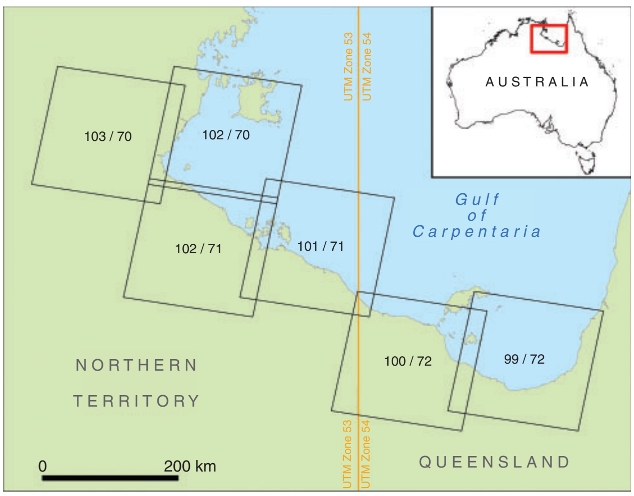


Fig. 5. Southern coast of the Gulf of Carpentaria showing the coverage of the Landsat scenes (Path/Row; see also Table 1). UTM, Universal Transverse Mercator.

To set the baseline extent of mangrove coverage for 2015, an iterative per-pixel unsupervised classification approach using an iterative self-organising data analysis technique (ISODATA) algorithm based on all but the cirrus band of Landsat 8 was used to classify the mangroves at a spatial resolution of 30 m. Using ancillary data (e.g. Google Earth; https://www.google.com/earth/, accessed 3 August 2016), on-screen manual editing was then performed to remove any erroneously classified mangrove pixels.

A normalised difference vegetation index (NDVI) was produced from each of the four surface reflectance mosaics. The NDVI was calculated using the following formula:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{red})}{(\mathrm{NIR} + \mathrm{red})}$$

For Landsat 8, the near-infrared (NIR) spectral band and the red spectral band are collected within the wavelength range of 0.845–0.885 μm and 0.630–0.680 μm respectively. For each UTM zone, a NDVI difference image was then created by subtracting the 2016 NDVI image from the 2015 image. To identify areas of

Table 1. Landsat 8 image products used in the mangrove change detection procedure (see Fig. 5)
WRS-2, Worldwide Reference System; UTM, Universal Transverse Mercator

Scene ID	WRS-2 path/row	Acquisition date	Projected UTM zone
LC81010712015112 LGN00	101/71	22 April 2015	53
LC81020702015119 LGN00	102/70	29 April 2015	53
LC81020712015119 LGN00	102/71	29 April 2015	53
LC81030702015094 LGN00	103/70	15 April 2015	53
LC81030702016081 LGN00	103/70	21 March 2016	53
LC80990722015114 LGN00	99/72	24 April 2015	54
LC81000722015121 LGN00	100/72	1 May 2015	54
LC81010712016115 LGN00	101/71	24 April 2016	53
LC81020702016106 LGN00	102/70	15 April 2016	53
LC81020712016106 LGN00	102/71	15 April 2016	53
LC80990722016117 LGN00	99/72	26 April 2016	54
LC81000722016108 LGN00	100/72	17 April 2016	54

mangrove loss, thresholding of the NDVI differenced image was performed for areas identified as mangrove from the aforementioned 2015 classification procedure. The threshold value was determined using visual inspection of the original imagery (see Fig. 4). Full imagery and enlarged scenes presented in Fig. 6 are available in the Supplementary material.

Aerial and field survey of affected shorelines

Aerial and field surveys of shorelines and mangrove areas were conducted on three occasions during 2016 (Fig. 3): (1) on 9 June, of the shoreline from Roper River to McArthur River in the Northern Territory (14°45′42″S, 135°23′38″E to 15°44′9″S, 136°33′48″E) supported by Northern Territory Government and JCU TropWATER Centre; (2) on 7 October, in the vicinity of Karumba in Queensland (17°26′49.65″S, 140°50′4.64″E to 17°17′42.78″S, 140°54′11.89″E) supported by WWF, The Ocean Agency and Carpentaria Land Council Aboriginal Corporation (CLCAC); and (3) on 17 November along the shoreline around the Nicholson, Albert and Leichhardt rivers (17°22′50.60″S, 139°26′13.26″E to 17°37′4.30″S, 140°32′5.92″E) supported by CLCAC.

In each case, aerial helicopter surveys were conducted along significant portions of affected shorelines as both a fact-finding mission and an opportunity to further validate interpretations made from satellite imagery. The aircraft used were Robinson 44 helicopters, operated by either North Australian Helicopters (www.northaustralianhelicopters.com.au) (1 above) or Cloncurry Mustering Company (www.cloncurryhelicopterservices.com.au) (2 and 3 above). Concurrent on-ground field inspections were undertaken to evaluate selected mangrove sites during each flight. In each case, a number of key features were observed, including the species of trees and shrubs affected, the impact status (classified primarily as lethal or sublethal), the presence of canopy foliage (living and dead), the impact on saltmarsh plants, the presence of leaf litter on the sediment surface and the presence of fauna.

Results

Mapping areas of mangrove dieback

Areas of shoreline and estuaries mapped extended from the Walter and Roper rivers in the Northern Territory to the Norman River and Brannigans Creek in Queensland (Fig. 5). Selected scenes from along this shoreline are shown in Fig. 6 displaying examples of the patterns of dieback observed, along with the extent and severity of the dieback.

