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Assessing the vulnerability of Torres Strait fisheries and supporting habitats to climate change

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AFMA Project Number 2013/0014

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Table of Contents

Table of Figures

Table of Tables

Non-technical Summary

Climate change is considered to be a major environmental threat and there is a national priority to better establish the likely effects of climate change on Australia's fisheries. Positive and negative impacts of climate change on marine fisheries are already being observed in tropical regions, including the GBR and Pacific. In the Torres Strait region, fisheries impacts are likely to manifest in changes to species stock structure, phenology, distribution shifts, and indirectly through habitat changes. Torres Strait Islanders have a long history of association with their marine resources and fisheries species are of significant cultural, social and economic importance. Any impacts of climate change on marine fisheries stocks and the habitats that support them will affect Torres Strait communities and potentially include changes in the accessibility of target species, changes in the reliability of food supply, and reduced sustainability of fisheries. Therefore, there is an imperative for Traditional Owners, Torres Strait communities, fishers and managers to understand what these impacts are likely to be, which fisheries are expected to be most vulnerable, and to use this information to prepare for negative effects and capitalize on opportunities.

We assessed the relative vulnerability of Torres Strait fisheries by conducting a vulnerability assessment on 15 key fishery species. We applied a structured semi-quantitative approach for the vulnerability assessments based on a widely-adopted framework that includes the elements of Exposure, Sensitivity and Adaptive Capacity proposed by the Intergovernmental Panel on Climate Change and United Nations Framework Convention on Climate Change. The assessments were informed by comprehensive literature reviews of Torres Strait climate (observed and projected), key fishery habitats and their vulnerability to climate change, and species reviews for 10 fishery groups that covered fishery characteristics, species life cycles and sensitivity to environmental changes. The assessments were further informed by results of interviews with Torres Strait Islanders.

The results of the vulnerability assessments identified species with high, medium and low relative vulnerability to climate change. The species identified as having the highest relative vulnerability were: black teatfish, black-lipped pearl oyster, dugong, and trochus. When vulnerability was combined with the level of importance of each species to fisheries in Torres Strait (using a measure of cultural and economic value), a priority list of five species was identified for future action by management. These species were: dugong, turtle, tropical rock lobster, trochus and gold-lipped pearl oyster.

This project concludes that there are a number of environmental changes that will be experienced in the Torres Strait by 2030, including habitat impacts that will have flow-on effects on a number of key fisheries. The main drivers are likely to be increases in sea surface temperature, increased severity of storms, and habitat changes particularly to coral reefs and seagrass meadows. The report also provides a range of recommendations on future actions and research that should arise from this project. These are grouped into three themes: (1) improving assessment accuracy, (2) extension of results to communities and decision-makers, and (3) research to address key knowledge gaps.

The relatively healthy condition of most fisheries in the Torres Strait will aid in the success of any adaptation options implemented. Adaptations that focus on sustainable management of stocks, habitat preservation (coral reefs and seagrass) and diversification of fisheries species hold the most promise for fisheries under climate change. Strong local governance is also important in an uncertain and changing future.

Acknowledgements

The authors would like to thank the Australian Fisheries Management Authority and the Protected Zone Joint Authority for funding this project. They would also like to thank the Torres Strait Regional Authority for their assistance in liaising with and contacting appropriate local stakeholders and experts, and providing background data for the literature review component. We also thank the many local stakeholders who gave up their time to speak to us about their activities and experiences in the Torres Strait, which contributed important information to the assessment. The many experts who commented on the draft assessment greatly improved the quality of the results, and we thank Dr Gretta Pecl, Dr Julie Robins, Professor Helene Marsh, Dr Mark Hamann, Dr Ashley Williams, Professor Morgan Pratchett, Dr Steve Purcell, Dr Tony Courtney, Dr Rik Buckworth along with their various institutions for their assistance.

1. Background

This project was developed at the request of the Australian Fisheries Management Authority (AFMA) and the Torres Strait Scientific Advisory Committee (TSSAC) to address one of the key challenges facing Torres Strait (TS) fisheries: climate change. The project directly addresses priority actions of the Torres Strait Climate Change Strategy 2010-2013 (TSRA 2010) (Risk science to inform planning) and the TSSAC 2012 Operational Plan for Torres Strait fisheries. In addressing these priority research areas, this project draws on results and lessons learnt from recently completed climate change vulnerability assessments for the Great Barrier Reef (GBR; Johnson and Marshall 2007) and for tropical Pacific fisheries (Bell et al. 2011a). The project also complements a current FRDC Project (#2010/565) that is using the same structured approach to assess the vulnerability of key fisheries in northern Australian to climate change. The project draws on recent and ongoing research on climate change impacts and sensitivity of fisheries species (e.g. Torres Strait tropical rock lobster, northern prawn fishery, east coast otter trawl fishery, GBR/TS reef line fishery) that is directly relevant to the species assessed in this project. Linking with this complementary research enabled the use of the best available science for the vulnerability assessment of TS fisheries.

In developing the approach used in this project, and conducting the vulnerability assessment, we consulted with various end-user groups to ensure the needs of Torres Strait fishers are being addressed. This included AFMA, the Torres Strait Regional Authority, and the TSRA Portfolio Member for Fisheries (Cr Kenny Bedford), who assisted with contact lists of fishers who have a long history in the TS region and were willing to provide information for the project.

2. Need

Climate change is considered to be a major environmental threat and there is a national priority to better establish the likely impacts of climate change on Australia's fisheries. The impacts of climate change on marine fisheries are already being observed in tropical regions, including the GBR and Pacific. In the Torres Strait region, fisheries impacts are likely to manifest in changes to stock structure, phenology, distribution shifts, and indirectly through habitat changes. TS Islanders have a long history of association with their marine resources and fisheries species are of significant cultural, social and economic importance. Any impacts of climate change on marine fisheries stocks and the habitats that support them will affect TS communities and potentially include changes in the accessibility of target species, less reliable food supply, and reduced sustainability of fisheries. There are also indications that climate change may increase the risk of ciguatera in seafood with health implications for Islanders that consume large quantities. Therefore, there is an imperative for Traditional Owners, TS communities, fishers and managers to understand what these impacts are likely to be, which fisheries are expected to be most vulnerable, and to use this information to prepare for negative effects and capitalize on opportunities.

Climate change vulnerability assessments have been conducted for the adjacent GBR (Johnson and Marshall 2007) and the tropical Pacific, including for Papua New Guinea (PNG; Bell et al. 2011a,b) that shares a border with TS and has access to jointly managed fisheries resources. Fisheries in the TS region target many of the same species and stocks as these adjacent regions, and a complementary vulnerability assessment using the same approach was employed for this project. Understanding which fisheries will be most vulnerable to climate change, the source of this vulnerability and when impacts are likely to manifest will provide targets for management and adaptation.

3. Objectives

1. Identify key fisheries and supporting habitats in the Torres Strait region for assessment.
2. Document observed climate trends and projected climate for Torres Strait for 2030 and 2070.
3. Determine the Torres Strait fisheries likely to be vulnerable (at highest risk) to climate change, and the influencing climate factors.
4. Communicate all findings through a formal report and fact sheet appropriate for TS communities.

4. Introduction

The Torres Strait region covers an area of 48,000 km^2, of which 2.6% is terrestrial land, 6.2% is tidally inundated reef flats, and 91.2% open seas, most of which are relatively shallow (20–60 m). The region is protected from swell by the northern Great Barrier Reef, and has strong tidal currents and irregular bathymetry with a narrow continental shelf. There are more than 247 islands, 18 that are inhabited and support an estimated 7,000 people. There are also numerous coral reefs, cays, sandbanks and seagrass meadows scattered throughout the region, which stretches 200 kilometres from the tip of the Cape York Peninsula to the southwest coast of PNG (Figure 1).

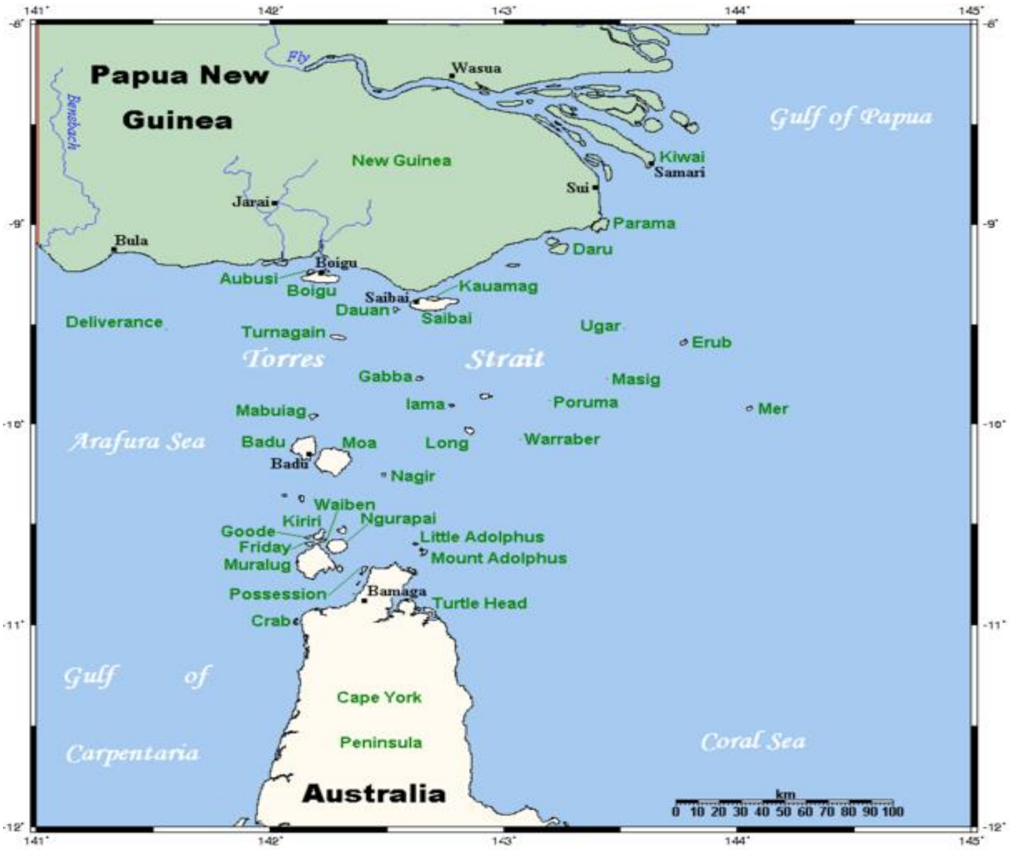

Figure 1. Map showing the Torres Strait region with the major islands indicated.

The region has one of the highest proportions of Indigenous people in Australia with the traditional Islanders being of Melanesian origin, many of whom have strong affiliation with their land and sea and depend heavily on their marine resources for food and livelihoods. TS Islanders have some of the highest seafood consumptions rates in the region, with estimates of an average ~41 kg per person per year (Johannes and McFarlane 1993) being higher than in mainland Australia and neighbouring Melanesian countries (e.g. PNG, Solomon Islands, Vanuatu, see Bell et al. 2011b). Fisheries in the region are exploited for food security (e.g. coral reef fish, Spanish mackerel, tropical rock lobster and mud crab), local livelihoods (e.g. tropical rock lobster, finfish, prawn, trochus, sea cucumber and pearl shell), and traditional hunting (marine turtle and dugong).

Located at the junction of the Arafura Sea and Pacific Ocean, the TS marine environment is of national and international significance and is a major shipping route between the Indian and Pacific Oceans. TS shares international borders with PNG and Indonesia, and the Torres Strait Treaty between PNG and Australia establishes the Torres Strait Protected Zone and other mechanisms for the shared governance of the region, including access to and management of its marine resources, particularly fisheries.

Global pressures such as climate change will have complex impacts on the marine resources of TS, particularly the fisheries resources and supporting habitats that Islanders depend on. The effects of climate change threaten the islands themselves through sea level rise, as well as marine ecosystems; and therefore the life, livelihoods and unique culture of Torres Strait Islanders. This uncertain future will present challenges for achieving sustainable fisheries and communities in the Torres Strait.

This report provides a Torres Strait-specific compendium of current information on: past and projected climate; habitats that support fisheries and how they are likely to be impacted by future climate; and the characteristics of key fisheries species in the region. This information is used to provide an improved understanding of the climate-related changes predicted for the TS region, and the ability of key species' to respond to environmental variation, informing the 'exposure', 'sensitivity' and 'adaptive capacity' elements of the climate change vulnerability assessment.

5. Methods

Overview

This project had a number of stages to achieve the objectives of the project, including a selection process for choosing the key fisheries species to assess, a literature review of observed and projected climate in Torres Strait, an assessment of habitat changes due to climate change, and the structured semi-quantitative vulnerability assessment. The project used a structured approach to assess the vulnerability of select Torres Strait fisheries to projected climate change. The key underlying framework was the vulnerability assessment framework adopted by the Intergovernmental Panel for Climate Change (IPCC) for their global assessment process (Schroter et al. 2004, Schneider et al. 2007). This framework has been used in assessing the vulnerability of species groups and habitats of the GBR to climate change (Johnson and Marshall 2007), for global relative species vulnerability assessments (Foden et al. 2013), and for fisheries and aquaculture in the tropical Pacific to identify adaptive management options that protect fisheries resources for subsistence and commercial fisheries (Bell et al. 2011a).The methods for each of these stages are outlined below, and incorporated an expert/stakeholder review approach where possible to ensure outputs that were relevant and appropriate for TS fisheries.

Geographic scope of project

The project focused on key fisheries in the Torres Strait which covers an area of 48,000 km^2 and is managed under the Torres Strait Treaty between PNG and Australia. This Treaty establishes the Torres Strait Protected Zone (TSPZ) and other mechanisms for the shared governance of the region, including marine resources, particularly fisheries (Figure 2). The geographic limit of interest covers the Torres Strait from approximately Cape York in mainland Australia to the northern boundary of the Torres Strait Protection Zone, a border shared with PNG.

Figure 2. Map showing the Australian maritime zones in the Torres Strait region.

Species of interest

The Torres Strait fisheries chosen for assessment were based on the level of harvest as well as economic, cultural and social values, with input from the TSSAC. A final total of 15 key target species were included in the vulnerability assessment (Table 1). The sea cucumber fishery includes several species and the two included (sandfish and black teatfish) are both important species that also represent contrasting biology and ecology for the purpose of the assessment.

Table 1. Summary of the key Torres Strait fishery species assessed and the fishery sector to which they predominantly belong.

Common name	Scientific name	Fishery type
Brown tiger prawn	*Penaeus esculentus*	Commercial
Blue endeavour prawn	*Metapenaeus endeavouri*	Commercial
Tropical rock lobster	*Panulirus ornatus*	Commercial. subsistence
Mud crab	*Scylla serrata*	Commercial. subsistence
Gold-lipped pearl oyster	*Pinctada maxima*	Commercial
Black-lipped pearl oyster	*Pinctada margaritifera*	Commercial
Trochus (topshell)	*Trochus niloticus*	Commercial. subsistence
Spanish mackerel	*Scomberomorus commerson*	Commercial. subsistence, recreational
Common coral trout	*Plectropomus leopardus*	Commercial. subsistence, recreational
Bar-cheek coral trout	*Plectropomus maculatus*	Commercial. subsistence, recreational
Passionfruit coral trout	*Plectropomus areolatus*	Commercial. subsistence, recreational
Sandfish	*Holothuria scabra*	Commercial
Black teatfish	*Holothuria whitmaei*	Commercial
Dugong	*Dugong dugon*	Subsistence
Turtle	Principally *Chelonia mydas*	Subsistence

Literature review

Observed climate

We collated data for observed ocean and surface climate for variables that tropical fisheries are most likely to be sensitive to, based on known sensitivities of selected fisheries species (see Bell et al. 2011a, Johnson and Marshall 2007, Welch et al. in prep). The information was drawn from a range of sources, particularly recent climate modelling for the Torres Strait commissioned by the Torres Strait Regional Authority (Suppiah et al. 2010), the Pacific Climate Change Science Program (BoM and CSIRO 2011), relevant chapters of the Pacific vulnerability assessment (Ganachaud et al. 2011, Lough et al. 2011) as well as other key literature (e.g. Lough and Hobday 2011, Puotinen 2004, 2007 (for tropical cyclones); TSRA 2011a (for sea level); and Climate Commission 2013 (for links between climate change and extreme events)). The summary of observed climate covered historic temporal periods when the data are most reliable, and the data sources for both observed and projected climate are in Table 2.

Table 2. Climate variables selected for climate projections and data sources.

Variable	Data source
Surface temperature: air and sea	Suppiah et al. 2010
Rainfall and river flow	Suppiah et al.2010, BoM and CSIRO 2011
El Niño –Southern Oscillation (ENSO)	BoM and CSIRO 2011, Lough and Hobday 2011
Storms and cyclones	Puotinen 2004, 2007, BoM 2008, Knutson et al. 2010, BoM and CSIRO 2011
Ocean chemistry	Ganachaud et al. 2011
Sea level	Suppiah et al. 2010, Ganachaud et al. 2011, TSRA 2011a
Ocean circulation	BoM and CSIRO 2011, Ganachaud et al. 2011
Ocean salinity	BoM and CSIRO 2011
Solar radiation	Suppiah et al. 2010

Projected climate

The climate projections for this project are all based on the outputs of global climate models. A climate model is a numerical description that represents our understanding of the physics, and in some cases chemistry and biology, of the ocean, atmosphere, land surface and ice regions. All models are state-of-the-art 'coupled' models, meaning that ocean, atmosphere, land and ice models are coupled together, with information continuously being exchanged between these components to produce an estimate of global climate. These climate models are run for hundreds of simulation-years subject to constant, pre-industrial (1870) forcing, i.e. constant solar energy and appropriate greenhouse gas levels to develop a baseline. The 20th century simulations incorporate increasing greenhouse gases in the atmosphere in line with historic emissions and using observed natural forcing (e.g. changes in solar radiation, volcanic eruptions). At the end of the 20th century, projection simulations are carried out based on predefined 'plausible' future emission trajectories.

The climate projections used were based on the IPCC-AR4 global climate model outputs (IPCC 2007) recently downscaled for the TS and PNG (Suppiah et al. 2010, BoM and CSIRO 2011, Lough et al. 2011, Ganachaud et al. 2011) for 2030 and 2070 (or the nearest available projection years) for the B1 (low emissions), A2 and A1FI (high emissions) IPCC Special Report on Emission Scenarios (SRES) storylines (Nakicenovic and Swart 2000).

Torres Strait habitats

We conducted a literature review to summarise information on documented habitat types and extent in Torres Strait, and known sensitivities of these habitats to climate drivers, including results from related projects that have yet to publish their results (Welch et al. in prep, FRDC project 2010/565).

The vulnerability of Torres Strait habitats to projected climate change was based largely on a review and synthesis of available vulnerability assessment results. The habitats considered in this project – estuaries, seagrasses, mangroves and coral reefs – have been assessed in adjacent regions using the structured vulnerability assessment framework with the elements of Exposure, Sensitivity and Adaptive Capacity. Therefore, this project reviewed and selected comparable results from comprehensive habitat vulnerability assessments conducted for habitats in the adjacent GBR (Johnson and Marshall 2007) and Pacific region (Bell et al. 2011a), particularly Papua New Guinea. The assessment of vulnerability was tailored to the Torres Strait, taking into consideration observed and projected climate for the region, the extent and location of habitats and the scale of the region.

Key fisheries species

Reviews of each of the main species identified from the key fisheries focused on information that would inform the vulnerability assessment process, particularly their sensitivity to climate drivers and adaptive capacity. The reviews synthesised existing literature and unpublished work and were comprised of three sections: fisheries characteristics, species life cycle characteristics, and known or inferred sensitivity of the species to environmental factors. Information about the fishery characteristics included aspects such as status of stocks, the current operational characteristics, historic harvest levels, and the nature of existing management strategies. Information about the species life cycle included aspects such as the productivity of the species, critical life history stages, level of plasticity in biological characteristics (e.g. spawning times, maturity, growth), habitat use and movement capabilities. Information about the sensitivity of species to environmental changes (e.g. sea temperature, pH, sea level, rainfall/river flow, currents and wind) included information on whether species are likely to respond to changes in particular environmental variables and the nature of that change, critical life history stages most sensitive to changes, and their potential capacity to cope with changes.

