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Mangrove and Freshwater Wetland Habitat Status of the Torres Strait Islands
Biodiversity, Biomass and Changing Condition of Wetlands

Norman C. Duke, Damien Burrows and Jock Mackenzie

Australian Government
Department of the Environment

Reef & Rainforest
RESEARCH CENTRE

Mangrove and Freshwater Wetland Habitat Status of the Torres Strait Islands

Biodiversity, Biomass, Changing Condition of Wetlands

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Acronyms Used In This Report

NERP .... National Environmental Research Program

QDEHP .... Queensland Department of Environment and Heritage Protection

JCU .... James Cook University

PNG .... Papua New Guinea

TropWATER . Centre for Tropical Water and Aquatic Ecosystem Research

TSRA .... Torres Strait Regional Authority

Abbreviations Used In This Report

Is. .... Island

GIS .... Geographical information system

S-VAM........... Shoreline Video Assessment Method

STP .... sewage treatment plant

sp. .... species

MSL............... mean sea level

yrs................. years

ft.................... feet

m .... meters

ha .... hectares

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We are grateful for the assistance and support provided by the Torres Strait Regional Authority (TSRA), its Ranger Program, and the Rangers on each of the islands visited during these NERP-funded surveys conducted from 2012–2014.

We also fully acknowledge the support and guidance of the island elders and community members.

SUMMARY POINTS

1. This report documents important findings from the mangrove and freshwater habitat surveys for 2012–2014 directed by Dr Norm Duke and Dr Damien Burrows under NERP-funded project 2.2, with contributions from the TSRA and its Ranger program. Project operations were coordinated and facilitated by Jock Mackenzie.
2. The bulk of data presented in this report were collected in the field from a number of Torres Strait islands during 2012–2014.

Wetland and Mangrove Biodiversity

1. A key data output of the project includes observations on the biodiversity of the mangrove vegetation throughout the Torres Straits. These data are essential pre-requisite information for companion studies of biomass, carbon accumulation, and condition of mangrove tidal wetlands in Torres Strait.
2. The total number of mangroves in Torres Strait totals 35 species, with 2 of these being hybrids. No individual island has all these species.
3. *Avicennia officinalis*, a waters edge mangrove species common to SE Asia and New Guinea, is now confirmed to occur on Boigu and Saibai Islands, in Torres Strait and Australia.
4. *Sonneratia ovata,* an uncommon upland fringe mangrove species in Asia and New Guinea, is now confirmed to occur on Boigu Island, in Torres Strait and Australia.
5. *Acanthus ebracteatus* subsp. *ebarbatus*, an undercanopy mangrove species of the Northern Territory top end, is now confirmed to occur on Dauan, Boigu, Saibai, Iama and Zagai Islands, in Torres Strait and Queensland.
6. Species hybrids only occurred where both parental species grew in nearby locations. The hybrid intermediate forms are considered as separate species in the list because they are notable, distinctive plant types in the field, and they maintain morphological character consistently wherever they occur. Additional hybrid taxa are likely occurring also in Torres Strait. A key with known and likely species is supplied with this report.
7. The species are from 18 genera, representing 14 different plant families. This is very high diversity in such a specific plant habitat group. The most well-represented family is the Rhizophoraceae with 13 species and hybrids, while the second is the Acanthaceae family with 5, and the Lythraceae with 4.

8. The number of mangrove species (in brackets) recorded for the following selection of Torres Strait islands/islets is: Tuesday (7); Wednesday (17); Thursday (8); Prince of Wales (14); Friday (3); Hammond (14); Horn (22); Mua (20); Badu (18); Mabiaug (18); Dauan (22); Gebar (24); Iama 'Yam' (27); Boigu Island (32); Saibai (30); Turnagain (7); Zagai (19); Sassie (17); Erub 'Darnley', Garsau, Sermad (11); Cap (13); Tudu (9); Warraber (7); and Mer 'Murray' (4). These records can be viewed using the Atlas of Living Australia supported mangrove species database, Mangrove Floristic Surveys; http://www.mangrovewatch.org.au/index.php?option=com_wrapper&view=wrapper&Itemid=300390.
9. Mangrove maximal spatial extent is influenced by island size. Smaller islands had smaller areas of mangrove vegetation than larger islands. For the above islands of Torres Strait, land area ranges from 20–20,431 ha. While high islands, around 20 ha had less than 10 ha of mangroves, larger islands of around 20,000 ha had around 1,400 ha of mangroves. Large depositional islands, like Boigu and Saibai, did not conform with this trend.
10. Mangrove maximal species diversity was influenced by island size. Smaller islands had less species than larger islands. Despite island shape and topography, the islands with greatest areas of mangrove vegetation had the greatest number and diversity of mangrove species present.

Mangrove Biomass and Carbon Evaluation

1. A key data output of the project includes observations on the structure of the dominant mangrove vegetation units (based on upper canopy species) in each of the five islands in the northern Torres Strait. For each, there are now baseline primary data on local mangrove stands of stand biomass, diversity, density, basal area and canopy height. From these measures, it has been possible to derive realistic, preliminary estimates of stand carbon content for the specific vegetation units being quantified in the mapping component of this NERP project. Note that estimates of tree and stand biomass mentioned below are approximately double the carbon content.
2. For a scaling up from mapping surveys, an equation was derived for estimates from mapped vegetation units, coupled with mean observed estimates of canopy height. This equation may be used in both demonstration sites and for each national inventory. The equation is the significant linear relationship, Total Mangrove Carbon (as living above ground biomass plus below ground biomass) = 19.051*L-Hgt – 14.23, where carbon is

dry weight in $t.ha^{-1}$, and height is the weighted canopy measure (Lorey's height) in metres.

3. Data have been collected for 3 dominant vegetation assemblages of mangrove stands of 5 northern Torres Strait islands. All measured and derived estimates of stand biomass, density, height and basal area with this project compare closely with literature values for similar mangrove vegetative stands in Asia and elsewhere in the World. The structure and biomass of mangrove forests in the five islands depends on the species present, the zonal position, and on the canopy height of the climax stands surveyed.
4. For Geber Island, mangrove biomass data were collected from 5 plots for one dominant mangrove vegetation assemblage consisting of two *Rhizophora* species, *R. apiculata* and *R. stylosa*. *Rhizophora apiculata* tree heights ranged around 12.0 m with a total living mangrove biomass of 619.7 $t.ha^{-1}$. *Rhizophora stylosa* tree heights ranged around 8.8 m with a total living mangrove biomass of 359.1 $t.ha^{-1}$.
5. For Iama (Yam) Island, mangrove biomass data were collected from 7 plots for 3 dominant mangrove vegetation assemblages consisting of *Bruguiera exaristata*, *Rhizophora apiculata* and *Ceriops australis*. *Bruguiera exaristata* tree heights ranged around 5.1 m with a total living mangrove biomass of 281.3 $t.ha^{-1}$. *Rhizophora apiculata* tree heights ranged around 13.3 m with a total living mangrove biomass of 478.2 $t.ha^{-1}$. *Ceriops australis* tree heights ranged around 5.7 m with a total living mangrove biomass of 274.1 $t.ha^{-1}$.
6. For Zagai Island, mangrove biomass data were collected from 2 plots for one dominant mangrove vegetation assemblage, consisting of *Rhizophora stylosa*. Tree heights ranged around 11.4 m with a total living mangrove biomass of 487.5 $t.ha^{-1}$.
7. For Boigu Island, mangrove biomass data were collected from 11 plots for 2 dominant mangrove vegetation assemblages consisting of *Rhizophora apiculata*, *Rhizophora stylosa* and *Ceriops australis*. *Rhizophora apiculata* tree heights ranged around 17.1 m with a total living mangrove biomass of 681.1 $t.ha^{-1}$. *Rhizophora stylosa* tree heights ranged around 19.0 m with a total living mangrove biomass of 441.5 $t.ha^{-1}$. *Ceriops tagal* tree heights ranged around 11.0 m with a total living mangrove biomass of 473.9 $t.ha^{-1}$.
8. For Sabai Island, mangrove biomass data were collected from 7 plots for 3 dominant mangrove vegetation assemblages, *Bruguiera exaristata*, *Bruguiera gymnorhiza*, *Rhizophora apiculata*, *Rhizophora stylosa* and *Ceriops tagal*. *Bruguiera exaristata* tree heights ranged around 7.4 m with a total living mangrove biomass of 476.9 $t.ha^{-1}$. *Bruguiera gymnorhiza* tree heights ranged around 16.9 m with a total living mangrove biomass of 705.2 $t.ha^{-1}$. *Rhizophora apiculata* tree heights ranged around 18.1 m with a

total living mangrove biomass of 702.0 $t.ha^{-1}$. *Rhizophora stylosa* tree heights ranged around 8.3 m with a total living mangrove biomass of 159.0 $t.ha^{-1}$. *Ceriops tagal* tree heights ranged around 11.8 m with a total living mangrove biomass of 726.9 $t.ha^{-1}$.

9. *Bruguiera* species assemblages were sampled only in Saibai and Zagai. Tree heights ranged 5.1–16.9 m with a total living mangrove biomass of 281.3–705.2 $t.ha^{-1}$.
10. *Rhizophora* species assemblages were sampled in all five islands, Gebar, Iama, Zagai, Boigu and Saibai. Tree heights ranged from 8–19 m with a total living mangrove biomass of 159–702 $t.ha^{-1}$.
11. *Ceriops* species assemblages were sampled in three islands, Iama, Boigu and Saibai. Tree heights ranged from 5.7–11.8 m with a total living mangrove biomass of 274–726.9 $t.ha^{-1}$.
12. The overall mean above and belowground biomass for all 32 plots was 482.5 $t.ha^{-1}$. This was averaged for all species included in these surveys. These species are considered representative of mangrove forests throughout the islands. Extrapolation of the total carbon stored in the total area of Torres Strait mangroves, noted below, equals ~6,285,528 tonnes of carbon, present in living vegetation. In addition, based on current literature, there is likely to be up to 5 times more carbon in sediment peat deposits beneath these mangrove forests. This carbon will only remain bound whist mangrove forests remain intact and healthy.

Wetland Habitat Extent

1. A key data output of the project includes assessments of change in mangrove and freshwater habitat extent in each of the 14 islands surveyed in Torres Strait.
2. There are reportedly 31,390 ha of wetlands throughout Torres Strait; with 83% being tidal mangrove wetlands; this equates to around 26,054 ha of mangrove forests through the islands.
3. Updated mangrove mapping for 14 Islands and 300 km of island shorelines.
4. Mean extent of mangrove cover is 67% of shorelines.
5. Fringing mangrove is important for ecosystem service provision
6. Mangrove islands Sassie, Zagai and Buru are unique and important mangrove habitats in Torres Strait. These islands should be provided the highest conservation status.

7. Rocky outcrop islands have a high mangrove exposure. These fringing mangroves are most at risk from marine-based threats.
8. Protection and management of the mangrove fringe should be reviewed for all islands.

Shoreline Habitat Condition

1. A chief data output of the project includes assessments of shoreline mangrove condition around each of the 14 islands surveyed in Torres Strait.
2. Mean shoreline mangrove in a healthy state is 59%.
3. Mean shoreline mangrove in poor condition is 18%.
4. This data provides a baseline of mangrove condition in Torres Strait.
5. High proportion of poor condition mangroves is indicative of the dynamic coastal environment in Torres Strait and highlights that fringing mangroves are exposed to natural pressures.
6. Sea level rise may be exacerbating the effect of wind and waves on fringing mangrove habitat.
7. Gebar mangroves are in very poor condition. This requires further investigation to establish the cause of mangrove degradation.
8. Saibai, Boigu and Mua Islands have the greatest extent of mangroves in poor condition.

Processes Influencing Shorelines

1. A key data output of the project includes assessments of shoreline processes driving change for each of the 14 islands surveyed in Torres Strait.
2. Shoreline processes affecting mangroves vary between islands.
3. Overall the dominant shoreline process is erosion (21% greater than expansion).
4. Sassie and Zagai islands are undergoing substantial change with both mangrove loss and expansion occurring.
5. There is a high proportion of expanding shoreline and depositional gain on Erub Island due to land-based sediment runoff.
6. There is a high proportion of mangrove expansion in Iama Island.
7. Gebar Island is experiencing a high degree of shoreline retreat, with an overall net loss of mangroves currently occurring.

8. Mangrove loss and gain may not be balanced at an island scale, but may be balanced across regional scales.

Drivers of Change and Threats to Tidal Wetland Habitat

1. A key data output of the project includes assessments of key threats and the drivers of change influencing shorelines around each of the 14 islands surveyed in Torres Strait.
2. Nine (9) human related drivers of change were identified as impacting mangroves and shorelines of the Torres Strait islands.
3. Mua Island has the highest number of mangrove management issues present (7).
4. Mangrove cutting is threatening mangrove habitat in the Torres Strait; 2% of mangroves in Torres Strait are estimated to be impacted by cutting.
5. Elevated nutrient loads from STP's threaten mangrove climate change resilience but may facilitate mangrove expansion.
6. Chemical leachate from waste disposal is likely entering mangrove habitat. This poses a threat to human health related to chemical exposure of mangrove fisheries resources.
7. Only a small proportion of mangroves are at risk from localized oil and fuel spills.
8. Mangrove root burial from sediment runoff is impacting 34% of mangroves on Erub Island.
9. Sea level rise appears to be directly threatening 13% of Torres Strait mangrove habitat. Our new observations show how mangrove shorelines seem to have responded to changes in sea level over the last 10–15 years. Some of the change processes identified are newly identified for this powerful driver of change.

Changing Shoreline Conditions and Community Issues

1. A key data output of the project includes assessment of historical change influencing shoreline habitats for 11 islands surveyed in Torres Strait.
2. Updated and refined mangrove maps for 11 Torres Strait Islands.
3. Updated mangrove area assessment has increased the known area of mangroves in Torres Strait by 6% (316 ha).
4. There is an estimated 2% annual increase in mangrove area based on mangrove change assessment of Buru, Sassie, Zagai, Iama and Tudu Islands.

5. Mangrove expansion reflects the low level of direct anthropogenic pressure on mangrove habitats in Torres Strait.
6. Large mangrove increases were observed on Erub and Iama Islands.
7. Iama Island has undergone large-scale change in mangrove extent in the past 30 years, with a net increase in mangrove area of 13% in 37 years (1974 to 2011).
8. Mangrove expansion likely reflects a recent *drop* in sea level during the 1980's and 1990's and has potentially been facilitated by elevated nutrient loads.
9. On Iama Island, 6% of mangroves are recent regrowth. Mangrove regrowth has occurred in most historically cleared areas
10. Regrowth appears to be reflecting a new high mean sea level position on Iama Island, and others that may indicate sea level rise.
11. Mangroves are sensitive to variations in sea level and respond rapidly to sea level variations.

Freshwater Wetlands, Exotic Species and Sea Level Rise

1. A key data output of the project includes observations on the biodiversity of the freshwater habitats in Torres Straits. These data extent information on wetlands observations on native as well as exotic, invasive species in Torres Strait.
2. Torres Strait remains a significant potential pathway for the entry into Australia, of serious pest fish species from New Guinea, which already hosts many such exotic pests. Exotic species of fish, like the newly introduced Climbing Perch, were found commonly in northern islands of Torres Strait. The artificial waterbodies on Horn and Thursday Island are in special need of systematic sampling for the presence of pest fish, one species of which (Gambusia) has already been observed on Thursday Island.
3. Preventing the spread of exotic species requires regular monitoring in combination with a concerted public education campaign amongst island residents and visitors. Our work has shown that in their new range, these species may occupy different habitats to their native range, thus studies on the ecology and environmental tolerances of these species within their new habitats are worthwhile. In addition, new technologies such as being able to determine the presence of various species from their DNA in water samples, could be used to greatly increase monitoring detection efficiency. Research to further these technologies should be considered.

4. There are key management threats to freshwater habitats, especially from introduced animals such as pigs, deer and cane toads, as well as weeds. With so few freshwater habitats present, some of these may be in need of management attention to ensure their integrity. In consultation with traditional owners, this could include fencing to exclude these large introduced animals.
5. Given the likelihood of sea level rise affecting low-lying islands such as Boigu and Saibai, gaining an understanding of the salinity dynamics of the wetlands on the island is important to monitoring any changes that are likely to result from sea level rise.

Introduction

Mangrove Tidal Wetlands of the Torres Straits

Mangroves are the most common vegetation community in the Torres Strait and provide the most extensive forested habitat (Long and McLeod 1997, Stanton et al. 2008). Mangroves are believed to be the 'coastal canaries', where they identify and quantify change processes occurring to shorelines, in runoff from surrounding catchments, to downstream nearshore habitats of seagrass meadows and coral reefs.

The mangrove and freshwater wetland ecosystems of the Torres Strait are considered places of immense cultural, ecological and economic significance (Shnukal 2004). However, little is known about these important values and benefits. The location of Torres Strait at the northernmost tip of Australia, and the close proximity to Papua New Guinea (PNG), provides a climatic environment, supporting a rich and tropical diversity with exotic species and unique biotic assemblages. This rich biodiversity of this immense natural resource is closely linked with Torres Strait Islander culture, particularly regarding the innate identity of Islanders for their marine and coastal environments. These special and long-managed natural environments are therefore expected to be of high cultural significance to the region, and Australia.

A primary objective of the Mangrove and Freshwater Wetlands Program was to provide a comprehensive survey of wetland habitats within Torres Strait. To achieve effective management and protection of wetland habitats requires primarily, a detailed assessment of their flora and fauna, vegetation assemblages, their current condition and the present and future threats. The unique climatic and geological conditions of each of the Torres Strait islands is such that each island must be assessed separately, as broad-scale generalisations regarding habitat structure, composition and threats are likely to be invalid. And, these assessments are integral to the design of effective and lasting management strategies for the preservation of such beneficial natural resources.

As outlined previously, this component of the NERP Mangrove and Freshwater Wetland surveys project has 4 key activities in the northern islands of Torres Strait; including: (A) mapping and verification; floristics and biodiversity (B); biomass and carbon evaluation (C); and (D) shoreline health monitoring. This combination of activities makes up an important part of a baseline Coastal Health Archive and Monitoring Program for the region.

The biomass and carbon component of the work has only been possible after acquisition of primary data for 5 Islands. These data have been carefully assessed and processed. Key observations and derivations from these data are summarised in this report.

Mangroves provide important goods and services to coastal environments that support and protect local economies, and social, cultural and heritage values of island communities in Torres Strait.

These values are commonly referred to as ‘ecosystem services’. Mangroves provide six key ecosystem services to Torres Strait Islanders:

1. Provision of fish habitat & supporting nearshore fisheries (Manson et al. 2005)
2. Shoreline protection (McIvor et al. 2013)
3. Water quality improvement (Adame et al. 2010)
4. Carbon storage (Donato et al. 2011)
5. Support local biodiversity (Traill et al. 2011)
6. Cultural heritage and traditional use values (Duke 2006)

For further information on mangrove ecosystem services refer to Lee et al. (2014).

Despite their importance, mangroves continue to be directly destroyed and degraded by poor catchment and coastal zone management. Globally, 30% of the world’s mangroves have been lost in the past 30 years (Duke et al. 2007). In the state of Queensland, mangroves are protected under the Fisheries Act 1994, yet here too they continue to be destroyed for development (Duke et al. 2003). Mangroves are increasingly threatened by urban development, pollutants and altered hydrology in the coastal zone. These factors may not reduce mangrove extent, but they do influence habitat quality, reducing the capacity of mangroves to provide ecosystem services. Mangrove habitat degradation greatly reduces the capacity of mangroves to respond to the impact of future climate change (Gilman et al. 2008, Ellison 2014). The location of mangroves at the shoreline edge places them in the direct line of climate change impacts; sea level rise, more severe and frequent storms and more frequent drought and floods (Nitto et al. 2014). Reduced habitat condition, reduced biodiversity and habitat complexity and altered ecosystem processes reduce the capacity of mangroves to withstand climate impacts and their capacity of mangroves to buffer these impacts and protect adjacent coastal areas (McLeod and Salm 2006)

Prior to undertaking this assessment of mangroves in Torres Strait, local and regional natural resource managers expressed a concern regarding the current state of mangroves in Torres

Strait and the lack of available information regarding mangrove threats to inform better mangrove management. The primary concerns were:

1. *Lack of information on mangrove extent and biodiversity.*
2. *The need for quantification of mangrove values in Torres Strait.*
3. *Better understanding of mangrove local use and threats posed by anthropogenic disturbance.*
4. *The threat of climate change and implications for mangrove habitat in Torres Strait.*

To effectively address these issues, it was necessary to undertake a broad-scale baseline assessment of mangrove habitat in Torres Strait.

The mangroves of Torres Strait are likely to be threatened by climate change, including more severe and frequent storm events, sea level rise and altered rainfall patterns (Gilman et al. 2006, Green et al. 2010b). While it is not possible to prevent climate change at the local scale, it is possible to reduce direct human related impacts that are likely to reduce capacity of mangroves to resist and recover from climate change impacts. The capacity of mangroves to respond to climate change impacts depends directly on improving local mangrove management (Gilman et al. 2008). This assessment focuses on examining historical mangrove change, quantifying current mangrove condition and identifying existing impacts and likely risk factors that could influence mangrove climate change resilience.

Freshwater Wetlands of the Torres Straits

Despite the high rainfall in the Torres Straits, freshwater wetlands, especially permanent ones, are rare. The strong seasonality by which rainfall falls, combined with the high evaporation rate and limited catchment area on most islands, restrain the development of freshwater wetlands and waterbodies. Wetland extent in Torres Strait has been mapped by theQueensland Department of Environment and Heritage Protection (QDEHP 2012), which can be located at http://wetlandinfo.ehp.qld.gov.au/wetlands/facts-maps/

They found that of the total of 31,390 ha of wetlands mapped, only 17% were freshwater wetlands, the majority of which are seasonal. The islands with the most wetland area are the larger inner islands such as Muralag (which was not part of the study area), Moa Island and the northern mud islands (Saibai and Boigu) where most of our freshwater work occurred.

The Torres Straits are believed to have been emergent from the sea, for most of the last 100,000-80,000 years (Woodroffe et al. 2000), providing a much larger land area than today, and continuous terrestrial connections between Australia and PNG. At this time, with more land and larger catchment areas being present, the freshwater fauna of the area which are now the Torres Strait islands, was most likely more diverse and extensive than today, including elements of both the north Australian and PNG biotas. Resubmergence of the shelf began 8,000 years ago and was complete by 6,000-5,800 years ago (Woodroffe et al. 2000), producing the network of >100 islands and 600 reefs seen today. In the present era, although located between the differing habitats and faunas of northern Australia and southern PNG, freshwater faunal diversity of the Torres Strait islands is depauperate, containing only a fraction of the freshwater species found in either northern Cape York Peninsula or southern PNG. This is the same situation that has been found for terrestrial vertebrate diversity of Torres Strait islands, which is depauperate compared to either northern Cape York Peninsula or southern PNG (Lavery et al. 2012). The low diversity of freshwater fauna can be attributed to the limited freshwater resources present. Those species that are present have drought coping strategies (such as aestivation or burying into muds/bedsands during the dry season) or able to cope with a degree of salinity, by occupying estuarine locations during the dry season. Indeed, the majority of fish species present in freshwaters are essentially brackish/upper estuarine species that also occupy freshwaters. Although the diversity of freshwater species is low, those species that are present may be of interest or special importance, having survived and evolved during a period when other species became locally extinct. The genetic relatedness of these species to either their southern or northern neighbours, or indeed to their conspecifics on other Torres Strait islands, would be of some interest. This could not be specifically pursued during the course of this study, but genetic samples of various species have been collected and sent to relevant experts to be utilised as part of wider studies of biogeography and genetic connectedness.

Lack of permanent freshwater resources, not only constrained freshwater fauna diversity, but it also restricted availability of drinking water, making it a contributory factor limiting the development or larger populations on Torres Strait islands (McNiven and Hitchcock 2004). With the limited permanence of freshwater in streams and other waterbodies, freshwater for drinking and subsistence was historically obtained from wells and small springs. Nowadays, most inhabited islands have artificial water storages to supply domestic needs and in many cases, the historic wells have become degraded or dysfunctional due to lack of maintenance.

Some of the northern islands manipulated their seasonal freshwater resources, maintaining a complex system of mounds and irrigation ditches to sustain an agricultural system (Barham et al. 2004). This was most prevalent on Saibai Island and these formations, although no longer in use, can still be observed today.

Methodology

Biodiversity Surveys

The information presented within this review draws heavily upon reports contained within the grey literature, as there are few peer-reviewed studies that have detailed Torres Strait wetland habitats. As such, this review represents a key opportunity to disseminate existing knowledge of Torres Strait wetlands to the public and to provide an important baseline for future work. This report provides a comprehensive list of indentified wetland plant species within the Torres Strait bioregion.

A complete list of wetland plant species for Torres Strait was compiled by comparing a list of wetland flora species potentially found in Torres Strait against lists of all recorded plant species in the region (Duke 1985, Duke 2006). The list of potential wetland plant species was generated from a number of available sources detailed in Table 1. The wetland plant list was divided into 5 distinct habitat units based on the general habitat of the species, salinity and inundation tolerance. The four categories used were Mangrove, Saltmarsh and saline grassland, Saline swamp, Tidal Wetland Associate, and Freshwater wetland species (*see* Wetland Plant Definitions). The classification of mangrove plants was defined according to Duke (2006). Saltmarsh plants and saline swamp species are classified with reference to Saintilan (2009) and Wightman et al. (2004). Mangroves and saltmarsh plants together form the broader Tidal Wetland classification. Tidal wetland associates were considered to be plants that occur adjacent to, and occasionally within, tidal wetland systems, but are not exclusively located within the tidal zone. The list of tidal wetland associates was derived from plants included in mangrove plant lists of Wightman (2004, 2006) and detailed within the list of tidal wetland vascular plants on the Australian mangrove and saltmarsh resource (ALA 2014), that were not already classified within tidal wetland categories. Freshwater wetland species were derived from the list of freshwater hydrophytes and freshwater indicator species lists from the Queensland wetland mapping program (QDEHP 2012–2014).

Wetland plant definitions

Mangrove species:

- *a tree, shrub, palm or ground fern, generally exceeding one half metre in height, that normally grows above mean sea level in the intertidal zone of marine coastal environments and estuarine margins* (Duke, 2006).

Saltpan and Saline grassland species:

- *salt tolerant herbs, small shrubs, grasses and sedges usually less than <0.5 m tall, found within the inter-tidal zone or saline influenced areas that are highly adapted to harsh growing conditions such as high salinity, full light exposure and moisture extremes* (Adam, 1993). These plants can occur in non-tidal habitats, but are mostly restricted to the inter-tidal zone. 3 broad sub-categories of saltmarsh plants can be defined based on their salt-tolerance and vegetation community structure. ***Saltpan vegetation*** – *species usually occupying open, flat, tidal areas with extreme salinity and waterlogging variability*. Often referred to as samphire communities. ***Saline grassland vegetation –*** *species occupying densely vegetated, upper intertidal saltmarsh areas that receive regular but infrequent tidal inundation*.

Saline swamp species:

- *species occupying areas with near continuous waterlogging as a result of ponding or continuous freshwater flow into tidal and saline influenced area*s.

Freshwater wetland species:

- *plants that naturally occur, achieve maturity and successfully reproduce in areas that experience wet conditions, where the root zone becomes saturated or inundated with freshwater during the growing season* (DEH 2014).

Tidal Wetland Associates:

- *plants that have some degree of salt tolerance that are regularly found near or adjacent to tidal wetland areas, but predominantly occur outside the tidal zone* (Duke 2006).

The list of recorded plant species for Torres Strait was sourced from Stanton, Fell & Gooding (2008) and the Atlas of Living Australia (ALA 2014) records for the Torres Strait natural resource management area (accessed June 2014). The ALA is an online database of all herbarium records within Australia.

Table 1. Published plant species lists used to determine the presence of wetland flora in Torres Strait.