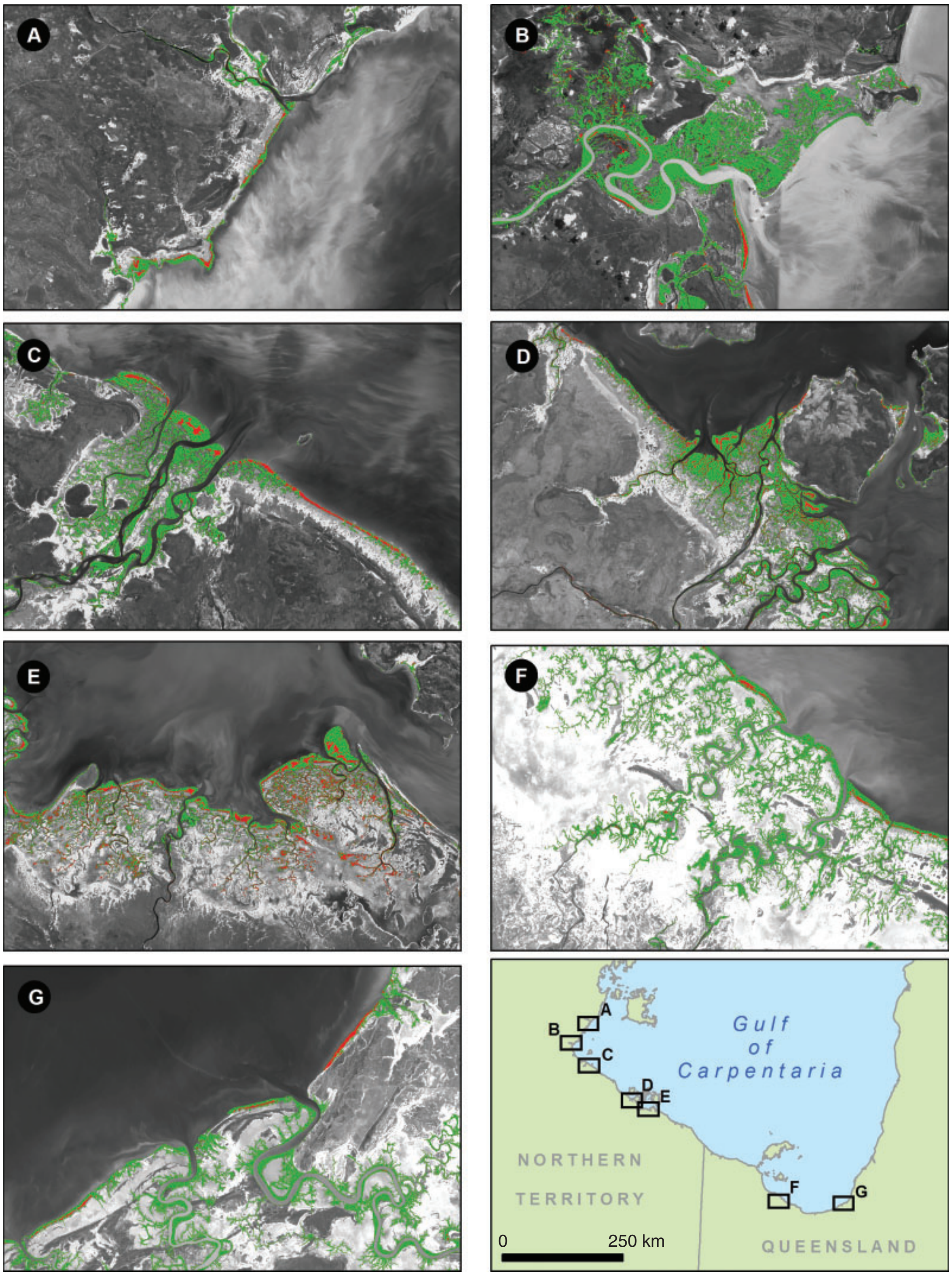
Three notable observations were apparent from the NDVI difference images: (1) the dieback of mangroves was severe and widespread; (2) the patches of mangrove dieback were often quite large (100–200 m wide); and (3) there were distinctive patterns associated with the dieback areas, for example mangroves along estuarine water courses were less affected.

Mangrove extent mapping and NDVI difference images were used to estimate the total area of dieback. This was then compared with our estimate of the total area of mangroves in each of the 14 catchment areas. The total areas of mangrove dieback and total mangrove cover observed in 2015–16 satellite imagery are listed in Table 2. These data show that most losses, up to ~5500 ha, were in the Northern Territory, amounting to ~9% of mangroves in the area. Losses in Queensland were less, but still amounted to more than 3% of affected mangroves in that area of the state. Overall, this amounted to more than 7400 ha of mangrove loss across the southern Gulf. This figure represents ~6% of mangroves across the entire region.

Patterns and features of mangrove dieback

At least three primary response patterns were observed in vegetation affected by dieback based on mapping and aerial surveys (see Fig. 7), including: (1) more or less complete loss of the shoreline fringing zone (Fig. 7*a*); (2) upper margin loss of mangroves bordering saltpans and saltmarsh flats (Fig. 7*b*); and (3) mostly intact, healthy fringes along estuarine channel margins and upstream riverine stands (Fig. 7*c*), even where these enter the sea.

A key notable feature of this recent mangrove dieback incident was its synchronous occurrence along more than 1000 km of shoreline. At smaller scales, there are several alternative drivers also likely to cause dieback (Duke 2014). These include disturbances, dieback and loss of mangrove vegetation like: the common presence of small circular light gaps (50–100 m wide) attributed to lightning strikes (Duke 2001; Amir 2012); shoreline erosion from severe cyclonic storms (Baldwin *et al.* 2001); shoreline erosion associated with



Background imagery: Landsat 8 OLI B and 4 (Red) collected April 2015

Fig. 6. Seven example scenes (A–G) distributed across the southern Gulf, as indicated on the map at the bottom right, showing areas of mangrove loss (red) detected in Normalised Difference Vegetation Index (NDVI) difference images of Landsat 8 scenes from April 2015 to April 2016. Also shown are the surviving mangrove areas (green). Central locations for respective views were as follows: Location A, 14°20′17.08″S, 135°42′12.61″E; Location B, 14°42′46.00″S, 135°22′55.92″E; Location C, 15°6′53.95″S, 135°44′11.03″E; Location D, 15°44′36.09″S, 136°33′19.50″E; Location E, 15°54′47.23″S, 136°52′34.33″E; Location F, 17°31′10.33″S, 139°29′38.46″E; and Location G, 17°28′50.97″S, 140°47′17.22″E. Operational Land Imager (OLI). Note: enlarged versions of these scenes (Figs S1–S7), and difference images of the entire affected shoreline (GIS shape files), are available in Supplementary material to this article.