Assessing vulnerability

The vulnerability assessments were carried out as a desktop study on a species-specific basis except for turtles and sea cucumbers. For turtles, although several species are present in the Torres Strait, the assessment was based on information about the green turtle, *Chelonia mydas*, since it is the most common and widely targeted turtle species in the Torres Strait. For sea cucumbers, although several different species are harvested, the assessment was based on the sandfish *Holothuria scabra*, as the species historically targeted due to their value (despite a current ban on harvest), and black teatfish *H. whitmaei* that has very different life history characteristics.

We applied a structured semi-quantitative approach for the vulnerability assessments based on a widely-adopted framework that includes the elements of Exposure, Sensitivity and Adaptive Capacity proposed by the IPCC and United Nations Framework Convention on Climate Change (UNFCCC) (adapted from Schroter et al. 2004; Figure 3). This framework provides a structured approach for determining the potential impacts of climate change on fisheries systems and their relative level of vulnerability. The framework also provides transparency to stakeholders by incorporating adaptive capacity and allowing for potential adaptation responses for relevant fisheries stakeholder groups to consider.

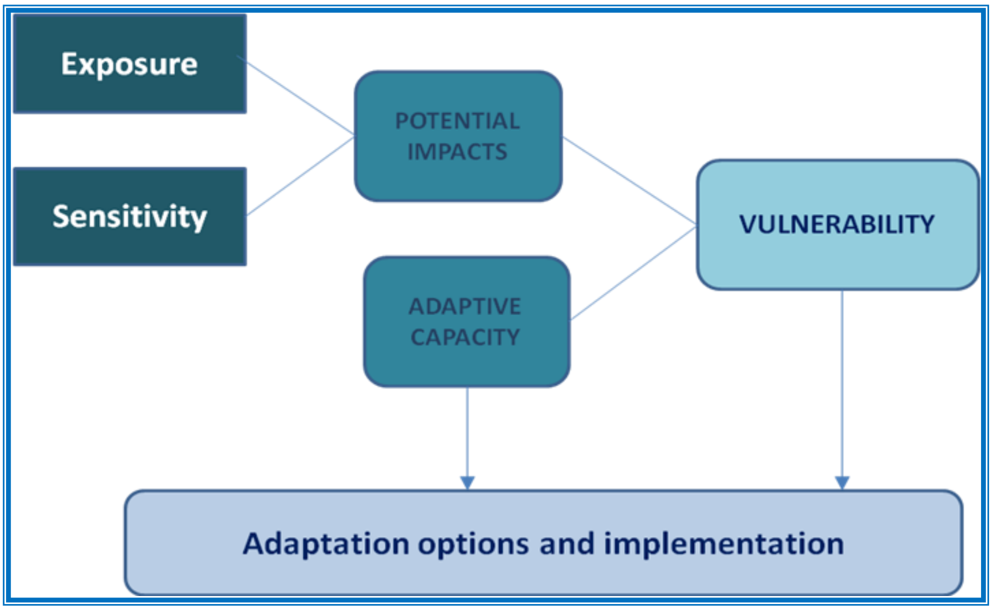

Figure 3. Vulnerability assessment framework adopted by the Intergovernmental Panel for Climate Change (adapted from Schroter et al. 2004).

Indicators

The indicators used for each of the elements Exposure, Sensitivity and Adaptive Capacity underwent a rigorous selection and review process by the project team and relevant experts. Indicators for Exposure were based on climate projections for the TS region (e.g. Suppiah et al. 2010, BoM and CSIRO 2011), and for Sensitivity and Adaptive Capacity were adapted from previous studies (e.g. Marshall and Marshall 2007, Johnson and Welch 2010, Pecl et al. 2011a) as well as key literature. Table 3 outlines all the indicators used for the assessment and the rationale for their selection.

Table 3. Indicators for Exposure, Sensitivity and Adaptive Capacity; their source and rationale.

		Rationale
Exposure (2030 A2 and A1FI scenarios)	Surface temperature increase +0.62 to +1.27 °C	Based on climate projections for Torres Strait (Suppiah et al. 2010)
	Rainfall change -2.97 to +6.27%	Based on climate projections for Torres Strait (Suppiah et al. 2010)
	pH decline 0.1 unit	Based on climate projections for the tropical Pacific (Ganachaud et al. 2011)
	Salinity decrease -0.1 psu	Based on climate projections for the tropical Pacific (BoM and CSIRO 2011)
	Habitat changes (loss of productivity, structure or function)	Based on predicted changes to Torres Strait habitats that support fisheries – pelagic, coral reefs, seagrass, mangroves and estuaries – from assessment in Results habitat section
	Altered wind/currents	Based on climate projections for the tropical Pacific (BoM and CSIRO 2011, Ganachaud et al. 2011)

	Tropical cyclone intensity +2 to +11%	Based on modelled tropical cyclone characteristics in the Southern Hemisphere (Puotinen 2004, 2007, Knutson et al. 2010) and projections for the tropical Pacific (BoM and CSIRO 2011)
	More extreme river flow	Based on rainfall projections for Torres Strait for 2030 (Suppiah et al. 2010) and the expected influence of extreme rainfall on river flow
Sensitivity	Fecundity - egg production	Measure of species abundance that represents its intrinsic rate of population increase (Pecl et al. 2011a)
	Average age at maturity	Measure of species abundance that represents its carrying capacity (Pecl et al. 2011a)
	Generalist v specialist (food & habitat)	Measure of species dependence on particular habitat or food resources, and a proxy for its sensitivity to changes in these resources (i.e. habitat degradation) (Pecl et al. 2011a)
	Early development duration (dispersal capacity of larvae/young)	Dispersal is a key step for a species undergoing distributional change and was used as a proxy for capacity to change distribution under changing conditions (Pecl et al. 2011a)
	Physiological tolerance of stock	The physiological tolerance of a fisheries stock can be demonstrated by threshold responses where a relatively small change in environmental conditions may cause a significant or irreversible change
	Reliance on environmental cues (for spawning, breeding or settlement)	Phenology indicator assessing the interaction between climate variables and biological processes that influence the timing of species life-cycle events (Pecl et al. 2011a)
	Reliance on temporal cues (duration of spawning, moulting or breeding)	Phenology indicator assessing sensitivity to temporal mismatches of life-cycle events in relation to spawning, breeding or moulting season (Pecl et al. 2011a)
Adaptive Capacity	Stock status	Measure of existing fishing pressure on the stock that can heighten the response of the stock to acute and chronic disturbances (Kirby et al. 2009, Brander 2010)
	Replenishment potential	Reproductive capacity to increase population and recover from disturbance
	Ability to range shift	Ability of a species to expand or shift their range in response to environmental changes, such as increasing SST, and maintain a viable stock in an alternative location based on habitat availability
	Species mobility	Ability to avoid short-term disturbances, such as periods of high SST, by temporarily moving to alternative locations with more favourable conditions (e.g. cooler deeper waters)
	Non-fishing pressures on stock	Measure of existing non-fishing pressures on the stock that can heighten the response of species to acute and chronic disturbances and/or inhibit recovery post-disturbance
	Resource dependence	Specificity of the fishery, in terms of the number of species they can target and specialised gear, since fishing communities that are dependent on a limited number of species are more vulnerable to fluctuations in stocks, whether due to climate change or other causes (Marshall and Marshall 2007, Brander 2010)
	Willingness to change fishing practices	Level of interest or willingness of fishers to change their practices (Marshall and Marshall 2007)
	Climate change awareness	Awareness of climate change as an issue and perception of risks for Torres Strait fisheries (Marshall and Marshall 2007)
	Governance	The capacity of governance and institutional environments to support adaptation depends on their flexibility and effectiveness of policy and decision-making (Brander 2010, Park et al. 2013)

The criteria for scoring Sensitivity were adapted from Pecl et al. (2011a) who provided a detailed explanation of the development of these criteria that included expert review. The indicators are based on different aspects of a species life history that can be affected by climate change: abundance, distribution and phenology. ‘Abundance’ relates to the capacity of a population to recover, which is essentially their productivity level. More productive species are deemed to be less sensitive to impacts because of their greater capacity to recover. ‘Distribution’ relates to the likelihood and capacity for a species to alter its range in response to environmental changes. ‘Phenology’ relates to the likelihood that environmental changes will result in changes to the timing of life cycle events (e.g. spawning). The Sensitivity indicators and their criteria are shown in Table 4.

Table 4. Sensitivity indicators and criteria for scoring.

		Low=1	Medium=2	High=3
Sensitivity	Fecundity – egg production	>20,000 eggs/year	100-20,000 eggs/year	<100 eggs/year or live young
	Average age at maturity	≤ 2 years	3-10 years	> 10 years
	Generalist v specialist (food & habitat)	reliance on neither habitat or prey	reliance on either habitat or prey	reliance on both habitat and prey
	Early development duration (dispersal capacity of larvae/young)	> 8 weeks	2-8 weeks	< 2 weeks or no larval stage
	Physiological tolerance of stock	Threshold unlikely to be exceeded for any climate variable	Physiological thresholds unknown	Threshold likely to be exceeded for one or more environmental variables
	Reliance on environmental cues (for spawning, breeding or settlement)	No apparent correlation to environmental variable	Weak correlation to environmental variable	Strong correlation to environmental variable
	Reliance on temporal cues (duration of spawning, moulting or breeding)	Continuous spawning duration; >4 months	Moderate spawning duration; 2-4 months	Brief spawning duration; <2 months

The criteria for scoring the indicators for Exposure and Adaptive Capacity were developed based on previous assessments and research (see Marshall and Marshall 2007, Allison et al. 2009, Johnson and Welch 2010, Bell et al. 2011a, Pecl et al. 2011a). The criteria for scoring each of the Exposure indicators were based on the likelihood that a species would experience a change in that variable based on the habitats they depend on for shelter, breeding and food and how much time they spend in habitats expected to experience environmental change. Criteria for scoring the Adaptive Capacity indicators were based on the inherent resilience characteristics of the species (e.g. stock status) and resilience characteristics of the fishery itself (e.g. resource dependence) (Table 5).

Table 5. Exposure and Adaptive Capacity indicators and criteria for scoring.

		Low=1	Medium=2	High=3
Exposure (2030 A2 and A1FI scenarios)	Surface temperature increase +0.62 to +1.27 °C	spends <50% of time in surface (<25 m) waters	spends 50-80% of time in surface (<25 m) waters	spends 80-100% of time in surface (<25 m) waters
	Rainfall change -2.97 to +6.27%	spends no time in estuarine or freshwater habitats during any life history phase	spends <50% of time in estuarine or freshwater habitats; no critical life history phase	spends >50% of time or has critical part of life cycle in estuarine or freshwater habitats
	pH decline 0.1 unit	open ocean or deep water species	continental shelf species	inshore or estuarine species or calcareous parts
	Salinity decrease -0.1 psu	open ocean or deep water species	continental shelf species	inshore or estuarine species
	Habitat changes (loss of productivity, structure or function)	species not habitat dependent	species dependent on pelagic or mangrove habitats	species dependent on seagrass or coral reef habitats
	Altered wind/currents	live young/egg bearers or no dependence on wind/current for larval dispersal	proximate dispersal of young not entirely dependent on wind/current dispersal	dispersal of young 100% dependent on wind/currents
	Tropical cyclone intensity +2 to +11%	deep water or highly mobile species	shallow water (< 25 m) and moderately mobile species	shallow water (< 25 m) or low mobility species
	More extreme river flow	spends no time in estuarine or freshwater habitats during any life history phase	spends <50% of time in estuarine or freshwater habitats; no critical life history phase	spends >50% of time or has critical part of life cycle in estuarine or freshwater habitats
Adaptive Capacity	Stock status	overfished or on the verge of overfishing	moderate fishing levels or status unknown	not overfished
	Replenishment potential	late maturing (> 6 yrs), slow growth or few young	matures at 3-6 yrs, moderate growth or numbers of young	early maturing, fast growing or many young
	Ability to range shift	low availability of habitat outside range or currently near northern edge of range	some availability of habitat outside range or currently near middle of range	high availability of habitat outside range and currently near middle of range
	Species mobility	low mobility; can travel <2 km/day	moderately mobile; can travel 2-10 km/day	highly mobile; can travel >10 km/day
	Non-fishing pressures on stock	multiple chronic pressures (e.g. poor water quality, disease)	some acute pressures (e.g. cyclones, storms, floods)	no or minimal other pressures
	Resource dependence	no alternate species and/or significant gear/practice modifications required to target other species	some alternate species that could be targeted with gear/practice modifications	multiple alternate target species that could be targeted without any gear/practice modifications
	Willingness to change fishing practices	not willing to change	willing to change with support	willingness to change
	Climate change awareness	unaware	aware and no planning undertaken	aware and has taken preparatory action
	Governance	inflexible or non-existent	flexible or adaptive (not both)	flexible and adaptive

Scoring indicators

Each indicator was scored as “1” (Low), “2” (Medium) or “3” (High) based on the criteria outlined in Tables 3 and 4. Pecl et al (2011a) demonstrated that this simple 3-level approach is sufficient for resolving species rankings, and for using expert judgement while avoiding the need to determine precise rankings. For each element, an index was calculated by dividing the total score by the number of indicators (i.e. the average score; e.g. Exposure Index = total score/8).

The Potential Impact index (PI) was determined as the product of the Exposure and Sensitivity Indices. However, since this scoring framework does not accommodate the direction of an impact (ie. whether it is a positive or negative impact), we derived the final PI index by incorporating a “direction of impact” (DI) value. This was determined as: negative impact = 1; unknown or neutral impact = 0; and positive impact = -1. Therefore the final PI index was calculated by:

$$PI = E*S\ (+DI)$$

Since Adaptive Capacity (AC) actually tempers vulnerability and is the inverse of the other elements (i.e. a high AC score reduces vulnerability whereas a high index value for Exposure or Sensitivity increases vulnerability), we standardised the AC Index to a value between 0.0 and 1.0, and used the value of 1 - AC in the calculation of the relative vulnerability score for each species. Vulnerability was therefore calculated using the following equation:

$$V = PI*(1-AC) + 1$$

NB. Due to the effect of standardisation adding one was done to avoid zero values, which may imply a species has no vulnerability. This means that the species with the lowest relative vulnerability will have a vulnerability index of 1.00.

The vulnerability assessments were done in two phases: initially as a desktop assessment by the project team, and then refined based on feedback from: (i) scientific experts on the respective species (n=9), and (ii) Torres Strait locals with expert knowledge (n=10). The assessment framework was explained to expert participants and a worked example provided. Incorporating this expert feedback and local knowledge on the fisheries resulted in comprehensive and informed assessments of vulnerability. Vulnerability assessments of Torres Strait fishery species therefore used three major lines of determination: (i) information synthesised from the climate and habitat reviews, (ii) information provided in the species reviews, and (iii) expert/stakeholder opinion.

Reporting and extension

At the start of the project a community flyer was prepared and disseminated to TS stakeholders with the assistance of the TSRA and AFMA (see Appendix 1). This was to raise awareness of the project and to inform TS local fishers of the project prior to being interviewed. These interviews were conducted via telephone using a pre-determined set of questions to establish Islander experiences with fisheries, climate induced changes and their attitudes and awareness of climate change. The results were used to inform the assessment, particularly the Adaptive Capacity element. A project fact sheet was also produced at the conclusion of the project to summarise the key project outcomes, and was developed in consultation with the AFMA, TSRA and TSSAC.

6. Results and Discussion

Climate in the Torres Strait

Observed climate

The climate in the TS region is characterised by two seasons, the wet monsoon (October to April) dominated by north-westerly winds, and the dry season (May to September) dominated by south-easterly trade winds. The region is also part of the western tropical Pacific, and influenced by large-scale ocean and atmospheric circulation patterns that affect air and sea temperatures, rainfall, currents and tropical cyclone activity.

Surface temperatures: air and sea

The average annual air temperature is 26.8 °C. December is the warmest month with 28.1 °C and August is the coolest with 25.3 °C. Since 1960, maximum, minimum and mean air temperatures have shown an increasing trend with strong inter-annual variability (Table 6) (Suppiah et al. 2010).

Table 6. Air temperature trends in Torres Strait measured at Thursday-Horn Islands between 1960 and 2009 showing warming that has accelerated since the mid-1990s.

	1960 – mid-1990s	mid-1990s – 2009
Maximum temperature (°C)	+0.32	+0.67
Minimum temperature (°C)	+0.18	+0.35
Mean temperature (°C)	+0.25	+0.51

The average sea surface temperature (SST) in the region is 28.0 °C with little variation throughout the year. The long-term average for the wet season is 28.3 °C and for the dry season is 27.4 °C. Since 1950, average annual SSTs have increased by 0.16 – 0.18 °C per decade. SST anomalies have also increased since 1980, based on the 1961-1990 average (Figure 4; Suppiah et al. 2010).

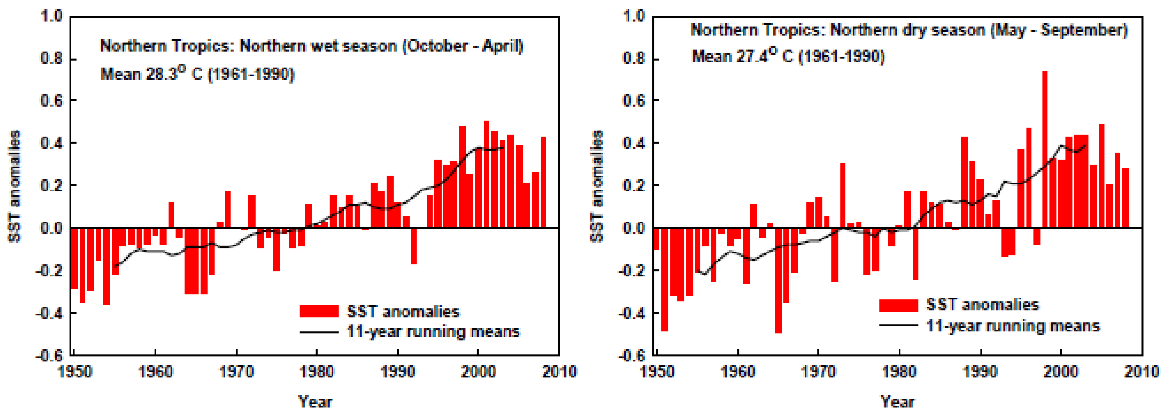

Figure 4. Sea surface temperature anomalies for the wet and dry seasons in the northern tropics (relative to the 1961 – 1990 mean). Black line shows decadal trends (Source: Australian Bureau of Meteorology).

Rainfall and River flow

The TS region has strong inter-seasonal and intra-decadal variation in rainfall influenced by the West Pacific Monsoon and ENSO, respectively (BoM and CSIRO 2011). Average annual rainfall is 1755 mm during the wet monsoon (October to April), and 90 mm during the dry season (Suppiah et al. 2010). The region experiences extreme rainfall events, particularly during the onset and active periods of the monsoon; part of a large-scale atmospheric circulation pattern. Clear evidence is now emerging for a recent acceleration in the global hydrological cycle (Helm et al. 2010).

In the Torres Strait, there is an absence of large rivers and catchments with only a few small freshwater river systems restricted to the larger continental islands (e.g. Horn, Badu and Moa; Duke et al. 2012a). These do not have large enough flows to significantly influence coastal marine habitats, even in the wet season. However, in the northern Torres Strait, marine habitats are strongly influenced by the Fly River and other large rivers along the southern Papua New Guinea coast (Duke et al. 2012a). The Fly River is the largest river in the region and flood plumes regularly influence the northern Torres Strait, transporting large quantities of sediment and nutrients to marine habitats (Gehrke et al. 2011). The influence of agricultural runoff from PNG delivered by these large river flows has been identified as a major threat to seagrass in TS (Coles et al. 2012).