Type	Source	Online Database Location
Wetland Plant Species Lists		
Regional Wetland Plant Species	DEH, 2012a	http://www.ehp.qld.gov.au/wildlife/wildlife-online/
Queensland Hydrophytes - Wetland Flora Indicator Species	DEH, 2012b	http://wetlandinfo.derm.qld.gov.au/wetlands/factsfigures/FloraAndFauna/Flora/IndicatorSpeciesList.html
Mangrove Species	Duke, 2006	http://wiki.trin.org.au/Mangroves/KeyToMangrovePlantSpeciesOfAustralia
Mangrove & Saltmarsh Species	Wightman, 2006	
Saltmarsh Species	Johns, 2006	http://www.alocasia.com.au/qld_saltmarsh_plants/
Saltmarsh species	Adam, 1981a	
Tidal Wetland Species	Australian Mangrove & Saltmarsh Resource, 2012	http://wiki.trin.org.au/Mangroves/Vascular_Plants
Torres Strait General Flora Species Lists		
Regional Ecosystem Mapping assessment	Stanton, Fell & Gooding, 2008	
Darnley, Erub and Yorke Island vegetation	Freebody, 2006	
Australian Herbarium Records, Torres Strait Natural Resource Management Area	Atlas of Living Australia, 2012	http://www.ala.org.au/
Badu Island Vegetation	Garnett & Jackes, 1984	
Torres Strait Wetland Species lists		
Mangroves of Torres Strait	Bunt, Williams & Duke, 1982	
Mangroves of Torres Strait	Duke (pers obs), 2012	
Tidal Wetland plants of Torres Strait	Wightman, 2004	http://www.environment.gov.au/coasts/mbp/publications/north/pubs/n-key-species.pdf
Boigu Island Wetland Vegetation	Burrows (ed), 2010	http://www-public.jcu.edu.au/public/groups/everyone/documents/technical_report/jcuprd1_072508.pdf
Daru Port - Mangrove Survey	Boto & Duke, 1984	
Wetland Mapping & Extent Data		
Mangroves	Long & McLeod, 1996	
Wetlands	DEH, 2012b	http://wetlandinfo.derm.qld.gov.au/wetlands/MappingFandD/WetlandMapsAndData/WetlandMaps.html
Other Sources not cited fully due to lack of availability		
Torres Strait Vegetation mapping and Surveys	Freebody, 2002	
Torres Strait Vegetation mapping and surveys	ESS, 1994	
Vegetaion of Mua and Mer Islands.	Wannan & Bousi, 2003	
Vegetation communities of Torres Strait	Neldner, 1998	

Mangrove Biomass Studies

Measuring mangrove stand structure and biomass - the context for using the Long Plot methodology

Mangroves have the distinction of forming a unique marine habitat that is both forest and wetland. As such, they form an important component of a number of international conventions that recognize their uniqueness and immense value to both coastal and marine communities, and mankind in general (e.g. Duke et al. 2007). It is essential that the assessment of such a valuable resource be conducted in a rigorous and practical way.

The Long Plot methodology was developed specifically to meet such needs. The method allows quantification of the biomass of mangrove forests in a way that is scientifically reliable, accurate, low cost, low-skilled, simple, pragmatic and relevant. The essential distinguishing characteristic of the Long Plot method is that it uses a set number of trees rather than a fixed plot area. The method takes in measures sequentially so the measures created can be evaluated to show accumulative consistency and covariance in the data. And, these observations can be readily verified and checked after collection in the field. The aim of this methodology has been to demonstrate plot homogeneity with statistical rigor. This has been a primary question in the collection of data from different mangrove vegetation units, or zones – as observed in the field and from remote sensing – to ensure a sufficient, but minimal number trees and area of habitat are measured.

Definition of mangrove habitat – essential knowledge for site selection

The method does rely on at least one observer present having a reasonable knowledge of what is, and what is not a mangrove stand. It cannot be assumed that there is a clear distinction between mangroves and other plant habitats. While it maybe surprising, it is not always clear exactly what is a mangrove or what vegetation is considered mangrove habitat. So, it is important to review briefly the definition of mangroves. Mangroves are the tidal wetland habitat comprised of salt-tolerant trees and shrubs that inhabit the elevation zone from above mean sea level up to the highest tidal level. And, as with rainforests, mangroves have a mixture of plant types from a diverse array of plant families. Specifically, the definition of a mangrove is a tree, shrub, palm or ground fern, generally exceeding one half metre in height, that normally grows above mean sea level in the intertidal zone of marine coastal environments and estuarine margins. Mangroves share this intertidal niche with saltmarsh plants, as well as a number of dedicated epiphytes and parasitic plants plus some occasional associates from neighbouring upland habitats.

Mangrove plants mostly consist of trees and shrubs of varying stature and structure. And, since the larger plants as trees form the substantive part of any stand structure, the description of mangrove stands has many similarities with upland forestry methods. However, there are notable differences as evidenced by the distinctive structural features of their above ground roots as well as their often extraordinary stem structures. Both these characteristics of mangrove forest stands have significant implications for the way mangrove trees and shrubs are measured.

Weighted stand canopy height – Lorey's Height

Estimates of the weighted mean canopy height (see: http://fennerschool-associated.anu.edu.au/) – especially since these canopy trees are the ones observed in remote sensing imagery for mapping of vegetation units. Lorey's mean height weights the contribution of trees to the overall stand height by their basal area. Lorey's mean height is calculated by multiplying tree height (H) by their basal area (as the cross section area of stems per unit area), and then dividing the sum of this calculation by the total stand basal area (G).

Estimating biomass and carbon content

As with general forestry practice, allometric equations offer a convenient and non-destructive way of sampling forest biomass. Such equations have long been used to estimate mangrove forest biomass from field measures of density, stem diameter and height (Snedaker and Snedaker 1984). Over the years, improvements have been made with the reporting of more specific equations for different species (e.g. Clough and Scott 1989), and for a greater range of climatic regions and mangrove habits (e.g. Clough et al. 1997). The bulk of these estimates relate to the relatively easy to measure biomass above-ground (also see Fromard et al. 1998). However, there are a limited number of equations that also include below-ground biomass (Poungparn et al. 2002, Ong et al. 2004, Komiyama et al. 2005, Comley and McGuinness 2005).

Ong et al. (2004), working with *Rhizophora apiculata*, observed that his allometric equations were not very site specific. And, partitioning of biomass was quite variable for smaller trees (diam. <15 cm) but relatively constant for larger trees. The ratio of all the components, except for trunk, to total biomass was larger and more variable for the smaller trees. For larger trees, 4.5% was allocated to below-ground roots, 12.5% to stilts, 71.7% to trunk, 8.1% to branches, twigs and fruits and 3.2% to leaves, i.e. 17% is apportioned to roots and 11.3% to the canopy (branches, twigs, leaves, flowers and fruits), which is a bottom-heavy stable structure.

Komiyama et al. (2008) reviewed 72 published articles to elucidate further characteristics of biomass allocation and productivity of mangrove forests. The biomass of mangrove forests varies with age, dominant species, and locality. In primary mangrove forests, the above-ground biomass tends to be relatively low near the sea and increases inland. On a global scale, mangrove forests in the tropics have much higher above-ground biomass than those in temperate areas. Mangroves often accumulate large amounts of biomass in their roots, and the above-ground biomass to below-ground biomass ratio of mangrove forests is significantly low compared to that of upland forests. Litter fall production is generally high in mangrove forests. Moreover, in many mangrove forests, the rate of soil respiration is low, possibly because of the anaerobic soil conditions. These trends in biomass allocation, net primary production, and soil respiration will result in high net ecosystem production, making mangrove forests highly efficient carbon sinks in the tropics. Komiyama et al. (2005) identified common allometric equations, ideally applicable to key mangrove species depending on their stem wood density. These equations can be used to estimate the weight of trunk, leaf, other above ground parts, and roots. The allometric relationships for these weights were attained, when stem diameter was selected as the independent variable.

The value of allometric equations depends on the strength of the relationship between component dry weight (W) and stem diameter (D), and/or tree height (H). Stem diameter (often derived from stem girth or circumference) is measured more conveniently and more easily than height, so the latter is less often used in biomass estimations.

Choosing allometric equations for this study

For calculating the biomass of individual trees (above and below ground) with this project, it was essential to first review available allometric equations. This was considered essential in the absence of local country equations for the dominant species present.

There are a number of equations from studies elsewhere (see Appendix 1; Komiyama et al. 2008). These quantify the relationship between simple structural measures (like stem diameter of trees) and dry weight of above and below ground biomass (AGB and BGB, respectively). Equations vary between species. By summing the amounts of biomass for respective species and individual plants present, this amount equates directly to amounts of carbon stored in various mangrove plots and zones. Importantly, because there are a number of species to consider, there are common equations that apply to multiple species (Komiyama et al. 2005, Chave et al. 2005). These become specific-specific with the input of cited measures of specific wood density for particular species (see Appendix 2). The choice therefore is to either use an equation for each species (these preferably are developed locally), or to use the common equation that uses these species-specific values of wood density (*p*). The current approach is to use a common equation, but the actual choice requires additional justification and validation.

The common equations for biomass estimates of mangrove forests include:

W_{AGB} 1 = 0.251*p*D^2.46 (Komiyama et al. 2005)

W_{AGB} 2 = 0.168*p*D^2.47 (Chave et al. 2005)

$W_{AGB/H}$ = 0.0509*p*D^2.H (Chave et al. 2005)

W_{BGB} = 0.199*p*^0.899D^2.22 (Komiyama et al. 2005)

Note: a) Explanation of equation parameters - where W_{AGB} is above ground dry weight in kg, W_{BGB} is below ground dry weight in kg, D is stem diameter in cm, and *p* is wood density for individual species in t/m3. Wood densities *ρ* have been calculated from the ratio of *W*S/*V*S, where *W*S is trunk (stem) dry weight in t (=tonnes =kg/1000), and *V*S is trunk (stem) wet wood volume in m^3. Height (H) is included in one equation, and this is considered more realistic across a variety of climatic zones. There is uncertainty in the literature as to whether W_{AGB} should include *Rhizophora* prop roots, or not. While it may seem logical that prop roots would be part of W_{BGB} often this is either not stated or inconsistent. For this treatment, it is assumed that W_{AGB} does not include prop roots, and W_{BGB} does. Hence, the ratio of W_{AGB} to W_{BGB} will represent the Stem to Root ratio often used in forest descriptions.

Note: b) There is another serious question surrounding the protocol for measuring stem diameter (D). Slight differences in this measure can create considerable differences and errors in biomass and carbon calculations when using allometric equations. The terrestrial forestry standard has stem diameter at 1.3 m above the ground – called, diameter at breast height (DBH). However, while a standard rule for all trees is understandable, important and desirable, unfortunately there are considerable difficulties in applying the DBH rule to mangrove plants – as a collection of ferns, a palm, shrubs and trees. In Appendix 3, stem characteristics of most Indo West Pacific mangroves are compared and assessed for their relevance in using DBH. In more than 50% of species listed, DBH cannot be strictly applied to the measurement of stem diameter, where these either do not have stems, or they are too short, or they are shrubs with low branching, or they have highly placed prop roots or buttresses. For the remaining 21 species, the DBH rule applies only for a minority of occasions. Therefore, in the majority of instances when stem diameter is measured in mangroves, amendments to the DBH rule are applied. This is strong justification for questioning why the DBH standard is applied at all. And, it is strong justification for the adoption of a more appropriate and unequivocal standard guideline. A more realistic protocol for appropriate measurement of stem diameter for mangrove plants is needed. While alternate measurement rules have been proposed (see Komiyama et al. 2005), in general, these have not been widely adopted, and there is incongruity and inconsistency between studies. This is of concern when applying someone else's equation, as this requires the use of their method – and often this is not clearly stated. The importance of this distinction has been greatly elevated by recent requirements for more precise and reproducible measures of sequestered carbon in mangrove forests. In this study, while we will collect data applicable to existing equations, it is our intention to also measure stem girth using a more pragmatic standard in an effort to be part of a process of refinement in this methodology. For this reason, stem girth has been measured, where possible, above the highest prop root and below the lowest branch. The application of this rule to each species and form is shown in Appendices 3 and 4.

Note: c) In addition, for those plants with multiple stems at their base (a common occurrence in mangrove habitats), the rule is that each stem will be measured, while making reference to their other branches.

Note: d) It is recognised further that there are some mangrove stands, like stunted *Rhizophora* thickets, that defy all attempts to apply some standard measures, and to non-destructively quantify their structural characteristics. In some tangled thickets, it is sometimes impossible to tell where stems differ from branches or above ground roots, and even where different individual trees begin and end. In these cases, the only solution maybe to physically cut up and sample representative area plots and equate these to canopy height as the proxy for biomass.

Calculations of biomass and carbon content of mangrove vegetation units

After estimating the biomass (W in kg) for each individual tree in both above and below ground components, the sum these was taken for each sample plot. Calculation was then made of the total biomass per unit area, dividing the biomass by the plot area (A in m^2). Make comparable estimates for each set of plots in each vegetation unit, in each study area.

Calculation of the mean carbon stock for above and belowground biomass of each component is made by converting plant dry weight estimates to amounts of carbon. This is a primary goal – to determine the amount of carbon accumulated in a mangrove stand. For this calculation, the volume of carbon as dry biomass is quantified for the various forest components, including: woody stems, branches, leaves – using the conversion coefficients 0.4535, 0.4800, 0.5025, respectively (note that these coefficients vary and require local confirmation for particular species). Carbon accumulation is calculated by multiplying the dry weight biomass estimates (W) by the carbon coefficients. The total carbon accumulation of trees is the total of all the component parts. For overall calculation of carbon amounts in total biomass, the carbon coefficient is usually roughly averaged at 0.5. However, this calculation would benefit from using a more accurate coefficient for the particular stand.

A subsequent step might also be to calculate the absorption of carbon dioxide by forests by converting carbon estimates to carbon dioxide equivalents. This is calculated by the method of NIRI (Institute Nissho Iwai-Japan) where the CO_2 absorbed equals the carbon accumulation times 44/12, where 1 ton of carbon is equal to 3.67 tons of CO_2.

Remote estimation of mangrove forest carbon – something for the future

It seems likely that in the future, biomass and carbon estimates made from field locations will be verified and scaled up from remotely operated sensors on either satellites or from specially equipped aircraft. These are not expected to replace field assessments, but such tools would be useful for, a regional collation of plot inventories, monitoring plot condition and general review for on-going compliance and plot maintenance.

There are at least two approaches described: (1) spatial quantification based on geographic area of vegetation units – use normal wavebands in high definition satellite imagery; and (2) direct estimates of biomass based on stand height and ground truth – using LIDAR as radar wavebands. The latter are expensive but this is a tool that may be used by national and regional groups to verify claims made by community groups as custodians of the forested areas.

The first method, by Proisy et al. (2007), used Fourier-based textural ordination (FOTO) to estimate mangrove forest biomass from very high-resolution (VHR) IKONOS images. The method identified and characterized high biomass tropical forest from standardized measures of canopy grain characteristics. In the case study presented, multiple linear regression using the three main textural indices yielded accurate predictions of mangrove total aboveground biomass over 8000 ha of unexplored, poorly accessible mangrove.

The other method, described by Simard et al. (2006), produced a landscape scale map of mangrove tree height using elevation data from the Shuttle Radar Topography Mission (SRTM). This data was calibrated using airborne LIDAR (X-ray) data and a high resolution USGS digital elevation model. The authors further used field data to derive a relationship between mean forest stand height and biomass in order to map the spatial distribution of standing biomass of mangroves, and the total mangrove standing biomass.

For this NERP-funded project, it was not possible to utilize such techniques, but intermediate remote assessments were conducted using geo-referenced video with the Shoreline Video Assessment Methodology (S-VAM). With S-VAM, it has been demonstrated that observations of biomass and carbon were quantified. The technique has the benefit of linking mapping and field verification to gain not only a spatial quantification with measures of structure and biodiversity, but also to measure habitat condition and key drivers of change.

Field data collection strategy

Mangrove stands and particularly the distinct zones, are often relatively narrow. The location and orientation of plots were standardised to accommodate these characteristics. Plots were kept narrow and orientated along tidal contours – notably laid out parallel to the sea or channel edge. This had the desired effect of minimising variability of species composition and structural assemblages dependant largely on inundation frequency and elevation. Specific plot sites were referenced using GPS coordinates for later location on remote sensing images ranging from aerial photographs to those on Google Earth, or others.

Study areas were selected within mangrove stands on each of five islands. For each site, a small number of plots were sampled for their forest structural characteristics. The number of plot measured depended on the number of mangrove zones (species assemblage types) within the respective areas. The objective was to measure multiple plots for each dominant vegetation type of each site.

Our primary objective was to rapidly and accurately determine key biodiversity and structural characteristics of selected mangrove stands for the calculation of biomass and carbon content. Specific characteristics included: species, stem density, canopy height and stem diameter. The basic assessment unit was the plot of sampled trees, along with the record of accompanying information, like species dominating the canopy – as observed from remote sensing imagery – plus the condition of trees in each plot. A standard field data sheet was used.

The transect layout of the Long Plot methodology was developed specifically, to accommodate the special features of mangrove forests. Plots of 4 metre wide were laid out as prescribed – within single mangrove vegetation zones. The length of the plots depended on the density of trees, and the zone's extent. The number of trees sampled varied around 30–50. Tree height was determined using height measuring laser hypsometers.

Data management following field data collection

Once data were collected from the field, they were input into a dedicated, pre-formatted Excel spreadsheet with fields and columns matching the field data sheet. These fields have all the necessary information for determination of plot area (A), plus stem diameter (D) and tree height (H) as well as details of the location markers, like GPS coordinates, plus places to add comments about tree condition, like live or dead condition, whether they are unhealthy, and how trees died.

Shoreline Video Assessment – S-VAM

The MangroveWatch S-VAM approach enables a whole-of-system assessment of shoreline mangrove forest structure and condition using georeferenced continuous digital video recording of shoreline. Video imagery is collected using a Sony Handycam from a low flying helicopter travelling parallel to the shoreline at a height of ~100 ft. and distance of ~100m, at a speed between 70 and 100 km/hr (Figure 1). The video camera is positioned to record directly perpendicular to the direction of travel at all times. Shoreline video imagery is collected with a concurrent time-synchronized 1-second interval GPS track to provide spatial reference to the imagery. Voice recording of observations on mangrove species composition, structure, condition and threats are made during recording.

Figure 1. Shoreline Video Assessment Method (S-VAM) in action.

Video imagery assessment

Shoreline mangrove forest features are recorded from the video using visual criteria-based classification. The video is first divided into 1-second jpeg frame images. The video time stamp and GPS track enable each frame to be related to a position along the shoreline (+/- 10 m). Using ArcGIS 10.0, the shoreline is divided into 50m sections depending on island size. Each shoreline section is related to a video frame using the ArcGIS 10.0 “near table” tool such that the imagery seen between 2 frame locations represents 50m of shoreline. The 50m sections of coastline are then classified according to a set of visual criteria designed by the MangroveWatch Hub at JCU.

Features assessed and criteria used

Mangrove Forest Presence

The presence of mangrove forest located along the shoreline is recorded as present or absent.

Mangrove Forest Condition

Mangrove forest condition describes the overall health of the fringing mangrove forest. Mangrove condition is visually assessed using presence of canopy dieback and dead trees. Dieback presence describes the presence of visible dead stems and branches ranked from 0 to 2, with 0 being forest with no dieback present. Dead tree presence describes the presence and number of dead trees present within the frame assessed ranked from 0 to 2, with 0 being forest with no dead trees present. All classification is based on the visible fringing mangroves intersecting the centre line of the frame. Mangroves are classified as “Healthy” if no dieback or dead trees are visible. Mangroves are classified as “Poor Condition” if a 2 is scored for either dieback or dead trees.

Shoreline Mangrove Forest Condition

Shoreline mangrove forest condition describes the overall health of the fringing mangrove forest. Mangrove condition is visually assessed using presence of canopy dieback and dead trees. Dieback describes the presence of visible dead stems and branches ranked from 0 to 2; with 0 being forest with no dieback present, 1 being low-level dieback present and 2 being severe dieback present. Dead trees describes the presence and number of dead trees present within the frame assessed ranked from 0 to 2; with 0 being forest with no dead trees present, 1 being one or two dead trees present and 2 being many dead trees present. All classification is based on the visible fringing mangroves intersecting the centre line of the frame. Mangroves are classified as “Healthy” if no dieback or dead trees are visible. Mangroves are classified as “Poor Condition” if a 2 is scored for either dieback or dead trees.

Inner Fringing Forest Condition

As for to shoreline mangrove forest condition, the condition of the inner mangrove fringe forest was assessed using visual indicators of dieback and dead tree presence. The inner fringe forest was defined as forest comprising of *Bruguiera* and *Rhizophora* present directly behind the shoreline mangrove margin. As not all inner fringe forest is visible all the time, this data is used for reference and visual groundtruthing purposes only.

Shoreline and mangrove forest process

Mangrove forest process describes shoreline mangrove habitat identified as either retreating, stable or expanding. Visual indicators were used to classify these conditions. Mangrove retreat describes locations where mangrove margins are fragmented with a visible ‘jagged’ edge, and dead and fallen mangroves are present. Mangrove expansion describes the presence of young trees and or dense seedling shoreward of the main mangrove shoreline fringe indicating recent shoreward colonization. A gradually decreasing tree height gradient from the fringe landward to shoreward margins was also used to indicate mangrove expansion.

Table 2. Aerial survey dates and locations (see Figure 2).

Island	*Date Surveyed*
Mua	November 2011
Badu	November 2011
Mabuiag	July/August 2012
Dauan	July/August 2012
Buru	July/August 2012
Boigu	July/August 2012
Saibai	July/August 2012
Iama	July/August 2013
Gebar	July/August 2013
Tudu	July/August 2013
Cap	July/August 2013
Sassie	July/August 2013
Zagai	July/August 2013
Erub	July/August 2013

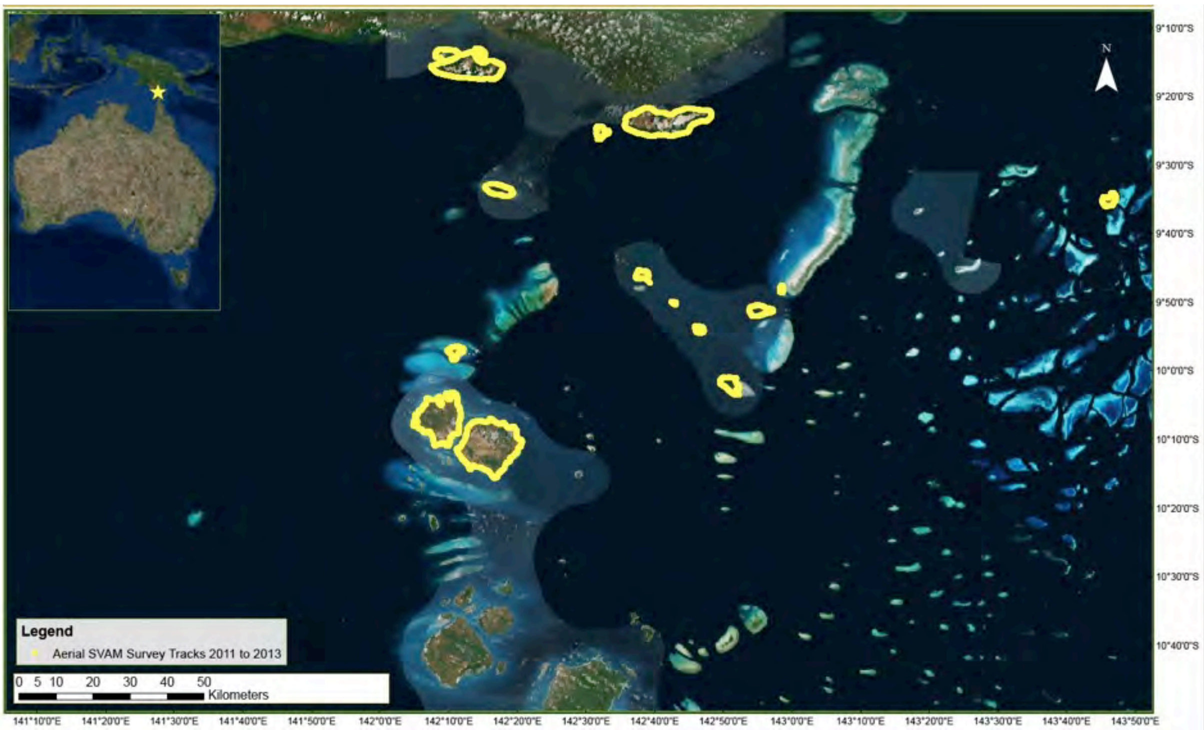


Figure 2. Torres Strait mangrove survey locations and tracks.

Habitat Mapping, Historical Mangrove Change Assessment and Threat Mapping

Current Mangrove Extent

Mangrove habitat was mapped on the 14 islands assessed through manual polygon construction and visual interpretation of a combination of recent (2011 to 2014) orthorectified aerial imagery and satellite imagery using ArcGIS 10.0. Existing wetlands and regional ecosystem mapping is available for all Torres Strait Islands, with varying degrees of accuracy and age. Existing mangrove layers were used as a guide to inform current extent. SVAM data on mangrove shoreline presence and the extensive image database collated during aerial surveys were used to inform image interpretation. Mangrove habitat has distinct colour and texture in aerial imagery and can generally easily be distinguished from adjacent terrestrial forest and urban landscapes.

Historical Mangrove Change Assessment

A comparison of the existing mangrove extent from regional ecosystem mapping undertaken by (Stanton et al. 2008) and current extent mapping was used as the basis for historical change assessment on all islands except Iama. ArcGIS 10.0 was used to identify areas of mangrove expansion and mangrove loss from overlays of the two mangrove extent layers.

Historical Change - Iama Island Case Study

A more detailed assessment of mangrove historical change was undertaken for Iama Island. Here, mangroves were mapped from orthorectified historical imagery from 1974, 1987, 1998 and 2011. The current extent of mangroves on Iama Island was mapped as per the description above, with unsupervised image classification in ArcGIS 10.0 also informing manual interpretation. The current mangrove extent layer was used to guide historical change. Mangrove change was classified as loss, expansion or regrowth. Regrowth defines mangrove presence in areas that were previously classified as loss in previous time periods. A comparison of 1974 and 2011 mangrove extent was included in the overall mangrove change assessment above.

The presence of mangrove drivers of change and threats to mangroves was determined from aerial survey, ground surveys and discussion with traditional owners and TSRA land and sea rangers.

Threat Mapping

Cutting

Manual polygon construction surrounding mangrove locations where cutting was observed during ground surveys. As mangrove cutting is not generally visible from the air or from satellite or aerial imagery, these figures provide an estimate only based on ground survey observations and are therefore likely to underestimate the total area impacted.

Altered Hydrology

Manual polygon construction surrounding areas of mangrove experiencing reduced condition (dead trees and dieback) as a result of observed altered hydrology

Nutrients

Mangroves within 2 km of a nutrient point source, a sewage treatmen plant (STP).

Chemical Leachate

Mangroves within 1 km of a waste disposal location, with direct tidal connectivity or reasonably assumed to have groundwater connectivity.

Oil

Mangrove areas within 1 km of a boat ramp and having direct tidal connectivity.

Sea Level Rise and Root Burial

The presence of mangrove forest collapse and damage within the inner fringing forest was used as an indicator of sea level rise impacts. Assessment of inner fringing forest from aerial surveys was used to guide visual detection of damage and dieback in interior forests (Figure 3). Areas of inner fringe forest in this condition were mapped using the most recent aerial imagery. As this was a visual classification, there is likely to be some error in assessment and the data provides an estimate only.

The presence of root burial was similarly mapped based on aerial and ground survey observations.

Figure 3. Inner fringe forest in poor condition, Sassie Island.

Results and Discussion

Tidal Wetland Biodiversity

Island size and wetland areas in Torres Strait

There was a notable and significant relationship between island area and the area of wetland habitat. This applied to both freshwater and mangrove wetlands. In Figure 4 a,b, notice the positive linear relationships showing larger islands had larger wetland areas.