Table 2. Summary of mangrove vegetation cover within the Gulf of Carpentaria and along its southern shoreline
The Gulf shoreline extends across two regional jurisdictions of Australia, namely the Northern Territory (NT) and the state of Queensland (Qld). The National Vegetation Information System (NVIS) was accessed in June 2016 (National Vegetation Information System 2016). Note, although there were notable differences between NVIS mapping estimates and those made in the present study for the southern Gulf areas, these are likely to be methodological errors (Rogers *et al.* 2016) rather than actual measures of change in mangrove vegetation cover. UTM, Universal Transverse Mercator

Gulf section	Feature and image source	Mangrove/saltmarsh vegetation cover (ha)		
		UTM Zone 53 (NT)	UTM Zone 54 (Qld)	Total zones (NT and Qld)
Total Gulf	Mangrove: extrapolated/NVIS mapping	74 405/49 203	131 780/172 441	206 185/221 644
	Saltmarsh/saltpan: NVIS mapping	233 002	182 731	415 733
	Tidal wetland: extrapolated/NVIS mapping	282 205/308 399	355 172/354 931	637 377/663 330
Southern Gulf	Mangrove: Landsat 8 April 2015/NVIS mapping	58 139/38 452	64 364/85 263	122 503/123 715
	Dieback loss: Landsat 8 April 2015–16	5493	1912	7405
	Percentage loss	9.4	3.0	6.0

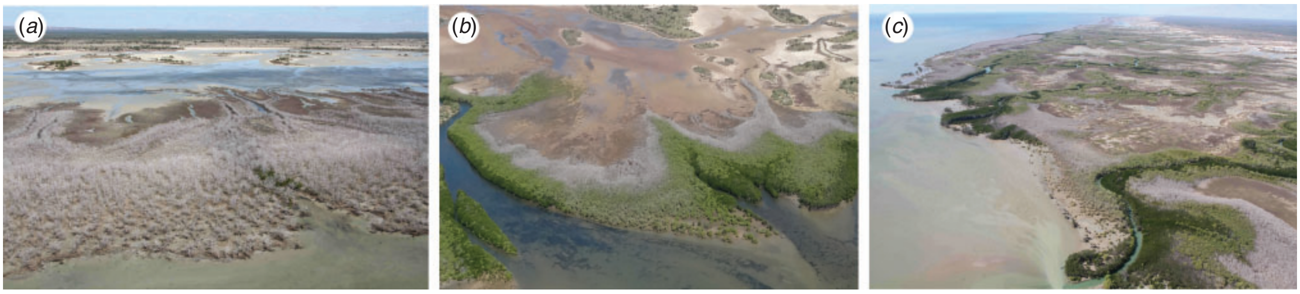


Fig. 7. Indicative patterns in vegetation zones relate to the severity of mangrove dieback, including (*a*) the more-or-less entire dieback of the shoreline zone, (*b*) the dieback of the inner edge bordering saltmarsh and saltpans and (*c*) dense normal fringing vegetation along tidal channels. Images were taken during the aerial survey on 9 June 2016 between Centre Island and the mouth of Limmen Bight River, Northern Territory.

sea level rise (Lovelock *et al.* 2015; and, depositional gain with mangrove islands and mud banks forming at river mouths (Asbridge *et al.* 2016). Still other drivers include impoundment with blockages to tidal drainage resulting in altered hydrology and root burial from rapid sediment deposition.

An understanding of such indicators and their associated drivers of change underpinned our interpretation of the current dieback. One key pattern was ubiquitous across the affected area, shown in the example image (Fig. 7*b*) of dieback along an inner stand margin. This appears to be an instance of ecotone shift (Duke 2014). In such a case, mangrove loss appears to have progressed in a unidirectional contraction of the inner mangrove zone margin, matched by a corresponding expansion of the lower elevation margin of saltmarsh and saltpan. This was consistent with the progressive loss of mangroves attributed to unusually low moisture levels associated with tidal inundation.

There were also other distinctive features of this incident. For example, there was a concurrent loss of vegetation from two species zone ecotones at the same time. Two dominant species zones within several mangrove stands in the Gulf each showed signs of ecotone shift with the dieback (Fig. 8). This was shown further by an unusual co-occurrence of dieback along two parallel fronts: one for *Avicennia marina* and another for *Rhizophora stylosa*. Judging by the zone of sublethal damage (yellowed and partially defoliated canopies) at the lower profile margins, there appeared to be a unidirectional loss (contraction) towards the water's edge margin.

These observations show that multiple mangrove species were affected by the dieback and each had retreated from its respective intertidal profile position (Fig. 9). In this way, mangrove losses followed distinct patterns consistent with the contraction of species zones away from their inner and higher elevation margins.

In more extreme instances, notable sections of seaward shoreline mangrove stands were completely lost. This explains the instances (such as Fig. 7*a* and almost the case in Fig. 8*b*) where either the zone or the entire shoreline margin had died back.

Furthermore, although mangroves are predominantly restricted to coastal areas, they are known to be influenced by conditions within upstream catchment areas (cf. Duke *et al.* 1998). It was considered useful for ongoing assessments to quantify mangrove dieback within individual catchments across the affected region. These regional variations in mangrove canopy loss are shown in 14 catchment areas across the assessment region (Fig. 10). A minimal level of 0.4% was measured for Groot Eylandt (Catchment area 1) compared with a maximal level of ~26% within the Robinson River (Catchment area 8). Dieback severity was greatest (~8–25%) in mangrove areas of the catchments of the Rosie (Catchment area 6), McArthur (Catchment area 7), Robinson (Catchment area 8) and Calvert (Catchment area 9) rivers. It is an important question as to why the severity levels were highest in these systems.