El Niño –Southern Oscillation

The El Niño –Southern Oscillation (ENSO) is a major source of inter-annual climate variability in the TS region with La Niña producing cooler wet conditions and El Niño producing hot dry conditions (Lough and Hobday 2011). During typical El Niño events, the summer monsoon circulation is weaker than normal and is associated with more frequent south-easterly winds. Cloud cover is reduced, increasing radiation and elevating SST, with considerably lower rainfall than in La Niña years. During typical La Niña events, the summer monsoon circulation is stronger than normal with north-westerly winds, cloud cover and rainfall all higher than average. ENSO drives the strength of the summer monsoon circulation, and therefore influences rainfall, sea level and the risk of tropical cyclones (BoM and CSIRO 2011).

Tropical cyclones

The TS has experienced six tropical cyclones since 1906 (BoM 2008), which is a relatively small number compared with nearby areas in northeast Australia and the western Pacific. However, many more tropical cyclones have passed close enough to the TS to cause impacts (Green et al. 2010; see Figure 5). These include physical damage to marine habitats (coral reefs, seagrass meadows and mangroves) caused by strong winds, high energy waves and storm surge (Puotinen 2004, 2007). Most of the tropical cyclones that affect the TS form in the Pacific Ocean, however, recent analysis indicates that cyclones located west of TS in the Gulf of Carpentaria have the greatest influence on water levels in TS since they interact with and enhance the monsoon effect (TSRA 2011a). No significant trends in the number of tropical cyclones, or the number of intense tropical cyclones have been observed in the south Pacific Ocean since satellite measurements started in 1981 (BoM and CSIRO 2011).

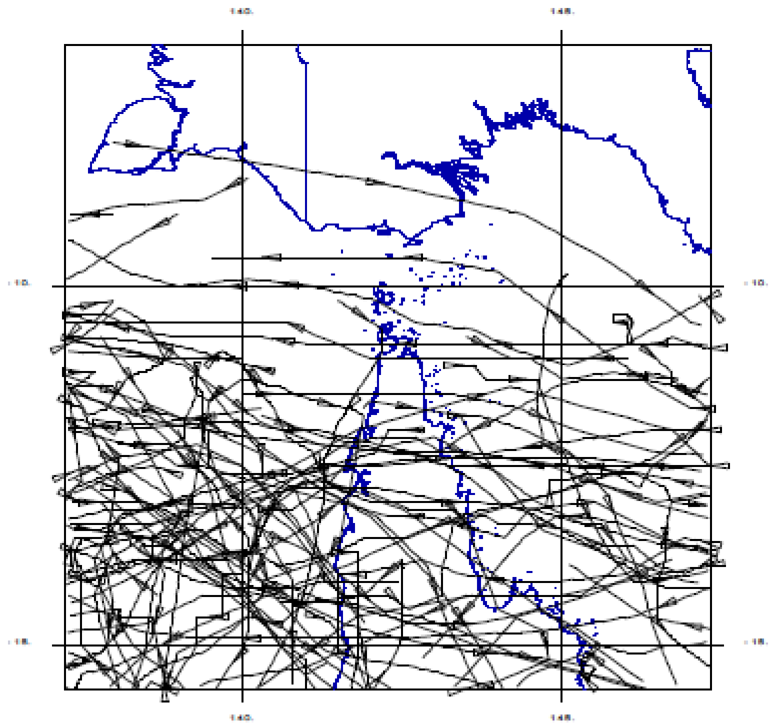

Figure 5. Tropical cyclone tracks within 500 km of Thursday Island for the 50-year period 1959/60 to 2008/09 (TSRA 2011a).

Ocean chemistry

The concentration of the main greenhouse gas, carbon dioxide (CO_2), has increased by ~40% since the late 18th century and ~30% of this extra CO_2 has been absorbed by the oceans. This increased CO_2 has decreased the pH of the tropical Pacific Ocean by 0.06 pH units, making the ocean more acidic and causing a decline in the associated aragonite saturation state (Ganachaud et al. 2011). This ocean acidification and reduced aragonite saturation state is such that calcareous organisms, such as corals, planktonic species and shell-forming organisms, may already be experiencing reduced growth rates or a weakening in their shells and skeletal structures, reducing their fitness and resistance to predation or storm damage (Bell et al. 2011a).

Sea level

The sea level has risen by about 17 cm globally since pre-industrial times and 6 cm since 1960 (Figure 6). In the TS region, sea level has been rising at ~0.6 cm per year between 1993–2010 (Suppiah et al. 2010). The rate of rise appears to be increasing due to accelerated ice melt and thermal expansion of the upper ocean and is currently ~ 2.5 cm per decade (Ganachaud et al. 2011).

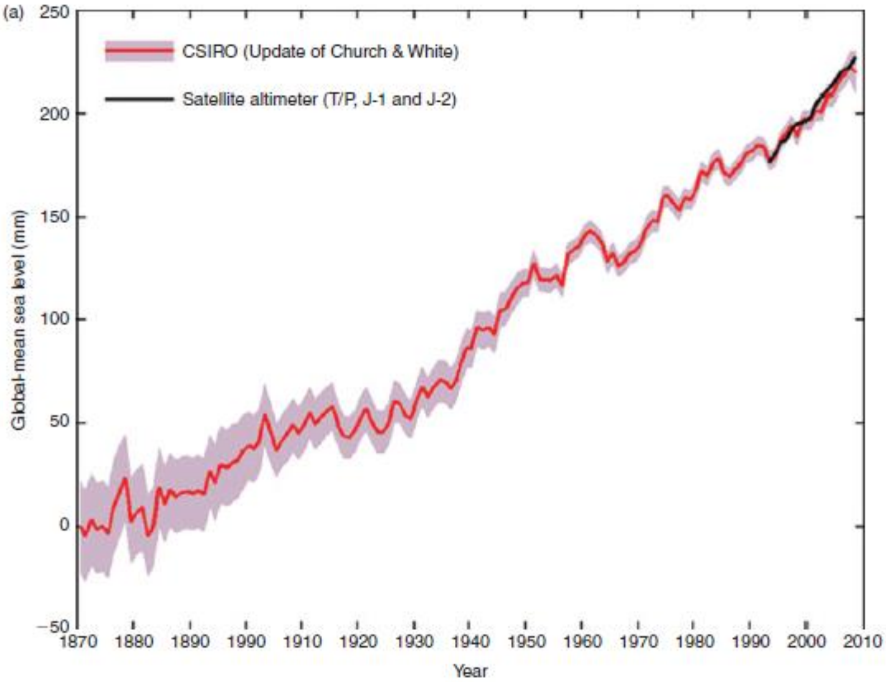

Figure 6. Global sea level 1870 – 2008 (Church and White 2006, BoM and CSIRO 2011).

Coastal island environments in the TS are often inundated by seawater due to king tides, storm surge and inter-seasonal variability, and the impacts of sea-level rise on the frequency and extent of inundation are already being observed with major flood events in 2005, 2006, 2009 and 2010 (Climate Commission 2013a). Studies of extreme seawater inundation in the TS at present show that based on a 5-year return period (equivalent to a 20% chance in any year) five communities are particularly vulnerable to inundation; Saibai, Boigu, Masig, Warraber and Iama Islands (TSRA 2011a). Future sea level rise will exacerbate this existing issue, with inundation events likely to occur more frequently, resulting in implications for coastal habitats in the TS and the fisheries they support.

Ocean stratification, upwelling and currents

The Torres Strait has a series of narrow channels that connect two entirely different oceanic tidal regimes making currents extremely complex, and tidal heights frequently deviate significantly from those predicted. Very strong tidal streams occur throughout the TS region and rates of up to 8 knots may be experienced (Waterhouse et al. 2013). Larger-scale climate trends have been observed in the western Pacific region that influences ocean currents, salinity, stratification, upwelling and SST patterns; these are expected to also influence the TS. The two longest existing time-series of oceanographic data in the tropical Pacific indicate that there has been a decrease in nutrient supply, consistent with increased stratification. The observed warming of SSTs in the Pacific region in combination with observed salinity decreases has resulted in increased upper ocean stratification, which limits the vertical exchange of water and has major implications for nutrient supply to the food webs that support fisheries (BoM and CSIRO 2011, Ganachaud et al. 2011).

Projected climate

The climate projections presented here are based on the IPCC-AR4 global climate model outputs recently downscaled for the TS and PNG (Suppiah et al. 2010, BoM and CSIRO 2011, Lough et al. 2011, Ganachaud et al. 2011) for 2030 and 2070 (or the nearest available projection years) for the B1, A2 and A1FI IPCC emissions scenarios (IPCC 2007). The projections don't show significant divergence by 2030 under the different SRES emissions scenarios but do by 2070. The results show that changes in sea surface temperatures, rainfall, sea level, ocean chemistry and salinity are expected to occur, which are likely to alter biological productivity of marine environments. Although changes in *average* climate conditions are expected to cause major impacts on the TS marine environment, changes to the intensity and frequency of climate *extremes* such as tropical cyclones and floods are likely to be even more significant, as witnessed during the 2012/13 Austral summer (Climate Commission 2013b).

Surface temperatures: air and sea

The projections for temperature in Torres Strait are for surface temperatures, which includes both air and sea. Surface (air and sea) temperatures are expected to continue warming this century, affecting maximum, minimum and mean temperatures (Table 7).

Table 7. Projected increases in surface temperatures for the Torres Strait region (Suppiah et al. 2010).

	2030 (A2 & A1FI)	2070 (A2)	2070 (A1FI)
Maximum temperature (°C)	+0.55 to +1.38	+1.5 to +2.72	+1.74 to +3.31
Minimum temperature (°C)	+0.55 to +1.31	+1.52 to +2.6	+1.75 to +3.16
Mean temperature (°C)	+0.62 to +1.27	+1.65 to +2.56	+1.94 to +3.01

Rainfall and River flow

Projected rainfall changes are more variable and uncertain, with both increases and decreases expected (Table 8). Projected increases will amplify the seasonal cycle, with increases in wet season months relatively larger than for dry season months (e.g. June to August), and extreme rainfall events projected to occur more frequently (BoM and CSIRO 2011).

Table 8. Projected changes in rainfall for the TS region (Suppiah et al. 2010)

	2030 (A2)	2030 (A1FI)	2070 (A2)	2070 (A1FI)
Annual average rainfall (%)	+1.24	+1.46	+3.21	+3.78
Range of rainfall change (%)	-2.97 to + 5.33	-3.49 to +6.27	-7.57 to +14.09	-8.9 to +16.57

Predicting river flow changes is largely based on rainfall projections, and the highly seasonal and variable rainfall regime of tropical regions in Australia also results in highly variable river flows (Lough and Hobday 2011). More extreme rainfall in TS will most likely result in more extreme flood events that will influence coastal habitats and fisheries.

El Niño –Southern Oscillation

The current generation of global climate models are not good at representing the variability associated with ENSO, and show little consensus on the simulation of likely changes in the frequency, intensity and patterns of future El Niño and La Niña events (BoM and CSIRO 2011). Therefore, all that can be said about ENSO in the future is that it will continue to be a source of inter-decadal variability in the region (Lough and Hobday 2011).

Tropical cyclones

There is large uncertainty about how tropical cyclones will change under a warmer climate. However, a review of modelled tropical cyclone characteristics predict a likely increase in the maximum intensity of tropical cyclones as the mean global temperature rises, of between +3% to +21% by 2100, or between +2% and +11% if expressed as maximum wind speed (Knutson et al. 2010). The consensus from many advanced modelling studies is that the frequency of tropical cyclones will either stay the same or decrease, ranging from -6% to -34% globally by 2100 (Knutson et al. 2010), and these projected patterns are largely expected to play out in Torres Strait (TSRA 2011a). Ultimately, tropical cyclone numbers are projected to decline in the southwest Pacific (BoM and CSIRO 2011) in the future but those that do occur are likely to be more intense (Lough et al. 2011).

Ocean chemistry

Increases in atmospheric CO_2 are projected to lead to substantial additional acidification of the ocean, reducing the pH of the ocean by 0.2–0.3 units (under B1 and A2) by 2100. At such rates of change, aragonite saturation levels in the tropical Pacific Ocean are expected to fall below 3.5 by 2030 (under A2), potentially jeopardising the growth of corals, shellfish and some plankton (BoM and CSIRO 2011). Projections for the mid-term are that ocean pH will decline by 0.1 units by 2035 under the A2 IPCC emission scenario (Ganachaud et al. 2011). The aragonite saturation level is expected to decrease to 2.4 in 2100 (under A2), with potentially severe consequences for the formation of coral reef habitats and many reef organisms (Ganachaud et al. 2011, BoM and CSIRO 2011).

Sea level

As a consequence of continued ice melt, and thermal expansion of the upper ocean layers, the rate of sea-level rise is expected to accelerate. The projections from IPCC–AR4, that sea level will rise between 18 cm (under B1) to 51 cm (under A2) by 2100, are now considered to be conservative because they do not include the effects of increased solid ice flow (Ganachaud et al. 2011). More recent estimates using the CMIP3 models, simulate a sea-level rise of 5 – 15 cm by 2030 and 20 – 60 cm by 2090 (under A2) (BoM and CSIRO 2011). Even the lower estimates would mean a profound change for coastal habitats.

Under this projected future climate, the existing five communities that are already affected by seawater inundation – Saibai, Boigu, Masig, Warraber and Iama – will be further impacted by sea level rise. By 2100, with a projected 20 – 60 cm sea level rise and increased tropical cyclone intensity, a total of 13 islands in TS will be affected beyond the 5-year return period (TSRA 2011a). This has serious implications for coastal habitats that support fisheries, such as mangroves and estuaries.

Ocean stratification, upwelling and currents

Projected alterations in the speed and direction of some major Pacific Ocean currents – for example, a progressive weakening of the South Equatorial Current (SEC) to 26% by 2100 under A2 (Ganachaud et al. 2011) – will have potential implications for currents, stratification and productivity in the TS region. Changes in the highly variable and complex tidal regime in TS will have implications for species life cycles, and larval and nutrient exchange in the region. The projected increased stratification of the upper layers of the ocean is a major factor influencing the supply of nutrients from the deep ocean to the surface zone and will impact on primary productivity and ultimately fisheries in the region (BoM and CSIRO 2011).

Ocean salinity and Solar radiation

Other ocean climate variables that are expected to influence fisheries in TS and supporting habitats are ocean salinity and solar radiation. Salinity can have direct effects on fish species and life cycle stages, while solar radiation is important for the growth and maintenance of seagrass meadows, a critical habitat for many fisheries species in TS.

A reduction in salinity, or freshening, has been observed over recent decades in the western tropical Pacific Ocean (Cravatte et al. 2009). Sea surface salinity is projected to continue to decrease by 0.1 psu (on the practical salinity scale) by 2030, and 0.34 psu by 2090 under the A2 IPCC scenario (BoM and CSIRO 2011).

Projected changes in solar radiation are for decreases, with the projected annual change for 2030 being -0.31% under the A2 emission scenario and -0.43% under the A1FI scenario. Larger decreases are projected for 2070, -0.79% for the A2 emission scenario and -1.10% for the A1FI scenario. Seasonal changes are also dominated by decreases (Suppiah et al. 2010).

Fisheries habitats in the Torres Strait

Located on one of the world's most extensive continental shelves, the Torres Strait has been recognised for its ecological complexity and biodiversity. The region has significant tropical marine ecosystems and populations of important and vulnerable marine species, including the most important dugong habitat in the world (Marsh et al. 2004). The region has a multitude of habitats including coral reefs, mangroves and extensive seagrass meadows. The clear waters and coral reefs to the east provide rich fishing grounds. Extensive seagrass beds in the west and north support the largest population of dugong globally, and the region is a critical feeding and nesting area for green turtles while other marine turtle species also use the area. Both dugongs and turtles are important species for traditional hunting in the region.

Strong physical drivers in Torres Strait – large tidal ranges, strong currents and turbidity – have influenced the formation and character of the ~1,200 coral reefs, with an east-west elongation of reefs. Coral reefs dominate in the clear warm waters on the eastern shelf and form the northern extent of the GBR system, while seagrass habitats dominate in the more turbid and sediment-laden conditions in the west that are influenced by a number of small coastal rivers flowing into the Gulf of Papua (Figures 7 and 8) (Haywood et al. 2007). The large sediment discharges from the Fly River, PNG affect an area of reefs in the northern TS (Wolanski et al. 2013), resulting in reefs with muddy carbonate sediments (Sweatman and Berkelmans 2012) while sediments in the south and west are mainly reef-derived with > 80% carbonates. The geological structures of reefs, particularly in the more sediment-rich waters of the western TS, include extensive reef tops and reef flats covered in soft sediments and seagrasses as well as growing reef edges and slopes that have more hard substrates and corals (Sweatman and Berkelmans 2012).

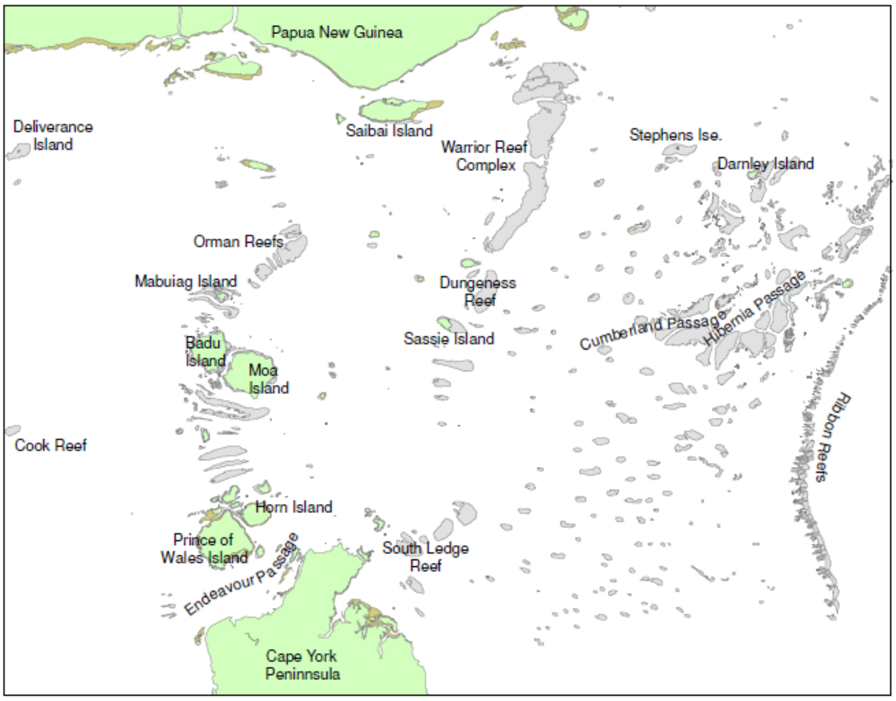

Figure 7. Spatial distribution of coral reefs (grey) in TS region (data source: AUSLIG; Haywood et al. 2007).

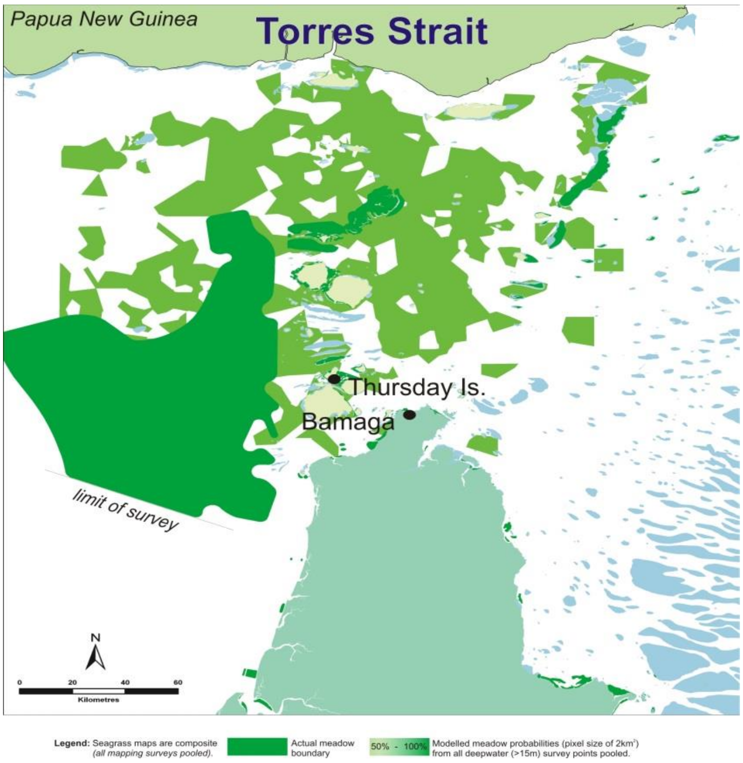

Figure 8. Spatial distribution of seagrasses in the TS region showing actual monitored meadow boundary (dark green) and modelled meadow boundary (light green) (McKenzie et al. 2010).