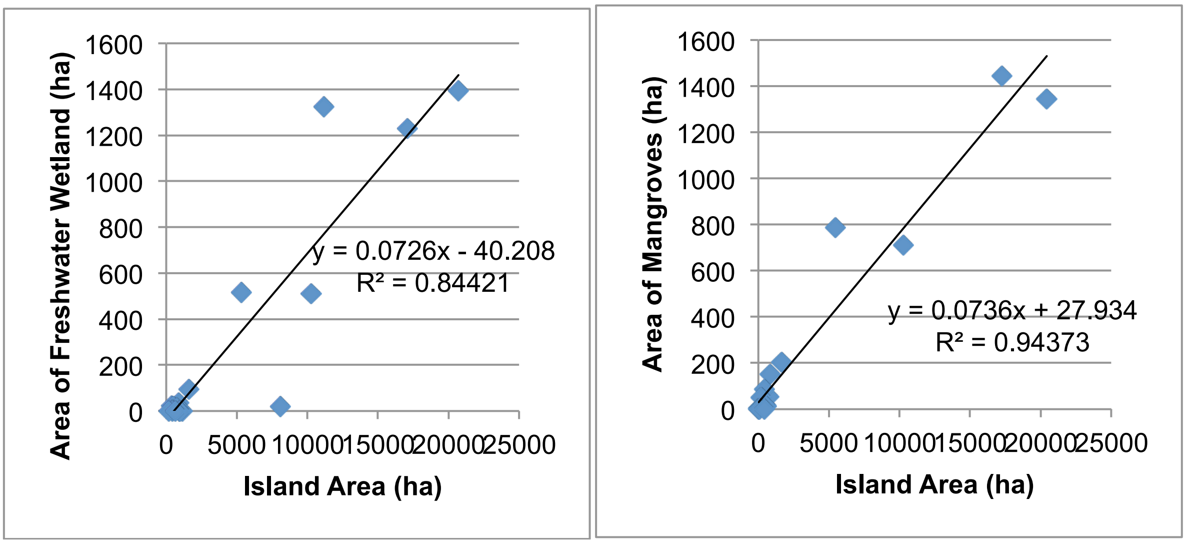


Figure 4. In Torres Strait, there were notable relationships between island area (ha) relative to the area of freshwater wetlands (Figure 4a), and mangrove tidal wetlands (Figure 4b). The latter relationship for mangrove areas only applied to islands of rocky, hilly topography, rather than flat, depositional mangrove islands, like Boigu and Saibai.

It was notable that depositional islands, like Boigu and Saibai, did not conform with area relationship for rocky, hilly islands. For mangrove depositional islands, such a relationship is self-evident already.

Irrespective of island type, islands with larger mangrove areas had greater diversity of mangrove species (see Figure 5). This no doubt is influenced by the greater diversity and expanse of niches available in larger areas.

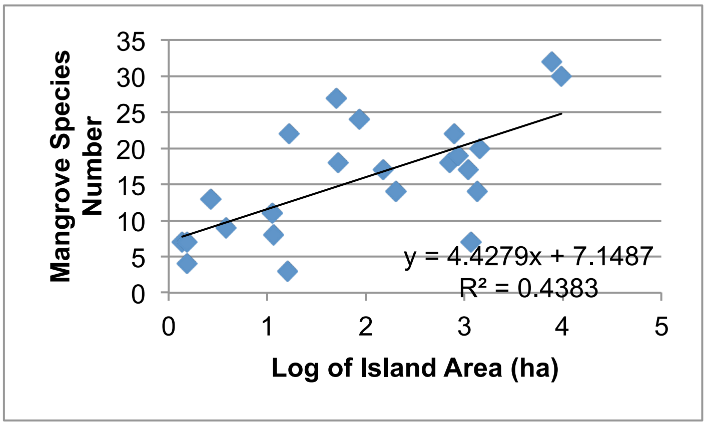


Figure 5. For Torres Strait islands, there was a relationship between island mangrove area (ha) and numbers of species recorded.

In Torres Strait, there were 35 mangrove species recorded, including 2 varieties and 2 hybrids (see Table 3).

The Torres Strait region represents an area of high mangrove biodiversity. However, there are a number of species not known within the region despite occurrences recorded in nearby PNG and the Jardine River on Cape York Peninsula. These include Bunt's (1982) observations of *Avicennia rumphiana, Avicennia officinalis* and *Sonneratia ovata* from Daru Island. These species were not recorded within Australian borders (Duke 2006). But, following our recent surveys, *Avicennia officinalis* and *Sonneratia ovata* Duke (2010; see Figure 6) have been recorded now for Boigu and Saibai Islands in Torres Strait. Additionally, the upstream species *Dolichandrone spathaceae* and *Barringtonia racemosa*, all of which are found in Cape York rivers, are also absent. These species are likely to be restricted by the absence of larger rivers and catchments coupled with the highly seasonal rainfall patterns of the region. Such physiognomic factors have been shown to be strongly correlated with mangrove species diversity (Duke et al. 1998). The recent observations of *Sonneratia ovata* and *Avicennia officinalis*, species not previously reported in Australia, implies that the northern mud islands may provide suitable habitat for additional species not previously reported. The discovery of other species may occur with further comprehensive field surveys in collaboration with traditional owners. Both Boigu and Saibai island plants are strongly influenced by the Fly River and other large rivers along the southern PNG coast. These islands can thus be considered 'mangrove depositional islands' formed from sediments washed down from the large New Guinea catchments. The plant diversity shown on these islands will therefore be unlike that recorded on rocky and coral islands. These unusual circumstances appear to explain the higher than expected mangrove biodiversity on Saibai and Boigu islands.

Figure 6. Discovery of *Sonneratia ovata* on Boigu Island in 2010.

Table 3. Mangrove species of Torres Strait, includes cited authors, publication dates plus NERP survey records. The confirmed number of mangrove species in Torres Strait was 35.

Mangrove Species/Taxa	Bunt (1982)[1]	Wightman (2004)	Stanton, Fell & Gooding (2008)	Duke (2012-2014)	Atlas of Living Australia (2014)	Wetland Info (2014)	**Total Record Likely**	**NERP surveys**
Acanthus ebracteatus subsp. *ebarbatus*		X		**X**	X		*3*	**X**
Acanthus ilicifolius[1]	X	X	X	**X**	X	X	*6*	**X**
Acrostichum aureum						X	*1*	
Acrostichum speciosum	X	X	X	**X**	X	X	*6*	**X**
Aegialitis annulata	X	X	X	**X**	X	X	*6*	**X**
Aegiceras corniculatum	X	X	X	**X**	X	X	*6*	**X**
Avicennia marina subsp. *australasica*			X				*1*	
Avicennia marina subsp. *eucalyptifolia*	X	X	X	**X**	X	X	*6*	**X**
Avicennia officinalis[1]	X			**X**			*2*	**X**
Avicennia rumphiana[1]	X						*1*[1]	
Barringtonia racemosa			X			X	*2*	
Bruguiera cylindrica	X	X	X	**X**	X	X	*6*	**X**
Bruguiera exaristata	X	X	X	**X**	X	X	*6*	**X**
Bruguiera gymnorhiza	X	X	X	**X**	X	X	*6*	**X**
Bruguiera parviflora[1]	X	X	X	**X**	X	X	*6*	**X**
Bruguiera rhynchopetala				**X**			*1*	**X**
Bruguiera sexangula[1]	X	X		**X**	X	X	*4*	**X**
Camptostemon schultzii	X	X	X	**X**		X	*5*	**X**

Ceriops australis				**X**	X		*2*	**X**
Ceriops pseudodecandra	X	X		**X**	X	X	*5*	**X**
Ceriops tagal	X	X	X	**X**	X	X	*6*	**X**
Cynometra iripa[2]		X		**X**			*1*	**X**
Diospyros littorea			X	**X**	X	X	*4*	**X**
Dolichandrone spathaceae[1]	X						*1*[1]	
Excoecaria agallocha	X	X	X	**X**	X	X	*6*	**X**
Heritiera littoralis[1]	X	X	X	**X**	X	X	*6*	**X**
Lumnitzera littorea		X	X	**X**	X	X	*5*	**X**
Lumnitzera racemosa	X	X	X	**X**	X	X	*6*	**X**
Nypa fruticans[1]	X	X	X	**X**	X	X	*6*	**X**
Osbornia octodonta	X	X	X	**X**	X	X	*6*	**X**
Pemphis acidula	X	X	X	**X**	X	X	*6*	**X**
Rhizophora apiculata[1]	X	X	X	**X**	X	X	*6*	**X**
Rhizophora lamarckii				**X**			*1*	**X**
Rhizophora mucronata[1]	X			**X**			*2*	**X**
Rhizophora stylosa	X	X	X	**X**	X	X	*6*	**X**
Scyphiphora hydrophylacea	X	X	X	**X**	X	X	*6*	**X**
Sonneratia alba	X	X	X	**X**	X	X	*6*	**X**
Sonneratia ovata[1]	X			**X**	X		*3*	**X**
Xylocarpus granatum[1]	X	X	X	**X**	X	X	*6*	**X**
Xylocarpus moluccensis[1]	X	X	X	**X**	X	X	*6*	**X**
Totals	30	28	27	35	29	29	39	**35**

X = species recorded. [1]Species recorded by Bunt (1982) on Daru Is., in PNG waters. [2]Species recorded by Wightman (2004) with no specific location information and no herbarium voucher specimen available. NB: *Annona glabra* (Pond apple) may be described as a mangrove weed in Torres Strait due to its introduced presence primarily in mangrove habitat.

Saltmarsh assemblages

In Torres Strait, there are up to around 11 saltmarsh species, including 3 sub-species (see Table 4).

Northern Australia has the least diverse saltmarsh flora of bioregions in Australia, with only 18 of a total of 93 species represented in the Cape York bioregion (Saintilan 2009). The primary limiting factors for saltmarsh biodiversity are temperature and to some extent rainfall and tidal periodicity leading to hypersalinity (Saintilan 2009). Based on the available records, the Torres Strait islands have even fewer species represented than mainland northern Australia. There are some notable absences from saltmarsh species records in Torres Strait. The most notable absences are *Suaeda australis* and *Sarcocornia quinqueflora. Suaeda australis* and species from within the same genus are recorded throughout the Pacific region and along the entire eastern coast of Australia. *Sarcocornia* is a common genus represented on all southern continents. *Sarcocornia quinqueflora* is distributed similarly to *S. australis* along the east coast of Australia. Two other absent samphire species are *Tecticornia halocnemoides* and *Tecticornia pergranulata.* Both these species occur on Cape York and in the Gulf of Carpentaria. Like most saltmarsh chenopods these species are tide dispersed and it is unlikely that seed stock is limited in Torres Strait saltmarsh areas. The low biodiversity of saltmarsh flora in the Torres Strait may be a feature of limited field surveys to identify saltmarsh species, or other factors relating to saltmarsh distribution such as dispersal and climate.

Table 4. Saltmarsh species of Torres Strait – various authors and publication dates.

Saltmarsh Species	**Wightman (2004)***	**Stanton, Fell & Gooding (2008)**	**Atlas of Living Australia (2014)**	**Wetland Info (2014)**	***Total Count***
Saltpan					
Batis argillicola	**x**	**x**	**x**	**x**	*4*
Sesuvium portulacastrum	**x**	**x**	**x**	**x**	*4*
Tecticornia australasica	**x**				
Tecticornia indica subsp. *indica*	**x**				
Tecticornia indica subsp. *julacea*					
Tecticornia indica subsp. *leiostachya*					
Saline Grassland					
Cynanchum carnosum[1]	**x**	**x**	**x**	**x**	*4*
Cyperus polystachyos					
Fimbristylis cymosa					
Fimbristylis polytrichoides					
Salsola kali[2]					
Sporobolus virginicus					
	6				

*The absence of species from Wightman's list is likely due to the definition of mangrove used rather than the recognised absence of the species within the Torres Strait area. [1]*Salsola kali* is sometimes included as a saltmarsh plant, however this species generally occurs in beach strand areas, so may be removed from the list in future following a review of its occurrence within Torres Strait.

Brackish and saline wetland species

In Torres Strait, there are 24 brackish and saline swamp species, including 1 sub-species and 1 variety (see Table 5).

Table 5. Brackish and saline wetland species of Torres Strait – various authors and publication dates.

Brackish and saline wetland species	Stanton, Fell & Gooding (2008)	Atlas of Living Australia (2014)	WetlandInfo (2014)*	*Total Count*
Cynodon dactylon	X	X		*2*
Cyperus javanicus	X	X	X	*3*
Cyperus stoloniferus	X	X	X	*3*
Echinochloa colona	X	X		*2*
Eleocharis dulcis	X	X	X	*3*
Eleocharis spiralis	X	X	X	*3*
Fimbristylis ferruginea	X	X	X	*3*
Fimbristylis rara	X	X	X	*3*
Flagellaria indica	X	X	X	*3*
Leptochloa fusca	X	X		*2*
Melaleuca acacioides	X	X	X	*3*
Melaleuca cajuputi subsp. platyphylla	X			*1*
Melaleuca leucadendra	X	X	X	*3*
Melaleuca quinquenervia	X	X	X	*3*
Melaleuca viridiflora	X	X	X	*3*
Melaleuca viridiflora var. viridiflora	X			*1*
Paspalum vaginatum	X	X	X	*3*
Phragmites australis	X	X	X	*3*
Pseudoraphis spinescens	X	X	X	*3*
Ruppia maritima	X			*1*
Schoenoplectus litoralis	X	X	X	*4*
Schoenoplectus validus	X	X	X	*1*
Sesbania cannabina	X	X		*2*
Xerochloa imerbis[1]				*0*
Total	**23**	**20**	**16**	**24**

1 *Xerochloa imerbis* is described for Boigu in Burrows & Schaffer (2010) and Badu Island.

Freshwater wetland species

In Torres Strait, there are 50 freshwater wetland species, including 1 variety (see Table 6).

Table 6. Freshwater wetland species of Torres Strait – various authors and publication dates.

Freshwater Wetland Species	**Stanton, Fell & Gooding (2008)**	**Atlas of Living Australia (2014)**	**Wetland Info (2014)**	***Total Count***
Aeschynomene indica	x	x	x	*3*
Arundo donax	x	x	x	*3*
Baeckea frutescens	x	x		*2*
Bergia ammannioides	x	x	x	*3*
Blechnum indicum	x		x	*2*
Centrolepis exserta		x	x	*2*
Ceratophyllum demersum	x	x	x	*3*
Ceratopteris thalictroides	x	x	x	*3*
Cyperus difformis		x	x	*2*
Dicranopteris linearis var. linearis	x			*1*
Drosera spatulata	x		x	*2*
Eclipta prostrata	x	x	x	*3*
Eriocaulon setaceum		x	x	*2*
Fimbristylis dichotoma	x	x	x	*3*
Ipomoea aquatica	x	x	x	*3*
Lepironia articulata		x		*1*
Lophostemon suaveolens	x	x	x	*3*
Lycopodiella cernua		x		*1*
Lygodium microphyllum	x	x	x	*3*
Melaleuca argentea	x		x	*2*
Nymphaea nouchali		x		*1*
Nymphaea violacea	x	x	x	*3*
Nymphoides aurantiaca	x	x	x	*3*
Nymphoides exiliflora	x	x	x	*3*
Nymphoides parvifolia		x	x	*2*
Nymphoides triangularis	x	x	x	*3*
Panicum laevinode	x	x	x	*3*
Paspalum distichum	x	x	x	*3*
Philydrum lanuginosum		x	x	*2*
Phragmites vallatoria		x		*1*
Rhynchospora exserta	x	x	x	*3*
Rhynchospora heterochaeta	x	x	x	*3*
Rhynchospora leae	x	x	x	*3*
Rhynchospora longisetis	x	x	x	*3*
Rhynchospora pterochaeta	x	x	x	*3*
Rotala mexicana		x		*1*
Sacciolepis indica	x	x	x	*3*
Schoenoplectus subulatus			x	*1*
Thalassodendron ciliatum	x	x	x	*3*
Trachystylis stradbrokensis			x	*1*
Tricostularia undulata	x	x	x	*3*
Triglochin dubia		x	x	*2*
Urochloa mutica	x	x		*2*

Utricularia aurea			**x**	*1*
Utricularia bifida	**x**	**x**	**x**	*3*
Utricularia caerulea	**x**	**x**	**x**	*3*
Utricularia chrysantha	**x**	**x**	**x**	*3*
Utricularia gibba		**x**		*1*
Utricularia uliginosa		**x**	**x**	*2*
Xyris complanata	**x**	**x**	**x**	*3*
Total	**34**	**43**	**41**	**50**

Mangroves of the Torres Strait Islands

The list of mangroves of the Torres Strait Islands were updated from earlier accounts by Bunt, Williams and Duke (1982), Boto and Duke (1984), Duke (1985), QDEHP (2014), Duke (2006) and Wightman (2004, 2006). There were notable changes made from the Australian national record listed by Duke (2006) and others.

The total number of mangrove species taxa in all records plus the current surveys, totalled 35; with 2 being hybrids. No single island had all species types. It was notable that putative hybrids occurred as expected, where both parental forms grew in nearby locations. Hybrid intermediate forms were considered distinct species in the list because they are individually notable in the field. They also maintain their morphological features consistently wherever they occur. The total species are from 18 genera representing 14 different plant families. This is high diversity for a numerically small plant habitat assemblage. The most well-represented family is the Rhizophoraceae with 13 species and hybrids, while the second is the Acanthaceae with 5, and the Lythraceae with 4. For specific details, see Table 7 and the keys below.

The numbers of confirmed mangrove species in Torres Strait was increased during the current surveys by two from those listed in ‘Australia’s Mangroves’ (2006). At least 4 other species are recorded for Torres Strait for the first time. There were reasonable expectations that additional species will be located, with five listed as likely. The current status of biodiversity issues are listed in Table 7. To aid in future botanical surveys, the keys listed below, include likely key additional plants. Expectations are based on regional distribution patterns of each species, their ability to disperse, as well as the likelihood of certain hybrid species where parents are already present. There has been uncertainty also in some cases regarding the definition of mangrove species, as compared with mangrove associates. The definition has been explained in detail in various published texts; summarized by Duke (2006). In brief, a mangrove is determined mostly by its normal presence within the tidal zone between mean sea level and the high water mark; and, it's common absence from supra-tidal, upland locations.

Table 7. Mangrove plant species in the Torres Strait Islands. Observations following 2010-14 surveys by Dr NC Duke and team, with the TSRA Rangers. Note, those additional to 'Australia's Mangroves' (Duke 2006) listings in Queensland and Australia, with brackets (<X>), those newly listed in Torres Strait (X*), those also confirmed present are just underlined (X), and those likely present but not confirmed have a question mark (-?).

Mangrove species	Torres Strait Islands
Acanthus ebracteatus	X*
Acanthus ilicifolius	X
Acrostichum aureum	-?
Acrostichum speciosum	X
Aegialitis annulata	X
Aegiceras corniculatum	X
Avicennia marina	X
Avicennia officinalis	<X>
Barringtonia racemosa	-?
Bruguiera cylindrica	X
Bruguiera exaristata	X
Bruguiera gymnorhiza	X
Bruguiera parviflora	X
Bruguiera rhynchopetala	X*
Bruguiera sexangula	X
Camptostemon schultzii	X
Ceriops australis	X
Ceriops pseudodecandra	X
Ceriops tagal	X
Cynometra iripa	X
Diospyros littoralis	X*
Dolichandrone spathacea	-?
Excoecaria agallocha	X
Heritiera littoralis	X
Lumnitzera littorea	X
Lumnitzera racemosa	X
Lumnitzera rosea	-?
Nypa fruticans	X
Osbornia octodonta	X
Pemphis acidula	X
Rhizophora annamalayana	-?
Rhizophora apiculata	X
Rhizophora lamarckii	X*
Rhizophora mucronata	X
Rhizophora stylosa	X
Scyphiphora hydrophylacea	X
Sonneratia alba	X
Sonneratia lanceolata	-?

Sonneratia ovata	<X>
Xylocarpus granatum	X
Xylocarpus mollucensis	X
TOTAL Taxa present:	**35** +

The recent field survey has amended the record in large part, but there remains some uncertainty about the exact list of mangrove species present in the Torres Strait Islands. This uncertainty is reflected in the current listings where some species are noted as requiring confirmation. Notably, there are two notable additional species, extending those listed in the 'Australia's Mangroves' account.

In summary, of the confirmed records, there are 35 species (with a possibility of six more). As an aid for on-going field investigations, the following key, lists characters also for the likely additional mangrove species.

Key to mangrove species of the Torres Strait Islands

1. Palm or ground fern, both trunkless **2**
1*. Shrub or tree **3**

2. Palm to 10 m . . . . ***Nypa fruticans***
2*. Ground fern to 1 m . . . . Genus ***Acrostichum***

3. Exuding white sap (oozes from broken leaf or cut bark) . . . . . . ***Excoecaria agallocha***
3*. No exuding sap **4**

4. Compound leaves **5**
4*. Simple leaves **7**

5. Flower larger than 5 cm, seed pod long curved . . . . ***Dolichandrone spathacea***
5*. Flower less than 1 cm, seed pod rounded compact **6**

6. Seed pod rugose (bi-valved, pubescent, irregular), leaflet tip imarginate, buttresses or pneumatophores absent . . . . ***Cynometra iripa***
6*. Seed pod smooth (obscurely 4-valved, coriaceous, globate), leaflet tip apiculate, with conical pneumatophores or plank buttresses . . . . Genus ***Xylocarpus***

7. Simple opposite leaves **8**
7*. Simple alternate leaves **16**

8. Leaf undersurface pubescent (silvery grey appearance) . . . . Genus ***Avicennia***
8*. Leaf undersurface not pubescent **9**

9. Flower zygomorphic, leaf often spiny (small shrub to 2 m) . . . . Genus ***Acanthus***
9*. Flower symmetric, leaf never spiny (shrub or tree) **10**

10. Prop roots and/or buttresses, fruit germinates on tree, viviparous (long, >6 cm, green)**11**
10* Prop roots or buttresses absent, fruit with seeds, not viviparous (rounded, <6 cm, often not green) **13**

11. Fruit inverted pear-shaped, calyx lobes less than 6 (flat-expanded tube) **12**
11*. Fruit within calyx, calyx lobes 8-15 (turbinate tube) . . . . Genus ***Bruguiera***

12. Calyx lobes 5 (thick sinuous buttresses) . . . . Genus ***Ceriops***
12*. Calyx lobes 4 (sturdy prop roots) . . . . Genus ***Rhizophora***

13. Stipules persistent, pod deeply 8-ribbed (barrel-like). . . ***Scyphiphora hydrophylacea***
13*. Stipules absent, pod or fruit not deeply ribbed **14**

14. Fruit to 4 cm (globular), tree medium to large (leaves large >5 cm), pneumatophores present . . . . Genus ***Sonneratia***
14*. Fruit less than 1 cm (calyx pod), shrub to small tree (leaves small <2 cm), pneumatophores absent **15**

15. Leaf smooth (glabrous) with oil glands (aromatic when crushed), flower petals absent . . . . ***Osbornia octodonta***
15*. Leaf pubescent without oil glands, flower petals conspicuous. . . . . . ***Pemphis acidula***

16. Leaf undersurface pubescent (hairs or fine scales, silvery appearance) **17**
16*. Leaf undersurface not pubescent (glabrous) **18**

17. Leaf flat, less than 12 cm, seed pod ovate, scaly (less than 1 cm) . . . . ***Camptostemon schultzii***
17*. Leaf floppy, greater than 12 cm, seed pod keeled, smooth (greater than 5 cm) . . . . ***Heritiera littoralis***

18. Leaf petiole envelopes stem (leaving annular scars) . . . . ***Aegialitis annulata***
18*. Leaf petiole does not envelop stem **19**

19. Leaf tip imarginate, bark rough, pneumatophores wiry . . . . Genus ***Lumnitzera***
19*. Leaf tip not imarginate, bark finely fissured, pneumatophores absent **20**

20. Flower with more than 8 stamens, flowers on long raceme (>20 cm), fruit pod 4-cornered (leaf >20 cm) . . . . ***Barringtonia racemosa***
20*. Flower with less than 8 stamens, flowers not on raceme, fruit pods not 4-cornered (leaf <10 cm) **21**

21. Flower bud on simple umbel, fruit horn-like . . . . ***Aegiceras corniculatum***
21*. Flower bud on obscure peduncle, fruits ovoid . . . . ***Diospyros littorea***

Genus *Acanthus* – 2 species recorded in Torres Strait*

1. Corolla white mostly, one subspecies deep purple (subsp. ebarbatus); bracteoles absent; open flower 2-2.5 cm long; mature fruit capsule less than 2 cm long; seed approximately 5-7 mm wide; inflorescence variable; plant typically delicate, sometimes spiny …………**Acanthus ebracteatus***
1*. Corolla partly light blue or violet, rarely all white; 2 bracteoles, to 1 cm long; open flower 3.5-4 cm long; mature fruit capsule 2.5-3 cm long; seed approximately 10 mm wide; inflorescence usually longer than 10 cm; plant typically robust with spiny to very spiny leaves . . . . ***Acanthus ilicifolius****

Genus *Acrostichum* – one species recorded in Torres Strait*

1. Growth form small, no stem, fronds to 1 m long, sterile pinnae tapering to a narrow acuminate point, 10-20 cm long, restricted generally to upper tidal elevations . . . . ***Acrostichum speciosum****
1*. Growth form large, indistinct stem, fronds 1-3 m long, pinnae rounded or truncate, abruptly acuminate, 20-40 cm long, restricted to upper tidal elevations of runoff channels . . . . ***Acrostichum aureum***

Genus *Avicennia* – 2 species recorded in Torres Strait*

1. Leaf apex usually pointed; radicle glabrous except for short hairy collar about distal tip; pericarp puberulent; flower small 3-8 mm long, corolla diameter 3-7 mm, calyx 3-6 mm long; inflorescence spicate or capitate **2**
1*. Leaf apex usually rounded; radicle hairy along most, if not entire length; pericarp velvety or densely tomentose; flower variable in size 3-13 mm long, corolla diameter 4-12 mm, calyx 2-10 mm long; inflorescence capitate **3**

2. Inflorescence usually spicate; propagule very elongate with pointed distal end; style barely extended from ovary, minute; stigma positioned below lower edge of anthers; ovary glabrous on upper surface near style, pubescent below. (*Northern New Guinea, western Pacific, Indo-Malesia to western India,* **not** *Australia)* . . . . ***Avicennia alba***
2*. Inflorescence capitate; propagule ovoid with rounded distal end; style erect, short; stigma positioned between upper and lower edge of anthers; ovary pubescent below style. (*New Zealand, mainland Australia, southern New Guinea, south-western Pacific, Indo-Malesia, to southern China, to India, Persian Gulf, Red Sea and eastern Africa)* . . . . ***Avicennia marina****

3. Flower small, < 7 mm long, calyx < 4 mm long; style short; stigma positioned at lower edge of small (0.5 mm long) anthers; peduncle, small twigs and leaf undersurface yellowish to russet tomentose; propagule ovoid with rounded distal end; pericarp densely tomentose. (*New Guinea, Indo-Malesia and the Philippines,* **not** *Australia)* . . . . ***Avicennia rumphiana***
3*. Flower large, > 7 mm long, calyx 3 5 mm long; style elongate; stigma exserted or positioned at upper edge of large (> 1 mm long) anthers; peduncle, small twigs and leaf undersurface pale puberulent; propagule elongate with pointed distal end; pericarp velvety **4**

4. Sepal, bracteole and bract edges ciliate, or hairy; calyx small, < 7 mm long, < 5 mm wide (*Southern New Guinea, Indo-Malesia, the Philippines to western India, Australian Torres Straits* **only***)* . . . . ***Avicennia officinalis****
4*. Sepal, bracteole and bract edges entire; calyx large, 3 8 mm long, > 5 mm wide. (*Australian Northern Territory* **only***)* . . . . ***Avicennia integra***

Genus *Bruguiera* – 6 species taxa recorded in Torres Strait*

1 Flowers small, less than 3 mm wide; petal spine exceeds lobes; calyces with 8 lobes **2**
1* Flowers large, greater than 3 mm wide; petal spine shorter than lobes or absent; calyces with 10-14 lobes **3**

2 Fruit calyx ribbed, lobes adpressed (1/4-1/5 length of calyx) . . . . ***Bruguiera parviflora****
2* Fruit calyx smooth, lobes reflexed (1/2 length of calyx) . . . . ***Bruguiera cylindrical****

3 Flowers multiple (2-3 buds per inflorescence) mostly (*SE Asia to Solomon Islands,* **not** *Australia*) . . . . ***Bruguiera hainesii***
3* Flowers solitary (1 flower bud per inflorescence) always **4**

4 Petal spine absent or minute; calyces with 10 lobes. . . . . ***Bruguiera exaristata****

4* Petal spine shorter than lobes; calyces with 12-14 lobes. **5**

5 Petal bristles absent or minute . . . . ***Bruguiera sexangula****
5* Petal bristles 1-3 . . . . **6**

6 Petal bristles 1-2, less than 2 mm (*B.gymnorhiza* X *B.sexangula* hybrid) . . . . ***Bruguiera rhynchopetala****
6* Petal bristles 3, greater than 2 mm . . . . ***Bruguiera gymnorhiza****