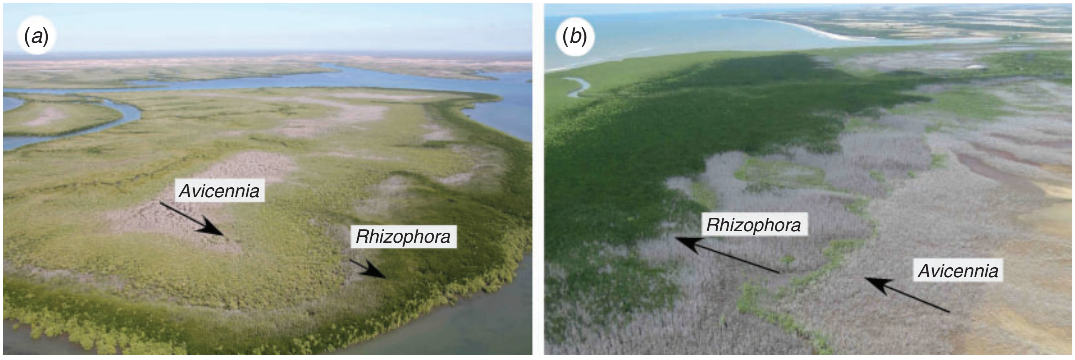


Fig. 8. Two views of mangrove zonation showing the sea edge *Avicennia marina*, then *Rhizophora stylosa*, and backed by another *A. marina* zone bordering the saltpan with saltmarsh (*a*) on the mainland shoreline west of Centre Island (Northern Territory) and (*b*) near the Leichhardt River estuary mouth (Queensland). The two mangrove species show separate dieback fronts at their respective higher elevation margins in several locations along the southern Gulf of Carpentaria coast.

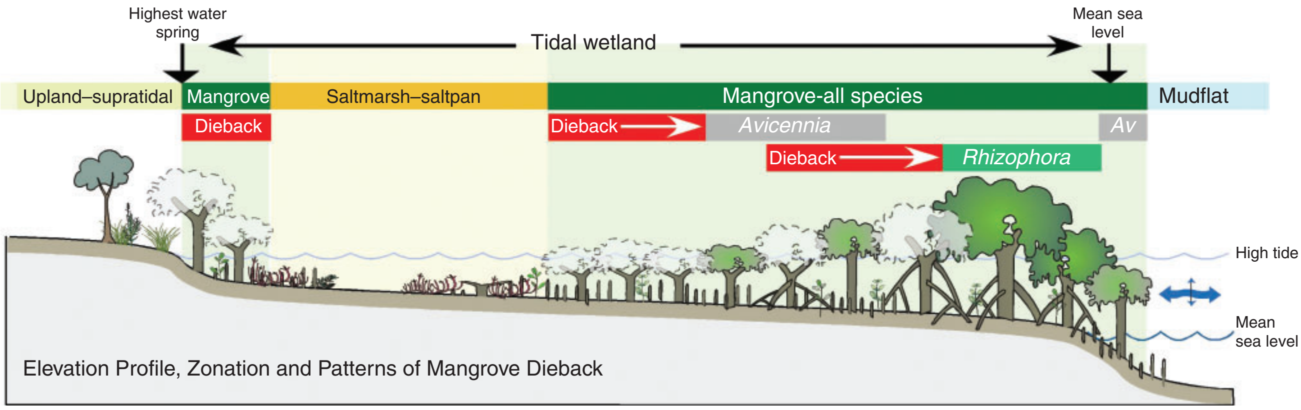


Fig. 9. Cross-section view of mangrove zonation with two species dominants (*Avicennia marina* and *Rhizophora stylosa*) having different fronts, or ecotones, of dieback patterns observed in the Gulf of Carpentaria.

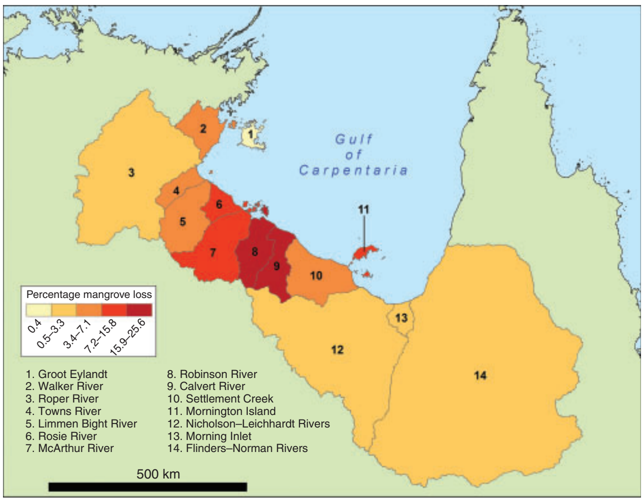


Fig. 10. Proportional losses of mangroves for 14 catchment areas bordering the southern shorelines of the Gulf of Carpentaria. For the loss groupings (interval classifications), we used the Jenks natural breaks approach (Jenks 1967). The question raised by these differences is why were Catchments 8 and 9 more severely affected than the others?

Timing of this occurrence of severe dieback

The timing of the mangrove dieback event in the Gulf appears to have been more or less synchronous along the entire affected shoreline. Evidence of the timing was first observed by concerned locals around mid to late November 2015. Just north of Karumba in Queensland, ~10-km section of mangrove seaward fringing shoreline was observed to be undergoing dieback. This was confirmed as a widespread response from satellite images taken over the period (e.g. see Table 3). It seems that mangrove areas were notably affected during November–December 2015, the end of the unusually long dry season. Based on anecdotal observations from community members, there may also have been concurrent losses of seagrass during the month earlier in November. However, this needs to be confirmed.