Coral cover is higher in the eastern TS, supporting a higher diversity and abundance of reef fish and sea cucumber (Haywood et al. 2007). A total of 323 fish species have been recorded in the region (Haywood et al. 2007, Osborne et al. 2013), and fish abundance is greatest on the eastern reefs. Lutjanids (snappers), Serranids (groupers) and Zanclids (Moorish idol) dominate on the Ribbon Reefs, and Caesonids (fusiliers) dominate in the central Warrior Reefs (Haywood et al. 2007). For both corals and reef fishes, the communities from central reefs differ from those in eastern reefs, reflecting a gradient in turbidity and wave exposure (Osborne et al. 2013).

Mean live coral cover is generally <30% and is highest on the eastern Ribbon Reefs (up to 47%) and very low on western reefs based on surveys conducted by CSIRO from 1994 – 2006 (Haywood et al. 2007). Recent surveys recorded 279 species of coral belonging to 60 genera (Osborne et al. 2013). Branching and digitate coral growth forms are the most commonly recorded in the region, with massive corals locally dominant on the Warrior Reefs (Haywood et al. 2007). Species richness varies along an east-west gradient, with the Acroporidae and Pocilloporidae coral families having higher richness on the eastern reefs and Poritidae, Fungiidae and Mussidae having higher richness on central reefs (Osborne et al. 2013).

Seagrasses cover an estimated 17,206 km^2 in the TS region and are found predominantly in the western and central (Warrior Reef) parts of the TS (McKenzie et al. 2010). The northern Warrior Reefs have a greater diversity of seagrasses (*Halodule, Thalassia*, *Thalassodendron* and *Cymodocea)*, while the south tends to be dominated by a single species of *Thalassia*. In the west, seagrass communities are more diverse to the north (*Halodule, Thalassia and Syringodium)*, around the Orman Reefs (Haywood et al. 2007). Seagrass-Watch monitoring data[1] have documented relatively diverse communities of seagrasses, with 13 species recorded in estuaries, reef flats and subtidal areas adjacent to continental islands (McKenzie et al. 2010). Seagrass meadows in reef and coastal habitats are the most diverse.

Coastal wetlands or mangrove forests are also found on low-lying alluvial islands in TS, and recent surveys have documented 31,390 ha of wetlands in TS, with 83% being tidally influenced mangrove forests found on most continental islands but not coral cays. The islands with the greatest area of mangroves are Boigu, Saibai and Turnagain in the north, and Moa in central TS (Poiner et al. 1997, Duke et al. 2012a). The TS region has high mangrove biodiversity with two endemic species documented in recent surveys (Duke et al. 2012b), which is not surprising since it is adjacent to PNG, the country with highest mangrove diversity globally (Ellison 2009). Mangrove communities are for the most part unimpacted and in very good condition due to low levels of human disturbance.

Climate change implications for TS habitats

The natural ecosystems that TS fisheries rely on have evolved to operate within a specific range of prevailing local climatic conditions – the coping range (e.g. Jones and Mearns 2005, Hoegh-Guldberg et al. 2007). Any changes in these specific climate conditions will influence the habitats that support fisheries as well as the resources themselves – stocks, species, populations and communities. Therefore understanding how climate change is likely to influence key habitats – coral reefs, seagrass meadows, mangroves and estuaries – is important when seeking to assess how these resources are likely to respond under future climate change. The information presented in this section draws on extensive assessments of vulnerability of tropical Pacific habitats (Bell et al. 2011a)

[1] http://seagrasswatch.org/Torres_strait_archived_data.html

and GBR habitats (Johnson and Marshall 2007) to climate change, and their known sensitivities to climate drivers.

These habitats will be exposed to a range of changing climate variables, and combined with their known sensitivities will provide insights into the potential impacts on these habitats and the fisheries they support. Tropical fisheries that target species dependent on habitats such as coral reefs, mangroves and seagrass meadows (e.g. tropical rock lobster, prawns, mud crabs, coral trout, sea cucumber, turtle and dugong), are likely to change as a result of climate related impacts on these habitats (Pratchett et al. 2009, Badjeck et al. 2010, Donnelly 2011, Pratchett et al. 2011, Bell et al. 2013).

Coastal wetlands and estuaries

The TS region has only limited estuarine area due to the few islands that have small rivers flowing into the ocean. Estuaries form a transition zone between land and ocean environments and are subject to both marine influences, such as tides, waves, and the influx of salt water; and riverine influences, such as flows of fresh water and sediment. These two influences provide high levels of nutrients in the water column and sediment, making estuaries among the most dynamic and productive natural habitats in the world. The potential impacts of climate change, and ultimately the vulnerability of estuaries, will depend on the dominant habitat, since they can be comprised of mangroves, shallow seagrass meadows and intertidal flats.

Estuaries and coastal bays may become warmer and more eutrophic in the future, offering less suitable habitat for key fisheries species. In some locations where seagrass and mangroves are the main components, there may be a reduced area of available habitat. Estuaries dominated by seagrasses, adjacent to rivers and exposed to increased terrestrial runoff, are likely to be more vulnerable to future rainfall changes, and physical disturbance from cyclones and storms. Estuaries dominated by mangrove habitats will be vulnerable to more intense storms and cyclones, decreasing rainfall and river flow, and sea-level rise with high sediment accumulation rates allowing some adaptation to rising sea levels (Waycott et al. 2011). More details on the specific impacts and vulnerability of mangroves and seagrass meadows to future climate change are provided below.

Coastal wetlands or mangrove forests provide nursery areas for many commonly harvested fish and invertebrates, and feeding grounds for many species of adult demersal fish and invertebrates targeted by fisheries (e.g. prawns, mud crab, emperors and snappers)(Waycott et al. 2011). Their location on the coastal fringe of low-lying alluvial islands makes them highly vulnerable to sea-level rise that will exacerbate extreme high tide flooding, storm surge and shoreline erosion, as well as more intense storms and cyclones (Duke et al. 2012a). The effects of current seawater inundation in the TS identified five islands that are particularly vulnerable to inundation, two of which have significant areas of mangroves: Saibai and Boigu (TSRA 2011a). This will be further exacerbated by sea-level rise, as will storm surge associated with increasing storm severity. More intense storms will further impact mangrove forests through the physical processes of erosion, burial, wind throw and lightning strikes. Projected changes in rainfall, particularly the amplification of the seasonal cycle has implications for mangrove growth depending on whether the rainfall changes coincide with the peak mangrove growing season (Duke et al. 2012a).

Mangroves have the ability to adapt to projected sea-level rise, if sediment accretion is fast enough and landward barriers, such as roads and developments, don’t constrain migration. Higher atmospheric CO_2 concentrations and greater rainfall will enhance this potential to expanding landward by increasing mangrove productivity (Steffen et al. 2009, Waycott et al. 2011). Ultimately, if mangroves cannot keep pace with sea-level rise (or their landward migration is inhibited) the area of available habitat will be reduced, with declines becoming greater over time.

Under the B1 and A1FI SRES emissions scenarios in 2030 and 2070, mangroves are projected to be highly vulnerable to sea-level rise (depending on rate of change), and moderately vulnerable to increasing cyclone intensity and declining rainfall that will influence growth rates (Table 9). Significant losses of available mangrove habitat are possible if they cannot adapt to sea-level rise, as has been seen in southern PNG with the gradual retreat of mangroves due to rising sea level (Ellison 1997).

Seagrass meadows

Seagrasses provide nursery areas for many commonly harvested fish and invertebrates (e.g. prawns, sea cucumbers, mud crab and emperors), and feeding grounds for many species of adult demersal fish targeted by fisheries (e.g. coral reef finfish and black jew) as well as green turtles and dugong. Seagrasses (and intertidal flats) are also permanent habitats for a wide range of invertebrates, such as sea cucumbers (Waycott et al. 2011).

Seagrasses face an array of pressures as human populations increase and the potential effects of climate change, such as increased storm activity, come into play (Waycott and McKenzie 2010, Grech and Coles 2010). Changes in nutrient dynamics and light penetration in coastal waters due to flood events – as is possible from the Fly River to the north – have been shown to impact on seagrass growth and reproduction (McKenzie et al. 2006, Orth et al. 2006). Chronic elevated nutrients have been reported to lower the availability of light to seagrasses due to increased growth of algae and epiphytes on the plants (Burkholder et al. 2007). Chronic and pulsed increases in suspended sediments that increase turbidity can also reduce light and result in reduced productivity and potentially seagrass loss (Waycott and McKenzie 2010). Importantly for the southern Warrior Reefs, large and slow-growing species, such as Thalassia spp. that dominate that area, tolerate prolonged periods of low light but can be slow to recover (Waycott et al. 2011), while the high seagrass diversity of the western TS means there will be a range of responses to low light.

The dynamics of tropical seagrasses are heavily influenced by weather patterns, including flood and cyclone events that have the potential to physically damage seagrass meadows, particularly in shallow locations (Waycott et al. 2011). For example, in the GBR, the extreme 2010/11 wet season that had severe flooding and tropical cyclone Yasi resulted in a 98% loss of intertidal seagrass area in the affected zone (McKenzie et al. 2012), which exacerbated the condition of seagrass meadows that were already reported to be in a state of decline (McKenzie et al 2010). Although the status of estuarine seagrasses in the TS is unknown (due to data deficiencies) recent analysis of coastal and reef seagrass meadow data have documented stable communities that are increasing in cover (Coles et al. 2012), and may therefore have some resilience to future projections of changing rainfall patterns and more severe cyclones and storms.

Seagrasses are expected to be vulnerable to increasing SST, decreased solar radiation, changing rainfall patterns, and increases in cyclone intensity (Table 9). Collectively, the impacts from climate change are projected to reduce seagrass area, with declines expected under both the B1 and A1FI SRES scenarios in the medium- (2030) and long-term (2070) (Waycott et al. 2011). There will therefore be less suitable habitat for key fisheries species, as well as reduced food resources for dugong and green turtles, which has been shown to have significant impacts on dugong health and populations in the GBR (Sobtzick et al. 2012).

Coral Reefs

Coral reefs are an important habitat in TS found mainly in the east of the region that support hundreds of fish and invertebrate species. Coral reefs support important fisheries for demersal fish (e.g. coral trout and emperors), some near shore pelagic fish (e.g. Spanish mackerel), and invertebrates targeted for livelihoods and food (e.g. tropical rock lobster and pearl shell). Maintaining the structural complexity of reef frameworks is vitally important to the continuation of these fisheries.

Coral reefs are most vulnerable to increasing SST and ocean acidification (Table 9), due to the sensitivity of corals themselves. Corals are particularly sensitivity to thermal stress, with thermal bleaching impacts documented for most reefs in Australia and around the world as a result of extended periods of above average SST (Wilkinson et al. 2008). The TS is dominated by branching and digitate corals, growth forms that are susceptible to thermal stress, and the first bleaching event was recorded in the TS in 2010[2]. Recent coral reef surveys recorded a reduced abundance of temperature-sensitive corals in the genus *Seriatopora*, which could be the result of thermal bleaching in recent years (Osborne et al. 2013). The projected increase in SST in TS of +1.65 to +3.01 °C by 2070 will result in further bleaching events that can undermine the structure and function of coral reef habitats. Effects may be evident as early as 2030, when mean SST is projected to be +0.62 to +1.27 °C warmer and the maximum even greater, temperatures known to cause coral bleaching (R. Berkelmans pers. comm.).

Ocean acidification is expected to increasingly slow the rate of reef accretion and enhance erosion over the coming decades (Silverman et al. 2009). Reductions in calcification rates at lower ocean pH suggests that corals, and the reefs they build, are highly vulnerable to ocean acidification, and that increases in atmospheric CO_2 above 450 ppm are likely to result in net erosion of coral reefs throughout the tropics (Bell et al. 2013). Studies in shallow CO_2 seeps in PNG (Fabricius et al. 2011) have observed reductions in coral diversity, recruitment and abundance of framework building corals, and shifts in competitive interactions between taxa as pH declines from 8.1 to 7.8 (the change expected if atmospheric CO_2 concentrations increase from 390 to 750 ppm by 2100). However, coral cover remained constant between pH 8.1 and ~7.8, as massive *Porites* corals dominated, despite low rates of calcification, and reef development ceased below pH 7.7.

Coral reefs in TS are expected to be moderately vulnerable to increases in cyclone and storm intensity, and those in the northeast to be highly vulnerable to changes in rainfall and terrestrial inputs from more intense floods from the Fly River (Table 9). Coral reefs will have low vulnerability to sea-level rise if the conservative projections of +20 to 60 cm by 2070 are realised but will have moderate vulnerability if glaciers and ice caps melt rapidly. An assessment of the implications of sea-level rise for coral reefs using historic reef records found that reef development was inhibited on the reef crest (+3 m) with a 2–3 m sea-level rise during the last interglacial period (Blanchon et al. 2009), which is a threshold that may be exceeded if the Antarctic and Greenland ice sheets melt rapidly.

[2] http://www.tsra.gov.au/the-tsra

The location of coral reefs in the TS will have a strong influence on their vulnerability to changes in ocean circulation and productivity; some will receive fewer nutrients and recruits, whereas others will receive more. Isolated reefs with limited connectivity to receive larvae are more likely to be vulnerable to climate change affects. This is supported by simulations by Munday et al. (2009) who showed that climate change is likely to to reduce population connectivity in coral reef ecosystems by reducing average larval dispersal distance, with naturally fragmented habitats likely to be at higher risk.

The range of potential impacts resulting from future climate change means that coral reef habitats are predicted to change, with coral cover expected to decline under both the B1 and A1FI SRES scenarios in the medium- (2030) and long-term (2070), and macroalgae (fleshy and turf algae) projected to become more dominant (Hoegh-Guldberg et al. 2011). Similarly, coral diversity is projected to decline with ocean acidification and increasing SST (Fabricius et al. 2011), resulting in simpler reef habitats. This will have implications for reef-dependent species, such as finfish and tropical rock lobster, as long-term studies have detected declines in reef fishery catches consistent with lagged impacts of habitat disturbance (Pistorius and Taylor 2009).

Summary of habitat vulnerability and changes

The different habitats of the TS region are predicted to show variable vulnerability depending on the different climate drivers that are projected to change under future climate change (Table 9). These vulnerabilities reflect the sensitivity of the species and communities that make up these habitats. How these vulnerabilities will change habitats is discussed earlier in this section, and the implications for key fisheries are discussed in the following sections.

Table 9. Vulnerability of TS habitats to projected changes in surface and ocean climate under the A2 (high) emissions scenario for 2070. Predictions for the A2 emissions scenario in 2030 follow the same trajectory with only slightly lower magnitudes of vulnerability. Adapted from: Bell et al. 2011a.

	Sea surface temperature	Solar radiation	Ocean chemistry	Cyclones and storms	Rainfall patterns/ riverflow	Sea level*	Productivity & circulation
Coastal wetlands	very low	low	very low	moderate	moderate	very high	moderate
Seagrasses	high	high	very low	high	moderate	moderate	moderate
Coral reefs	very high	low	very high	high	high	low	moderate

** Possibly underestimates vulnerability due to the significant uncertainty regarding the rate of sea-level rise.*

Key fishery species in the Torres Strait

Prawns (*Penaeus esculentus, Metapenaeus endeavouri, Melicertus longistylus*)

Fishery characteristics

The Torres Strait prawn fishery is an otter trawl fishery that operates within the TSPZ and in a small area to the south. The majority of fishing is concentrated in an area covering approximately 20% of the TSPZ (Turnbull and Rose 2007). Licence holders within the fishery belong exclusively to the non-traditional Transferable Vessel Holder (TVH) sector, and although 61 licences were issued in the past two years (2010 and 2011) only 21 and 17 respectively have been active. Most of the fleet operate in the fishery on a part-time basis as they also hold endorsements to fish in the Queensland east Coast Trawl fishery and/or the Northern Prawn fishery (Gulf of Carpentaria). The catch is dominated by the Brown tiger prawn (*Penaeus esculentus*) and the Blue endeavour prawn (*Metapenaeus endeavouri*), with a smaller quantity of Redspot king prawn (*Melicertus longistylus*) also caught essentially as bycatch (Figure 9). Total catch levels were 488 t and 293 t for 2010 and 2011 respectively, with tiger prawns comprising approximately 69 % and endeavour prawn approximately 23 % over this period. Both catch and effort have been decreasing over the past 10 years and this is likely to due to the decreasing profitability in this fishery over the corresponding period. The drivers of this trend have been shown to be increasing fuel prices and decreasing prawn prices (Skirtun and Vieira 2012). Product is sold domestically and internationally to USA, Japanese and European markets (Woodhams et al. 2012).

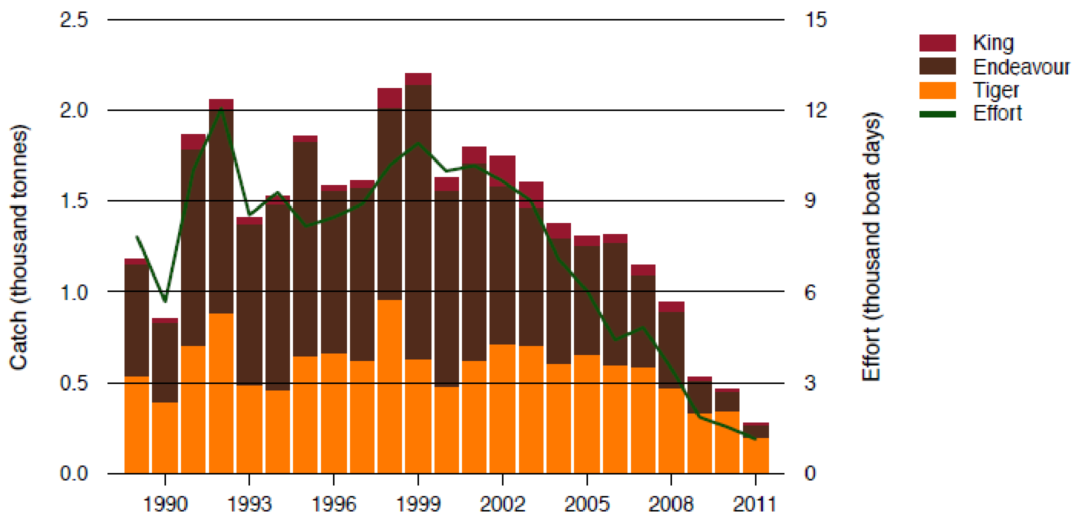

Figure 9. Catch and effort of the three prawn species taken in the Torres Strait prawn fishery from 1989 to 2011. (Source: Woodhams et al. 2012).

Management of the Torres Strait prawn fishery is by input controls, including a total allowable effort quota with individual transferable effort units, limited entry using licensing, restrictions on gear as well as vessel lengths, and extensive spatial and temporal closures. These closures have been implemented for a number of reasons including the protection of undersized tiger prawns, protection of pearl oyster shell beds and protection of breeding turtle populations. The closures effectively exclude the western half of the TSPZ from trawling (Woodhams et al. 2012).

Relative abundance data have been used for Torres Strait tiger prawns and endeavour prawns since 1980 in stock assessments, management strategy evaluations and fishery assessments (O'Neill and Turnbull 2006, Turnbull et al. 2009). Due to the very low level of fishing effort in recent years, annual catches of both tiger and endeavour prawns are well below historic catch levels and the estimated Maximum Sustainable Yield (MSY) for each species (O'Neill and Turnbull 2006, Turnbull et al. 2009). Since 2000, there has been an increase in tiger prawn CPUE and this is likely to be due to an increasing shift in targeting of tiger prawns in preference to endeavour prawns as well as higher abundance of tiger prawns. This is supported by stock assessments conducted in 2004 and 2006 (Robins and Turnbull in review).