Genus *Ceriops* – 3 species recorded in Torres Strait*

1. Petal apex with 3(-5) clavate appendages; inflorescence axis relatively long and slender (10-30 mm x 2 mm), bending downwards. **2**
1*. Petal apex fringed with 12-25 sinuate cilia; inflorescence axis relatively short and stout (3-10 mm x 3-4 mm), erect. **3**

2. Hypocotyl terete (without ridges) usually less than 10 cm long at maturity; base of calyx lobe in flowering 12-15 mm in width; stipule usually shorter than 1.2 cm long at extension stage (*New Guinea, Australia*) . . . . ***Ceriops australis****
2*. Hypocotyl angular (with ridges) 9-25 cm long at maturity; base of calyx lobe in flowering 18-25 mm in width; stipule usually longer than 1.2 cm long at extension stage (SE Asia, *New Guinea, Australia*) . . . . ***Ceriops tagal****

3. Inflorescence simple and head-like with 3-5 flowers; petals hairless along margins; persistent calyx tube short (2-3 mm) and disc-like (*SE Asia,* **not** *Australia*) . . . . ***Ceriops zippeliana***
3*. Inflorescence dense bifurcate cyme-like with 6-20 flowers; petal hairy at least along lower margins; persistent calyx tube long (4-9 mm) and hemi-globular (dome-like) **4**

4. Entire margins of petals with dense and long hairs (0.5 mm); style 2.5- 2.8 mm long, epicotyl 2-3 mm long; length ratio of fruit to calyx tube 1-1.5 at maturity (*SE Asia,* **not** *Australia*) . . . . ***Ceriops decandra***
4*. Lower half margins of petals with loose and short hairs (0.1 mm); style 1.4-1.5 mm long, epicotyl 10-12 mm long; length ratio of fruit to calyx tube 2-3 at maturity (*New Guinea, Australia*) . . . . ***Ceriops pseudodecandra****

Genus *Lumnitzera* – 2 species taxa recorded in Torres Strait*

1 Inflorescence terminal, style off-centre **2**
1* Inflorescence axillary, style central, petals white, stamens equal or slightly exceeding petals, shrub or small tree to 8 m (east Africa, *SE Asia, Australia*) . . . . ***Lumnitzera racemosa****

2 Petals pink, stamens equal or slightly exceeding petals (*L.racemosa* X *L.littorea* hybrid, **not** *Torres Strait*) . . . . ***Lumnitzera rosea***
2* Petals red, stamens twice as long as petals (*SE Asia, western Pacific, Australia*) . . . . ***Lumnitzera littorea****

Genus *Rhizophora* – 4 species taxa recorded in Torres Strait*[1]

1. Mature flower buds and fruit within leaves in leafy shoot, bracts smooth green, petals with marginal hairs, style greater than 2 mm long, stamens mostly 8-11 ....**2**

1*. Mature flower buds and fruit below leaves on leafy shoot, bracts corky brown, petals with no marginal hairs, style less than 2 mm long, stamens 10-12 ... ***Rhizophora apiculata****

2. Mature flower buds less than 15 mm long, petal margins very hairy, petals fully enclosing stamens, stamens around 8, calyx lobes less than 1 mm thick, mature fruits and hypocotyls seasonally present *Stylosa-mucronata Complex*................**3**
2*. Mature flower buds greater than 15 mm long, petal margins minutely hairy, petals not enclosing stamens, stamens 9-11, calyx lobes greater than 1 mm thick; mature fruits and hypocotyls absent *IWP hybrids*................**4**

3. Style length less than 2.1 mm; mature buds smooth and irregularly ovate, remaining pale green, calyx lobes yellow; bracts minute, margins often indistinct; dichotomous inflorescence branches 0-1 (-2), some with one or two pedicels and one sessile flower attached to the one peduncle; stamens (7-) 8 . . . . ***Rhizophora mucronata****
3*. Style length 2.1-6 mm; mature buds smooth, regular and slightly ovate, usually pale yellow in colour, bracts quite distinct with dark crenulate margins; dichotomous inflorescence branches (0-)2-4(-6); stamens (6-)8 . . . . ***Rhizophora stylosa****

4. Style length 1.4-2.0 mm (*R.apiculata* X *R.mucronata* hybrid)
....***Rhizophora annamalayana***
4*. Style length 2.1-6.0 mm (*R.apiculata* X *R.stylosa* hybrid)
.... ***Rhizophora lamarckii*** *

Genus *Sonneratia* – 2 species taxa recorded in Torres Strait*

1 Mature flower bud width at calyx lobes approximately equal to hypanthium width, noticeably constricted between; mature fruit calyx base cup-shaped, fruit width usually less than 4 cm, width less than or equal to hypanthium. **2**
1* Mature flower bud width at calyx lobes much greater than hypanthium width, usually not constricted between lobes and hypanthium; mature fruit calyx base flat-expanded, fruit width usually greater than 4 cm, width mostly 0.5 cm or more, greater than hypanthium.. . . **5**

2*. Petals white if present; stamens white; calyx shiny; fruit rounded dull; trees variably emergent. **3**
2 Petals red or red with white; stamens red or white; calyx satiny luster or dull; fruit often indented about style base, satiny; trees often emergent. **4**

3 Trees not noticeably emergent; leaves obovate without pronounced venation under, distinct mucronate tip folded under, 1-2 mm L; mature flower buds relatively slender 2-3.3 cm L, 1.2-2.2 cm W; calyx smooth shiny surface; calyx lobes on mature fruit 6-7 (-8), reflexed; seeds sickle shaped . . . . ***Sonneratia alba****
3* Trees often doubly emergent; leaves broadly ovate with pronounced venation under, broad folded lip at apex, 0.4 mm L; mature flower buds broad 3.4-3.8 cm L, 2.8-3.6 cm W; calyx finely dimpled surface; calyx lobes on mature fruit 6, curved upward; seeds granular (*S.alba* X *S.ovata* hybrid) . . . . ***Sonneratia hainanensis***

4. Leaves rounded, stamens red or red with white, calyx satiny (*S.alba* X *S.caseolaris* hybrid) . . . . ***Sonneratia gulngai***
4* Leaves apiculate, stamens white, calyx dull (*S.alba* X *S.lanceolata* hybrid) . . . . ***Sonneratia urama***

5. Petals absent; stamens white; style < 4.5 cm; peduncle terete; calyx lobes reflexed, adpressed; leaf base rounded to truncate to subcordate; leaf mucronate apex absent or minute. **6**

5*. Petals red, linear; stamens red or white or both; style > 5 cm; peduncle tetragonous; calyx lobes flat, expanded; leaf base attenuate, shortly so; leaf mucronate apex distinct
. . . . **7**

6 Calyx verruculose; leaves widely ovate, petiole short, midrib often red at base; veins inconspicuous, not prominent; filaments red below, white distally. . . . . . ***Sonneratia ovata****
6* Calyx slightly coriaceous or smooth; leaves obovate to suborbicular, petiole scarcely developed, midrib green; veins conspicuous, prominent on the upper blade surface; filaments white. . . . . ***Sonneratia griffithii***

7. Leaves rounded apiculate; mature flower bud with medial constriction; stamens red or red with white to distal end; calyx base grooved often deeply, surface satiny coriaceous.
. . . . ***Sonneratia caseolaris***
7* Leaves lanceolate or linear; mature flower bud with no medial constriction; stamens white or tinged red at base; calyx base rounded, surface dull smooth
. . . . ***Sonneratia lanceolata***

Genus *Xylocarpus* – 2 species recorded in Torres Strait*[2]

1. Leaflets usually 4, moreorless elliptic, the apex rounded or at most narrowed to a blunt point; inflorescence less than 8 cm long; root systems above ground as buttresses or pneumatophores; bark scaly or fissured; fruit mature around 8-25 cm in diameter. Mangrove species **2**
1*. Leaflets usually 4, 6 or 8, moreorless ovate and narrowed to a distinctly pointed apex; root systems not conspicuous above ground, buttresses absent; bark longitudinally fissured; fruit mature around 7-8 cm in diameter.
Associate of mangroves . . . . ***Xylocarpus rumphii*** [2]

2 Buttresses small, pneumatophores conical; bark grey, vertical fissured, flaky rough, mature fruit 8-12 cm in diameter; deciduous in early Spring.
. . . . ***Xylocarpus moluccensis****
2* Buttresses plank-like, sinuous, pneumatophores absent; bark pale orangy, flaky patches, smooth; mature fruit 10-25 cm in diameter; evergreen.
. . . . ***Xylocarpus granatum****

Notes:

1) The hybrids of *Rhizophora* occur quite predictably where-ever the two parent species exist. So, the hybrid species between *R. mucronata* and *R. apiculata*, *Rhizophora annamalayana*, previously not recorded in this country, is expected in many places, including Torres Strait. The diagnostic features are listed in the key above.

2) The *Xylocarpus* present in Torres Strait Islands have been referred to 2 species, *X. granatum* and *X. mollucensis*. However, there is another species, *X. rumphii*., a species not considered a mangrove, but it is occasionally found nearby. This is an associate species. It appears very similar to *X. granatum*.

Biomass and Carbon Content of Torres Strait Mangroves

Overall findings

In total, 32 long plots were established and measured on five islands including: Gebar, Iama, Zagai, Boigu and Saibai islands of northern Torres Strait. This resulted in the measurement of 1,737 tree stems covering a total area of 4,420 m^2 or 0.44 ha of mangrove forests (Table 8). These data for the first time provide measures of biomass and structure for at least three dominant genus vegetation units, as key zones of mangrove assemblages present in the Torres Strait region.

Table 8. Numbers of dominant mangrove vegetation units sampled, and numbers of long plots measured in the Torres Strait Islands during 2012–2014.

Dominant **Mangrove Vegetation Assemblage**	Gebar	Iama	Zagai	Boigu	Sabai	TOTAL per Veg Unit
Bruguiera exaristata	0	3	0	0	1	**4**
Bruguiera gymnorhiza	0	0	0	0	2	**2**
Rhizophora apiculata	2	1	0	3	1	**7**
Rhizophora stylosa	3	0	2	1	1	**7**
Ceriops australis	0	3	0	0	0	**3**
Ceriops tagal	0	0	0	7	2	**9**
TOTAL per Island	5	7	2	11	7	**32**

One assemblage type of *Rhizophora* species were sampled in all five islands, reflecting the common dominance of these vegetation types throughout the region. Two other species assemblages, *Ceriops* and *Bruguiera* specie were sampled in 3 and 2 islands, respectively. Other species were present within the plots, but these were notably less dominant (Figure 7).

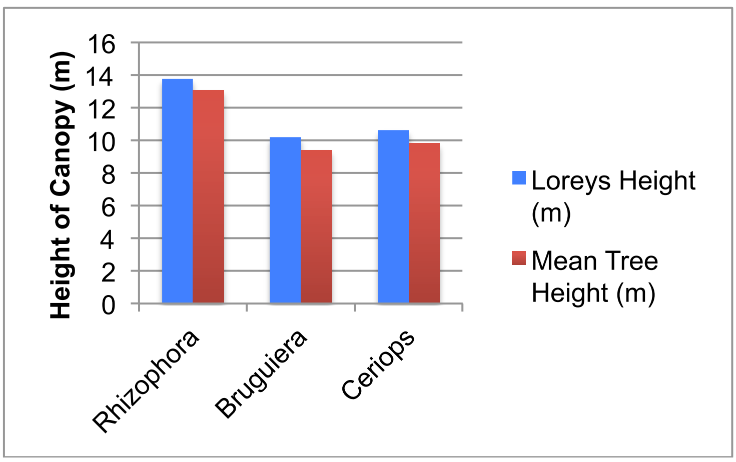


Figure 7. Mean canopy and tree heights of three key genera dominating mangrove plots surveyed in 5 islands of northern Torres Strait, shown in Table 8.

Canopy heights vary for each of the three genera groups, *Rhizophora*, *Bruguiera* and *Ceriops*. *Rhizohora* species were around 12–14 m (Figure 8). *Bruguiera* species were mostly around 9–11 m. *Ceriops* species were around 9–11 m.

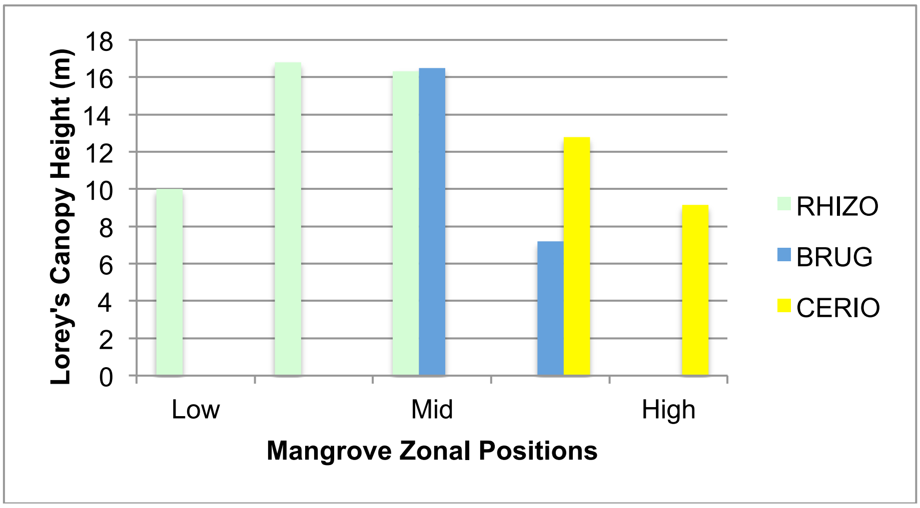


Figure 8. Mean canopy heights of three key genera dominating mangrove plots according to their intertidal position (Low, Mid and High intertidal) surveyed in 5 islands of northern Torres Strait, shown in Table 8.

Growth height differences define tidal zone positions with *Rhizophora* species at lower intertidal positions with heights peaking at around 16 m in mid to low-mid elevations, *Bruguiera* species at mid intertidal positions with heights up to 16m in mid elevations, and *Ceriops* species at higher zones with heights up to 12 m at mid-high elevations (Table 9).

Table 9. Summary of Biomass results for the 3 dominant mangrove vegetation units, *Rhizophora* species, *Bruguiera* species and *Ceriops* species, sampled in the Torres Strait Islands during 2012-2014. Parameters include Mean Tree Height, Loreys Canopy Height, Basal Area of Living Trees, Above Ground Biomass of Living Trees, Below Ground Biomass of Living Trees, Total Biomass of Living Trees plus Dead and damaged stems for respective vegetation units, and overall.

Dominant Genus **Assemblage**	No.	Tree Hgt (m)	Lorey Canopy (m)	Living BA	Living AGB (t/ha)	Living BGB (t/ha)	Living Total Biomass (t/ha)	Dead Total Biomass (t/ha)
Rhizophora	14	13.1	13.8	42.1	328	181	508	73
Bruguiera	6	9.4	10.2	48.8	272	183	455	333
Ceriops	12	9.8	10.6	47.8	278	188	466	152
Mean Total	**32**	**10.8**	**11.5**	**46.2**	**293**	**184**	**477**	**186**

The three dominant vegetation units were fairly represented in this study. *Rhizophora* forests sampled tended to be taller than *Ceriops* and *Bruguiera*. This relationship was generally reflected in the Living Biomass estimates. It was notable that levels of damage in many plots was severe, with considerable disturbances from cutting and access scored as high for 'Dead' or 'Cut' stumps as phantom Biomass estimates. Levels of disturbance far exceed natural levels, usually understood to be around 15% of total biomass (Duke 2001).

Vegetation unit measurements

Dominant vegetation unit - **Bruguiera** *species*

Arguably the most accessible of the vegetation units were sites dominated by *Bruguiera gymnorhiza* and *Bruguiera exaristata*. These species had regular, singular stems with modest trunk buttressing, relatively tall, making the sampling of these forests reasonably easy compared with other species. They also form a dominant component of the mangrove ecosystems in most parts of Torres Strait.

In Tables 10 and 11, canopy heights are shown chiefly to be taller for *B. gymnorhiza*, compared with the shorter stature of *B. exaristata*.

Table 10. For *Bruguiera gymnorhiza* derived mean estimates of average tree height (Hgt), weighted canopy height (CanW Hgt), biomass (in t.ha^{-1}) as Above Ground Biomass (AGB/H) from Chave et al. 2005, and Below Ground Biomass (BGB) from Komiyama et al. 2005, and Stand Basal Area (BA) for long plots in Torres Strait.

Country	MeanHgt(m)	**CanW Hgt(m)**	**AGB/H Chave**	AGB Chave	**BGB Komiyama**	**BA ($m^2.ha^{-1}$)**
Sabai	16.9	16.7	473.6	438.6	231.6	55.7

Note, for *Bruguiera gymnorhiza* in comparable plots from South Pacific Island countries of Samoa, Tonga, Fiji, Vanuatu and Solomon Islands had ABG/H of 125.3 to 463.0, and BGB of 148.8 to 283.7, respectively (Duke et al. 2013).

Table 11. For *Bruguiera exaristata* derived mean estimates of average tree height (Hgt), weighted canopy height (CanW Hgt), biomass (in t.ha^{-1}) as Above Ground Biomass (AGB/H) from Chave et al. 2005, and AGB from Chave et al. 2005, BGB from Komiyama et al. 2005, and Stand Basal Area (BA) for long plots in Torres Strait.

Country	MeanHgt(m)	**CanW Hgt(m)**	**AGB/H Chave**	AGB Chave	**BGB Komiyama**	**BA ($m^2.ha^{-1}$)**
Iama	5.1	5.5	138.9	207.9	142.4	44.7
Sabai	7.4	11.3	269.2	417.8	207.7	55.7

Taller stands generally have higher biomass. This is shown in Tables 10 and 11 and further in Figure 9 where plots from both islands are considered together. The equation used in this figure was that of Chave et al. (2005) using stem diameter and height, but the trend changed little between common equations. Likewise, this applies also with the use of Lorey's Height or the mean stand height. These parameters are presented as they are considered the more realistic in their quantification of biomass and canopy height.

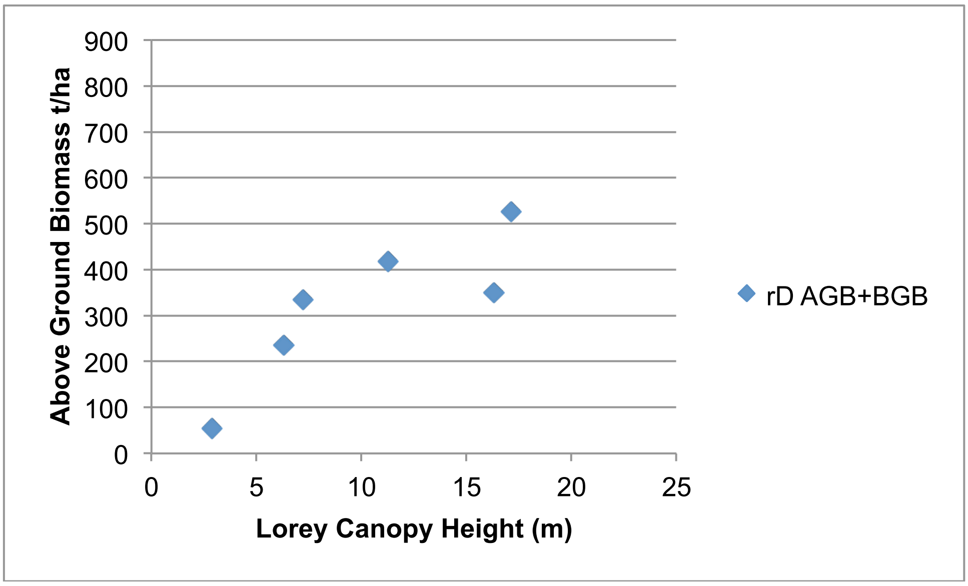


Figure 9. Above ground biomass of *Bruguiera* species for different height stands across two islands. Above Ground Biomass (AGB) derived from common equation using diameter and height by Chave et al. (2005).

These data describe a significant linear relationship between biomass and canopy height. This shows how canopy height can be used as a proxy for stand biomass, and later for living carbon content. The proviso in this, relates to the range of stands presented in these plots, based on their range of canopy heights and stem diameters.

Dominant vegetation unit* – Rhizophora *species

The *Rhizophora* species are perhaps the most difficult to sample because of their tangles of above ground roots and their multi-stemmed structure. These vegetation assemblages are also dominant across all five islands (Tables 12 and 13). And, together with the *Bruguiera* species, these two genera are expected to be present within the bulk of mangrove habitats. This is confirmed with the mapping of these habitats and islands.

Note, for *Rhizophora* species in comparable plots from South Pacific Island countries of Samoa, Tonga, Fiji, Vanuatu and Solomon Islands had ABG/H of 39.1 to 553.8, and BGB of 54.4 to 262.8, respectively (Duke et al. 2013).

Table 12. For *Rhizophora apiculata* derived mean estimates of average tree height (Hgt), weighted canopy height (CanW Hgt), biomass (in t.ha^{-1}) as Above Ground Biomass (AGB/H) from Chave et al. 2005, and Below Ground Biomass (BGB) from Komiyama et al. 2005, and Stand Basal Area (BA) for long plots in Torres Strait.

Country	MeanHgt(m)	**CanW Hgt(m)**	**AGB/H Chave**	AGB Chave	**BGB Komiyama**	**BA (m^2.ha^{-1})**
Gebar	12.0	15.0	400.6	413.3	219.1	52.1
Iama	13.3	14.6	306.0	325.0	172.2	40.0
Boigu	17.1	17.4	463.2	415.0	217.9	49.4
Sabai	18.1	18.3	494.4	363.6	207.6	51.8

Table 13. For *Rhizophora stylosa* derived mean estimates of average tree height (Hgt), weighted canopy height (CanW Hgt), biomass (in t.ha^{-1}) as Above Ground Biomass (AGB/H) from Chave et al. 2005, and Below Ground Biomass (BGB) from Komiyama et al. 2005, and Stand Basal Area (BA) for long plots in Torres Strait.

Country	MeanHgt(m)	**CanW Hgt(m)**	**AGB/H Chave**	AGB Chave	**BGB Komiyama**	**BA (m^2.ha^{-1})**
Gebar	8.8	9.6	200.8	291.5	158.3	35.4
Zagai	11.4	11.2	298.8	334.6	188.7	44.4
Boigu	19.0	17.3	303.8	258.8	137.7	32.0
Sabai	8.3	9.0	91.4	102.4	67.6	18.5

These data describe a significant linear relationship between biomass and canopy height for *Rhizophora* species assemblages (see Figure 10). This shows further how canopy height can be used as a proxy for stand biomass, and later for living carbon content. The proviso in this, relates to the range of stands presented in these plots, based on the range of canopy heights and stem diameters.

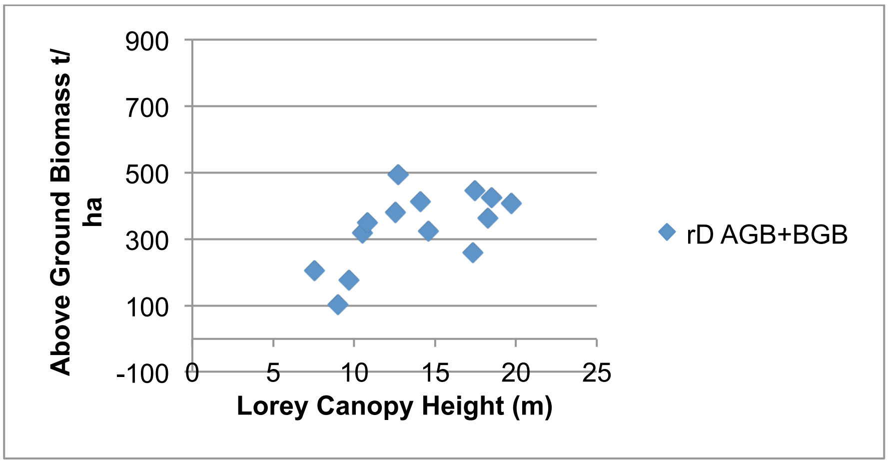


Figure 10. Above ground biomass of *Rhizophora* species for different height stands across all four islands. Above Ground Biomass (AGB) derived from common equation using diameter and height by Chave et al. (2005).

Dominant vegetation unit -* Ceriops *species

Ceriops species vegetation assemblages are relatively open stands of straight slender stems with moderate low buttressing. They can be prone to multi-stemmed structures in more arid regions. Such stands are less common in this area, especially as these species occur commonly only in inner stands.

In Tables 14 and 15, canopy heights are varied between species, rather than between each island, with smaller 5.7 m stands of *C. australis* in Iama, compared to taller stands of *C. tagal* in Boigu and Saibai.

Table 14. For *Ceriops australis* derived mean estimates of average tree height (Hgt), weighted canopy height (CanW Hgt), biomass (in t.ha^{-1}) as Above Ground Biomass (AGB/H) from Chave et al. 2005, and Below Ground Biomass (BGB) from Komiyama et al. 2005, and Stand Basal Area (BA) for long plots in Torres Strait.

Country	MeanHgt(m)	**CanW Hgt(m)**	**AGB/H Chave**	AGB Chave	**BGB Komiyama**	**BA (m^2.ha^{-1})**
Iama	5.7	5.4	128.4	205.2	145.7	46.4

Table 15. For *Ceriops tagal* derived mean estimates of average tree height (Hgt), weighted canopy height (CanW Hgt), biomass (in t.ha^{-1}) as Above Ground Biomass (AGB/H) from Chave et al. 2005, and Below Ground Biomass (BGB) from Komiyama et al. 2005, and Stand Basal Area (BA) for long plots in Torres Strait. Occasional large trees of *Avicennia marina* bolstered the Saibai biomass results.

Country	MeanHgt(m)	**CanW Hgt(m)**	**AGB/H Chave**	AGB Chave	**BGB Komiyama**	**BA (m^2.ha^{-1})**
Boigu	11.0	12.1	296.0	304.1	177.9	44.4

Sabai	11.8	13.3	441.5	590.9	285.4	61.9

Note, for *Ceriops tagal* in comparable plots from South Pacific Island countries of Vanuatu and Solomon Islands had ABG/H of 148.8 and 296.1, and BGB of 133.4 and 181.8, respectively (Duke et al. 2013).

The taller stands have higher amounts of biomass. This is shown in Tables 14 and 15 and further in Figure 11 where plots from the three islands are considered together. The equation used in this figure was that of Chave et al. (2005) using stem diameter and height, but the trend changed little between common equations. Likewise, this applies also with the use of Lorey's Height as representing mean stand height. As before, these parameters are presented as they are considered the more realistic in their quantification of biomass and canopy height.

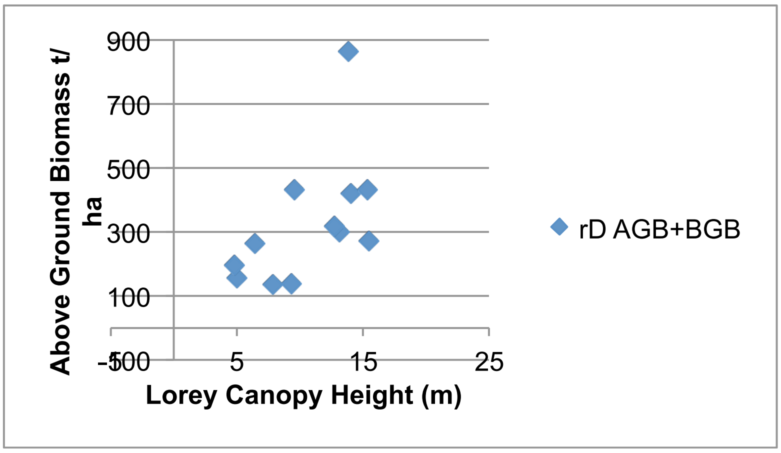


Figure 11. Above ground biomass of *Ceriops* species for different height stands in three islands. Above Ground Biomass (AGB) derived from common equation using diameter and height by Chave et al., 2005.

These data further describe a significant linear relationship between biomass and canopy height. This shows how canopy height can be used as a proxy for stand biomass, and later for living carbon content. The proviso in this, relates to the range of stands presented in these plots, based on their range of canopy heights and stem diameter.

Standard mangrove biomass measures

There are a limited number of published measures of above-ground biomass, below-ground biomass, canopy height and basal area in mangrove forests comparable with those in the SW Pacific. In Table 16, measures have been compiled from three of the comparable dominant vegetation units measured in SE Asia. Differences between vegetation assemblages are largely insignificant considering the differences in canopy height represented within these data. In these data, the ‘shoot to root’ (AGB:BGB) ratios vary from 2.4–2.7, 1.1–2.0 and 1.1–4.7, respectively for *Bruguiera*, *Rhizophora* and *Ceriops* species.