Discussion

The extent and severity of mangrove dieback in Australia's southern Gulf of Carpentaria appears to be unprecedented. There had been no previous reports of mangrove dieback at this scale or within such a short time frame. The respective factors, along with observations of spatial patterns described at local (Figs 8, 9) and regional (Fig. 10) scales, combined with temporal

Table 3. Observations of the onset and timing of severe mangrove dieback

Satellite images were used to quantify the timing of impacts on mangrove dieback along the shoreline north of the Norman River mouth near Karumba, Gulf of Carpentaria. Reference data include regional rainfall and the duration of the 2015 dry season. nv, not visible

Date	Tide level	Seagrass intertidal	Mangrove seaward zone	Mangrove landward zone	Regional rainfall (mm)	Number of dry season months
30 August 2015	Mid	nv	Intact, full and dense	Intact, sparse, patchy	0.7	7
1 October 2015	Low	Intact, full and dense	Intact, full and dense	Intact, sparse, patchy	0.1	8
2 November 2015	Very low	Mostly absent, some patches	Intact, full and dense	Intact, sparse, patchy	0.4	9
4 December 2015	Low	Mostly absent, some patches	Reduced canopies, sparse, patchy	Sparse, patchy	28.4	10
5 January 2016	Low	Mostly absent, some patches	Mostly absent, sparse, patchy	Mostly absent, sparse, patchy	257.9	Wet season

observations (Table 3), are each considered potentially influential and indicative of the likely cause.

Although this incident of mangrove dieback in the Gulf also coincided with effects of hot water on corals in north-eastern Australia (Normille 2016; Pratchett and Lough 2016), we suspect additional factors were responsible for the severe dieback of mangroves in the Gulf. The most likely factors appeared to be those consistent with severe moisture deficit and the extreme weather conditions at the time.

Monthly satellite imagery was used to show changes to mangrove areas before November 2015 and after mangroves had died back significantly. The timing of peak dieback appeared to be synchronous with the end of the extreme weather conditions (e.g. National Academies of Sciences, Engineering, and Medicine 2016). Significantly, the region was affected by above-record air temperatures, as well as high sea temperatures. Although there may have been some link with higher sea temperatures on Australia's north-east coast (Wolanski 2016), this was not the only factor likely to have caused mangrove dieback. In addition, the bulk of mangrove dieback occurred in relative unison towards the end of the unusually extended dry season that affected southern parts of the Gulf of Carpentaria (Australian Broadcasting Corporation 2015). Based on such observations, a working hypothesis is that mangroves died from localised moisture stress.

Was this severe dieback the first instance of climate change-induced 'longer, hotter droughts' affecting mangrove forests by moisture stress? The likelihood of stress-related dieback from such weather conditions leading to extended water deficit within mangroves is very concerning, because the frequency of severe drought reportedly increased worldwide (Dai 2013; Trenberth *et al.* 2014; Moise *et al.* 2015; Clark *et al.* 2016). In addition, these droughts have also become hotter (Intergovernmental Panel on Climate Change 2014). Concerns remain about anthropogenic effects where climate change-induced drought has reportedly caused increased forest tree mortality (McDowell and Allen 2015), as well as degradation of forest structure and function generally (Clark *et al.* 2016).

Large-scale mangrove retreat at high intertidal saltmarsh–mangrove ecotones, referred to as ecotone shift (Duke 2014), has been reported for longer periods of drying in eastern Australia (e.g. Eslami-Andargoli *et al.* 2013). However, these have occurred over decadal periods (N. C. Duke, A. Basile, C. Field, J. R. Mackenzie, J.-O. Meynecke and A. L. Wood, unpubl. data), rather than the rapid, sudden loss reported for the current incident.

Comparable incidents and functional processes

To further understand the reasoning behind our conclusions, it is useful to briefly evaluate the various types of condition states in mangrove and tidal wetland ecosystems around the world. Overall, the dominant vegetation type in temperate tidal wetlands is saltmarsh (Duke *et al.* 1998). In contrast, mangroves dominate wet tropical and subtropical tidal wetlands where saltmarsh plants and saltpan microphytes are also present coexisting in varying proportions with mangroves, depending on longer-term rainfall conditions (N. C. Duke *et al.*, unpubl. data).

In semi-arid tropical locations, like Australia's Gulf of Carpentaria, the habitat types co-occur, with mangroves occupying less than 50% of the tidal wetland niche, and tropical saltmarsh and saltpans occupying the rest. In such drier tropical and subtropical situations, these habitat states appear constrained by moisture (rainfall) conditions, rather than by temperature (N. C. Duke *et al.*, unpubl. data). This is a globally significant distinction (Osland *et al.* 2016; Ward *et al.* 2016).

Overall, the case studies of changes of mangrove dieback observed can be grouped into three types of incidents coincidental with extreme weather events, other than severe storms or large waves. These incidents result in often notable responses as shifts between alternative tidal wetland vegetation state types. However, not all have been consistent with reported longer-term trends in weather conditions (see Alongi 2015). Overall, these incident types include the following.

1. Temperature-dominated changes to mangrove *v.* saltmarsh vegetation at mangrove higher latitude limits, because mangrove expansion is linked to warmer conditions (Gilman *et al.* 2008; Osland *et al.* 2013, 2016; Saintilan *et al.* 2014) or the alternative, mangrove dieback or retreat, is linked to severe frosts (Kao *et al.* 2004; Ross *et al.* 2009; Feller *et al.* 2010; Saintilan *et al.* 2014).
2. Rainfall-dominated changes to mangrove *v.* saltmarsh vegetation within the latitudinal limits of mangroves, because

mangrove expansion is linked to wetter conditions (Duke *et al.* 2003; Gilman *et al.* 2008; Eslami-Andargoli *et al.* 2013; Duke 2014; Osland *et al.* 2014, 2016) or the alternative, mangrove losses or retreat, are linked to drought and decreased precipitation (Duke *et al.* 2003; Gilman *et al.* 2008; Duke 2014).

3. Rainfall-dominated saltmarsh dieback at, or beyond, higher latitudinal limits of mangroves linked to drought, decreasing rainfall and sea level changes (McKee *et al.* 2004; Silliman *et al.* 2005).