Life cycles

Brown tiger prawn and Blue endeavour prawn

The life cycle of the two major prawn species taken in the Torres Strait are virtually identical and so are treated here together, unless otherwise noted. Both species are endemic to northern Australia and have a typical type-3 penaeid prawn life cycle (Dall et al. 1990). Adult prawns spawn in coastal waters usually less than 50 m in depth. Both species spawn throughout the year in the Torres Strait with the main source of recruits coming from August and October (i.e. winter/spring) spawning and a second peak in summer (January to March) that contributes a second (smaller) pulse of recruits (Buckworth 1985). The main spawning cohort recruits to the fishery during February–March.

Pelagic larvae of brown tiger prawn occur in high salinity water (i.e. 30 to 35 ppt; Rothlisberg and Jackson 1987). After approximately three weeks, prawn–like post larvae generally settle in estuarine and nearshore seagrass and algal nursery grounds for which they have a strong association (Young and Carpenter 1977, Young 1978, Coles and Lee Long 1985, Staples et al. 1985, Coles et al. 1987, Loneragan et al. 1994, O'Brien 1994). The juveniles feed and grow in the nursery grounds for approximately two months and then migrate back to adjacent deeper water (Figure 10). Juvenile tiger prawns are found on the tops of coral reef platforms, where they remain until they migrate into inter-reef areas as sub-adults (Robins and Turnbull in review). Both species become sexually mature at about six months and tend to move only relatively short distances (30 - 60 km) (Somers and Kirkwood 1984, Watson and Turnbull 1995). Because of this limited movement, stocks of both species in the Torres Strait are considered to be separate from other adjacent fisheries in northern Queensland and the Gulf of Carpentaria. Adults of the brown tiger are known to prefer habitats with coarse, sandy sediments (Somers 1987, Somers et al. 1987).

Tiger prawns eat a variety of prey items including bivalves, gastropods, ophiuroids, crustaceans and polychaetes (Wassenberg and Hill 1987) and are eaten by a variety of predatory fish.

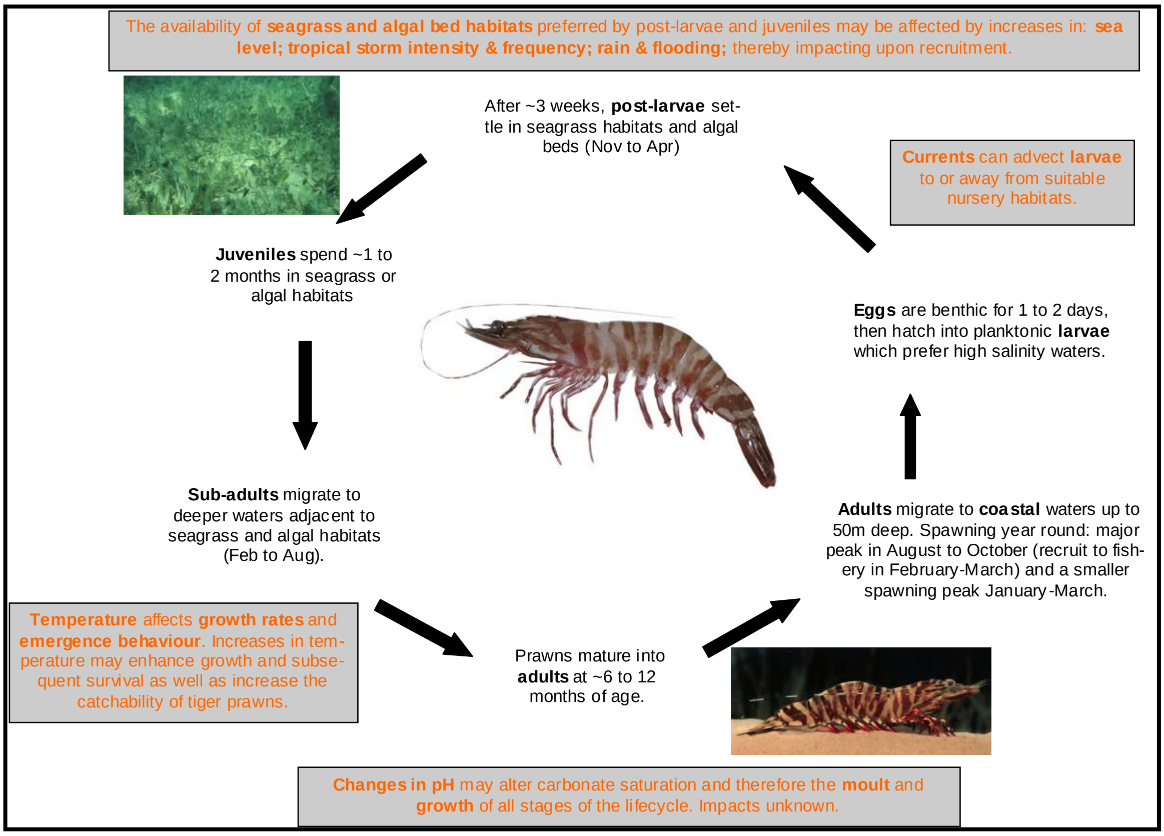

Figure 10. Generalised life cycle diagram for the brown tiger prawn (*Penaeus esculentus*) and the Blue endeavour prawn (*Metapenaeus endeavouri*). Adapted from: Robins and Turnbull (in review).

Red spot king prawn

Red spot king prawns are the least researched of the main commercial penaeid species of northern Australia and so reliable data about their biology and ecology are limited (Robins in review). The red spot king prawn also has a type-3 penaeid prawn life cycle (Dall et al. 1990), however they differ in that they are not associated with estuarine or coastal environments. Adults are sedentary and live in inter-reef and lagoon areas on coralline sandy sediments up to 60 m deep. They have an extended spawning season (May to October) with peak spawning thought to occur between July and August (Courtney and Dredge 1988). They live for less than two years and their life cycle is completed within 12 months (Figure 11).

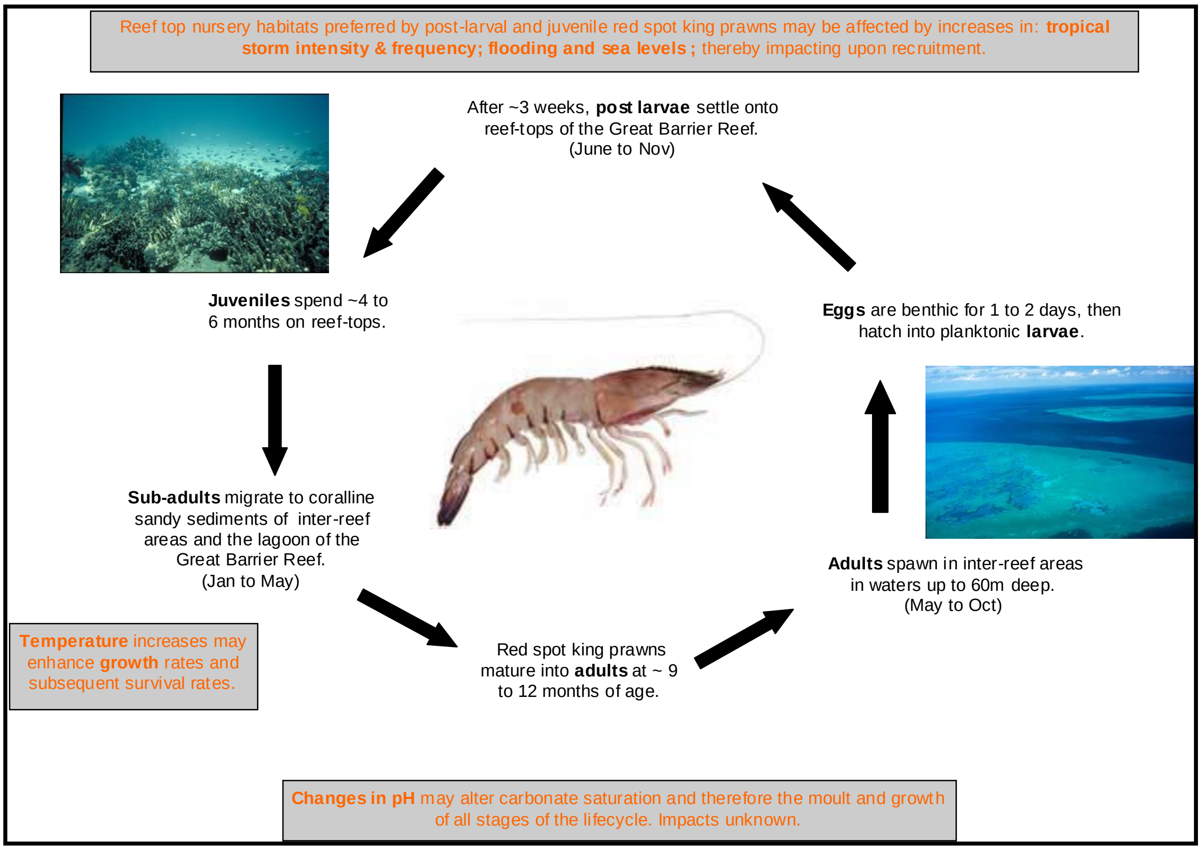

Figure 11. Generalised life cycle diagram for the red spot king prawn (*Melicertus longistylus*). Adapted from: Robins (in review).

Climate sensitivity

Brown tiger and Blue endeavour prawns

Laboratory studies have found that juvenile brown tiger prawns are relatively euryhaline (i.e. able to tolerate a wide range of salinities) but are less tolerant of wide ranges in sea temperature, which can impact on growth rates, survival and distribution (O'Brien 1994, Robins and Turnbull in review). Fisheries catches of both tiger prawns and endeavour prawns have been shown to be positively related to river flow (rainfall) and the Southern Oscillation Index (SOI) suggesting that increased catches occur when the SOI is positive (indicative of La Nina events and increased rainfall) (Meynecke and Lee 2011, Vance et al. 1985). Anecdotal reports from fishers operating in the Torres Strait Prawn fishery suggest that a dry preceding year favours tiger prawn recruitment while a wet preceding year favours endeavour prawn recruitment (Robins and Turnbull in review).

Given the strong association of brown tiger and blue endeavour prawns with seagrass and algal beds as nursery habitats, any impact on the abundance, distribution and quality of these habitats will impact growth and survival of these species. A Western Australian study showed that recruitment and survival of tiger prawns can be impacted by cyclones, with the effect depending on timing (Penn and Caputi 1986). When cyclones and associated rainfall occurred early in the wet season, reduced salinity affected nearshore juvenile habitats and resulted in reduced recruitment. Cyclones that occurred later in the wet season caused increased water turbidity which in turn was the probable cause of reduced predation of sub-adult and adult tiger prawns that had moved away from shallow nursery habitats. Both species also prefer sandy substrate rather than muddy so changes in substrate type may also influence their distribution (Somers 1987).

Water temperature is thought to be a major factor restricting the distribution of the brown tiger prawn (*P. esculentus*) in Australia (O'Brien 1994). The Torres Strait is near the northern limit of the Australian range of both brown tiger prawn and blue endeavour prawn and so increases in temperature may compromise growth and survival and in the longer term may result in a southerly contraction of their range. Vance et al. (1985) found a significant negative correlation between wet season temperature and annual prawn catch in the Karumba region (Gulf of Carpentaria), where the water temperature regularly exceeds 30 °C. Temperature has also been found to influence the behaviour of blue endeavour prawns. This species spends daylight hours within the substrate and generally emerges during dusk and until dawn when they bury themselves again. Park and Loneragan (1999) found that at elevated sea temperatures (32 °C) activity was reduced with some *M. endeavouri* remaining emerged for much less time and starting to bury themselves shortly after midnight. Such behaviour would reduce their catchability.

Red spot king prawn

Very little is documented about the sensitivity of red spot king prawns to environmental change. As juveniles this species remains on reef tops for four to six months thereby exposing them to the impacts of the cyclone season i.e. January to April, and Queensland-based trawler fishers have expressed concern that the recruitment may be negatively impacted by cyclones (Morison and Pears 2012). Given the preference of red spot king prawns for coral reef habitats, there may be negative impacts on their growth and survival in the face of habitat changes such as localised coral loss.

All prawns will be exposed to changes in ocean pH and any effect on calcium carbonate formation and moulting are highly uncertain. An extended spawning season in all Torres Strait prawn species may make them more resilient to changes in some environmental cues, such as water temperature.

Tropical rock lobster (*Panulirus ornatus*)

Fishery characteristics

The tropical rock lobster fishery is the most important commercial fishery to Torres Strait Islanders; a single species fishery targeting the ornate lobster, *Panulirus ornatus*. The fishery is dive-based (hookah or freediving) with commercial collection by hand, nooses (snares), or in some cases using hand spears. Divers work around coral reefs in depths up to 20 m and operate almost exclusively during daylight hours (Woodhams et al. 2012, DEEDI 2011). There is a small domestic market for tropical rock lobsters but most are exported overseas to mainland China via Hong Kong (Pitcher et al. 2005). The major product form is frozen tails, but there is also a live component (Woodhams et al. 2012, DEEDI, 2011).

The Torres Strait fishery occurs from Cape York to the northern border of the Torres Strait Protected Zone. The commercial fishery within this zone is shared between Australia and PNG under a formal arrangement (Woodhams et al. 2012). There is also a recreational fishery within the Torres Strait however this is small (Welch and Robins in review). The Torres Strait commercial fishery is comprised of two sectors – the non-Indigenous (TVH) sector and the Traditional Inhabitant (TIB) sector (Woodhams et al. 2012). Dive operations consist either of a mother vessel from which a number of smaller (4-6 m) tender vessels operate with divers working from each tender (TVH operators), or of a small 4-6 m vessel with divers using solely freediving (TIB). There are 13 TVH primary licences with 34 tenders attached to these, while in the TIB sector there are currently 470 licenses of which only 293 are active (as of September 2010) (Woodhams et al. 2012).

The fishery is managed using a catch quota system with an annual Total Allowable Catch (TAC) shared between Australia and PNG. The historic annual catch is variable and is thought to be driven largely by variable recruitment (Welch and Robins in review). In 2011, the total catch from the fishery was valued at $AU28.3 million and was comprised of 704 t (live weight) for the Australian portion (Figure 12) and 165 t for the PNG portion. Between 1989 and 2009, PNG fishers took approximately 31% (range: 19 – 57%) of the total Torres Strait catch annually. The TVH sector has historically taken the majority of the Australian catch, but in recent years most of the Australian catch was taken by the TIB sector, due to effort controls (regulated and voluntary). In 2011 however, the TIB sector took 29% of the Australian catch (Welch and Robins in review). Despite the fishery taking more than the nominal TAC in 2011 (803 t), it is currently assessed as not overfished nor subject to overfishing (Woodhams et al. 2012).

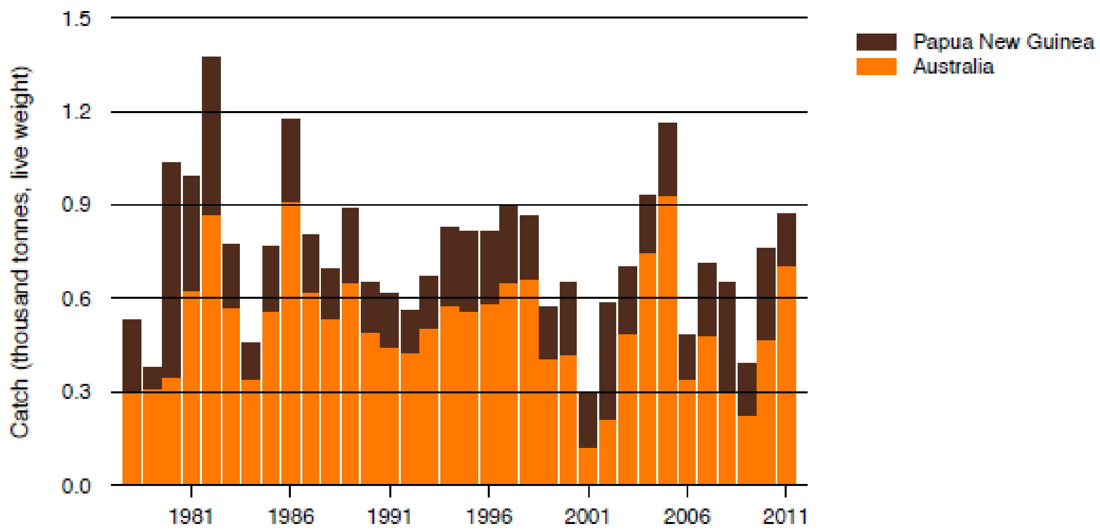

Figure 12. Commercial catch (thousand tonnes live weight) from the Torres Strait Tropical Rock Lobster Fishery from 1978 to 2011 indicating both Australian and Papua New Guinea portions of the catch. (Source: Woodhams et al. 2012).

The fishery is managed under the Torres Strait Fisheries Act 1984 and through policies agreed to under the Protected Zone Joint Management Authority. Regulations include restrictions on the number of TVH licenses and number of tenders per primary vessel. There is no limit on the number of TIB licenses issued. Other regulations include: the taking of lobsters only by hand or hand-held implements; a ban on the use of hookah during December and January; a minimum tail size of 115 mm or a minimum carapace length of 90 mm; and bag limits of three lobsters per person or six per dinghy for recreational fishers and traditional fishing (Welch and Robins in review).

Life cycle

P. ornatus are known to have a broad habitat use including deep (> 200 m) oceanic waters, reef tops, reef slopes, rocky inter-reef areas and muddy reef areas adjacent to estuaries and river mouths, which reflects a very wide distribution (Pitcher et al. 2005). In the Torres Strait they can be found across the entire continental shelf.

The breeding season for adult tropical rock lobsters is between November and April when adult breeding *P. ornatus* migrate to breeding areas. This occurs at 2.5 to 3 years old and females outnumber males in the breeding migrations by 2:1, however large males and one-year-old lobsters do not migrate. On the northeast coast of Queensland, migrations average approximately 70 km, whilst larger migrations are undertaken by lobsters in Torres Strait (up to 511 km) (Moore and MacFarlane 1984). Breeding areas are in deep water (40 to 120 m) on the continental shelf outside the GBR and Yule Island in the Gulf of Papua. Breeding sites on the GBR are predominantly in the far north, but breeding sites also occur south to at least Townsville (19 °S) (Bell et al. 1987). Adults migrate from reefs in Torres Strait between August and November and lobsters that migrate to Yule Island generally do not survive after breeding (Pitcher et al. 2005).

Adult *P. ornatus* are highly fecund and multiple broods may be carried and reared during one spawning season. The first brood is thought to represent the major spawning within a season. In captivity (and held at 28 °C), females produce an average of three batches each breeding season (M. Kenway pers. comm.). Queensland and Torres Strait *P. ornatus* are considered to be a single genetic stock, with Torres Strait and far northeast Queensland source populations for areas of the GBR further south (Pitcher et al. 2005).

Eggs are fertilised as they exit the female's body and attach to the pleopods, where they are carried for about 35 days at 29 °C (Pitcher et al. 2005). Larvae hatch as phyllosoma that are carried by wind and tides in the plankton of oceanic waters of the northwest Coral Sea and go through up to 24 morphological stages over approximately 6 months (Pitcher et al. 2005, Smith et al. 2009). After this period the larvae develop into a peurulus, which is an active non-feeding swimming stage that seeks out suitable benthic habitat on the continental shelf to settle in coastal areas as benthic juveniles. Sub-adult lobsters (~95 mm carapace length) move off-shore during March/April to mid-shelf reefs (Figure 13). In the Torres Strait, sub-adults move widely throughout the region seeking suitable reef habitat and/or large beds of bastard shell, *Pinctada albina* (Welch and Robins in review, M. Kenway pers. comm.).

In the northeast Australian region, the distribution of *P. ornatus* phyllosomas and pueruli in relation to ocean currents support the hypothesis that phyllosomas are transported from the Gulf of Papua breeding grounds by the Hiri Boundary Current into the Coral Sea Gyre and then by surface onshore currents onto the Queensland coast, Torres Strait and south eastern PNG. There appears to be distinct regions that act as recruitment 'sources' and 'sinks' which are determined by the bifurcation of the South Equatorial Current off the GBR approximately adjacent to Cooktown on the northeast coast of Queensland. Areas to the north of this bifurcation act as both 'source' and 'sink' regions and areas to the south act as a 'sink' region (Dennis et al. 2001, Pitcher et al. 2005). The peak timing of settlement in north east Queensland occurs during winter (i.e. June to August) in most years, but the seasonality of settlement is highly variable (Welch and Robins in review).