Table 16. Published estimates of measured biomass of four dominant mangrove vegetation genus units, *Bruguiera*, *Rhizophora*, *Ceriops* for various locations in SE Asia (summarised from Komiyama et al. 2008, plus updates by Pandey et al. 2013).

Dominant **Mangrove Vegetation Assemblage**	Height (m)	AGB ($t.ha^{-1}$)	BGB ($t.ha^{-1}$)	BA ($m^2.ha^{-1}$)
Bruguiera gymnorhiza	22-26	281-436	106-181	31-36
Rhizophora species	2-30	13-619	12-306	3-44
Ceriops tagal	2-5	14-92	3-88	~15

The measures compare closely with the above ground biomass estimates derived from our Torres Strait plots with the common equation of Chave et al. (2005) using stem diameter and height (Table 17). In these data, the ‘shoot to root’ (AGB:BGB) ratios vary from 0.8–1.6, 0.7–2.1 and 1.1–1.6, respectively for *Bruguiera*, *Rhizophora* and *Ceriops* species. Again, these Torres Straits Island survey estimates compare well with published measures from elsewhere (also see Duke et al. 2013).

Table 17. Derived estimates of biomass of three dominant mangrove vegetation units, *Bruguiera gymnorhiza*, *Rhizophora* species, and *Ceriops tagal*, for long plots from the 2012-2014 Torres Strait island surveys.

Dominant **Mangrove Vegetation Assemblage**	Lorey’s Height (m)	AGB/H ($t.ha^{-1}$)	BGB ($t.ha^{-1}$)	BA ($m^2.ha^{-1}$)
Bruguiera species	5-22	125-463	149-284	34-74
Rhizophora species	4-17	39-554	54-263	16-60
Ceriops species	7-13	149-296	133-182	32-42

The reason for most differences in these parameters appears more to do with the relationship between biomass and canopy height (see Figure 12), than with any other factor. For example, note how the published estimates for *Ceriops tagal* mostly represent shorter stands, where those in this study were much taller. A similar interpretation can be made of the other vegetation assemblages surveyed.

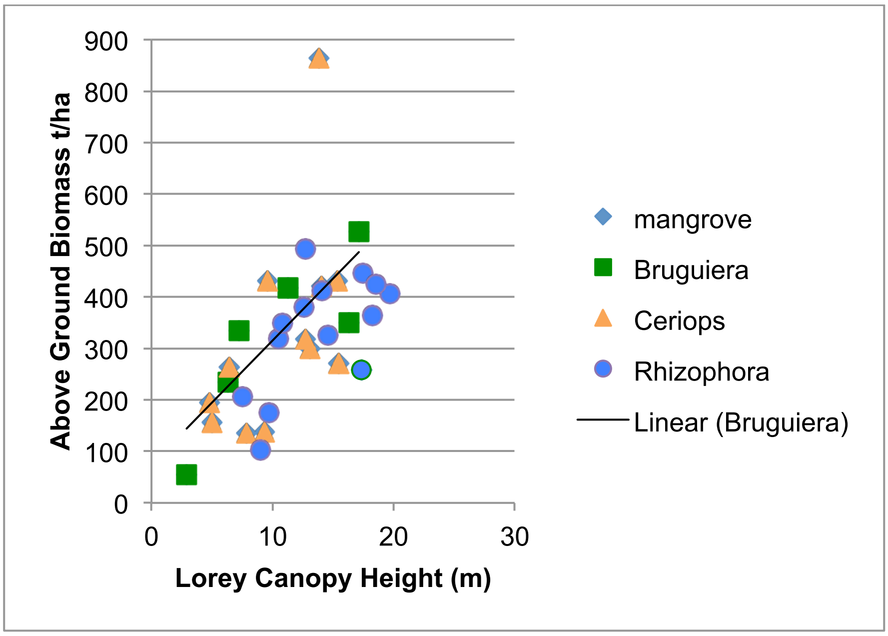


Figure 12. The relationships between weighted height (Lorey's Height) and Above-ground Biomass (using common equation, AGB/H of Chave et al. 2005) for the current study of four dominant vegetation units of *Bruguiera*, *Rhizophora*, and *Ceriops* species.

These deductions were only possible because of the broad array of plots sampled in the current study. The veracity of data collected in the current study is also confirmed where estimates derived from the current study are so closely comparable with data collected elsewhere. It is useful also to note how closely each of the vegetation assemblages compare with each other when presented together.

Estimation of mangrove carbon resources

The derived estimates from these long plot surveys reasonably provide for the estimation of living biomass and carbon in mangrove forest stands across all islands. All that is required to make these estimates are the areas of mangroves present and area representative field observations to affirm average canopy heights (see Figure 13). For the species present, there appears to be little difference in their respective biomass estimates compared to the notable differences in stand canopy heights.

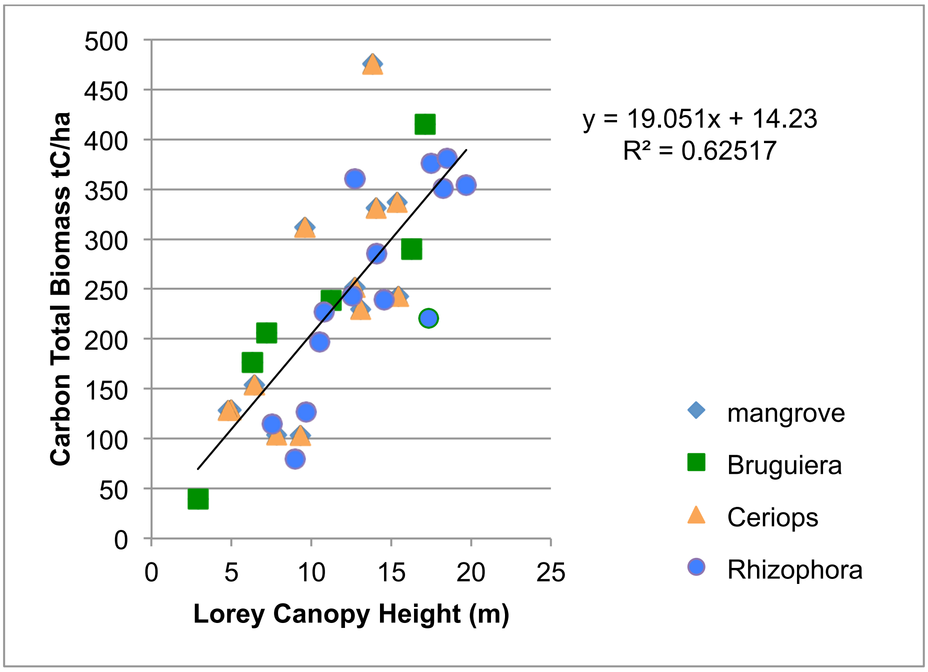


Figure 13. Total carbon biomass in mangrove living forests above and below ground compared with canopy height across all plots and islands. This relationship is based on climax forests of the dominant mangrove vegetation assemblages.

Overall and for each country there are notable trends with canopy height, where each trend clearly depends on the range of stand heights included in the survey. The overall trend across all countries can be summarised in the formula of the linear best fit (r^2 = 0.62517; n = 32) as: Total Carbon (AGB+BGB) = 19.051*L-Hgt – 14.23, where carbon is dry weight in $t.ha^{-1}$, and canopy height is in metres. It appears the full relationship is curvi-linear, especially for trees larger than 20 m in height. This is shown notably in the trend for plots in some plots where trees are considerably larger than the other five islands. However, the noted linear relationship is applicable for the bulk of mangrove forests observed.

There are also likely to be detrimental influences of cutting and harvesting; affecting these estimates. More precise data on these influences and their effects are needed to quantify the changes in biomass and carbon accumulation.

There were reportedly 31,390 ha of wetlands throughout Torres Strait; with 83% being tidal mangrove wetlands; this equated to around 26,054 ha of mangrove forests through the islands.

The overall mean above and belowground biomass for all 32 plots was 482.5 $t.ha^{-1}$. This was averaged for all species included in these surveys. These species are considered representative of mangrove forests throughout the islands. Based on total area figures, Extrapolation of the total carbon stored in the total area of Torres Strait mangroves, noted at ~6,285,528 tons of carbon, present in living vegetation. In addition, based on current literature, there is likely to be up to 5 times more carbon in sediment peat deposits beneath these mangrove forests. This carbon will only remain bound whist mangrove forests remain intact and healthy.

Notes and specific feedback

The long plot method has been implemented as the standard mangrove forest biomass assessment method for this project. This practical methodology has the advantage of being relatively simple to learn and use, being rapidly undertaken, with easy follow-up for uploading data into the standard assessment format. Field operations are relatively easy and predictable, measuring a set number of stems rather than a fixed plot area. Furthermore, the incremental accumulation of plot measures provides the means to test statistical variance to affirm attainment of sufficient numbers of stems for calculation of biomass for each plot.

Some on-going practical feedback with specific comments, as follows:

1) Long Plot biomass data must be collected, where possible, for each dominant vegetation type of mangrove stands present on each island;
2) Ensure start and end trees are marked with permanent tags – and labelled for future reference (plot number, start/end); and GPS coordinates taken;
3) Include scores of both live and dead trees, where possible, measuring stem diameter of both, listing species where possible and cause of death or damage;
4) Two additional tasks can be implemented in future surveys. These include additional tasks like, a) depth of peat measures, and b) carbon content and bulk density of biomass/carbon in sediments;
5) Estimates of biomass and carbon will characterize and quantify each dominant vegetation type, along with appropriate error terms – for scaling up from areas derived from the mapping of these same vegetation units to area estimates; and
6) It is considered important to undertake specific allometric studies (involving cutting down and weighing 15–30 trees from smallest to largest, for each dominant species) to develop and affirm allometric equations for Torres Strait and Australia. This requires supervised field surveys with experienced technical support of the JCU project team.

Torres Strait Shoreline Extent, Condition and Threats – Case Studies

Mangrove Extent

Key points:

- Updated mangrove mapping for 14 Islands.
- Mean shoreline mangrove cover documented at 67%.
- Fringing mangrove is important for ecosystem service provision.
- Mangrove islands Sassie, Zagai and Buru are unique and important mangrove habitats in Torres Strait. These islands should be included provided the highest conservation status.
- Rocky outcrop islands have a high mangrove exposure. These fringing mangroves are most at risk from marine-based threats.
- Protection and management of the mangrove fringe should be reviewed for all islands.

Detailed mapping of mangroves on surveyed islands updates existing tidal wetland habitat mapping. For many islands, particularly uninhabited islands, mangrove mapping was out-dated and in some cases more than 30 years old. Many of the inhabited islands included in this study have recently been assessed in more detail during regional ecosystem mapping (Stanton et al. 2008). However, this assessment provides a specific focus on mangroves that has enabled refinement and provides even greater habitat extent resolution assisted by shoreline oblique aerial imagery collected during NERP-funded surveys.

Access to up to date habitat maps is essential for planning and conservation management by local and regional natural resource managers, particularly for habitats such as tidal wetlands that are increasingly threatened by climate change. The data presented here includes quantification of small shoreline mangrove stands that have previously not be included in prior mapping. These small stands often fall outside of extent and height criteria for vegetation mapping. Yet, these small isolated stands provide important fish habitat along otherwise sparsely vegetated coastlines. Additionally, isolated mangrove stands can serve to anchor otherwise mobile sediments and assist mangrove expansion in dynamic coastal settings. Isolated patches present shoreward of the main mangrove forest fringe are also indicators of mangrove expansion and depositional gain.

Mangrove Islands

Of the islands assessed, Boigu and Saibai have the greatest mangrove extent, owing to their underlying mud substrate and low topographic relief. Often classified as 'mangrove islands' these islands are actually composites of complex and unique tidal wetland and brackish marsh vegetation assemblages that include samphire, sedges and saltpan. For instance, Saibai Is. is only 59% mangrove forest, with the remaining island landmass occupied by saltpan, sedge, saline grassland and mangrove fern (*Acrostichum sp.)*. Detailed assessment of specific vegetation communities present on these islands and most other islands in Torres Strait is reported in (Stanton et al. 2008)

In addition to Boigu and Saibai, there are three other predominantly 'mangrove' islands in Torres Strait; Sassie, Zagai and Buru (Table 18). Mangrove forests on these islands are dense, tall (>20 m height) and well developed (Figure 14). These forests have developed on shallow sandy substrate deposited on, and adjacent to, exposed coral reef flat. These islands provide important habitat and breeding grounds for fish and mud crabs, as well as shorebirds, bats, reptiles, Torres Strait Pigeon, Saltwater Crocodile and Turtles. Sassie Island is the world's largest Hawksbill Turtle rookery (Limpus and Fien 2009) and is renown locally for the high abundance of mud crab and as an important mud crab nursery (Pers. Comm., L. Pearson, TSRA Land & Sea Ranger 2012). Biomass data presented in this report indicates these islands are also important carbon reserves and likely contribute greatly to regional coastal productivity. The habitat value of these mangrove islands is closely associated with their cultural importance as traditional food sources and hunting grounds (Shnukal 2004). The low topographic relief of these islands makes them highly susceptible to sea level rise and their future is uncertain. Due to their high ecological and cultural significance and potentially threatened status, these islands should be protected with the highest level of national conservation.

The mangrove fringe; narrow in width, but vitally important

Granite and basaltic islands in Torres Strait generally have less mangrove areal extent (Table 18) due to steep coastal topography and exposed shoreline, unsuitable for extensive mangrove development. Despite this, the majority of islands surveyed have a high proportion of shoreline occupied by mangrove habitat (Figure 15). Mean shoreline mangrove cover for islands surveyed is 67%. Mangrove fringes, although narrow in width, provide numerous ecosystem services, with ecosystem service delivery often varying non-linearly with distance from the shoreline due to the high degree of interaction of this zone with adjacent marine habitats. Narrow fringing habitat also provides direct connectivity with adjacent terrestrial habitat (Koch et al. 2009). The mangrove exposure score is an indicator of both mangrove habitat marine connectivity and the degree to which an islands' mangroves would be impacted by marine drivers of change, for instance an offshore oil spill, cyclone, or sea level rise. The overall mean exposure score for surveyed islands is (0.1). Erub, Mabuiag, Mua and Cap Islet all have mangrove exposure scores significantly greater than the mean. These islands are therefore the most at risk of losing mangrove habitat as a result of a marine-based threat, and have the greatest mangrove connectivity, with high capacity for ecosystem service provision related to fish and wildlife habitat values, coastal productivity, water quality improvement function and shoreline protection. Protection and management of the mangrove fringe should be reviewed for these islands.

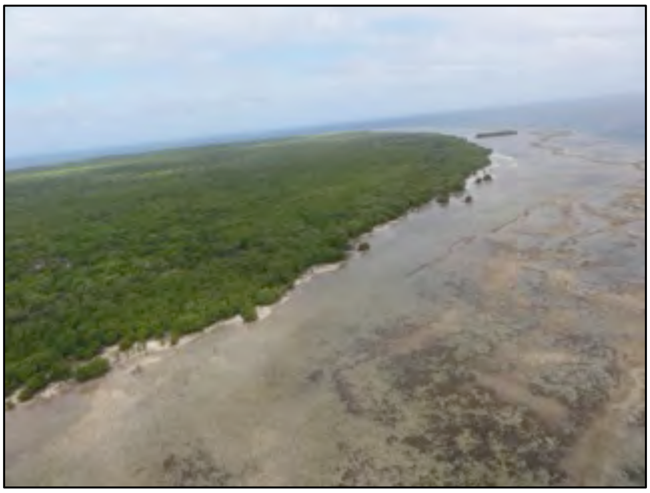


Figure 14. Zagai Island mangroves

Figure 15. Narrow, but extensive shoreline mangrove cover on Mabuiag Island

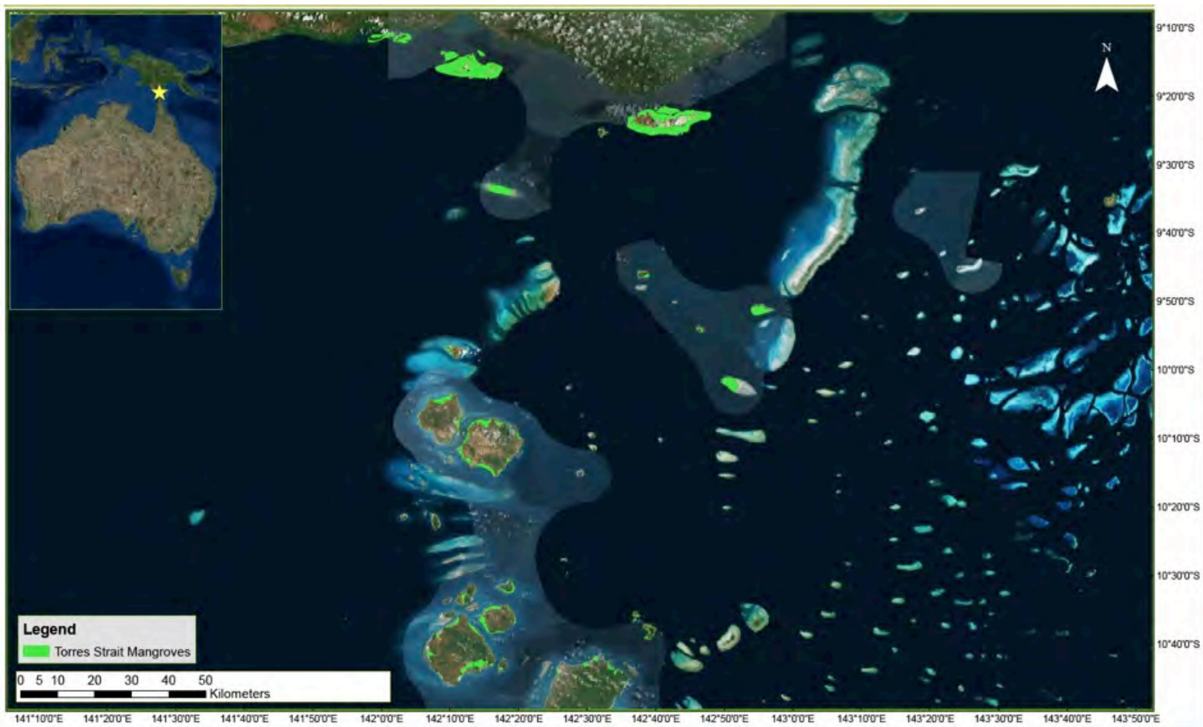


Figure 16. Torres Strait mangrove distribution.

The results presented here highlight the importance of undertaking oblique continuous georeferenced image-based assessment of mangrove habitat in conjunction with satellite and aerial imagery and on-ground surveys to accurately quantify habitat extent.

Table 18. Mangrove extent data from selected Torres Strait Islands.

Island	Island Group	Geology	Island Area (ha)	Tidal Wetland Area (ha)	Proportion of Island Mangrove (%)	Proportion Shoreline Mangrove (%)	Mangrove Exposure Score
Mua	*Near Western*	*Granite*	17004.2	1717.2	10	70	0.033
Badu	*Near Western*	*Granite*	10082.9	667.13	7	46	0.054
Mabuiag	*Near Western*	*Granite*	641.96	44.2	7	78	0.267
Sassie	*Central*	*Sand*	1091.6	1078.3	99	94	0.031
Zagai	*Central*	*Sand*	934.96	930.59	99.5	99.5	0.024
Tudu	*Central*	*Sand Cay*	50.97	18.6	36	18	0.035
Iama	*Central*	*Granite*	208.46	78.49	38	81	0.121
Cap	*Central*	*Granite & Sand Cay*	20.04	1.94	10	21	0.31

Gebar	*Central*	*Granite*	426.3	95.5	22	58	0.056
Erub	*Eastern*	*Basalt*	602.2	13.97	2	37	0.35
Buru	*Top Western*	*Sand*	1193.85	1173.5	98	100	0.016
Dauan	*Top Western*	*Granite*	364.84	32.35	9	33	0.144
Saibai	*Top Western*	*Mud*	10488	6157.71	59	98	0.009
Boigu	*Top Western*	*Mud*	7244.85	5805.93	80	99	0.009

Shoreline Mangrove Condition

Key points:

- Mean shoreline mangroves in a healthy state 59%.
- Mean shoreline mangroves in poor condition 18%.
- This data provides a baseline of mangrove condition in Torres Strait.
- High proportion of poor condition mangroves is indicative of the dynamic coastal environment in Torres Strait and highlights that fringing mangroves are exposed to natural pressures.
- Sea level rise may be exacerbating the effect of wind and waves on fringing mangrove habitat.
- Gebar mangroves are in very poor condition. This requires further investigation to establish the cause of mangrove degradation.
- Saibai, Boigu and Mua Islands have the greatest extent of mangroves in poor condition.

Figure 17. Mangrove dieback on Mua Island.

The capacity of mangroves to provide ecosystem services is dependent on ecosystem structure and function. Mangrove habitat in poor condition is less likely to provide ecosystem services due to loss of ecosystem productivity. The capacity of mangroves to withstand and recover from natural and anthropogenic pressures is also influenced by ecosystem condition. As for coral reefs, mangrove resilience to climate change is dependent on maintaining healthy habitat such that the ecosystem can adequately and effectively respond to change.

An indicator of mangrove ecosystem condition is aggregated tree health. Mangroves experiencing stress exhibit crown retreat and leaf loss in the upper canopy. If the stress exceeds a certain threshold, the tree dies (Figure 17). Consequently, dieback and the presence of dead trees are visual indicators of mangrove ecosystem condition. Mangroves can experience stress through multiple pathways; due to mechanical damage from wind or herbivory causing leaf loss, lack of oxygen availability due to root burial or sediment waterlogging, increased salinity exposure and loss of water supply and nutrient availability due to reduced tidal flushing, reduced rainfall and overland freshwater flows, increased tidal frequency, root exposure or damage reducing water and nutrient availability or chemical inhibition of photosynthetic pathways due to herbicide. Most common mangrove species tend to have a wide tolerance for many environmental variables present in the tidal zone, however once established, individuals become specifically adapted to prevailing conditions, such that small changes may cause stress and reduce functional capacity (Krauss et al. 2008, Friess et al. 2012)

Here we provide an overview of the condition of shoreline fringing mangrove habitat as indicated by the frequency and intensity of dieback and dead trees along the mangrove fringe observed during aerial surveys. Only severe dieback and the presence of many dead trees was used to indicate poor condition as there is always likely to be a low level of dieback and individual dead trees in any mangrove forest stand (Table 19).

Overall the majority of mangrove shoreline assessed was in a healthy state experiencing no visible signs of stress (mean = 59%). A mean total of 18% of shoreline mangroves were in poor condition. Islands where the proportion of mangrove shoreline was greater than the overall mean include Gebar, Cap, Zagai, Mua, and Tudu. When the total mangrove in poor condition relative to healthy mangrove factored for mangrove shoreline length is considered, the islands with high levels of poor condition mangrove are Saibai, Boigu and Mua, which also have the greatest length of shoreline mangrove.

The presence of such a high proportion of poor condition shoreline mangroves was unexpected for Torres Strait due to the lack of human environmental modification and influence. These results indicate that Torres Strait mangroves are subjected to high levels of stress related to marine influences in the form of wind and wave activity. Mangroves exposed to the south-easterly and north-westerly monsoon winds appear, which also coincide with king tides (Duce et al. 2010) appear to have higher proportion of poor condition mangroves than those in sheltered embayments and along shorelines protected from wind (Figure 18). This observation is being examined in further detail as a result of the findings of this assessment.

Sea level rise in the Torres Strait may be exacerbating the effects of wind on shoreline mangrove forest, resulting in reduced resilience. Increased speed resulting from climate change (Green et al. 2010a) will also likely impact future mangrove condition and function.

Table 19. Shoreline mangrove condition (expressed as proportion of mangrove shoreline).

Island	Healthy Mangrove (%)	Mangroves in Poor Condition (%)	Poor to Healthy Condition Ratio	Weighted Condition Score*
Mua	80	20	0.25	11.4
Badu	84	16	0.19	4.75
Mabuiag	71	18	0.25	2.99
Sassie	52	15	0.29	9.61

Zagai	48	24	0.50	10.06
Tudu	64	19	0.30	0.19
Iama	64	13	0.20	1.94
Cap	38	21	0.55	0.33
Gebar	28	34	1.21	6.50
Erub	77	15	0.19	0.95
Buru	39	11	0.28	5.42
Dauan	67	12	0.18	0.83
Boigu	58	15	0.26	13.13
Saibai	59	18	0.31	17.23

*The weighted condition score provides an indication of the extent of poor condition mangroves relative to island size.

Figure 18. Map of Zagai Island showing location of poor condition mangroves along exposed shoreline.

Shoreline Processes Affecting Mangroves

Key points:

- Shoreline processes affecting mangroves vary between islands.

- Overall the dominant shoreline process is erosion (21% greater than expansion).
- Sassie and Zagai islands are undergoing substantial change with both mangrove loss and expansion occurring.
- There is a high proportion of expanding shoreline and depositional gain on Erub Island due to land-based sediment runoff.
- There is a high proportion of mangrove expansion in Iama Island.
- Gebar Island is experiencing a high degree of shoreline retreat, with an overall net loss of mangroves currently occurring.
- Mangrove loss and gain may not be balanced at an island scale, but may be balanced across regional scales.

Shorelines are dynamic environments subject to change. Mangroves are subjected to tidal currents, waves and wind that cause erosion and subsequent loss of mangrove habitat and shoreline retreat. Conversely, newly deposited sediment resulting from gradual long shore and marine sediment transport, land-based sediment runoff and large storms and waves can raise shoreline elevation above mean sea level creating suitable habitat for mangrove colonization and mangrove expansion. This process is also referred herein as depositional gain.

Based on findings from similar studies in estuarine setting, it is expected that any shoreline retreat resulting in mangrove loss will be offset by sediment deposition in another location, allowing new mangrove forest colonization. As mangroves provide effective shoreline protection the rate of loss due to erosion is also not expected to be high. An imbalance in the ratio of mangrove loss to mangrove gain may indicate unusual processes occurring. For instance, sea level rise is expected to result in increased levels of shoreline erosion. Alternately, increased mangrove expansion will occur if there is a high degree of land-based sediment runoff due to poor vegetation management.

Based on anecdotal reports received prior to undertaking this assessment, it was expected that erosion would be an influential factor affecting mangrove habitat in the Torres Strait. These reports were due in part to local concerns regarding shoreline erosion near settlements and reported trends in increasing sea level (Duce et al. 2010).

Overall mangrove shoreline retreat is highly variable across the Torres Strait with some islands experiencing more than 25% observed mangrove shoreline retreat, such as Zagai and Gebar (Table 20). Whereas other islands such as Erub, Mabuiag, Iama and Badu had a very low proportion of shoreline mangroves affected by mangrove retreat. Mean proportion of mangrove shoreline undergoing mangrove retreat is 13.9%. Six (6) out of the 14 islands surveyed had observed shoreline mangrove retreat greater than the mean.

Comparatively, depositional gain and mangrove expansion was also highly variable. Mean proportion of mangrove shoreline undergoing mangrove expansion was 11.8%. Very little mangrove expansion was observed on the mostly rocky islands of Mua, Badu and Dauan, as well as Erub, Buru and Saibai. Whereas the sand islands, Zagai and Sassie and Iama Island had more than one-third mangrove expansion observed.

Examination of the retreat to expansion ratio shows that some islands are experiencing much greater erosion than deposition as was expected. Dauan, Gebar and Buru all have very a high proportion of mangrove loss compared to gain. However, other islands such as Erub, Iama and Mabuiag, have much greater mangrove expansion compared to loss. These findings do not appear to be consistent with island location, geology or topography and are likely influenced by localsied hydrodynamic processes.

Mangrove expansion on Erub and Iama is likely to be human influenced. Large-scale land clearing on Erub Island in the early part of last century for cattle grazing denuded the fragile basaltic landscape resulting in high rates of erosion from the islands steep slopes. Compared to other volcanic islands in the region, such as Murray Island, Erub has much greater extent of mangroves (Murray Is. has only one very small stand of mangroves). Mangrove development may have occurred on Erub relatively recently as a result of land clearing, although further investigation is required to confirm this. The mangrove expansion on Erub observed during this assessment is likely part of the longer-term sediment deposition resulting from hillslope erosion. On Iama Island, similar human environmental modification has occurred, with landscape modification for urban development and construction of the island airstrip, which included mangrove removal. Island modification in conjunction with mangrove regrowth and elevated nutrient loads may be in part related to the high proportion of mangrove expansion. A more detailed assessment of Iama Island historical mangrove change is provided later in this report.