Although mangrove dieback in the Gulf had seemingly similar associated factors to those described for saltmarsh in Incident type 3 above, they were distinctive and different because the dieback affected saltmarsh plants only, and not mangroves. This was not the case in the first two incident types. In contrast, these types showed a shift between mangrove-dominated and saltmarsh-dominated vegetation communities within the same tidal wetland niche. Each involved the expansion of one state–type at the expense of the other. This created a seemingly common feature of ecotone shift between the alternative vegetation states. The shift direction appeared primarily dependent on trends within the chief influencing factors of temperature and rainfall.

Accordingly, where there had been mangrove expansion at mangrove poleward limits, like the eastern coast of North America (Osland *et al.* 2013), this involved a corresponding replacement or loss of saltmarsh habitat. It was significant that the Gulf dieback occurred well within the latitudinal range of the species affected. Therefore, it seems more likely that the Gulf dieback corresponds to a Type 2 incident, influenced mostly by rainfall. In addition, this implies that there may have been a severe moisture deficit.

Extreme weather conditions associated with mangrove dieback in the Gulf

It was significant that the Gulf instance of severe mangrove dieback was more or less coincidental with unusually hot water temperatures observed off the Australian north-east coast (Normille 2016; Wolanski 2016). Although mangroves are known to be reasonably heat tolerant (Medina 1999), there were exceptionally high temperatures recorded at the time when mangrove dieback peaked (Bureau of Meteorology 2015; Hope *et al.* 2016). Record high temperatures were recorded during the preceding 5–6 months of the extended dry season (Fig. 11*a*).

But also present, there were at least two additional severe weather and hydrological conditions likely to affect mangrove vegetation. These included an unusually prolonged severe drought, and a temporary drop in sea level during the latter months of that drought period. The low rainfall conditions experienced in November 2015 are shown in Fig. 11*b*. These dry season conditions prevailed for an unusually long period of ~10–11 months.

A third factor, sea level, was observed to have dropped temporarily by up to 20 cm in the Gulf at the time of the severe dieback. This is shown in the map of Pacific Ocean seawater levels during October 2015 (Fig. 11*c*). Although there remain questions about how the mean drop would have interacted with tidal levels, it is likely that upper areas of mangroves would have been less inundated during normal high tide periods of the critical months when these upper zone plant habitats were both heat stressed and in moisture deficit.

It is highly likely that the combination of these three factors at least contributed to the severe dieback observed. It is further significant that all these parameters were each correlated with the Southern Oscillation Index (SOI) and the El Niño–Southern Oscillation (ENSO) cycle for this region (Becker *et al.* 2012; Hilbert *et al.* 2014). Although it is difficult to be sure about the exact trigger causing this severe mangrove dieback, it is understood that it had not occurred on such a scale before. In addition, although it was also synchronous with the late 2015 period, it is also apparent there was more than one variable involved.

All things considered, it appears that stresses on mangrove plants were not only present, but also would likely have been cumulative. For instance, we have looked closely at the duration of contiguous days where monthly rainfall had not reached recognised 'wet season' levels. Such climate variables were analysed for each of the five local Bureau of Meteorology stations (www.bom.gov.au) with averaged data extending back up to ~30 years. This assessment has shown the period up to October–November 2015 as unusual.

In a further line of inquiry, the patterns and distribution of dieback were assessed from the mapping. The occurrences of severe dieback along mostly upper elevation contour zones (Figs 8, 9) were consistent with circumstances of severe moisture stress along vegetation zone margins. Given the hot, dry weather conditions at the time, coupled with lower sea levels, each of these factors would have contributed to a decrease in soil moisture, with stresses on the plants extending down the tidal profile from higher and inner mangrove zones. In addition, given the synchronicity of drought conditions with the timing of peak dieback, this implies that a lack of moisture was a likely trigger, occurring at the end of an unusually prolonged drought period.

These longer-term changes describe the unusual congruence of key detrimental growth factors towards the end of the long 2015 dry season (Fig. 12). Key evidence for the likely cause of this occurrence of severe mangrove dieback in the Gulf, are summarised as follows:

- unprecedented large patches of dead and defoliated mangrove vegetation adding up to more than 7400 ha spread across 1000 km of shoreline
- dieback areas matched zonation contours, extending down profile from mostly higher elevation contour levels
- dieback involved key dominant species present (*A. marina*, *R. stylosa* and *Ceriops tagal*) and at their respective higher zonation ecotones along upper tidal profile elevations
- dieback was synchronous with the end of the unusually long dry season of ~9–10 months in November–December 2015, a period of unusually extended high evapotranspiration
- dieback occurred when regional annual rainfall levels were low, temperatures were high (see also Bureau of Meteorology 2015) and sea levels were notably lower at the time.
- the severity of dieback was variable across coastal catchment areas, with up to 25% mangrove losses in the more-or-less central subcatchment area (Fig. 10).