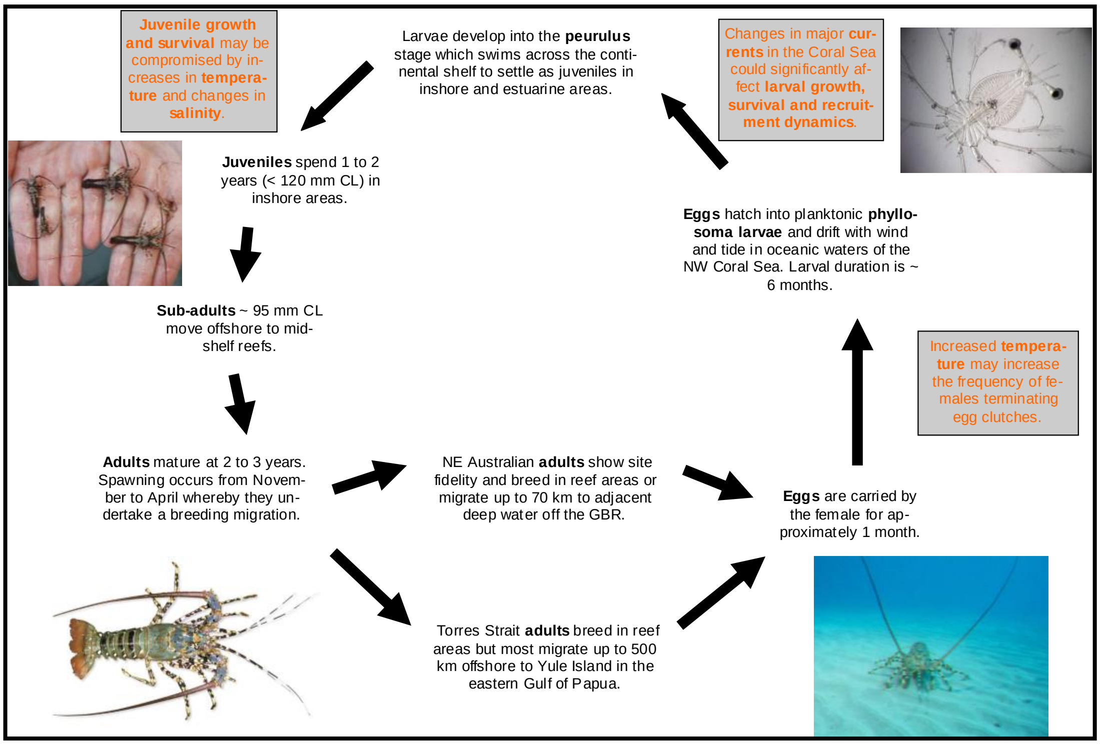

Figure 13. Generalised life cycle of the ornate rock lobster, *Panulirus ornatus*. Source: Welch and Robins (in review).

P. ornatus is an unusually fast growing lobster (Plagányi et al. 2009) but growth rates are spatially and temporally variable (Skewes et al. 1997). Growth is affected by water temperature and possibly food availability. Longevity is estimated to be about eight years, at which *P. ornatus* have a carapace length of about 150 mm (Phillips et al. 1992, Skewes et al. 1997). In wild populations, larger individuals tend to be males, possibly as a consequence of higher natural mortality rates that apply to females from the annual breeding migration and egg brooding. *P. ornatus* are opportunistic carnivores that feed mainly on benthic invertebrates (Welch and Robins in review). Recent work has also found that *P. ornatus* across northern Australia, Indonesia and southeast Asia show very little genetic differentiation suggesting mixing across large spatial scales (Hoc, D.T., unpublished data).

Climate sensitivity

Norman-López *et al.* (2012) suggested that rock lobsters are sensitive to several climate factors (e.g. temperature, wind, ENSO events and ocean acidity) and thus may be particularly vulnerable to climate change. Growth in juvenile *P. ornatus* has been shown to be significantly affected by temperature with maximum growth occurring between 25 to 31 °C and an optimal temperature of 27 °C (Jones 2009). Given contemporary water temperatures in the Torres Strait, future increases in temperature may in the short-term promote faster growth however in the medium-term is more likely to have negative effects on growth. Norman-López et al. (2012) assessed growth of all life history stages to be at high risk of impact from climate change, primarily as a consequence of increased water temperatures. Larval supply was assessed as potentially increasing (by 7.5% by 2030), as was lobster growth (7.5% by 2030). They also identified that juvenile mortality rates may increase (by 10%) as a consequence of increased water temperatures and negative effects on the seagrass habitats of juvenile lobsters.

Sachlikidis et al. (2010) found that *P. ornatus* terminated their egg clutches in temperatures ≥ 32 °C. Juvenile growth and survival have also been shown to be affected by salinity with the lowest survival but fastest growth at 35 ppt.

The long larval phase of *P. ornatus* may be a significant limiting factor to successful recruitment depending on the nature of future change, particularly with respect to ocean currents in the northwest Coral Sea (Welch and Robins in review). Currents in the northwest Coral Sea are extremely important for carrying *P. ornatus* larvae and the determination of settlement areas (Pitcher et al. 2005) suggesting that changes in these currents may impact on settlement and recruitment rates. In Western Australia, the western rock lobster (*Panulirus cygnus*) is thought to have shown a decrease in size at maturity due to rising sea temperatures. The Leeuwin Current, which is influenced by ENSO cycles, is also thought to be a significant driver of successful puerulus settlement in Western Australia (Caputi et al. 2010).

Plaganyi et al. (2011) used the Torres Strait tropical rock lobster fishery as a case study to model the effects of climate change on stock productivity and economic factors. They found that outcomes could be either positive or negative depending on the severity of future climate change. In the worst case scenario there was a ~25% reduction in spawning biomass by 2030. This had negative consequences for the profitability of the fishery and those involved, with a greater relative impact on Torres Strait Islanders compared to non-Islanders. It should be noted that the model used assumed current fishing levels and management arrangements and so adaptive capacity was not incorporated, which would presumably mediate some negative impacts.

Mud crab (*Scylla serrata*)

Fishery characteristics

The Torres Strait crab fishery primarily targets mud crab (*Scylla* spp.; mostly *S. serrata*) and occasionally small quantities of blue simmer crab (*Portunus pelagicus*). This review focuses on *S. serrata*.

The Torres Strait crab fishery is limited to Traditional Inhabitants to maximise their opportunities. Mud crabs are generally captured by hand or using scoop nets. The level of participation in the commercial fishery is low due to other fisheries being relatively more profitable and therefore, although not reported, catch levels are thought to be low. Anecdotal information suggests that most of the fishing effort occurs in the north-western section of the TSPZ, in particular Saibai, Boigu and Dauan Islands. Some effort also occurs further south around the Cape York Peninsula[3]. In 2010 there were 78 Traditional Inhabitant vessels authorised to operate in the Torres Strait crab fishery. A small but unknown quantity of mud crabs are taken by subsistence fishing.

Regulations currently implemented in the crab fishery include a ban on the take or possession of female crabs, no vessels greater than 14 m in length, restrictions on the number of prescribed crab fishing apparatus to less than 50, and a minimum carapace length of 15 cm.

[3] www.pzja.gov.au

Life cycle

Mud crabs usually inhabit estuarine areas, sheltered coastal habitats and shallow tidal flats associated with mangrove communities (Hill et al. 1982). Juveniles are usually found in the intertidal zone amongst mangroves and adults tend to be more abundant in the sub-tidal zone (Hill et al. 1982).

The life cycle of the mud crab involves multiple stages that utilise both marine and estuarine environments (Figure 14) (Arriola, 1940). The mating process begins when a mature, hard-shelled male finds a female that is ready to moult (probably through the release of pheromones from the female). The male then carries the female with his first pair of walking legs for a period of three to four days before she moults and is subsequently inseminated (Ong 1966). The crabs remain paired typically for about five days when the females' shell hardens (Perrine 1978). The female stores the spermatophores for two to seven months (Ong 1966) during which time up to three batches of eggs can be fertilised (Heasman et al. 1983). The eggs are later extruded onto the ventral surface of the females' abdomen where they remain until hatching. Female mud crabs are highly fecund and egg batches can number from 2 – 11 million (Davis et al. 2004).

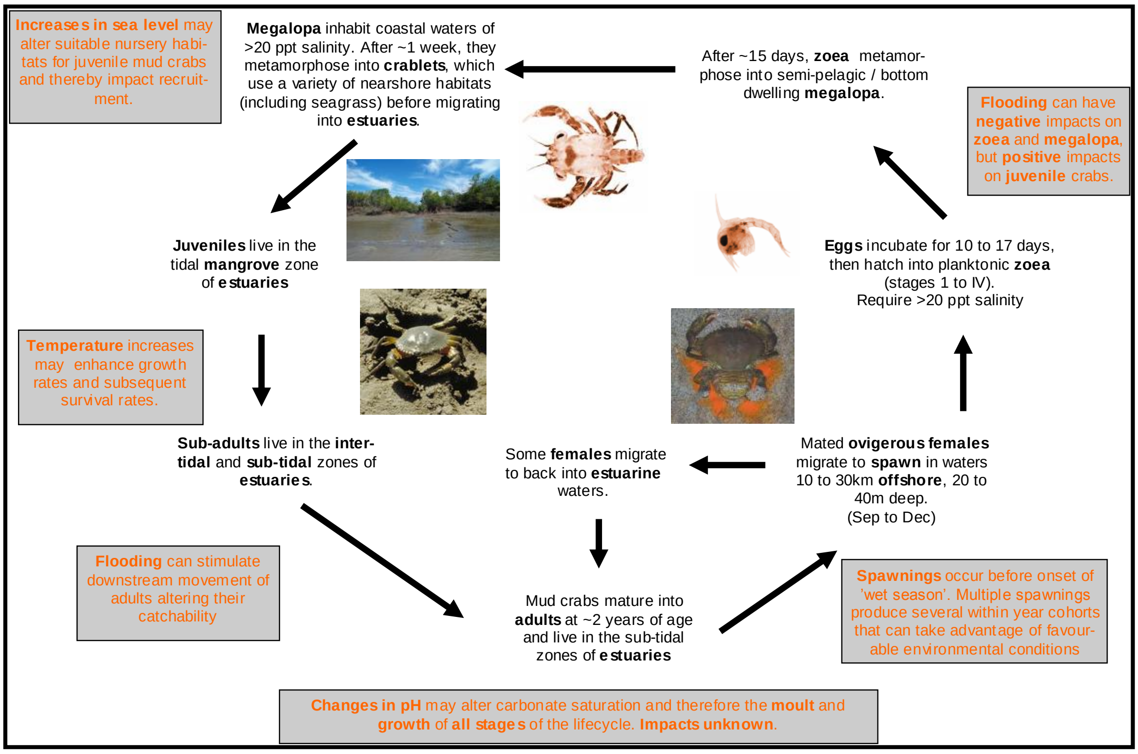

Figure 14. Generalised life cycle of the mud crab, *Scylla serrata*. Source: Lawson et al. (in review).

Once mated, the females often migrate up to 50 km offshore into waters 20 to 40 m deep (Hill 1994). The peak of the spawning event (comprising both migration and hatching) occurs from September to November (Heasman et al. 1985, Knuckey 1999). This timing is before the wet season, suggesting that migration is not triggered by low estuarine salinities (Hill 1994). The rate of egg and larval development in *Scylla* species is inversely proportional to temperature, with an optimal temperature of 29 °C (Hamasaki 2003). Salinity is also important for larval survival (Nurdiani and Zeng 2007) although experimental studies indicate that juvenile mud crabs can be reared at low salinities as long as temperature is greater than 25 °C (Ruscoe et al. 2004). Hatching occurs at about 12 days after extrusion and over the following 12 to 15 days the planktonic zoea pass through five discrete stages (Brown 1993). These become megalopae which are a semi-pelagic bottom-dwelling stage (Fielder and Heasman 1978), and which metamorphose into juvenile crabs after another 5 - 12 days in mangrove and seagrass habitats (Webley et al. 2009, Williams 2002). During these stages growth is rapid with frequent moults (Lawson et al. in review).

Mud crabs grow through a series of moults and have an inferred longevity of three to four years (Heasman 1980). They grow quickly and can reach 80-100 mm carapace width (CW) in their first year, 130-160 mm CW in their second year, and around 200 mm CW in their third year (Heasman 1980). In the Torres Strait mud crabs reach maturity in about 18 months (Fielder and Heasman 1978).

Climate sensitivity

Mud crabs prefer nearshore habitats and so are exposed to highly variable environments throughout their life. It is likely that recruitment levels are primarily influenced by factors such as currents, salinity, temperature, food supply, suitable habitat and predation (Lawson et al. in review). Sea-level rise may also influence future populations of mud crab by altering estuarine and mangrove habitat availability.

Research by Halliday and Robins (2007) on the GBR demonstrated significant correlations between mud crab catch (adjusted for effort) and autumn or spring river flows (lagged 2 years) and suggests that freshwater flows are important for successful recruitment to the estuary. Several other studies have also found freshwater flows, particularly during summer, to positively influence mud crab catches (Loneragan and Bunn 1999, Robins et al. 2005, Meynecke et al. 2012). Since early life stages of mud crab are not tolerant of low salinity it is likely that this is due to greater nutrient inputs from higher freshwater flows, resulting in enhanced food opportunities, faster growth rates, and higher survival (Lawson et al. in review). There is also evidence that excessive freshwater flows may have a negative influence on subsequent fishery catches possibly due to increased adult migration during high flow periods disrupting the spawning period (Helmke et al. 1998). The timing of these flows is also likely to be important.

Catch rates of crab are also influenced by water temperature (Williams and Hill 1982, Meynecke et al. 2012) however this is not likely to be a factor in the Torres Strait because of the year-round (relatively) high and stable temperatures. If temperature is a factor then warmer temperatures are more likely to result in higher catches due to higher activity levels of the crabs. For a detailed overview of studies correlating mud crab catches with environmental variables see Lawson et al. (in review). Several aspects of the life cycle of mud crabs are sensitive to temperature including survival and development of early life stages (Hamasaki 2003, Ruscoe et al. 2004), growth rates (Fielder and Heasman 1978, Brown 1993) and feeding activity (Williams and Hill 1982). No studies so far have examined the sensitivity of mud crabs to water temperatures above 35 °C.

The SOI has also been correlated with mud crab catches in northern Australia. Between 30% and 40% of the catch variability can be explained by La Niña phases which are associated with increased rainfall and higher temperatures over large parts of northern Australia (Meynecke et al. 2010).

Trochus

Fishery characteristics

The Torres Strait trochus fishery targets a single species commonly called the topshell, *Trochus niloticus,* within the TSPZ and the 'outside but near' area just to the south. The fishery is restricted to Traditional Inhabitants who must obtain a TIB licence and harvesting must be done by hand from free-diving or reef walking. Although the fishery is very small it can be an important income source for some Islanders. Subsistence fishing of trochus also occurs and has done for centuries, however harvest is considered to be low (SEWPaC 2012). The mother of pearl layer (nacre) in the shell of trochus is used mainly for buttons and jewellery that are exported. The ground shell can also be used in shampoo, floor tiles and paints (Woodhams et al. 2012) and trochus meat is also eaten (Murphy et al. 2010).

In the commercial fishery, as at 30 June 2011, there were 80 fishing permit holders in the Torres Strait, with a TAC of 150 t. Despite this, there has been very little effort since 2006 due to declining international mother of pearl prices (SEWPaC 2012). Most recently, reported catch of trochus was 0.7 t in 2010 and 0 t in 2011 (Woodhams et al. 2012). The fishery is managed by having limited entry, gear and vessel restrictions, a TAC and size limits (minimum of 80 mm and maximum of 125 mm basal shell width). The current status of trochus populations is considered uncertain due to low counts from monitoring surveys, probably due to the naturally patchy distribution and cryptic behaviour of trochus (Murphy et al. 2010).

Life cycle

The topshell is a tropical shellfish that can be found throughout the tropical belt from the eastern Indian Ocean to the western Pacific. They inhabit coral rubble reef flats, particularly juveniles, and adults can be found across intertidal and shallow subtidal zones down to 10 m (Chambers 2007). Adults are largely non-selective herbivorous grazers feeding on turf algae, and microscopic plankton (Castell 1997). They can grow to at least 15 cm base shell diameter (BSD) and live for 15 – 20 years. The size at sexual maturity varies among locations but ranges from 5 – 7 cm BSD after 2 – 3 years (Nash 1993, Castell 1997) (Figure 15).

Trochus have separate sexes, although males and females cannot be distinguished from external shell morphology. Trochus spawn asynchronously and in low latitudes such as Torres Strait, spawn at least once or twice each year and are capable of spawning most of the year. Spawning is most active during the summer months (Nash 1985). Trochus sometimes form spawning aggregations usually in the evenings around the new or full moon phases (FAO 1999). Spawning is external and first initiated by males which release sperm into the water column during the incoming tide inducing females in the vicinity to also release eggs into the water column (Chambers 2007). Females usually release between 100,000 and 1 million eggs (Heslinga and Helman 1981, Nash 1993) but can release up to 2 million eggs (Nash 1985). Successful fertilisation is likely to be dependent on the proximity of other trochus and so population density levels are probably important.

Approximately 12 hours after fertilisation eggs hatch into a lecithotrophic trochophore larvae. This stage disperses by swimming using several bands of cilia and is then followed by the veliger stage, which possesses greater dispersal capabilities. After 3 – 5 days the veliger settles on suitable habitat in the reef flat, usually among the coral rubble, and metamorphoses by shedding its velum (Nash 1985). They will then begin feeding on turf algae and small microorganisms. Although the planktonic larval stages of trochus are capable of being transported by currents, this is likely to be limited due to the very short larval duration (Bertram 1998).

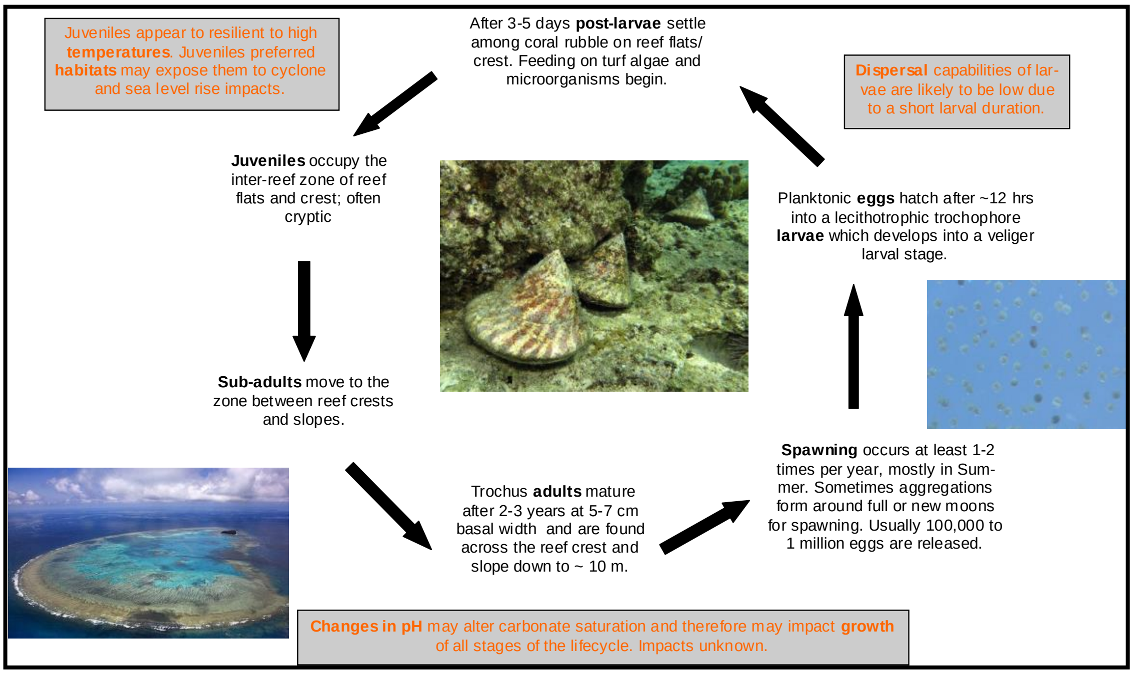

Figure 15. Generalised life cycle of the topshell (trochus), *Trochus niloticus*.