Assessment of the total length of surveyed shoreline undergoing mangrove expansion and retreat shows that there is 21% more mangrove loss than gain. This finding is consistent with our initial observation that mangrove retreat is the dominant shoreline process in the Torres Strait, but that there is a high degree of variability between islands. For island mangrove habitat, shoreline retreat may not be offset by mangrove gain at the island scale, but may occur at more regional scales. This finding warrants further investigation.

Table 20. Shoreline processes affecting shoreline mangrove habitat.

	Mangrove Expansion (%)	Mangrove Retreat (%)	Retreat - Expansion Ratio
Mua	3	7	2.3
Badu	5	3	0.6
Mabuiag	11	2	0.2
Sassie	33	24	0.7
Zagai	30	31	1.01
Tudu	0	0	0
Iama	44	6	0.14
Cap	0	13	*
Gebar	0.9	27	30
Erub	8	0.5	0.06
Dauan	0	13	*
Buru	4	24	6
Boigu	19	23	1.2
Saibai	7	21	3

	Mangrove Expansion	Mangrove Retreat	Retreat to Expansion Ratio
Total Shoreline Length (km)	40.3	48.8	1.21

Figure 19. Mangrove shoreline retreat, Gebar Island.

Figure 20. Mangrove expansion (depositional gain) Sassie Island.

Drivers of Change and Threats to Mangrove Habitat

Key points:

- Mua Island has the highest number of mangrove management issues present (7).
- Mangrove cutting is threatening mangrove habitat in the Torres Strait. 2% of mangroves in Torres Strait are estimated to be impacted by cutting.
- Elevated nutrient loads from STP's threaten mangrove climate change resilience but may facilitate mangrove expansion.
- Chemical leachate from waste disposal is likely entering mangrove habitat. This poses a threat to human health related to chemical exposure of mangrove fisheries resources.
- Only a small proportion of mangroves are at risk from localized oil and fuel spills.
- Sea level rise is potentially directly threatening 13% of Torres Strait mangrove habitat
- Mangrove root burial from sediment runoff is impacting 34% of mangroves in Erub Island.

Mangroves, at the dynamic interface between land and sea, are subjected to many natural drivers of change including, wind, waves and tidal currents. Their position along the coastal zone also places mangroves in direct competition with humans for space for urban development. In the Torres Strait, where most infrastructures is present along the coast, mangroves are subject to elevated nutrient loads from sewage treatments plants and septic tanks, and chemical leachate from poorly located refuse sites. As mangroves are the primary forest habitat of the Torres Strait, Torres Strait Islanders also use mangroves as source of timber for firewood, building and traditional carving. These human related pressures can lower mangrove resilience to existing natural pressures, including climate change. At the local and regional management level, there is very little that can be done to prevent climate change and reduce the impacts of cyclones and storm events on mangrove habitat. However, much can be done to reduce adverse anthropogenic impacts to ensure mangroves maintain healthy function and condition, and maximum resilience capacity.

Based on observation during ground and aerial surveys a GIS assessment of the potential and existing threats to mangroves was undertaken on selected islands. Here we focus on the human related drivers of change to inform future mangrove management. Results presented here also provide specific insight into the potential impact of sea level rise in Torres Strait, which may already be starting to cause dramatic change.

During surveys eight (8) human related drivers of change were identified that require future management response. These drivers were observed to be directly impacting mangroves or could have the potential to become major issues for mangrove function and resilience if not addressed. The presence of drivers observed is summarized in Table 21.

Table 21. Observed human related drivers of change impacting mangroves on Torres Strait Islands.

Driver	**Mua**	**Badu**	**Mabuiag**	**Sassie**	**Zagai**	**Tudu**	**Iama**	**Gebar**	**Erub**	**Dauan**	**Buru**	**Boigu**	**Saibai**
Feral Animal	1	1						1				1	1
Nutrients	1		1				1		1			1	1
Root Burial	1	1								1			1
Fire	1	1											
Vehicle Damage	1											1	
Cutting	1		1			1	1		1	1		1	1
Invasive Species (Pond Apple)		1								1			
Altered	1						1						

Hydrology													
Pollution			1				1			1		1	1
Total	7	4	3	0	0	1	4	1	2	4	0	5	5

Mua, Saibai and Boigu Islands have the most number of mangrove management issues requiring action (Table 22). Whilst, the uninhabited islands of Sassie, Zagai and Buru had no issues identified.

Table 22. Drivers of Change threatening mangrove habitat in Torres Strait (% Mangrove area).

	Drivers of Change						
	Direct Human Drivers	*Indirect Human Drivers*				*Not Obviously Human Drivers*	
Island	**Cutting**	**Altered Hydrology**	**Nutrients**	**Chemical Leachate**	**Oil***	**Sea Level Rise**	**Root Burial**
Mua	0	1	0	0	0	8	0.2
Badu	0	0	0	0	0	18	0.1
Mabuiag	19	0	19	8	0.34	29	0
Sassie	0	0	0	0	0	12	0
Zagai	0	0	0	0	0	15	0
Tudu	0.01	0	0	0	0	17	0
Iama	10	5	41	30	0.8	13	0
Cap	0	0	0	0	0	34	0
Gebar	0	0	0	0	0	37	0
Erub	0	0	3	0	0	45	34
Dauan	28	0	0	71	0	27	2
Buru	0	0	0	0	0	n/a	0
Boigu	5	0	1	2	0.25	n/a	0
Saibai	1	0	0.5	3	0.08	n/a	0.1

The area impacted by existing drivers of change and potential threats was mapped based on ground and aerial observations, proximity to threat location and using reasonable assumptions based on expert knowledge.

Mangrove Tree Cutting

The most frequently observed directly human related factor influencing mangrove habitat was mangrove cutting, including clearing and trimming (Figure 21). Mangrove cutting was observed on 8 out 14 islands surveyed and was present on all inhabited islands with the exception of Badu Island.

Most cutting observed was for timber resources, although on Mabuiag and Iama, mangroves are trimmed and have been historically cleared to maintain runway access and for infrastructure.

The largest area affected by mangrove cutting is estimated to be on Boigu Island (268 ha) where creeks and mangrove forest near the township are frequently accessed to harvest mangrove timber. Of the mangroves assessed, nearly 2% (361 ha) are impacted by mangrove cutting. Mangrove cutting is affecting a large proportion of mangroves on Dauan (28%) and Mabuiag (19%).

Cutting for timber appears to be mostly opportunistic, present in mangrove areas adjacent to townships. However on Iama, Boigu and Saibai, residents appear to seek out trees of the *Ceriops* genus as these have straight trunks and dense timber, useful as both firewood and building material. The selection of a single mangrove type may have implications for mangrove biodiversity. It has been suggested that the absence of the generally common *Xylocarpus granatum* (Cannonball Mangrove) from areas nearby the townships of Boigu and Saibai, may be related to the targeting of this species as a prized wood for carving (Pers. Comm. H, Warusam and N. Gibuma 2012). More importantly, the location of most cutting occurs closes to mangrove landward margins, along creek banks (in the case of Boigu and Saibai) and at the landward edge of the *Ceriops* zone. These ecotone locations are the most important to preserve intact as these areas are the most vulnerable to natural change. Healthy mangrove ecotones are also likely to assist effective landward mangrove migration in response to sea level rise. The cutting of easily accessible mangroves along creek banks, estuary margins and shorelines is also likely to increase mangrove vulnerability to erosion. In Mai Kassa and Wasi Kassa on Saibai Island, bank erosion appeared to be associated with heavy cutting presence.

Mangroves are protected plants under State Fisheries Legislation (Section 54; Queensland Fisheries Act 1994) and can attract high penalties for illegal removal. In Torres Strait it is unclear whether mangroves fall under similar traditional use exemptions as exists for turtles and dugong. Although clearly this should be the case as mangroves have been traditionally utilized extensively by Torres Strait Islanders. However, as for dugong and turtle, mangroves are under threat and a vitally important to Torres Strait Islanders. We therefore propose that, in consultation with Islanders, TSRA and Qld Fisheries, a targeted study be undertaken to examine the full impact of mangrove forest harvesting and if necessary develop island specific Mangrove Management Plans. The Mangrove Management Plans should identify acceptable mangrove timber harvest quotas based on natural forest turnover and provide designated mangrove harvest areas that can be used on a rotational basis. There is also potential to establish mangrove forest ‘plantations’ that would also serve to provide additional mangrove ecosystem services in addition to alleviating mangrove extraction pressure.

Figure 21. Recent mangrove cutting along a river bank on Saibai Island.

Altered Hydrology

Altered hydrology is a relatively minor issue affecting mangroves in the Torres Strait. Altered hydrology was observed to be impacting mangroves on Mua and Iama. On Mua Island, 1% of mangroves to the west of Kubin township are impacted by the airstrip and dams, which restrict freshwater flow to mangrove channels. A large area of mangrove dieback near the airstrip may be associated with altered hydrology in the area. On Iama Island, approximately 5% of mangroves are currently impacted by altered hydrology. The airstrip has restricted natural overland flow to an area of mangroves at the east of the island. In the same area a small, disused road through the mangroves constructed to assist airstrip construction also blocks freshwater flow has reduced tidal flow to few small mangrove areas. Severe mangrove die-off was observed in this area during aerial surveys highlighting that this area may now be more vulnerable to natural climate variability and sea level rise as a consequence.

Nutrients

Mangroves adjacent to sewage treatment plants (STP's) on inhabited islands are likely to be effected by elevated nutrient loads (Figure 22). Waterhouse et al. (2013) identified that whilst many of the STP's and sewage infrastructure on the islands had been recently upgraded, they still experience frequent maintenance issues resulting in leaks and untreated sewage discharge. Mangrove habitats provide an effective water quality improvement function, removing excess nutrients from the water column and protecting adjacent seagrass and coral habitats. However, continuously high nutrient loading may reduce mangrove resilience to natural wind and wave impacts and climate change and limit the effectiveness of mangroves as a natural shoreline defense against cyclones and storm surge. Nutrient enriched mangroves have been shown to have lower root to shoot ratios making them more likely to topple and be affected by erosion (Lovelock et al. 2009). Additionally, nutrient enriched mangroves have been demonstrated to be less resilient to rainfall variability, with reduced root mass to access water during periods of water stress (Lovelock et al. 2009). Other studies have shown nutrient enriched mangroves to be more susceptible to stem breakage, making them more vulnerable to wind and storm events (Santini et al. 2012). Conversely, nutrient enrichment may enhance the capacity of mangroves to withstand sea level rise (Graham and Mendelssohn 2014) . By increasing productivity, nutrient enrichment can assist mangrove accretion in response to elevated sea level. Increased nutrients may also improve osmoregulatory function in some species increasing mangrove tolerance to increased salinity from greater tidal exposure, this may also assist seedling establishment, the most vulnerable stage of mangrove life-history (Krauss et al. 2008).

Six (6) of the 14 islands surveyed were identified as having mangrove areas at risk from elevated nutrient loads. The greatest area estimated to be affected is on Boigu Island (~62 ha), with the highest proportion of mangroves affected on Iama Island (33%). On Iama Island, recent rapid mangrove expansion may have been facilitated by elevated nutrient loads.

The mangroves affected by elevated nutrient loads are primarily nearby township where shoreline protection is most needed. As nutrients are likely to reduce mangrove shoreline protection capacity, it is recommended that more be done to limit high nutrient loads to mangrove areas. Further investigation into threshold limits should be undertaken to investigate the capacity of mangroves to provide nutrient removal without compromising structural integrity as a means to improve water quality in the Torres Strait.

Figure 22. Mangrove expansion near the Iama sewage treatment plant (STP).

Chemical Leachate

Landfill is the primary waste disposal method on all inhabited islands of the Torres Strait (Waterhouse et al. 2013). On Dauan, Boigu, Saibai and Iama Islands, landfill sites are located within or directly adjacent to tidal wetland habitat and are subjected to tidal inundation during king tides. Runoff to adjacent marine habitat is likely during high rainfall events.

Heavy metals, hydrocarbons and pesticides are likely present at the landfill sites and may leach into mangroves through subsurface waters or direct flow from tide and rain. These chemicals are known to be harmful to mangrove flora. Other chemicals may be present that are harmful to mangrove fauna.

The extent to which mangroves may be impacted by chemical leachate was determined using proximity of mangroves to the pollutant source. It is estimated that nearly 2% of mangroves assessed are threatened by chemical leachate from landfill sites (Table 22), with 197 ha of mangrove at-risk on Saibai Island and nearly one-quarter of mangroves at-risk on Dauan and Iama.

During surveys of Saibai and Boigu, albino propagules were observed along shoreline to the west of the townships, near the local refuse sites (Figure 23). Mangrove albinism is a well-recognized indicator of hydrocarbon and heavy metal exposure. Whilst albinism per-se does not result in loss of ecosystem function, high frequencies within a population may reduce mangrove forest viability and limit genetic diversity. This is not necessarily the case on Boigu and Saibai. The presence of albino propagules does however indicate that chemical leachate may be present in the mangrove forests and thus entering other more vulnerable marine ecosystems. The mangroves near the Boigu and Saibai township are heavily utilized for mangrove shell collection, crabbing and fishing and fauna may also have elevated levels of toxins as a result of their proximity to landfill. If mangrove flora is impacted by pollutants, it is possible that mangrove fauna is also affected and this may be a human health issue. It is recommended that a more targeted assessment of mangrove pollution be undertaken at Boigu, Saibai and Iama to determine if mangrove exposure to pollutants is a human health issue. Targeted surveys to determine albino population frequency should also be undertaken by local TSRA Land & Sea Rangers to assess whether albinism is occurring at frequencies higher than the expected natural frequency and the extent of trees affected by albinism as an indicator of the pollutant impact zone.

Figure 23. Albino *Rhizophora* propagule on Boigu Island.

Oil

Shipping is the primary means of goods transport in the Torres Strait. Additionally Torres Strait is a major international shipping route. Mangroves adjacent to boat loading facilities are at an increased risk of fuel and oil spills from vessel discharge. The presence of albino propagules on Saibai and Boigu Island as previously mentioned may also be related to hydrocarbon exposure, in addition to chemical leachate from waste disposal.

Six (6) islands are identified as having mangroves at-risk from localized oil spills. Oil is estimated to only impact a small area on each island as localized spills are likely to be relatively small and travel less than 1 km in near shore areas, depending on tide, wind and currents. Mua Is. has the greatest area of mangrove at risk from an oil spill with 1 ha potentially impacted. A total of 24 ha of mangroves are at risk from localized oil spills in Torres Strait. Less than 1% of mangroves are likely to impacted on all islands.

The potential for a large-scale oil spill along major shipping routes is summarized (Figure 24) in Waterhouse et al. (2013). Islands in the southern Torres Strait are most at risk from a large marine oil spill, as has occurred previously (cs. ‘Oceanic Grandeur’ oil spill in 1970, Duke et al. 1998b, Duke and Burns 1999). Of concern is the potential threat that a large oil spill poses to the ecologically sensitive and important mangrove areas on Sassie and Zagai Islands.

Sea Level Rise and Root Burial

The presence of mangrove forest collapse and damage within the inner lower intertidal forest is thought to be an indicator of sea level rise. This phenomena needs to be investigated further with detailed assessment. Data presented here provides an estimate of impacted extent only. However for the purposes of this assessment it was deemed important to highlight that large areas of mangrove forest are currently in poor condition, approximating ecosystem collapse, as indicated by the presence of large canopy gaps with many dead and fallen trees, mostly located within the interior lower intertidal forest. Initially, these areas were classified as storm and wind damage. However, no record of recent cyclones or large storms could be found and local anecdotal observations suggest no large widespread storm or cyclone has affected the Torres Strait Region (>30 years) within a period to explain the observations. The location of the mangrove collapse phenomena within a specific tidal zone that relates closely to the 1.5 m contour line is further indication that this phenomenon may be related to sea level rise. Similarly, extensive mangrove dieback at the landward margin was observed on Saibai, Boigu, Tudu, Sassie, Zagai and Iama, which may also be related to sea level rise effects.

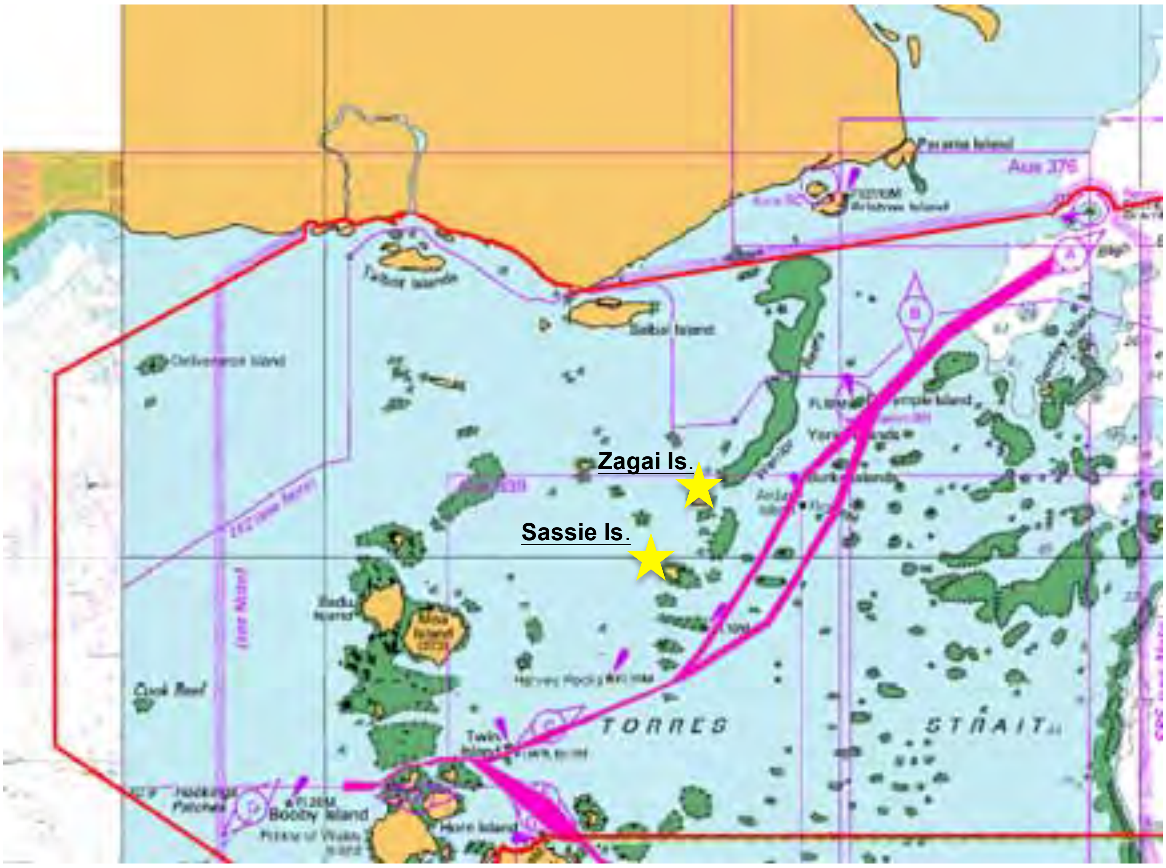


Figure 24. Major shipping routes through Torres Strait (pink) showing proximity to Sassie and Zagai Islands (starred). ***Source: Australian Navy (www.navy.gov.au).***

It is possible that with increasing sea level, as has been recorded in Torres Strait, the mangrove forest becomes more vulnerable to strong winds during the seasonal monsoon periods, resulting in an effect similar to that usually associated with storm damage.

Sea level rise impacts (assumed) were observed to be present on all mangrove islands, with forest damage and collapse present on all islands except Tudu. On Tudu Island, mangroves appear to be suffering extensive landward retreat as a consequence of increasing sand deposition blocking the major tidal channel flowing through the island interior.

Due to large extent of mangroves on Boigu and Saibai, an estimate of sea level rise impacts was not undertaken and warrants more detailed remote sensing assessment. Based on observations these islands are the most impacted by sea level rise.

Of the islands assessed, Zagai and Sassie Islands have the greatest area of inner lower intertidal fringe forest in poor condition with ~136 ha and ~134 ha impacted respectively. Gebar Island, Cap Islet and Erub Island had the greatest proportion of mangrove affected

(>30%). Of all mangrove assessed, ~10% or 3470 ha were observed to be potentially impacted by sea level rise. This represents a large portion of mangrove and should be cause for concern. The high proportion of mangroves possibly affected by sea level rise on Gebar Is. is consistent with observations of shoreline retreat and mangrove condition.

Root burial causing mangrove death on Mua, Badu and Saibai Islands may also be related to sea level rise. As sea level increases, sand deposition within the mangrove forest also increases associated with shoreline transgression. This sediment smothers mangrove aerial roots resulting in death. On Dauan Island, root burial near the island heli-pad may be related to increased sand deposition during dredging for the new boat ramp (Pers. Comm., T.Elisala, Dauan TSRA Land & Sea Ranger 2012). On Erub Island, a large area of mangroves in the island's main mangrove area is in poor condition due to root burial from sediment runoff due to hillslope erosion. This is estimated to be impacting ~34% of mangroves on Erub Is.

Although it is as yet unconfirmed that the observed mangroves in poor condition are undergoing change and collapse due to sea level rise. The results presented here show there is some agent affecting Torres Strait fringing mangroves causing large-scale loss of structural integrity and therefore functional capacity (Figure 25). While there remains uncertainty as to how mangroves might actually respond to sea level rise, these data offer compelling evidence. And, the response also appears sensitive to small fluctuations in tidal amplitude over decades. Projected linear response models of shoreline retreat with concurrent landward migration of mangroves as sea level rises may not be accurate and as with studied other ecosystem climate change responses, mangroves appear to be responding non-linearly and in unexpected ways.

Other Drivers Affecting Mangroves in Torres Strait

Feral Animals – Pigs and Deer

Feral pigs were observed to be affecting all wetland habitats, including tidal wetlands on Mua and Badu Island.

Rusa deer were observed in mangrove habitat on Boigu and Saibai Islands, however, limited impact was observed. Rusa deer have the potential to greatly impact mangroves at dense populations. In New Caledonia, Rusa deer cause widespread damage to mangrove and tidal wetland habitat (Duke et al. 2010).

Vehicle Damage

A small tidal wetland area near Kubin township on Mua Is. was observed to be affected by recreational vehicle use.

Fire

Fire on Badu and Mua Islands impacts fringing mangrove and saltmarsh vegetation at the landward margins of tidal wetland habitats. Although the effect was not extensive it is necessary to consider how fire may impact the capacity of tidal wetlands to respond to sea level rise and whether fire hinders landward migration. These Torres Strait Islands provide perfect test case to assess the impact of fire on tidal wetland climate change resilience in the dry tropics.

Invasive Species

Pond Apple (*Annona glabra*) is a weed of national significance that grows in mangrove forest. In the Florida Everglades this weed has replaced large areas of upper intertidal mangrove forest and it is becoming an increasing problem in Cape York mangrove habitat. Pond Apple was reported to occur on Badu Island and Dauan Island, although no direct sighting was established. If present, this weed should be removed immediately.

Figure 25. Inner fringe forest collapse on Gebar Island.

Historical Change in Mangrove Extent

Mangroves occupy dynamic coastal environments and are subject to change due to natural shoreline process. Mangroves are also impacted by human modification with mangroves often replaced for coastal infrastructure and development. Sea level rise is likely to cause widespread change in mangrove extent in Torres Strait. To better understand how mangroves will respond to sea level rise in the future it is important to understand how they have changed in the past.

Wetlands mapping produced by the Queensland Wetlands Mapping program suggests that there has been very little change in mangrove extent in Torres Strait in recent years (1999 to 2012. However, assessment of shoreline process and visual examination of historical aerial imagery suggests this may not be the case.

Here we used the most recent assessment of fine-scale habitat mapping produced by 3D Environmental and TSRA (Stanton et al. 2008) to assess mangrove change using the most recent available imagery for Torres Strait Islands. Current mangrove extent was produced through manual on-screen image interpretation relative to the existing base map and guided by oblique shoreline imagery collected during SVAM surveys.

Large discrepancies between existing mangrove mapping and current mangrove extent were detected. This is in part likely because of the quality of the historical aerial images used for mangrove mapping in 2008. More recent satellite imagery and aerial photography is of high quality and allows more fine-scale resolution mapping. Consequently it appears that large changes in mangrove extent have occurred in recent years, when in fact this is in part a consequence of more accurate mapping. Unfortunately for this assessment, the original imagery used for regional ecosystem mapping was not readily available.

Through review of mangrove extent on selected islands in Torres Strait, an additionally 316 ha of mangrove habitat have been mapped (Table 23). This is an increase of 6% for selected islands.

Using only islands where there is a high level of accuracy in mangrove change, an overall nett average annual increase in mangrove extent of 2% appears to be occurring in Torres Strait. This is contrary to what is expected to occur under current sea level rise projections. Globally, mangroves are reducing in extent by an estimated 1% per annum, largely due to human interference (Duke et al. 2007).

Two islands, Iama and Erub, were recorded having very high mangrove change compared to the mean, both with large increases in mangrove extent recorded. Mangrove change on Iama is examined in more detail below. Erub Island mangroves appear to be undergoing expansion due to hillslope erosion and depositional gain. Although only having a moderate accuracy this data still represents an overall trend towards rapid mangrove expansion.

Table 23. Historical mangrove change on 11 surveyed Torres Strait Islands.

	Mua*	Badu*	Mabuiag*	Sassie[t]	Zagai[t]	Tudu[t]	Iama[t]	Gebar*	Erub^	Dauan^	Buru[t]
Current Mangrove Extent	1717.8	667.1	44.2	1078.31	930.59	18.6	78.49	95.5	13.97	32.35	1173.5
Time Period Assessed	1974-2014	1974-2014	1999-2011	1973-2012	1999-2012	1974-2012	1974-2012	1988-2012	1999-2011	1988-2012	1999-2012
Years Assessed	40	40	12	39	13	38	38	24	12	26	13
Mangrove Loss (ha)	43.38	22.19	4.34	7.82	0	0.22	4.83	0.28	0.93	0.14	0
Proportion of Current Extent (%)	3	3	10	1	0	1	6	0.3	7	0.4	0
Mangrove Gain (ha)	133.0	44.06	17.81	88.83	72.58	0.57	14.09	8.47	3.83	3.18	13.26
Proportion of Current Extent (%)	8	7	40	8	8	3	18	9	27	10	1
Nett Change (ha)	89.62	21.87	13.47	81.01	72.58	0.35	9.26	8.19	2.9	3.04	13.26
Nett Annual Change (ha yr^{-1})	2.24	0.55	1.12	2.08	5.58	0.01	0.24	0.34	0.24	0.12	1.02
Percentage change (% yr^{-1})	0.13	0.08	2.54	0.19	0.60	0.05	0.31	0.36	1.73	0.36	0.09

**Low accuracy - Large areas of mangroves were misclassified in available Regional Ecosystem mapping data. ^Moderate accuracy – some areas misclassified in original mapping. [t]High accuracy – represents true change in mangrove extent*

Historical Change - the Iama Island Case Study

Iama Island is one of the most densely populated of the Torres Strait islands outside the main population centre of Thursday Island. The island's vegetation has been modified extensively by human settlement. In the past 30 years, rapid urban and infrastructure development has occurred on the island.

Mangroves are the dominant vegetation community on the island, representing 39% of the island landmass above MSL (Table 24). Mangroves remain an important resource for Iama islanders and are heavily utilized as a food and timber resource. Mangroves also provide a number of additional important ecosystem services to the Iama island community including shoreline protection and water quality improvement.

There are presently 78.49 ha of mangrove on Iama Island. Estimates of change in mangrove extent between 1974 and 2011 revealed there has been large-scale change in mangrove area during this period (Table 24). A high proportion of the Iama Island shoreline is also undergoing mangrove expansion (44%); a value much greater than other Torres Strait Islands.

An assessment of mangrove extent was undertaken to assess incremental mangrove change using historical aerial photographs. Since 1974, Iama Is has experienced large-scale change to mangrove habitat. But, this change is not linear with fluctuating expansion, loss and regrowth occurring over time. Overall the nett increase of 10.56 ha of mangrove on Iama Island in the past 38 years masks this inter-period variation. Over all periods, mangroves have been removed for urban and infrastructure development, with very minor loss of mangrove at the shoreline fringe. This loss has however been offset by rapid and continuous mangrove expansion at the shoreward margin owing to depositional gain. For the most part, the largest areas of mangroves cleared have recovered over time.