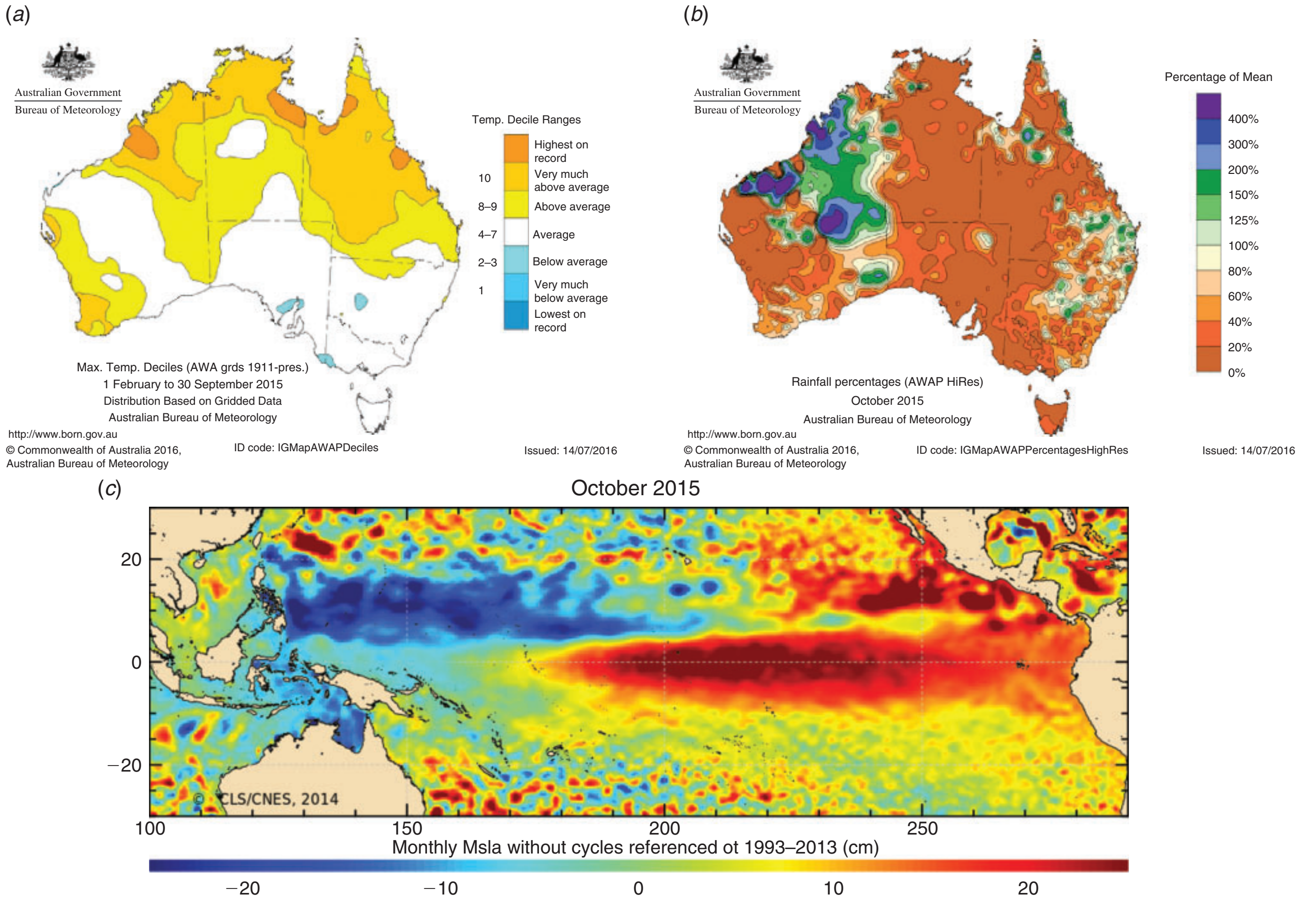


Fig. 11. Three notable factors (Bureau of Meteorology 2015) concurrent with the severe mangrove dieback in the Gulf include (*a*) maximum temperature levels (February–September 2015 in Australia), coincident with the hottest March days on record, (*b*) low rainfall percentages for October 2015 in Australia, coincident with an unusually prolonged dry season, and (*c*) the temporary sea level anomaly for October 2015 in the Pacific region, coincident with a temporary drop of 20 cm in sea level that was consistent with the El Niño–Southern Oscillation (ENSO) cycle affecting subsurface heat across the Pacific Basin. The top images were supplied by Andrew Watkins with the Australian Bureau of Meteorology (BOM). The lower image was found on the Aviso website (www.aviso.altimetry.fr). AWAP HiRes, Australian Water Availability (BOM) Project High Resolution imagery; AWA grds, Australian Water Availability grids; CLS/CNES, Collecte Localisation Satellites Group, Centre National d'Etudes Spatiales (French Space Agency).

Based on the present findings, it is concluded that the most likely cause of this unusual and unprecedented incidence of severe mangrove dieback was the unusually long duration of arid, hot conditions in the southern Gulf of Carpentaria region towards the end of the 2015 dry season. These conditions (Bureau of Meteorology 2015) were synchronous with local high temperatures, low rainfall, extended drought period, and a temporary fall in sea level. A notable correlate of these weather and sea level variables was the SOI.

Implications of severe dieback in mangrove ecosystems

This incident of severe and extensive dieback has immediate implications with likely consequences for the ecosystem services previously provided by the damaged mangrove habitat. The areas most likely affected by the loss of mangrove area and health are those associated with fisheries and fishing, with the Gulf also being an extremely popular area for recreational fishing. The total value of the Gulf fishery is worth ~A$30 million per annum (Dambacher *et al.* 2015; QDEEDI 2011). The Gulf is also the hub of the northern prawn fishery, one of Australia's most valuable and iconic commercial fisheries, targeting banana prawns and tiger prawns. The long-term average annual catch is valued at ~A$12 million (Dambacher *et al.* 2015). In addition, the total commercial harvest of mud crabs, *Scylla serata*, is ~1190 tonnes (Mg), worth ~A$19 million, with recreational fishers harvesting at least 50% of the total catch (Queensland Department of Employment Economic Development and Innovation 2011).

Commercial fisheries in the Queensland section alone grossed a total value of A$14 million in 2006 with ~2300 Mg (Greiner and Gregg 2010). The largest of the commercial fisheries, the Queensland Inshore Fin Fish Fishery, had a total harvest of 2365 Mg, worth ~A$15.5 million in 2012, with recreational fishers taking in less than 10% of the catch (Queensland Department of Agriculture Fisheries and Forestry 2014). Popular finfish in the fishery include barramundi *Lates calcarifer*, blue salmon *Eleutheronema tetradactylum*, grunter