Climate sensitivity

Trochus appear to be resilient to high temperatures as demonstrated by juvenile recovery after being exposed to temperatures as high as 40 °C. It is uncertain how other environmental variables such as salinity (altered by rainfall), ocean pH, sea-level rise or cyclones affect aspects of the life cycle of trochus and the combined effects of direct and indirect climate change on trochus growth and survival have previously been assessed as minor (Bell et al. 2011a).

Pearl oyster

Fishery characteristics

The fishery for pearl oyster in Torres Strait has a very long history dating back to at least the 1860s when they were harvested for the mother of pearl shell which was used to make buttons, implements and ornaments. During the early 1990s the pearl oyster fishery was the largest and most important fishery in Torres Strait (Torres Strait Fisheries Assessment Group 1999). Today they are only permitted to be collected live for pearl culture farms. Although there are seven species of pearl oyster that occur in the Torres Strait, the fishery is dominated by the gold-lipped pearl oyster, *Pinctada maxima*, with some smaller quantities of the black-lipped pearl oyster, *P. margaritifera*, also harvested historically. Harvesting is by hand collection only and there are no logbook requirements so the harvest is unknown. Status of stocks is therefore unknown. Past surveys have indicated that pearl shell abundance on the main fishing grounds are low and fishing effort is also thought to be at low levels in recent years[4] (Torres Strait Fisheries Assessment Group 1999).

There are currently both Islander and non-Islander licensees however new licences are only allowed to be issued to Traditional Inhabitants and there are restrictions on changes to operations for non-Inhabitants. There are also size limits in place to ensure that pearl oysters harvested are optimal for pearl culture as well as providing protection for small and very large mature animals. The size limit for *P. maxima* is between 130 and 230 mm shell length, while *P. margaritifera* are required to be greater than 90 mm[4]. The Torres Strait fishery is managed by the Protected Zone Joint Authority while pearl farms are managed by the Queensland Government.

Life cycle

P. maxima are found through the central Indo-Pacific region with an apparent population centre located in northern Australia and southeast Asia (Zhao et al. 2003). *P. margaritifera* are also found throughout the Indo-Pacific but are more widespread as far as the Red Sea and the California coast. In Australia they extend farther south than *P. maxima* into sub-tropical waters (Gervis and Sims 1992) and also prefer areas associated with coral reefs (Yukihira et al. 1998). Due to the greater importance and higher abundance of *P. maxima* in the Torres Strait this section will only deal with the gold-lipped pearl oyster.

P. maxima are the largest of the Australian pearl oyster species and can reach between 200 – 250 mm shell length (Gervis and Sims 1992). Their preferred habitat tends to be in depths from low tide to 60 m in continental shelf waters with mud, sand, gravel or reef substrate but always in association with fragmented material such as dead coral colonies or coral rubble, broken shell or pebbles (Torres Strait Fisheries Assessment Group 1999). Pearl oysters are non-selective filter feeders and are often found in high current areas.

It is reported that some *P. maxima* function as protandrous hermaphrodites meaning that they first mature as males and later change sex to be females. It is also thought that this sex change is reversible if the animal is stressed (see Gervis and Sims 1992). Spawning in the Torres Strait occurs from October to March with peaks during November and December, and a second peak during January to March. They are broadcast spawners with development of planktonic larvae occurring approximately 8 hours after fertilisation. Larvae are largely at the mercy of local currents but possess cilia which they use to maintain a position very near to the surface. After 1-2 days larvae become obligate planktotrophs meaning they need to feed on phytoplankton and zooplankton during the larval phase. They undergo several different stages during their larval period which lasts for approximately 21 days and are thought to have narrow physiological tolerances (Gervis and Sims 1992, Sims 1992, Torres Strait Fisheries Assessment Group 1999). When close to settlement stage, larvae grow a foot and use it to move across the substrate until they find suitable settlement habitat, usually broken stone or dead coral rubble, to which they attach as a juvenile stage (Figure 16). Settlement of *P. maxima* is influenced by benthic biofilm composition. In particular, settlement is higher where there are greater levels of bacteria, although algal composition may also be important (Zhao et al. 2003).

[4] www.pzja.gov.au accessed 12/06/2013

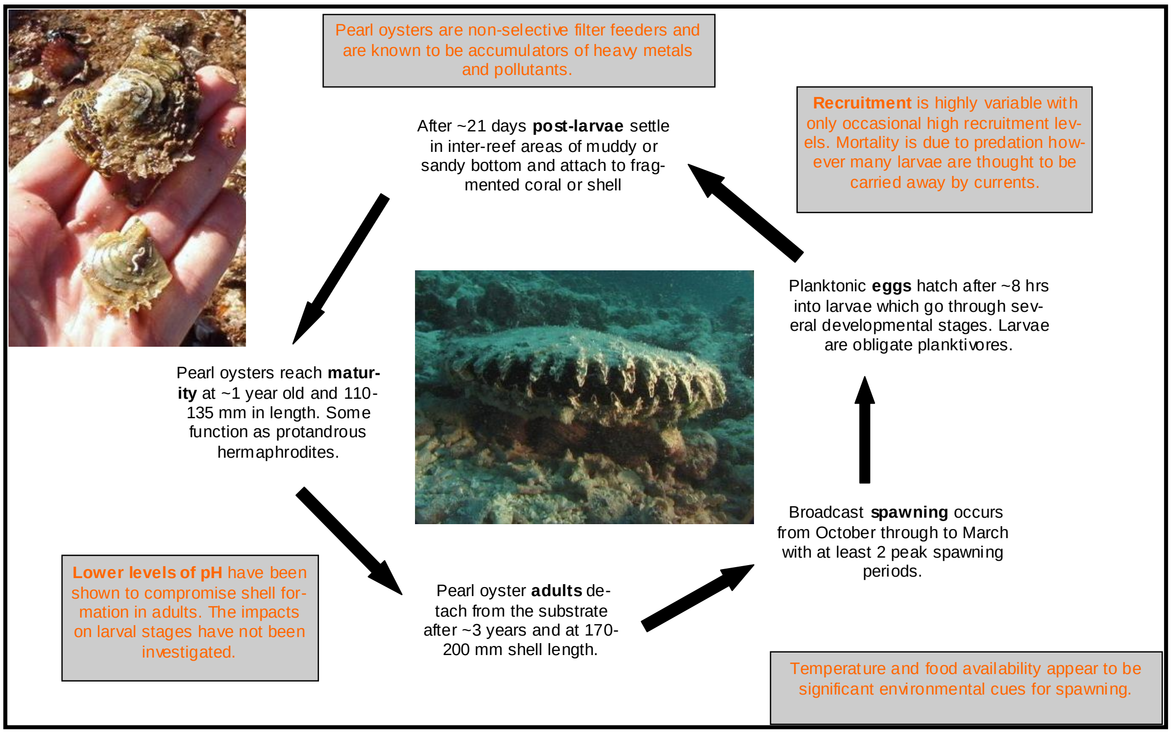

Figure 16. Generalised life cycle of the gold-lipped pearl oyster, *Pinctada maxima*.

Recruitment appears to be highly variable, sometimes with only occasional successful recruitments (Torres Strait Fisheries Assessment Group 1999), a finding that is consistent with other pearl oyster species (e.g. O'Connor 2002). Mortality is reported to be highest during the larval and settlement stages, mostly due to predation however many larvae are thought to be carried away from suitable settlement habitat by currents (Sims 1992). Gold-lipped pearl oysters reach maturity after their first year of life at around 110 – 135 mm. After around 3 years and at a size of 170 – 200 mm long they release their hold on the substrate and lie free on the bottom (Torres Strait Fisheries Assessment Group 1999).

Predation on pearl oysters is by a variety of animals including snails, starfish, octopus, fish, crabs and rays, and they are also prone to internal parasites and worms boring into their shells (Torres Strait Fisheries Assessment Group 1999).

Climate sensitivity

The optimum thermal range for *P. maxima* has been estimated to be from 23 °C to 32 °C and below this range they perform quite poorly. The performance of *P. margaritifera* on the other hand was poor at higher temperatures ~ 32 °C (Yukihira et al. 2000). These observations suggest that increasing temperatures in the Torres Strait may result in fewer black-lipped pearl oyster while for gold-lipped pearl oyster, although they may be more prevalent at higher latitudes along the eastern Australian coast, are not likely to change in relative abundance. The upper thermal limit for *P. maxima* has not been documented. Temperature is known to be a key factor in the regulation and timing of gamete maturation for spawning in bivalves, and in the tropics food supply (and therefore productivity levels) is also likely to be significant (Pouvreau et al. 2000). Fournier et al (2012) found this for *P. margaritifera* in tropical French Polynesia, where seasonal temperature fluctuations are relatively narrow and spawning is fairly continuous, with spawning peaks associated with periods of peak plankton concentration measured using chlorophyll *a* as a proxy. Peaks in plankton concentration were correlated with peaks in wind speed. In culture situations one of the most reliable methods to induce spawning in *P. maxima* (and many other cultured organisms) is through adjustment of the water temperature (Gervis and Sims 1992).

A study on *P. margaritifera* found that the development of larvae was optimal between 26 °C and 29 °C and above this temperature growth actually decreased, however optimal survival was achieved at temperatures closer to 20 °C (Doroudi et al. 1999). While the larvae of *P. margaritifera* were found to have a wide salinity tolerance of 25‰ to 35‰, *P. maxima* larvae have been found to cease growing at a salinity of 27‰. This is quite possible in northern Australian waters during the monsoonal season (Doroudi et al. 1999).

A study on a related pearl oyster species also found in Torres Strait, *P. fucata*, found that the strength and formation of shells were adversely affected by ocean acidification, potentially making them more prone to predation and infestation by borers. Further, nacre deposition was also shown to be affected which could affect the quality of pearl formation (Welladsen et al. 2010). It is quite possible that shell dissolution in the larval stage could impact on mortality rates substantially however this is untested. It should be noted for this study that the effects were evident at a pH of 7.8 or less; a level not expected until later this century. Further, the capacity for acclimation was not investigated.

Spanish mackerel

Fishery characteristics

The Torres Strait Spanish mackerel fishery targets the narrow-barred Spanish mackerel, *Scomberomorus commerson*, primarily by trolling. The fishery for Spanish mackerel is seasonal and principally targets fish near Bramble Cay in the northeast Torres Strait between August and March but fishing occurs throughout much of the eastern Torres Strait (Williams and O'Brien 1998, Woodhams et al. 2012). The fishery is made up of fishers in two licence categories: the TIB licences and the TVH licences. As part of negotiations with the Federal Government, in 2008 all TVH endorsements were bought out and surrendered to the Torres Strait Protected Zone Joint Authority with a few still operating through leasing arrangements under quota only. In the 2010/11 fishing season there were 7 TVH licenses with mackerel endorsements with only 5 active. In the 2009/10 season, there were 161 TIB licenses with mackerel endorsements with 55 active, however, in the 2010/11 season, although there were still 148 TIB mackerel endorsements, none of these licences were active (Woodhams et al. 2012).

Despite catch restrictions, the TVH sector of the fishery accounts for most of the effort and catch (100% in 2010/11) and have mandatory logbook reporting requirements while the TIB sector do not. Therefore the reported catch from the fishery is always an under-estimate as it does not include the TIB sector. Spanish mackerel are also an important component of the Torres Strait subsistence fishery and estimates of both subsistence and recreational catch are not available. The most recent years of total reported commercial catch is lower than previous years reflecting the reductions in active TVH fishery licences and in 2010/11 was 74 t, down from its peak of approximately 250 t in 2000/01 (Woodhams et al. 2012; Figure 17).

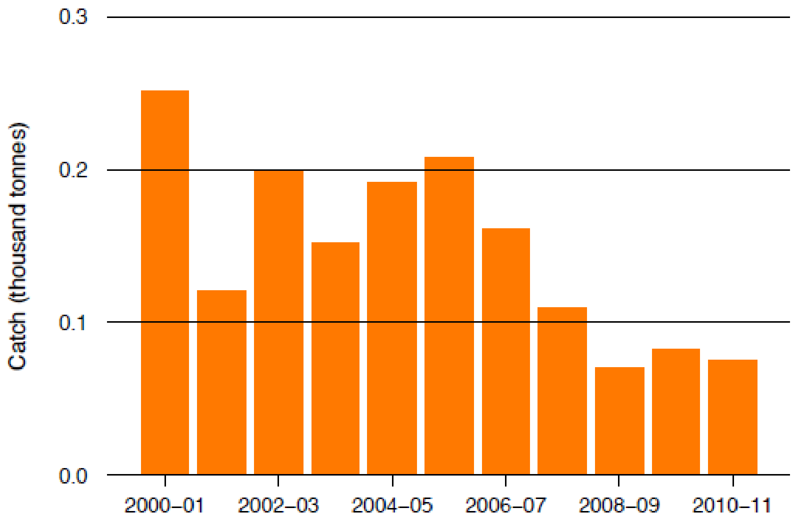

Figure 17. Catch history of Spanish mackerel from the Torres Strait TVH (non-Traditional owners) sector for the 2000/01 to 2010/11 fishing years. Source: Woodhams et al. (2012).

Life cycle

Spanish mackerel are a highly mobile epi-pelagic species usually associated with reefs, shoals or current lines (Collette and Nauen 1983). They can be found across the continental shelf waters of northern Australia and are usually associated with water temperatures of approximately 20 °C or warmer (Buckworth and Clarke 2001, McPherson 1992). Across northern Australia a meta-population stock structure is evident for *S. commerson* and the Torres Strait stock appear to be isolated from the adjacent east coast and Gulf of Carpentaria stocks (Buckworth et al. 2007), however the extent of the Torres Strait stock is unknown (Begg et al. 2006). In northern Australia Spanish mackerel appear to be more site-attached than those found on the east and west coasts that undertake lengthy seasonal migrations (Buckworth et al. 2005). Seasonality of catches in the Torres Strait may also suggest an annual migration however this is highly uncertain as tagging experiments conducted in the 1980s resulted in few recaptures and was only conducted in one area around Bramble Cay (McPherson 1988).

Torres Strait Spanish mackerel have a protracted spawning season that runs from August to March with a peak in October when fish are aggregated (McPherson 1981a, 1986) (Figure 18). One of the largest spawning aggregations occurs at Bramble Cay in the north-eastern Torres Strait and spawning occurs on reef slopes and deep edges. Spawning usually occurs during new and full moon phases in the late afternoon and early evening when feeding ceases. Spawning is determined by a combination of environmental factors particularly temperature (McPherson 1981a, Welch et al. in review). Feeding behaviour resumes immediately after spawning (McPherson 1981a, McPherson 1993). Over the course of the spawning season individual fish spawn several times (Munro 1942, Jenkins et al. 1985, McPherson 1993, Buckworth and Clarke 2001) and female Spanish mackerel are highly fecund (Moltibano et al. unpublished data).

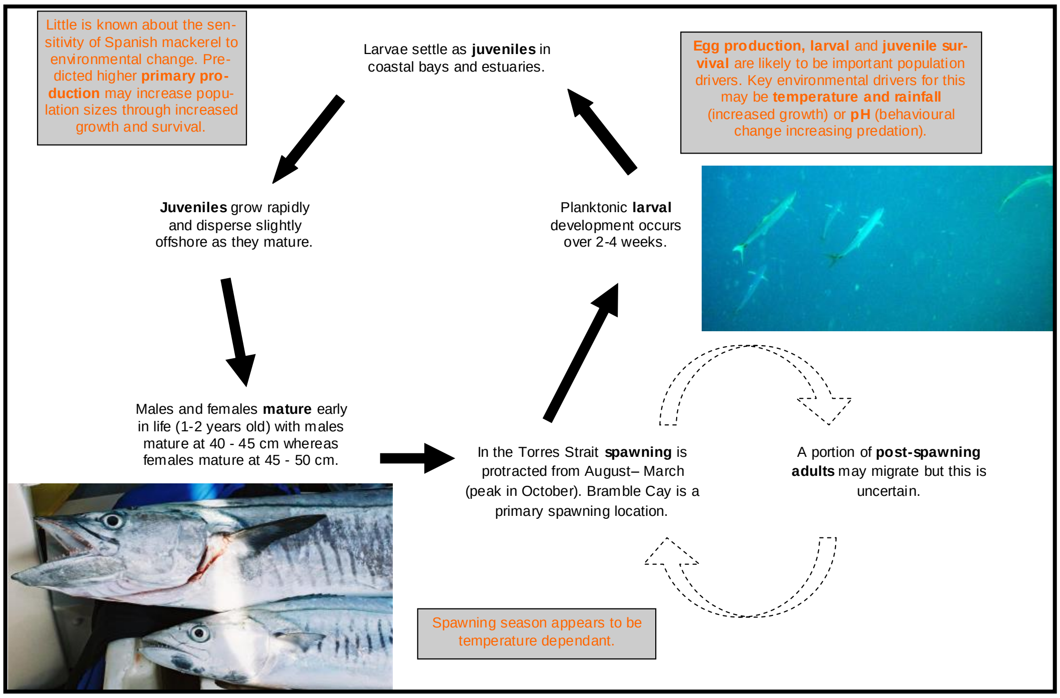

Figure 18. Generalised life cycle diagram for Spanish mackerel in the Torres Strait. Adapted from: Welch et al. (in review).

Eggs are released into the plankton where they develop and hatch as larvae at approximately 2.5 mm in length (Munro 1942). They develop minute teeth by the time they are 5.6 mm long and become juveniles at approximately 14.5 mm (Jones 1962). Larval duration is two to four weeks (Ovenden et al. 2007). The occurrence of larvae during spring and summer coincides with maximum productivity in the plankton. The high availability of food and higher water temperatures provide optimal conditions for rapid growth during the vulnerable early life stages. Larval *S. commerson* feed almost exclusively on larval fish and invertebrates (Jenkins et al. 1984). Larvae are found on continental shelf reef lagoon waters and settle as juveniles in estuarine and inshore nursery grounds. Studies on the Queensland east coast indicate the absence of Spanish mackerel larvae in coastal and estuarine habitats suggesting direct movement inshore by juvenile fish rather than passive transportation of eggs and larvae by currents and tides (Jenkins et al. 1985). Juvenile fish inhabit shallow estuaries and intertidal flats for approximately the first six months of life (McPherson 1981b). Juvenile fish between 15 and 40cm length are found in shallow coastal waters during February and March (Williams and O'Brien 1998). By May, juveniles leave inshore areas for offshore waters where fish around 50 cm begin to be represented in the catches of commercial fishers (McPherson 1981b). For the Torres Strait stock little is known about Spanish mackerel early life history stages and their habitats and dispersal patterns (Begg et al. 2006).

Juvenile and adult Spanish mackerel are piscivorous predators, feeding mainly on pelagic baitfish such as sardines, anchovies and pilchards, but also squids and prawns (McPherson 1987). Examples of age structure population 'snapshots', and from the very few time series of age structure data available, indicate inter-annual variability in recruitment strength (e.g. Tobin and Mapleston 2004). Variability in annual larval growth and survival is to be expected given natural variation in environmental conditions and primary production.

Spanish mackerel are fast growing and grow to a large size, with record fish exceeding 2 m in length and 100 kg in weight (McPherson 1992, Buckworth and Clarke 2001). Differential growth between sexes occurs with the females showing faster growth, greater maximum length and higher longevity, reaching at least 17 years in eastern Australia (McPherson 1992, Tobin and Mapleston 2004). Sexual maturity for males and females occurs around 2 years of age from about 79 cm fork length (McPherson 1993, Mackie et al. 2005, Montilbano et al. unpublished data).

Climate sensitivity

The sensitivity of Spanish mackerel to changes in the environment is poorly understood, although temperature has been postulated to strongly influence spawning seasonality and annual migrations (Welch et al. in review). With future predicted warming of the oceans, Spanish mackerel may become a far more important species in NSW on the east coast with the possibility of increasingly southwards migrations and/or an increasing presence through range shifting associated with the increased strength and southward extension of the East Australian Current over the past 60 years (Ridgeway and Hill 2009).