Table 24. Iama Island historical change in mangrove extent 1974 to 2011.

Year	1974	1987	1998	2011	*Totals 1974-2011*
Mangrove Extent (ha)	67.93	64.02	74.97	78.49	*78.49*
Mangrove Loss (ha)		7.95	2.43	2.25	*4.83*
Proportion of Extent (%)		12	3	3	*6*
Mangrove Expansion (ha)		4.04	6.87	4.72	*14.09*
Proportion of Extent (%)		6	9	6	*18*
Regrowth (ha)			6.51	1.05	*5.87*
Proportion of Extent (%)			9	1	*7*
Nett Change (ha)		-3.91	10.95	3.52	*10.56*
Nett Annual Change (ha yr.)		-0.30	1.00	0.27	*0.29*
Percentage change (% yr.)		-0.5	1.3	0.3	*0.4*

Between 1974 and 1987 large areas of mangrove were cleared for airport runway construction, resulting in a loss of ~8 ha (12%). These areas largely recovered through regrowth between 1987 and 1998, with some recovery continuing through to 2011. Overall 10% of the original 12% lost has recovered. Small areas of mangrove continue to be lost due to development, with current rates of loss at 0.2% yr^{-1}.

Interestingly, mangrove regrowth at the east of the airstrip has not extended to the original shoreline position (Figure 26). Mangroves occupy the intertidal zone above mean sea level. Mangroves cannot generally establish below mean sea level due to regular inundation. The shoreward extent of mangroves is therefore representative of the long-term trend in mean sea level position and can sometimes be a historical artifact if gradual sea level rise is occurring. The ‘new’ mangrove shoreline on Iama Island may represent a modern mean sea level position and be indicative of shoreline retreat in response to sea level rise. Estimates of sea level rise in Torres Strait suggest sea level is increasing at ~9mm yr^{-1} (Figure 26) (Green et al. 2010a). Preliminary assessment indicates that based on the intertidal slope, the difference in distance between the 1974 shoreline position and the 2011 mangrove shoreline position is indicative of a 13mm yr^{-1} sea level rise. This figure has yet to be confirmed through detailed analysis and further investigation is required (Figure 27).

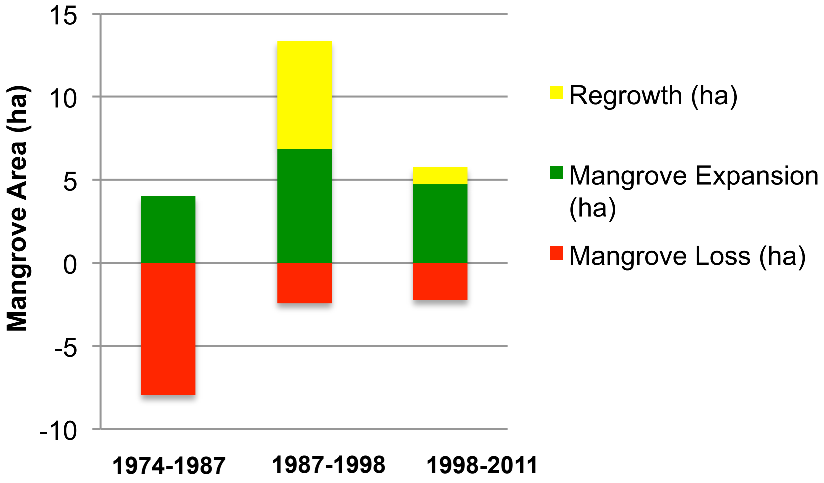


Figure 26. Graph of Iama Island mangrove change 1974 to 2011.

Figure 27. Shoreline mangrove dieback at the shoreward margin.

Mangrove loss has been offset by mangrove expansion at the shoreward margin. It should be noted that expansion data is in addition to data presented for 'regrowth'. Mapped mangrove expansion is consistent with observations made from aerial surveys. Figure 28 shows 30% more mangrove expansion occurred for the period 1987 to 1998 compared to the preceding and following periods. There are a number of factors that could be related to mangrove expansion in Iama Is. Causal factors of mangrove expansion are discussed in detail in above. Mangrove expansion can occur for two reasons; increase in shoreline elevation due to sediment deposition or a drop in mean sea level allowing mangrove establishment. Rainfall, hydrodynamics and nutrient supply are also factors important to mangrove establishment (Krauss et al. 2008).

Iama Island does not have a deep surface sediment horizon and mangrove sediment at the shoreward margin does not appear be terriginous in origin. It is not suspected that land-based runoff is a major driver of mangrove expansion on Iama Is. as it is on Erub Is. It is possible that mangrove expansion has occurred due to a localized *drop* in sea level during the main expansion phase of 1987 to 1998. Data presented by Green et al (2010a) shows sea level at the Darwin tide gauge decreased between 1975 and ~1985 (Figure 28), with sea level increasing again in the late 1990's. This pattern is consistent with the pattern observed for mangrove expansion. If this is true, then we expect to start to see mangrove retreat and loss of recently established mangrove in coming years.

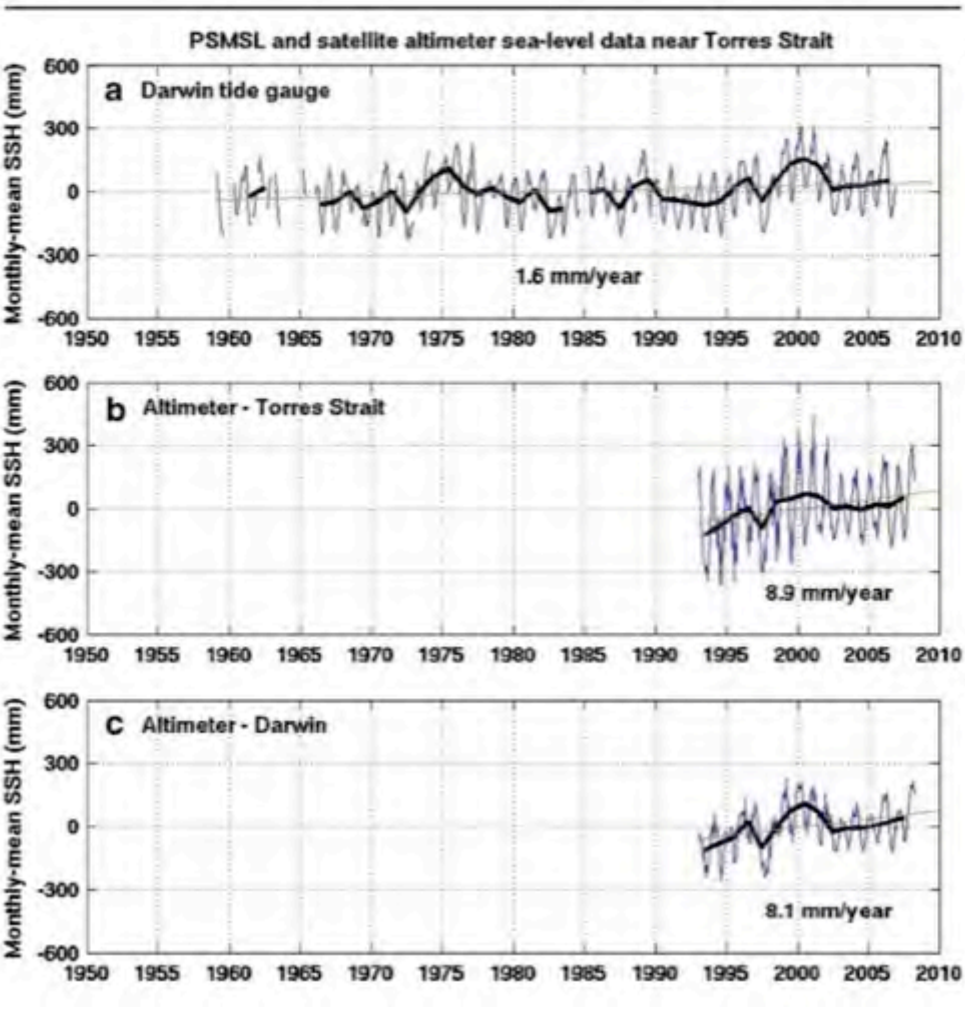


Figure 28. Monthly average sea levels as measured by a tide gauge at Darwin (a), and as measured by satellite altimeter in Torres Strait (b) near Darwin (c). ***(Green et al 2010a).***

Nutrient enrichment of mangroves from the Iama Island STP is likely to have facilitated mangrove expansion.

Shoreline mangrove condition on Iama Island was average and little shoreline mangrove retreat was observed to be occurring. However, dieback and death of some isolated trees at the shoreline margin was observed on the island's northern shoreline (Figure 29). Additionally, 13% of mangroves were impacted by inner fringe poor condition (Figure 30). A large area of higher intertidal mangroves on the eastern island are in very poor condition, with biomass plot data showing a very high proportion of dead trees in this area. These observations are all indicative of sea level rise effects on mangroves and may be the precursor to larger-scale and more dramatic change. Continued monitoring and further detailed investigation is warranted (Figure 31).

Figure 29. Map of Iama Island mangrove gain 1974 to 2011.

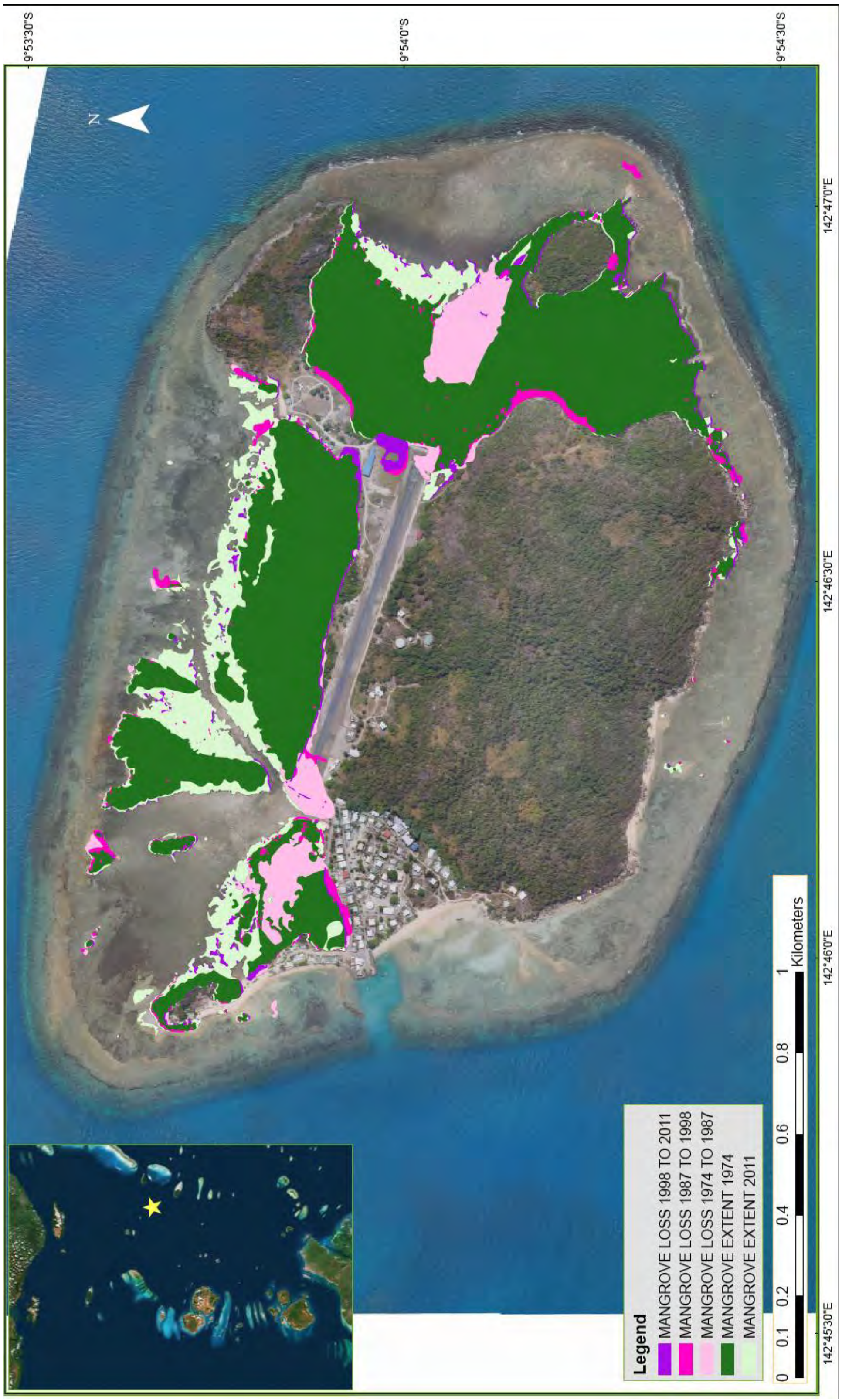


Figure 30. Map of Iama Island mangrove loss 1974 to 2011.

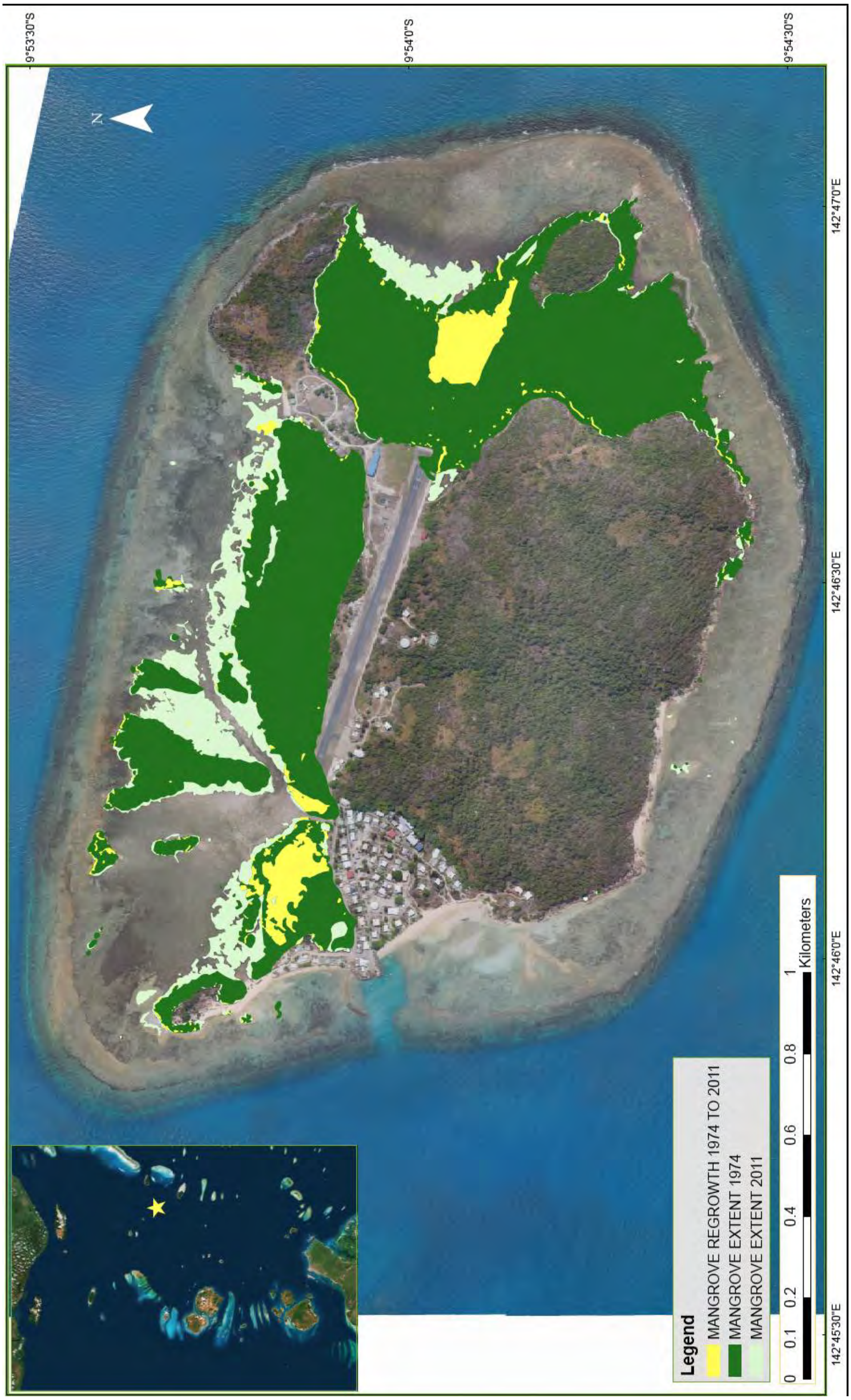


Figure 31. Map of Iama Island mangrove regrowth 1974 to 2011.

Freshwater Waterbodies of Torres Strait Islands

Vegetative aspects of freshwater wetlands have been discussed in various studies previously including the extensive vegetation surveys and regional ecosystem mapping of all Torres Strait islands by Stanton et al. (2008), the Sustainable Land Use studies of each individual island (accessible from the TSRA website at http://www.tsra.gov.au/the-tsra/programs-and-output/env-mgt-program/publications-and-resources) and the wetland type mapping conducted by the Queensland Department of Environment and Heritage Protection located at http://wetlandinfo.ehp.qld.gov.au/wetlands/

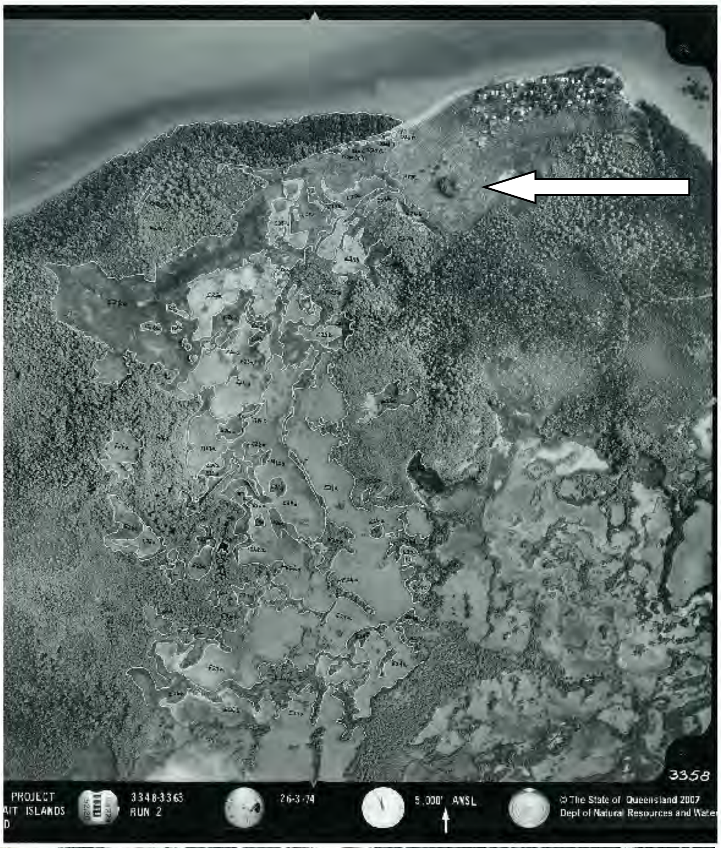
Significant freshwater habitats are found on Boigu, Saibai, Badu, Mua and Mabuiag islands and these five were the focus of freshwater-related fieldwork. The southern islands of Horn, Thursday and Muralag (Prince of Wales) islands also have significant freshwater habitats (albeit artificial on the first two), but these were not formally part of this study. However, there is existing literature on these islands and we were able to make some brief observations on visits there, so this information is included in this report for completeness. Some aspects of freshwater habitats on key islands are discussed below.

Boigu Island

Boigu Island is approximately 17 km long. For much of the year, the island is covered by water and is essentially one large, connected, wetland. The water that covers the island is relatively shallow (mostly 50–80 cm in May) and quite clear, such that the bottom can be clearly seen. The dominant vegetation is fresh and brackish water sedges on what is, during the late dry season, salt pans. The extensive shallow, swamp area, combined with extensive sedges, grasses and other vegetation, creates ideal conditions for high fisheries productivity. The interior swamps also contain numerous terrestrial 'islands', the larger of which host significant terrestrial vegetation communities (see Burrows and Schaffer 2010, Stanton et al. 2008; for details). Despite the abundance of water for most of the year, the island does dry out by the end of the dry season, and in fact, there are no permanent freshwater wetlands on the island. A few small springs do exist that supported villagers before the construction of modern water supplies. Several artificial waterbodies near the island village contain permanent water year round, though of brackish quality. We have measured salinity at more than 28 locations around the island during different seasonal periods in 2010 and 2014. Salinity of the islands interior swamps water ranges from 4,000-8,000 µS/cm, which is about 10-15% the strength of seawater (approx 57,000 µs/cm). The wetlands around the island village had salinity levels ranging from ~4,000–11,000 µS/cm, which is up to 20% of the strength of seawater. The salinity levels of all wetlands increases as the dry season progresses, commonly developing the same salinity content as seawater, and often becoming slightly hypersaline (up to 67,000 μS/cm). The salinity of the artificial wetlands around the village also increased over the dry season, but only to about one-third that of seawater, presumably due to lower relative evaporation rates in these deeper waterbodies. Some of these waterbodies previously served as residential drinking water sources for the community, but that would not have been possible at their current level of salinity. Historical records of their salinity were not able to be sourced. There have been suggestions that these now disused reservoirs could be used for garden water, but the current salinity level we measured would be too high for most garden and food plants. See Burrows and Schaffer (2010) and Waltham et al. (2014) for more discussion, data and photos of sites monitored.

Our ranger guides indicated to us that there are only two significant freshwater springs on the island, the largest of which (visible in the 1974 aerial photograph in Figure 32a and shown in close up in Figure 32b) was covered for construction of the island airstrip apparently about 1980 (Boigu Island Community Council 1991) (at the same time, a water supply dam was constructed near the school and the excavation pond on the other side of the airstrip also became a backup supply). This well was known as the big well or Koi Mai (Laade 1971) or Koey May (Boigu Island Community Council 1991). The other, smaller spring, is a considerable distance from the village and was not accessible during our trips. Laade (1971, p.83) recounted oral accounts of four wells on the island including Koi Mai, and Boigu Island Community Council (1991, p.66) listed three – Koey May, Katana May (apparently salty) and Thugeraw May. Neither of these books provide any further information on the location or habitats of these wells, so it is assumed they are minor compared to the ‘big well’.

a



b

Figure 32. a) 1974 Aerial photograph of Boigu Island. Arrow indicates location of former spring well south of the village, now part of the airstrip; and b) photo of the well Koi Mai or Koey May - the big well of Boigu island, covered over for the islands airstrip construction, apparently around 1980 (photo from Laade 1971).

Saibai Island

Saibai Island is a large (approx. 22 km long), but very low-lying, muddy, island. Like Boigu Island, it is mostly mangroves and salt marsh/pans, with extensive seasonal fresh and brackish water sedge swamps in the interior, punctuated with numerous grasslands and terrestrial vegetated islands (see Stanton et al. 2008 and Figure 33). Freshwater is limited on the island and the largest permanent freshwater water bodies are the artificial habitats created for the residents water supply (see Burrows and Perna 2009 a,b and the Sustainable Land Use Study for photos). Native wells, formerly used for drinking water in pre-modern times, are also present (Hitchcock 2008).

On both Boigu and Saibai islands, residents practiced mound and ditch agriculture in tandem with large-scale water management, the mounding and ditches being required to exclude saline water, due to the low-lying nature of the islands (Barham et al. 2014). On Saibai, these were particularly extensive, having been mapped as covering 650 hectares, most of which are on the islands eastern end, nearer the village (Laade 1971, Barham et al. 2014). Freshwater was sourced from constructed earth-rimmed wells, some of which were quite substantial and survive to this day.

Although very similar to Boigu Island, and like Boigu Island, it is a very low-lying island, Saibai Island is slightly higher than Boigu and thus it dries out earlier in the year and has slightly more freshwater resources, the basis of the extensive traditional agricultural systems. Waltham et al. (2014) provide salinity and physico-chemical water quality data for 19 sites on Saibai Island, which, like those on Boigu Island, show an increasing salinity trend as the year progresses, becoming hypersaline by years end.

a)

b)

Figure 33. Examples of Wetland Extent a) Boigu Island b) Saibai Island.

Badu, Mua and Mabuiag Islands

Badu Island is a lightly forested granite island. It has well-defined creeks that drain to the north and western coasts that contain small permanent waterholes. Waltham et al. (2014) provide salinity and physico-chemical water quality data for 13 sites on Badu Island, 11 of which were freshwater.

Mabuiag Island has two small streams (Sau Koesa and Kubarau Koesa) that retain permanent water (Hitchcock et al. 2012) and a freshwater swamp adjacent the airstrip (Aland 2013 a,b). Waltham et al. (2014) provide salinity and physico-chemical water quality data for 10 sites on Mabuiag Island, 3 of which were freshwater.

Mua Island is the second largest island in the Torres Straits. It is lightly vegetated and fringed by mangroves. It has probably the largest freshwater creek in the Torres Straits – Koey Kussa ('Big Creek'). Photographs of freshwater habitats of Kai Creek on Mua are shown in Aland (2013 a,b).

Muralag (Prince of Wales) Island

Largest of the Torres Strait islands, Muralag Island has green valleys and flats between its rocky ridges, yet was never developed for agriculture by its nomadic hunter-gatherer occupants. The island has permanent swamps and a handful of small, permanent waterholes along creeklines, some of which are in deep gorges. The most well known of these is Dugong Story waterhole which has red cliffs on three sides and a deep black waterhole containing many freshwater fishes.

The island has introduced deer, pigs and horses, all of which may be impacting upon these vulnerable waterholes late in the dry season, when they are at their smallest and most vulnerable to disturbance, but also when these animals will most need to access these habitats. Singe (1989) describes the damage done by well-trodden paths leading from the hills to swamps, waterholes and beaches by pigs and deer and that the pigs plough and furrow hundreds of metres of swamp margins.

Horn Island

Horn Island is a large but relatively flat island, with some elevation providing sandy creek lines that sustain seasonal waterbodies. The largest of these creeks is Vidgen Creek. Though small waterholes may survive in particularly wet years, these creeks are considered to be seasonal. There are only three permanent freshwater waterbodies on Horn Island and all are artificial. The island reservoir is a large waterbody several hundred metres long and wide and up to 30 m deep at the spillway (Chris Johnson, Pers. Comm.). There is an old gold mine quarry and tailings dam which were apparently abandoned about 20 years ago. Both create very large waterbodies and the quarry site is said to be up to 60 m deep. Both have very clear water, especially the quarry site, whilst the tailings dam site has fringing sedges and emergent grasses. Horn Island was not part of the official study so no formal survey occurred there, but some incidental observations have been made. Local opinion as to the fish fauna of the islands main dam varies, such that no community information can be put forward without formal survey, something that is recommended for the future. Estuarine crocodiles are reported from these reservoirs, and Burrows and Perna (2009 a,b) observed fresh slides at the tailings dam. The quarry and tailings dam have water quality issues that probably preclude the development of significant biotas. Freshwater turtles have been reported from the seasonal creeks on Horn Island and we did observe a long-necked turtle, thus confirming these reports. This species is known to inhabit seasonal creeks and is capable of aestivating in moist creek bed sands during the dry season.

Thursday Island

The indigenous name for Thursday Island is Waiben, which apparently means 'no water' (Hitchchock et al. 2012) and the island indeed has no natural waterbodies though three freshwater reservoirs have been constructed. The largest of these are the emergency town water supply (the regular water supply comes from the Horn Island reservoir) and the school irrigation dam (see photos in Burrows and Perna 2009 a,b) and the third is a 19th century dam below Green Hill. As for Horn Island, this island was not part of the study but formal survey of these waterbodies is warranted. Burrows and Perna (2009 a,b) observed large numbers of the introduced exotic species, eastern gambusia, in these waterbodies, providing the first record of this exotic fish species from the Torres Strait (none are known from anywhere on Cape York Peninsula either). Eastern Gambusia are the most widely distributed exotic fish species in Australia and they may well also be in one of the waterbodies on Horn Island too.

Other Islands

None of the other islands are known to have permanent waterbodies and were not part of the freshwater fieldwork apart from incidental observations during 'other travels'.

The seasonal stream adjacent to Iama airstrip was examined and no fish were observed were observed, though freshwater crabs, which can survive the seasonal complete drying of this creek may be present here. Erub and Mer islands both have small, seasonal streams. These are considered fishless, though there are anecdotal reports of eels in those streams.