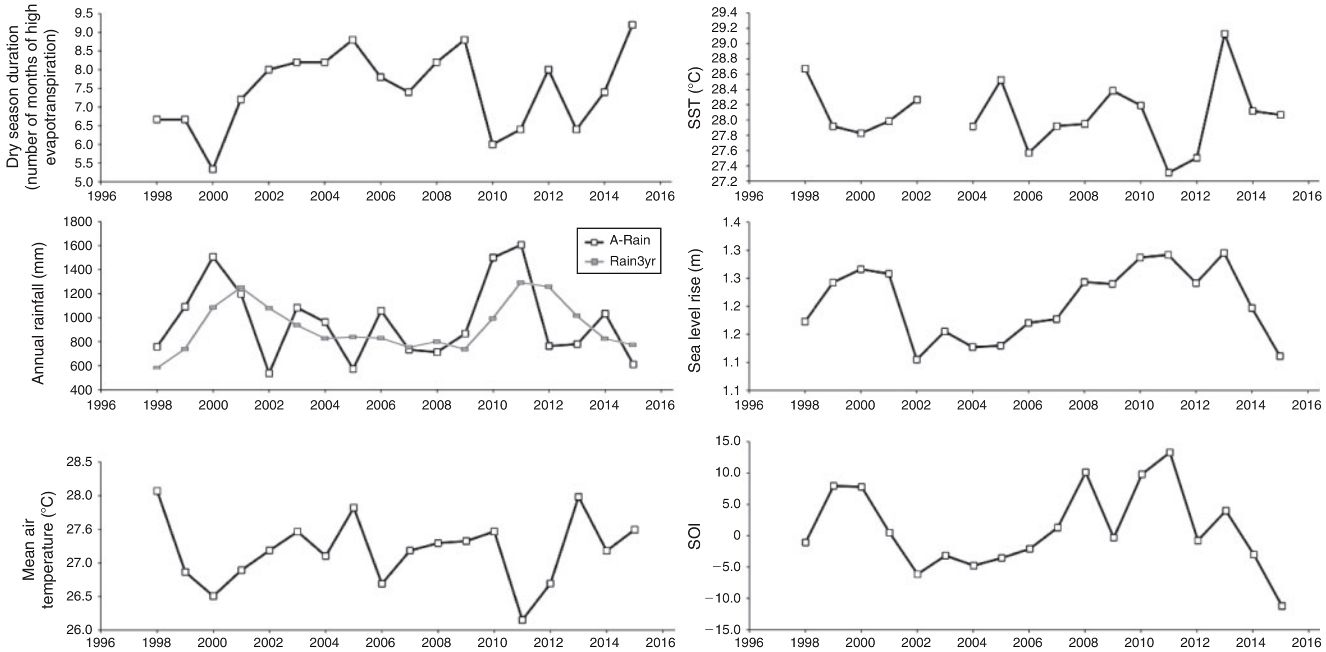


Fig. 12. Six factors likely to have influenced mangrove condition at the time include dry season duration, annual rainfall, mean air temperature, sea surface temperature (SST), sea level and the Southern Oscillation Index (SOI). Values were averaged for the region (where possible) for the 18-year period from 1998 to 2016. Data were sourced from the Australian Bureau of Meteorology, including stations (www.bom.gov.au) at Normanton, Burketown, Borroloola, McArthur River and Centre Island (also see Fig. 3).

Pomadasys kaakan, king salmon *Polydactylus macrochir* and mangrove jack *Lutjanus argentimaculatus*. All these species have close associations with, if not specific dependencies on, mangrove habitat, making the extent of dieback of mangroves of immense concern to commercial and recreational fisheries of the Gulf region.

The impacts on mangrove ecosystem services in the Gulf region also affect shoreline protection and carbon capture. There is a high risk of further losses of carbon to the atmosphere should there be more dieback or there is interrupted recovery of the 7400 ha of currently affected mangroves. For example, damage would be greatly exacerbated within the next 10 years should the area be struck by a tropical cyclone (Paling *et al.* 2008) while shoreline vegetation re-establishes exposed shoreline fringing stands. These points raise serious concerns for the future of mangroves and other habitats across the region, especially because they co-occur with the threats of sea level rise contributing to ongoing accelerated shoreline erosion and retreat.

Climate projections over the next several decades show higher temperatures, increased evaporation rates and warmer oceans (Moise *et al.* 2015). Accordingly, there is an increased likelihood of future severe and extended droughts across parts of Northern Australia (Dai 2013). This dieback incident revealed a previously unrecognised sensitivity and vulnerability of mangrove tidal wetland ecosystems to fluctuations in climate. A greater understanding of specific catchment-scale drivers of drought and other dieback effects is needed urgently to assist targeted management strategies for enhancing the resilience of mangrove shorelines faced with climate change. Such well-informed strategies are essential to government agencies at all levels needing to effectively manage longer-term adaptation goals. This incident is a wake-up call for the improvement of social and economic resilience of remote communities, along with the health of natural environments along Australia's northern shorelines.

Author contributions

N. C. Duke led the investigation, the compilation of data and writing the document. J. M. Kovacs, D. J. E. Hill and H. S. Morning were responsible for the satellite image change detection component of the investigation. A. D. Griffiths assisted with the aerial field survey and the writing. L. Preece assisted with the writing and searching for resources. P. van Oosterzee assisted with the writing and searching for resources. J. Mackenzie assisted with the writing and searching for resources. D. Burrows assisted with the writing and research support.

Supplementary material

Detailed imagery are available as Supplementary material to this paper, including enlarged versions of the seven image plates displayed in Fig. 6, plus GIS files of mangrove loss areas along the entire affected coast.

Acknowledgements

Early imagery and observations of the severe mangrove dieback in the Gulf were generously provided by Paul Barden (29 February 2016), Gavin ('Groover') New (Carpentaria Barra and Sport Fishing Charters; 1–3 March 2016) and Roger Jaensch (Jaensch Ornithology & Conservation; 13–14 April 2016). Project works were supported by TropWATER Centre, James Cook University. Support for aerial surveys are acknowledged in the article, but especially include that provided by the Parks and Wildlife Commission of the Northern Territory with the Department of Land Resource Management, and the Carpentaria Land Council Aboriginal Corporation. J. M. Kovacs acknowledges financial support through the Natural Sciences and Engineering Research Council of Canada (Grant #RGPIN-2014-06188).

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