Fish of Freshwater Habitats on Torres Strait Islands

Native Fish

At the beginning of this project, we co-authored a manuscript on the fishes of freshwater habitats of Torres Strat islands (see Hitchcock et al. 2012). This represented a desktop review of the knowledge of Torres Strait freshwater fish habitats at that time. Since then we have formally surveyed for fish at >100 sites on five islands (Boigu, Saibai, Badu, Moa and Mabuiag) and made observations on many others, as well as accessing museum records (of which they are many for Horn and Muralag islands). Our field surveys included backpack electrofishing, snorkelling, baited traps, underwater video cameras, cast nets, fyke nets and seine nets as well as night-time spotlighting. The variation in habitat types and access to sampling sites necessitated a wide variety of methods be deployed, limiting consistency between sites and islands. In addition, two other minor studies of fish on Badu and Mabuiag islands have also been made by other authors (see Aland 2013 a,b).

Hitchcock et al. (2012) located existing records for a total of 31 fish species, including two exotic species (climbing perch and eastern gambusia) as then being then known from the Torres Strait islands. Our surveys have added an additional 19 species, bringing the total now known to 50. Of these, only about a quarter would be considered to be genuinely freshwater species, and not even all of those actually breed in seawater. Most of the fish species found in freshwater habitats are actually more commonly known as inhabitants of brackish or estuarine waters. Thus, the freshwater fish fauna of Torres Strait is depauperate.

A compilation list of all fish species now known from freshwater/brackish habitats on Torres Strait islands across all known data sources, is provided in Table 25. In some cases, the taxonomy provided may not be correct due to changes in taxonomy since the records were first published, and possible incorrect identification in the literature.

Table 25. List of fishes recorded from fresh/brackish water habitats on Torres Strait Islands.

Species	Boigu	Saibai	Badu	Moa	Mabuiag	Horn	Muralag	Thursday
Exotic Species								
Climbing perch	*	*						

Species	Boigu	Saibai	Badu	Moa	Mabuiag	Horn	Muralag	Thursday
Anabas testudineus								
Eastern gambusia *Gambusia holbrooki*								*
Native Species								
Glass perch *Ambassis sp.*	*	*	*					
Sailfin glass perch *Ambassis agrammus*		*				*		
Elongate glassfish *Ambassis elongatus*						*		
Vachelli's glassfish *Ambassis vachelli*						*		
Mouth almighty *Glossamia aprion*	*							
Freshwater longtom *Strongylura krefftii*			*					
Barramundi *Lates calcarifer*	*	*	*					
Jungle perch *Kuhlia ruprestris*							*	
Milkfish *Chanos chanos*	*	*	*		*	*		
Silver ponyfish *Gerres subfasciatus*	*	*	*		*			
Ponyfish *Gerres filamentosus*	*	*						
Banded scat *Selenotoca multifasciata*	*	*	*		*	*		
Spotted scat *Scatophagus argus*	*							
Butter bream *Monodactylus argenteus*	*		*					
Crescent perch *Terapon jarbua*	*	*	*		*			
Yellowtail trumpeter *Amniataba caudavittata*	*	*	*		*	*		
Spotted blue-eye *Pseudomugil gertrudae*				*				
Pacific blue-eye *Pseudomugil signifer*	*	*	*	*	*	*	*	
Snub nosed garfish *Arrhamphus sclerolepis*	*							
Long nosed garfish *Zenarchopterus sp.*	*		*			*		
Boof-headed catfish *Neoarius leptaspis*	*	*				*		
Mullet *Mugil sp.*	*	*	*		*	*		
Bony bream *Nematalosa sp.*	*							
Giant herring *Elops hawaiensis*	*							
Oxeye herring *Megalops cyprinoides*	*	*	*	*	*	*	*	
Rainbow fish species								
Melanotaenia maccullochi				*				
Melanotaenia nigrans	*						*	
Melanotaenia splendida inornata		*	*	*			*	
Melanotaenia trifasciata			*					
Melantotaenia splendida rubrostriata	*	*						
Northern trout gudgeon *Mogurnda mogurnda*				*				

Species	Boigu	Saibai	Badu	Moa	Mabuiag	Horn	Muralag	Thursday
Spangled gudgeon *Oxyeleotris porocephala*							*	
Poreless gudgeon *Oxyeleotris nullipora*				*				
Barred gudgeon *Bostrichthys zonatus*		*	*	*		*		
Empire gudgeon *Hypseleotris compressa*						*	*	
Threadfin mangrove goby *Mugilgobius filifer.*			*		*			
Island mangrove goby *Mugiligobius platystomus*						*		
Goby *Pseudogobius sp.*	*	*	*					
New Guinea mudskipper *Periopthalmus novaeguineaensis*	*	*			*	*		
Long-finned eel *Anguilla sp.*	*	*	*			*		
Pacific short-finned eel *Anguilla obscura*			*		*			
Archer fish *Toxotes chatareus*			*					
Sole *Brachirus sp.*		*						
Mangrove jack *Lutjanus argentimaculatus*			*				*	
Moses perch *Lutjanus russelli*			*		*	*		
Whiting *Sillago sihama*	*		*		*			
Estuary cod *Epinephelus malabaricus*			*					
Milk-spotted toadfish *Chelonodon patoca*		*	*					
Golden lined spinefoot *Siganus lineatus*		*	*		*			
Smooth flutemouth *Fistularia commersonii*	*							
Trevally *Caranx sp.*	*		*					
Sea pike *Sphyraena obtusata*	*		*					

Exotic fish

The coastal catchments between Townsville and Cairns host up to 20 exotic species – the most of any region in Australia (Webb 2003, 2007, Burrows 2009, TropWATER Pest Fish website https://research.jcu.edu.au/tropwater/research-programs/aquatic-fauna-and-invasive-species with several of these species being considered serious pests. No exotic fishes are presently known from Cape York (Burrows and Perma 2009 a,b) with the exception of an established population of Mozambique tilapia in the Endeavour River, Cooktown. PNG has numerous exotic fishes that have been introduced there from SE Asia, Africa and South America, mostly as a food source. Because of the desire to establish these species in new localities as a food source, many of these fish species were specifically selected for their ability to be readily transported, breed rapidly and tolerate a wide range of environmental conditions. Thus, they have the attributes that would make them more likely to become an environmental pest species in locations to which they are introduced. There is concern that one or more of these fish species might be moved to Torres Strait islands or across the Torres Strait to Cape York, an area of high conservation value that is currently largely free of aquatic pests. Most of these fish species of concern are already declared as noxious species in Queensland under the *Fisheries Act 1994*, thus making their import illegal. The species of greatest concern are climbing perch, snakehead and walking catfish, as well as several tilapia and gourami species (see Table 26 for list of names and https://research.jcu.edu.au/tropwater/resources/torres-strait-2013-a-new-frontier-for-freshwater-fish-invasions-into-australia for fact sheets on each). Of these, climbing perch are already established on two islands in Torres Strait.

Table 26. Pest fishes currently known to occur in New Guinea considered high risk to Torres Strait/North Queensland.

Family	Common Name	Scientific Name	Native Range
Anabantidae	Climbing perch	*Anabas testudineus*	SE Asia
Channidae	Snakehead	*Channa striata*	SE Asia
Clariidae	Walking catfish	*Clarias batrachus*	SE Asia
Poeciliidae	Eastern Gambusia	*Gambusia holbrooki*	Central America
Cichlidae	Mozambique tilapia	*Oreochromis mossambicus*	Africa
Cichlidae	Spotted tilapia	*Tilapia mariae*	Africa
Cichlidae	Red-breasted tilapia	*Tilapia rendahli*	Africa
Characidae	Pacu	*Piaractus brachypomus*	South America
Osphronemidae	Giant gourami	*Osphronemus gouramy*	SE Asia
Osphronemidae	Snakeskin gourami	*Trichogaster pectoralis*	SE Asia
Osphronemidae	Three-spot gourami	*Trichogaster trichopterus*	SE Asia

Climbing perch are native to SE Asia from India to western Indonesia (Froese and Pauly 2008). They were probably brought to West Papua (the western part of New Guinea) with the transmigration of people settling there from other parts of Indonesia (Hitchcock 2008). From there, they have moved eastward through the rivers and wetlands around the southern coastline of New Guinea. Climbing perch are renowned for moving overland, especially during the wet season, and this is probably how they invaded the southern PNG coastal environments. However, they are also traded by villagers as food and have been known to move to new catchments via this means (Hitchcock 2002). They first crossed the border into PNG in the 1970's, being recorded from the Morehead River, near the Irian Jaya border in 1976 (Storey et al. 2002), the Bensbach River in 1985 (Hitchcock 2002), the Fly River in

1988 (Storey et al. 2002) and have for many years been found in rivers and wetlands on the southern coast of PNG that are directly opposite the Torres Straits (Hitchcock 2008, Gehrke et al. 2010). When exotic fishes like climbing perch first arrived in PNG coastal habitats, they were avoided but as their numbers have increased, they have become increasingly incorporated into the diets of villagers (Gehrke et al. 2010). This can then pose further risks of their spread to new locations and an increase in their value as a food source, although for now, villagers still consider these introduced species an inferior food source compared to their traditional, native food fishes (Gehrke et al. 2010).

In November 2005, reports of climbing perch were received from Saibai Island and confirmation of their existence there came from a photograph taken in January 2006 and sent to the Queensland Department of Primary Industries and Fisheries and the Queensland Museum who identified it as a climbing perch (see Hitchcock 2008). This photo was of a climbing perch making its way across the island's airstrip (something climbing parch are capable of doing). Hitchcock (2008) visited Saibai Island in January 2006 and locals reported to him that they had seen climbing perch moving overland within the village during the wet season and that they may have been present for 3–4 years before that (i.e. since 2002 or 2003). This provided evidence of their existence on the island but no specimens were located and no further information on their extent and locations there where they are found.

The first confirmed population of climbing perch was found on Saibai Island in November 2008 (Burrows and Perna 2009 a,b). These were in the islands reservoirs near the school. In May 2010, climbing perch were confirmed on Boigu Island (Burrows et al. 2010), again in an artificial waterbody adjacent to the island village (next to the airstrip) and later that year at a saline mangrove wetland further inland (Burrows et al. 2010). Climbing perch are only known as a freshwater species in their native range, but our finding of them living in amongst mangroves in full strength seawater, shows that they are very tolerant of seawater. According to the literature, they can also breed in seawater. This poses new concerns over their ability to survive on Torres Strait islands (which were previously thought to lack sufficient freshwater resources for their survival), and move between islands and to the mainland.

During the course of the present study, we monitored the spread of climbing perch throughout all of Saibai and Boigu Islands, and their rapid increase in numbers and density. From their initial introduction in the early to mid 2000's, they were in low numbers and of restricted distribution (mostly near the townships) in 2008–2010. They are now present across the entirety of both islands, in all habitats, fresh, brackish and upper estuarine.

Climbing perch have been seen by villagers moving through their streets during rain (they are well known for their ability to move overland during wet conditions). In 2014, on Saibai Island, in one tiny temporary waterbody, that could only be described as a puddle (see Figure 34), we extracted 150 climbing perch. We have trained the Land and Sea Rangers on Boigu and Saibai islands in how to catch and identify climbing perch, something they have proved exceedingly capable of. They kept several climbing perch alive in a bucket with no food and limited water changes, for many months, providing evidence of just how hardy these fish are, and how difficult they will be to control should they invade further habitats, especially mainland Australia.

Figure 34. Temporary ‘puddle’ from which 150 climbing perch were extracted.

Climbing Perch Biology

Climbing perch grow to 25 cm long and eat a variety of foods such as small crustaceans and insects, as well as other fish and plants. Climbing perch have a highly mobile operculum and strong spines on their pectoral fins that they can use to move over land (something we witnessed during our field work). When swallowed by predators, their strong fins are splayed outward and can lodge in the throat or stomach of their predators. Birds such as pelicans and cormorants have been observed to choke on climbing perch in this manner (Hitchcock 2008) as have fish and reptiles (Storey *et al.* 2002; Pers Obs.).

Climbing perch have an accessory air-breathing organ on their dorsal area behind their head. This allows them to tolerate low dissolved oxygen and even being out of water for considerable periods (even up to six days – Allen 1991; we were able to keep them in moist packages for 2 days). They can also burrow into the mud of drying pools and aestivate there during the dry season until water returns (Froese and Pauly 2008, Storey et al. 2002). This makes them a very tolerant and hardy fish and further illustrates their ability to survive the dry season in Torres Strait and their potential as a serious threat to Australian freshwaters.

Climbing perch are considered to be a freshwater species (Khan *et al.* 1976, Besra 1998), although they are also known to inhabit brackish to estuarine water (Storey *et al.* 2002). However, our records of catching them at several mangrove sites in slightly hypersaline water on Boigu and Saibai islands represent a considerable extension of their recorded salinity tolerance.

Climbing Perch Colonisation of Boigu and Saibai Islands

It is possible that they colonized Boigu and/or Saibai Island of their own accord when rivers of southern PNG flooded. Floodwaters and debris do wash ashore on the northern islands and we have observed, and it is reported in the literature, that climbing perch are able to tolerate seawater for considerable periods. However, it is also likely, especially given that PNG villagers are known to carry and move climbing perch around that they were deliberately brought to the northern islands. This may explain their being found only near the island villages in the first few years after they arrived. The arrival of boats from adjacent PNG villages is a regular occurrence to Boigu and Saibai with the boats docking within a few hundred metres of the pools we surveyed. These boats are inspected by the local quarantine officers but they do (legally) bring in live animals such as mud crabs. Climbing perch would have no trouble surviving the short canoe journey from PNG. We have discussed the issue of introduced fish with the local quarantine officers who were well aware of them. We left further educational material on climbing perch and other potential pest fish with relevant local authorities when on the islands. It is also theoretically possible, though highly unlikely, that birds inadvertently transferred them to the island (see Hitchcock 2008).

The distance of open water between Saibai Island and Cape York or the southerly islands of Torres Strait (e.g. 86 km to Mua Island and 136 km to Thursday Island) represents a barrier that exotic freshwater fishes such as climbing perch can only cross with human assistance. The Cape York townships of Seisia and Bamaga were settled by people from Saibai Island after World War 2 and there are thus strong family connections between the two locations. We are told that boats from Saibai and Boigu islands come to Seisia/Bamaga or more southerly islands regularly and there is a reasonable movement between the island by various other means, creating the potential for fish dispersal. This dispersal could come directly to Seisia, rather than island-hopping through the Torres Strait.

As they are generally depauperate of terrestrial fauna, there is a long history of trading and moving live animals between PNG villagers and Torres Strait island communities. Pigs, cassowaries, possums and macropods have all been introduced live into the Torres Strait islands at various times (McNiven and Hitchcock 2004). This may also have included dingoes being introduced to mainland Australia via this route (McNiven and Hitchcock 2004). A 1845 military visitor to Erub (Darnley) Island commented on the number and variety of animals kept as pets, including birds, dogs and cuscus from New Guinea (Allen and Corris 1977 in Singe 1993). However, the islanders have historically actively resisted animals they consider as pests from becoming established on their islands. Pigs were not known from any Torres Straits islands before the arrival of Europeans, even though villagers from the northern islands recognised their food value, visiting PNG to hunt for pigs (McNiven and Hitchcock 2004). It is believed that the islanders recognised that pigs would raid their valuable gardens, as they do in New Guinea communities.

PNG hosts many highly invasive exotic fish species, several of which (e.g. snakeheads, walking catfish and pacu) are found in wetlands along the southern coastline directly opposite Saibai and Boigu islands. People from villages along the southern coastline of PNG cross to Saibai Island in boats nearly every day and thus the potential for transport to Australian territory of the various exotic fishes now found in the wetlands of the southern PNG coastline is very real.

Given that climbing perch are widely established on Boigu and Saibai islands, eradication is impossible. Priority must be given to preventing their spread to more southerly islands and also to the mainland, of this, and other exotic species present in PNG. The best mechanism for this is public education. This must include relevant local authorities (rangers, quarantine officers, council offers) as well as the general public. As well as emphasising not to spread exotic fish, the education program needs to focus on identifying unusual fish species and the importance of reporting any unusual species to the relevant authorities.

Other Pest Fishes Present

Although not able to appropriately survey the dams on Thursday Island, we have observed gambusia (also called mosquitofish) from there, the first record of this exotic species from this region. Gambusia are one of the worlds worst pests and have been introduced to many countries. Currently, there are no exotic fish species in Cape York Peninsula north of Cooktown (Burrows et al. 2009). Gambusia could be transported from Thursday Island to the mainland and from there invade high value waterways of Cape York Peninsula. A local

Thursday Island shop sells various other exotic aquarium species (it is legal to do so) and this poses a new entry point for fishes to be introduced to new areas.

Public Education and Villager Knowledge of Pest Fish Issues

On most Torres Strait islands, most subsistence resources are gathered from the sea but on the northern islands of Saibai and Boigu, with the largest freshwater swamp areas in the region, the islanders are familiar with the fish fauna of these inner swamps. They are concerned that introduced fish species might impact upon their native fisheries resources, especially the prized barramundi. We found that many villagers were aware of the arrival of climbing perch, though much less aware of the ecology and potential impact of the species.

During all fieldwork, we were accompanied by Land and Sea Rangers from the respective islands we visited (see Figure 35). This facilitated two-way exchange of knowledge and training. We also held community meetings about the results of our fish surveys and gave presentations on fish habitat and pest fish issues to island schools (see Figure 36).

Figure 35. Rangers participating in field fish and water quality sampling.

a)

b)

Figure 36. Example of presentation to a) community meeting and b) school group.

TropWATER have established a website for exotic fish issues in Torres Strait, which includes downloadable fact sheets on 11 exotic fish species of greatest concern. This website can be accessed at https://research.jcu.edu.au/tropwater/resources/torres-strait-2013-a-new-frontier-for-freshwater-fish-invasions-into-australia

We are also in the process of producing short video clips on climbing perch, as these may be more effective in capturing a public audience.

Other Freshwater Fauna of Torres Strait Islands

Only one frog species is known from the Torres Strait islands – the Australian green tree frog *Litoria caerulea,* which has been recorded from all 17 inhabited islands of Torres Strait (Lavery et al. 2012). The introduced cane toad *Rhinella marina* has been recorded from several islands and continues to spread.

The only freshwater mammal recorded from Torres Strait is the water rat *Hydromys chrysogaster* which is reported from Badu Island only, and only on the basis of a headless and badly decayed road kill specimen (Lavery et al. 2012).

Only a single freshwater turtle species is known from the Torres Strait, this being the long-necked turtle *Macrochelodina rugosa*, previously reported from Saibai Island. We confirmed the existence of this population on Saibai, locating 5 specimens on two separate field trips. We were guided to their locations by the rangers that accompanied us. We did not locate any turtles on Boigu Island, and rangers and locals there said they were unaware of their presence there. We made the first records of these turtles in a sandy seasonal creek on Horn

Island, after locals reported to us that turtles were present there. It is likely that this species also occurs on nearby Muralag Island. The specimens on Saibai Island were found in two small remnant waterholes (Figure 37), both of which showed evidence of damage from feral deer, which inhabit the island. Large animals such as deer, could damage the nests of these turtles, which are laid just under the retreating waterline and are exposed as the water level drops. These remnant waterholes represent the last freshwater habitats that we could locate on Saibai Island during our field work and should be monitored more regularly to make sure their condition is maintained. Fortunately, these turtles are capable of burying into moist muds and bedsands during the dry season, so can survive the complete drying out of their waterholes.

a)

b)

Figure 37. The two remnant waterholes (a. and b. respectively) containing the long-necked turtle *Macrochelodina rugosa* on Saibai Island.

The Queensland Museum also holds a specimen of another turtle species – red-bellied short neck turtle, *Emydura subglobosa* – from Erub Island. The specimen is a hatchling and as Erub Island does not support suitable freshwater turtle habitat, and the specimen was collected sometime before 1910, it most likely came from another locality (Lavery et al. 2012), so should be disregarded. This species occurs in PNG and also in the Jardine River on Cape York Peninsula.

We collected the freshwater crayfish *Cherax rhyncotus* at three sites on Badu Island. Aland (2013a) also report this species from Mua Island. We collected/observed the freshwater crab *Austrothelphusa agustifrons* from Badu, Mabuiag and Horn islands and Aland (2013a) record them from Mua Island. The appearance of these specimens, especially their colour, is quite variable, though they probably still represent just the one species. We have taken specimens for taxonomic and genetic examination as part of a wider study of freshwater crabs in northern Australia being conducted by TropWATER.

Conclusions and Recommendations

Mangrove Extent and Diversity

Outcomes:

- 300 km of island shoreline assessed from 14 Torres Strait Islands.
- Mean shoreline mangrove cover is 67%.
- Fringing mangrove is important for ecosystem service provision.
- Mangrove Islands Sassie, Zagai and Buru are unique and important mangrove habitats in Torres Strait. These islands should be included provided the highest conservation status.
- Rocky outcrop islands have a high mangrove exposure. These fringing mangroves are most at risk from marine-based threats.
- Protection and management of the mangrove fringe should be reviewed for all islands.

Management Recommendations:

- Sassie, Zagai and Buru Islands should be protected with the highest conservation status available.
- Protection and management of the mangrove fringe on Torres Strait Islands should be reviewed.

Shoreline Condition

Outcomes:

- Mean shoreline mangrove in a healthy state is 59%.
- Mean shoreline mangrove in poor condition is 18%.
- This data provides a baseline of mangrove condition in Torres Strait.
- High proportion of poor condition mangroves is indicative of the dynamic coastal environment in Torres Strait and highlights that fringing mangroves are exposed to natural pressures.
- Sea level rise may be exacerbating the effect of wind and waves on fringing mangrove habitat.
- Gebar mangroves are in very poor condition.
- Saibai, Boigu and Mua Islands have the greatest extent of mangroves in poor condition.

Management Recommendations:

- Undertake targeted assessment of Gebar Island to determine cause of poor condition mangroves.
- Improve mangrove management and conservation on Boigu, Saibai and Mua Island.

Shoreline Processes and Drivers of Change

Outcomes:

- Shoreline processes affecting mangroves varies between islands.
- Overall the dominant shoreline process is erosion (21% greater than expansion).
- Sassie and Zagai islands are undergoing substantial change with both mangrove loss and expansion occurring.
- There is a high proportion of expanding shoreline and depositional gain on Erub Island due to land-based sediment runoff.
- There is a high proportion of mangrove expansion in Iama Island.
- Gebar Island is experiencing a high degree of shoreline retreat, with an overall net loss of mangroves currently occurring.
- Mangrove loss and gain may not be balanced at an island scale, but may be balanced across regional scales.

Management Recommendations:

- Address hillslope erosion on Erub Island.
- Investigate cause of shoreline mangrove retreat on Gebar Island.

Threats to Mangrove Tidal Wetlands

Outcomes:

- Nine (9) human related drivers of change identified as impacting mangroves in Torres Strait.
- Mua Island has the highest number of mangrove management issues present (7).
- Mangrove cutting is the most frequently observed human driver and is threatening mangrove habitat in the Torres Strait.
- 2% of mangroves in Torres Strait are estimated to be impacted by cutting.
- Elevated nutrient loads from STP's threaten mangrove climate change resilience but may facilitate mangrove expansion.
- Chemical leachate from waste disposal is likely entering mangrove habitat. This poses a threat to human health related to chemical exposure of mangrove fisheries resources.
- Only a small proportion of mangroves are at risk from localized oil and fuel spills.
- Sea level rise is potentially directly threatening 13% of Torres Strait mangrove habitat
- Mangrove root burial from sediment runoff is impacting 34% of mangroves in Erub Island.

Management Recommendations:

- Undertake a comprehensive review of mangrove timber extraction on Torres Strait Islands.
- Further limit elevated nutrient loads to mangrove habitat and investigate acceptable nutrient load limits for mangrove habitat.
- Investigate pollutant levels in mangrove fauna on Boigu, Saibai, Iama and Dauan
- Undertake further investigation of potential sea level rise impacts on Torres Strait Islands.
- Address hillslope erosion on Erub Island.
- Ensure rangers and local islanders are aware of Pond Apple.
- Investigate impacts of fire on tidal wetland climate change resilience.

Historical Changes to Shoreline Vegetation

Outcomes:

- Updated and refined mangrove maps for 11 Torres Strait Islands.
- Updated mangrove area assessment has increased mangrove area in Torres Strait by 6% (316 ha).
- There is an estimated 2% annual increase in mangrove area based on mangrove change assessment of Buru, Sassie, Zagai, Iama and Tudu Islands.
- Mangrove expansion reflects the low level of direct anthropogenic pressure on mangrove habitats in Torres Strait.
- Large mangrove increases were observed on Erub and Iama Islands.
- Iama Island has undergone large-scale change in mangrove extent in the past 30 years, with a net increase in mangrove area of 13% in 37 years (1974 to 2011).
- Mangrove expansion likely reflects a recent *drop* in sea level during the 1980's and 1990's and has potentially been facilitated by elevated nutrient loads.
- 6% of mangroves are recent regrowth. Mangrove regrowth has occurred in most historically cleared areas.
- Regrowth appears to be reflecting a new high mean sea level position that may indicate sea level rise.
- Mangroves are sensitive to variations in sea level and respond rapidly to sea level variations.

Management Recommendations:

- Update mangrove mapping for other Torres Strait Islands using 2014 aerial imagery
- Undertake more detailed historical mangrove change assessment using original aerial imagery.
- Undertake a comprehensive remote and on-ground assessment of mangrove change on Iama Island to determine cause of mangrove expansion.

Overall Summary for Tidal Wetlands

This report provides a baseline of mangrove extent, condition and threats to mangroves in Torres Strait.

Based on the results presented here, we recommend continued monitoring and assessment of Torres Strait mangroves to allow for detection of change over time and develop a greater understanding of mangrove processes and function to inform better mangrove management.

This can be achieved through the continuation of the TSRA Land and Sea Ranger MangroveWatch program.

We recommended that a specific Mangrove Management Plan be developed for each of the populated Torres Strait islands with mangrove habitat. Each Mangrove Management Plan should be designed to address local mangrove management issues identified here, with the main focus on mangrove timber resource use and climate change resilience. Mangrove Management Plans should be developed in consultation with Traditional Owners, TSRA, State mangrove management agencies and university researchers.

A separate targeted study on sea level rise impacts to Torres Strait mangroves is also necessary to follow on from observations made here. Torres Strait islands provide a unique setting to understand how mangroves will respond to increasing sea level with findings applicable across the Pacific Islands and Northern Australia to enhance mangrove management and conservation.

Concluding Remarks for Freshwater Wetlands

From this work, several key recommendations can be drawn:

1. We were not able to obtain traditional owner permission to formally survey the southern islands of Muralag, Horn and Thursday islands. The artificial waterbodies on Horn and Thursday Island are especially worthy of sampling for the presence of pest fish, one species of which (Gambusia) has already been observed on Thursday Island).

2. The genetic relationships of the freshwater species present in Torres Strait are worthy of further study as are their dependence on key habitats. Genetic relationships require being put into the context of wider geographic studies, including comparing to samples from Cape York and New Guinea. We have retained specimens from many species for this purpose to share with researchers in other studies. We have already included samples of freshwater crabs into a larger genetic study being conducted by TropWATER.

3. Torres Strait remains a significant potential pathway for the entry into Australia, of serious pest fish species from New Guinea, which already hosts many such exotic pests. Preventing such spread requires regular monitoring in combination with a

concerted public education campaign amongst island residents and visitors. Our work has shown that in their new range, these species may occupy different habitats to their native range, thus studies on the ecology and environmental tolerances of these species within their new habitats are worthwhile. In addition, new technologies such as being able to determine the presence of various species from their DNA in water samples, could be used to greatly increase monitoring detection efficiency. Research to further these technologies should be considered.

4. There are key management threats to freshwater habitats, especially from introduced animals such as pigs, deer and cane toads, as well as weeds. With so few freshwater habitats present, some of these may be in need of management attention to ensure their integrity. This could include fencing to exclude these large introduced animals. Some of these have already been identified in this study, especially on Saibai and Boigu Islands. Others on Prince of Wales and Horn islands could be identified by consultation with traditional owners and local residents.

5. Given the likelihood of sea level rise affecting low-lying islands such as Boigu and Saibai, gaining an understanding of the salinity dynamics of the wetlands on the island is important to monitoring any changes that are likely to result from sea level rise. We have begun such monitoring but water quality is highly variable and more data over should be collected over a longer period of time, and also including assessments of salinity in the wetlands before and immediately after king tides. This could be done as part of ranger work programs.

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