Given that Spanish mackerel settle as juveniles in inshore and estuarine nursery areas (McPherson 1981a, Williams and O'Brien 1998), their early survival and growth are potentially influenced by local rainfall and river flows as has been documented for other species with inshore early life history stages (e.g. Halliday et al. 2008, 2011).

Recent investigations of the influence of environmental variables on Spanish mackerel catch rates and recruitment have been equivocal. Analysis of temporal trends in year-class strength of *S. commerson* from catch curve residuals has demonstrated the existence of high levels of inter-year variability in recruitment. Strong and weak year classes have been shown to persist in the age-structure of the population and can be tracked across multiple years potentially suggesting that they may be related to environmental conditions. However, unlike estuarine species such as barramundi or king threadfin, coastal rainfall and river flow do not appear to have such a highly significant, linear effect on year-class strength in *S. commerson*. This is despite the fact that estuarine habitats are thought to be important in the early post-settlement life history phase of the species. Linear regression of variables such as sea surface temperature, chlorophyll *a* and the SOI indicates that they likely affect year-class strength, however clear casual mechanisms have not yet been established (Harry et al. unpublished data). These results support the notion that survival during the larval phase is a key determinant of year-class strength.

Coral trout

Fishery characteristics

The Torres Strait reef line fishery is predominantly a handline fishery carried out from 4-6 m dories with outboard motors. Commercial fishing operations normally have a primary vessel of 15-20 m from which the dories operate and are tendered to each night (Williams et al. 2008a). The western Torres Strait is closed to commercial reef line fishing so the fishery operates only in the eastern Torres Strait and mostly in the northeast (Woodhams et al. 2012). The fishery is a multi-species fishery that takes at least 56 different species however coral trout species are the primary target due to their high value (Williams et al. 2008a). The fishery is made up of fishers in two licence categories: TIB licences and the TVH licences. TVH licence holders currently have a pre-determined termination date for their licences and lease annual coral trout quota from Traditional Inhabitants through the Torres Strait Regional Authority (TSRA) (Woodhams et al. 2012).

There are currently (2010/11) 129 commercial licences or endorsements in the fishery with eight active vessels (two TVH and six TIB). The combined reported catch of coral trout from each sector in the 2010/11 fishing year was 42 t with a value of approximately AU$730,000 (Woodhams et al. 2012). Over the past 10 years reported catch of coral trout has been variable with a peak in 2003/04 of approximately 130 t (Figure 19). For the ten-year period prior to 2000, total catch of coral trout varied annually between approximately 30 t and 150 t but was generally greater than ~ 60 t (Williams et al. 2008a). Catch is not reported for by-product species.

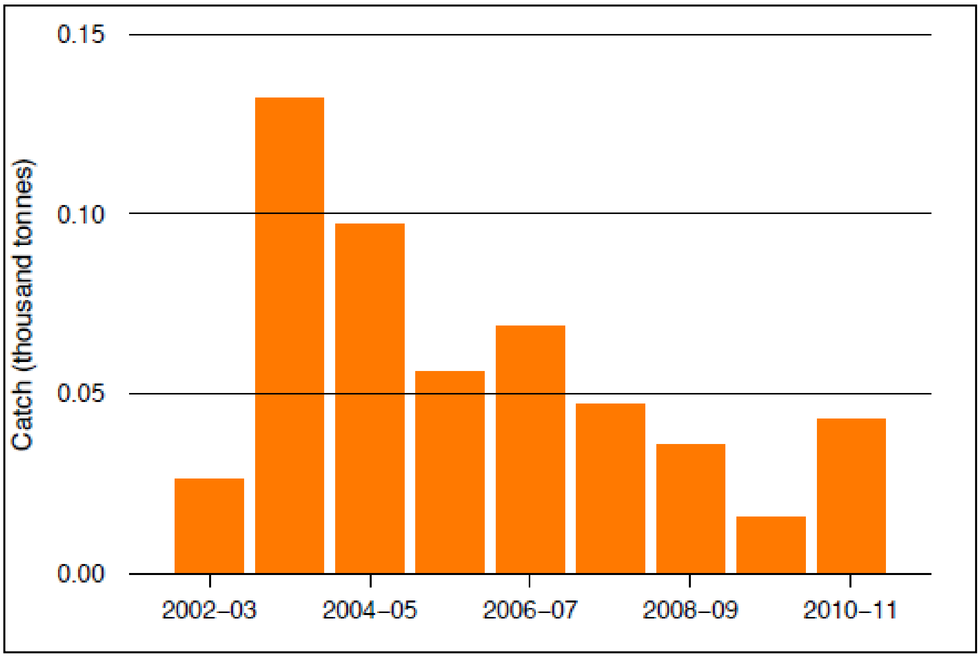

Figure 19. Reported commercial catch of coral trout from the Torres Strait for 2002-03 to 2010-11. Source: Woodhams et al. (2012).

Using observer surveys Williams et al. (2008a) showed that both the TIB and TVH sectors harvested more coral trout in total than other species caught. For the TIB sector, coral trout made up 71% of the total harvest compared to 85% for the TVH sector (by number). However for both sectors coral trout made up 66% of the total harvest by weight probably due to the TIB sector taking significantly more blue spot coral trout (*Plectropomus laevis*) than the TVH sector (Williams et al. 2008a). *P. laevis* are the largest of the coral trout species (Heupel et al. 2010). For both sectors *P. leopardus* is the major species harvested at around 80% of all coral trout. Both sectors also take bar-cheek coral trout, *P. maculatus*, and passionfruit coral trout, *P. areolatus*, as well as *P. laevis* (Figure 20; Williams et al. 2008a). Other species groups harvested as by-product are mostly comprised of snappers (Lutjanidae), emperors (Lethrinidae), cods (Serranidae), trevallies (Carangidae) and mackerels (Scombridae). The TIB sector is more likely to harvest by-product species and show different fishing characteristics to the TVH sector. Catch and effort in the TIB sector is higher during October to March and is concentrated on reefs near islands, while for the TVH sector catch and effort is highest from March to October and spatially extends over a greater area, with particular emphasis on the Cumberland Passage area (Williams et al. 2008a).

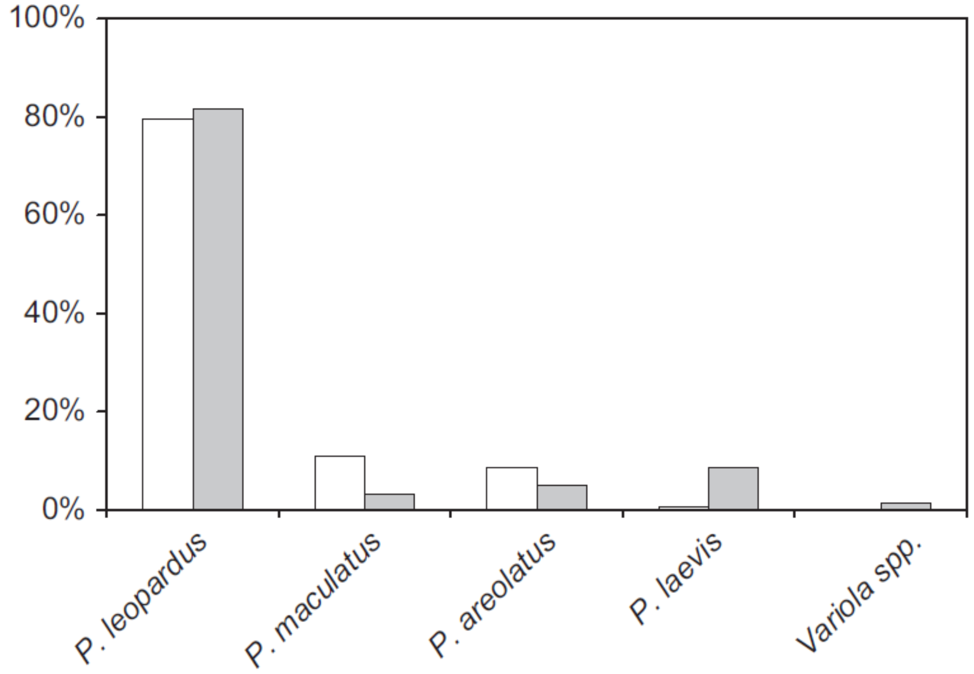

Figure 20. Species composition of the harvested catch of coral trout (in numbers) for both the TVH (non-Traditional Inhabitant; open bars) and TIB (Traditional Inhabitant; grey bars) in the Torres Strait. Source: Williams et al. (2008a).

Some of the overall TIB harvest (7.6%) is kept for subsistence; most of the snapper catch, all of the trevally catch, and smaller proportions of the emperor and coral trout catch were retained (Williams et al. 2008a).

Management of the fishery is by a combination of input and output controls including limited entry, restrictions on vessel sizes, bans on the take of some species, size limits and catch quota limits (leased). The product is sold frozen to both domestic and international markets. The fishery is considered to be fished sustainably at current levels of catch and effort (Woodhams et al. 2012).

Life cycle

Coral trout is the common name given to a number of different species in the Family Serranidae. In the Torres Strait these belong to the genera *Plectropomus* and *Variola* and their relative abundance and distribution varies. The most common and widespread species is the common coral trout or leopard coral grouper (*P. leopardus*). Bar-cheek coral trout (*P. maculatus*) and passionfruit coral trout (*P. areolatus*) are the next most common and are mostly found on the more northerly reefs in the eastern Torres Strait region. *P. laevis* are also present but with a more restricted distribution around outer (easternmost) reefs (Williams et al. 2008b). This review discusses coral trout life history generally but focuses largely on *P. leopardus* as the most commonly caught and studied coral trout species, as well as *P. maculatus* and *P. areolatus* which are also caught in the Torres Strait.

Coral trout are protogynous hermaphrodites meaning that they develop primarily as females and change sex during their life to become males (Goeden 1978, Ferreira 1995). Coral trout spawn either in pairs, small groups or large aggregations (>100 individuals) with peak spawning activity during new moons (Samoilys and Squire 1994, Ferreira 1995, Samoilys 1997). The timing of spawning varies among the three main species with *P. leopardus* spawning mostly during October and November although there is evidence that some spawn as early as July. *P. maculatus* appear to spawn mostly during September and October and *P. areolatus* spawn earlier around July and August however are capable of spawning at least into November (Williams et al. 2008b). The study however was not able to collect samples from December to February so it is possible that spawning is more protracted than currently known. The onset of spawning appears to be correlated with rising sea water temperatures (> 24 °C on the GBR; Samoilys 1997). They are broadcast spawners that rush to the surface in pairs to release gametes into the water column (Samoilys and Squire 1994).

Once spawned, coral trout eggs develop over a period of approximately 26 hours and have a size at hatching of 1.62 mm. The planktonic larval duration is approximately 25 days (Doherty 1996, Masuma et al. 1993). Masuma et al. (1993) give a detailed account of the developmental larval stages. Once hatched, larvae show competent swimming capabilities with directional movement (Leis and Carson-Ewart 1999). Variation in annual egg production and in the survival of larval and juvenile stages is significant and an important driver of population dynamics of coral trout with strong recruitment cohorts persisting over many years in GBR studies (Doherty and Williams 1988, Doherty 1996, Russ et al. 1996). Juvenile settlement occurs on reefs, primarily on reef slopes deeper than 4 m and fish show a strong preference for habitat with a high proportion of coral rubble, algae, sand and rock (Figure 21). Recruits also show strong site fidelity and increase their home range size as they grow in size (Light 1995). Light (1995) also presented evidence that earlier cohorts in a season, when temperatures are lower, exhibit slower initial growth compared with later cohorts when temperature is higher.

Longevity in *P. leopardus* is at least 17 years (Lou et al. 2005, Williams et al. 2008b) and estimated to be similar for both *P. maculatus and P. areolatus*. Growth of *P. leopardus* was first estimated by Ferreira and Russ (1994) for the northern GBR. Growth is fast in the first 2-3 years and slows to an asymptote as they get older. In the Torres Strait growth between *P. leopardus* and *P. maculatus* is similar but *P. areolatus* are larger for a given age and grow to a larger average maximum length (Williams et al. 2008b). *P. leopardus* can reach sizes in excess of 70 cm fork length and 7 kg in weight.

Size and age at first reproduction in *P. leopardus* was first estimated to be 24 – 36 cm fork length, and 2-4 years from samples collected in the northern GBR, while sex change can occur across a wide range of sizes and ages (Ferreira 1995). *P. maculatus* also show similar reproductive strategies as *P. leopardus* with first maturity at ~ 30 cm fork length and 2 years of age and sex change can occur across a wide range of sizes and ages (Ferreira 1993). More recent work from the Torres Strait indicate *P. maculatus* are capable of reaching maturity (~ 26 cm fork length) and changing sex at smaller sizes than *P. leopardus* (Williams et al. 2008b). *P. areolatus* appear to mature later (~ 32 cm fork length), change sex at larger sizes and older ages, and change sex across a more limited size range (Williams et al. 2008b).

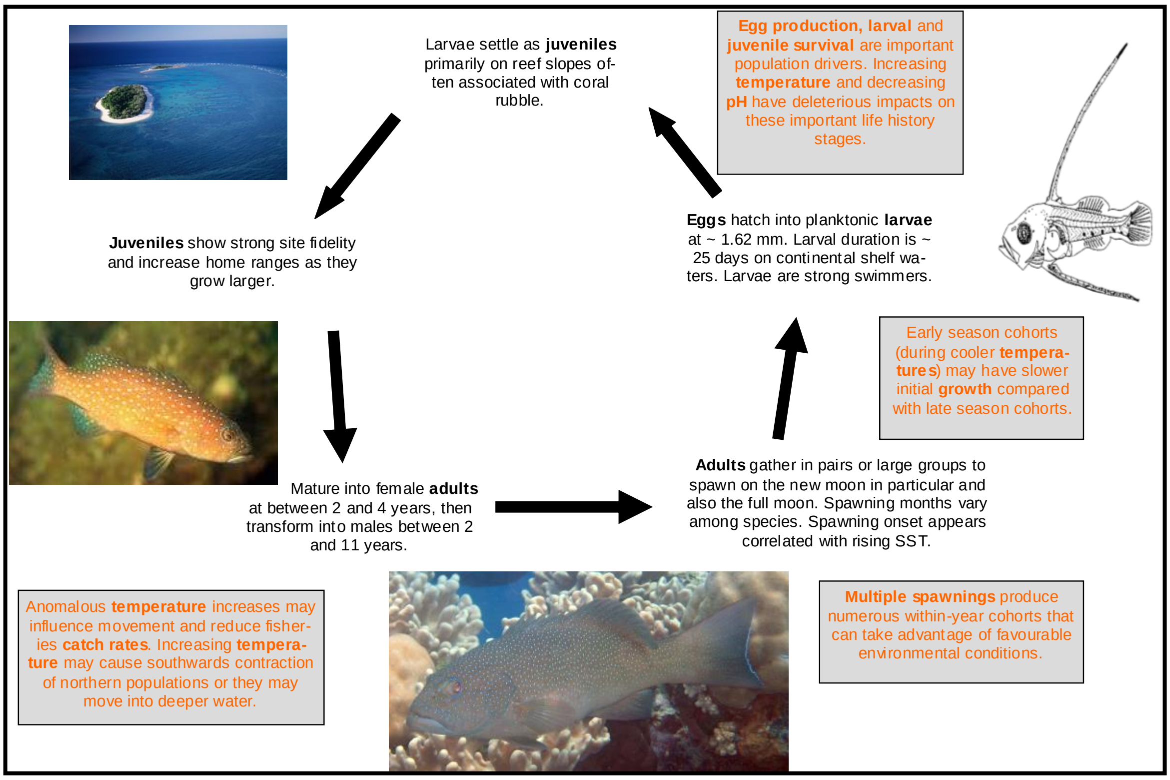

Figure 21. Generalised life cycle of coral trout (based on *P. leopardus*). Source: Welch et al. (in review).

In assessing microhabitat preferences for juvenile *P. maculatus*, although a range of different microhabitats were used, Wen et al. (2012) found that approximately 60% of all fishes (127/212) preferred *Acropora* corals situated on loose substrates (e.g. sand), despite this specific microhabitat accounting for only 12.8% of benthic cover in the study areas. It is likely that other species of coral trout will have preferred micro-habitats during early and adult life history stages. Given the broad diet of *P. leopardus*, and because the two major prey families (Pomacentridae and Labridae) are diverse and abundant on coral reefs, St John et al. (2001) concluded that coral trout are resilient to changes in abundances of particular prey species.

Climate sensitivity

Research by Tobin et al. (2010) demonstrated depressed catch rates of coral trout on the GBR following tropical cyclone (TC) Hamish in 2009, a large Category 5 cyclone. The impact on the fishery was environmental, social and economic as some boats had to move substantial distances to other ports to remain profitable, or remain in their home port resulting in loss of fishing time and crew. The shift to other regions also caused localised stock depletions in some areas and increased conflict regarding resource use. The research also examined TC Justin (1997) which, although a less intense system was a long-lived cyclone, and resulted in significant decreases in coral trout catch rates accompanied by significant increases in catch rates of red throat emperor (*Lethrinus miniatus*), the secondary target species of the GBR reef line fishery. Underwater visual surveys conducted following TC Hamish documented structural reef damage as high as 66% on some reefs however the same surveys also observed nominal increases in coral trout abundances. There was no apparent correlation between sea surface temperature and catch rate. For TC Justin however, a distinct cool water anomaly post-cyclone was found to be the most likely driver of decreased coral trout catch rates (reduced by up to ~50 %) and increased red throat emperor catch rates (increased by up to ~200%) (Tobin et al. 2010). The impacts were spatially and temporally variable for each TC making general statements about likely impacts of cyclones highly uncertain. Such water incursions can also be induced through upwelling and changes in water current patterns and pathways on the GBR are poorly understood.

Recent experimental studies on the effects of temperature and water chemistry on *P. leopardus* have greatly advanced our knowledge of the sensitivity of coral trout, and potentially other coral reef fish. Under different temperature regimes ranging from 24 °C to 33 °C, Pratchett et al. (2013) found that survival of larval coral trout is significantly reduced at increased temperatures above 28°C during the endogenous nutrition phase. The endogenous nutrition phase is the period between developing embryo and first feeding on live prey items (exogenous feeding). The study also found that at higher temperatures larvae had smaller initial yolk reserves, increased metabolic rate, were significantly smaller at the end of the endogenous phase, and had a more restrictive diet due to a smaller mouth gape, explaining the higher mortality observed. Further, at higher temperatures the duration of coral trout sperm motility was decreased, egg hatching rate was lower, and egg development showed increased irregularities. pH did not appear to have any impact on egg development and survival (Pratchett et al. 2013).

Pratchett et al. (2013) found no difference in thermal sensitivity between northern and southern coral trout populations (separated by > 1200 km). The implications of this are that northern populations, including those in the Torres Strait, that have higher mean sea temperatures are likely to express responses to warming waters before southern populations. This could be a contraction of the species range southwards or redistribution of fish to deeper waters. At temperatures greater than 30 °C the energy demands on coral trout became so great that normal function is likely to be compromised (Pratchett et al. 2013).

A related experimental study found that juvenile *P. leopardus* are sensitive to changes in water chemistry. At elevated levels of acidified water juvenile coral trout became more attracted to the odour of predators and were significantly more active and more inclined to move away from shelter, making them more vulnerable to predation. Munday et al. (2012) reared juvenile coral trout in laboratory conditions under different levels of pCO_2 (~495, 570, 700 and 960 µatm). The results showed that above 600 µatm CO_2 fish were more active and ventured further from shelter, and actually were attracted to the odour of predators. Similar research on a larval coral reef fish (*Amphiprion percula*) also showed a breakdown in the olfactory abilities in detecting predators with changes in water pH (Dixson et al. 2010). The levels of acidification above which negative responses became apparent are not projected to occur until later this century.

The thermal tolerances of coral trout would appear to have an upper threshold of approximately 30°C (Pratchett et al. 2013). This corresponds with known distributions for *P. leopardus*, *P.*

maculatus and *P. laevis* which occur across a wide range of latitudes with water temperature ranges from approximately 22 – 30 °C, suggesting a wide temperature tolerance. Coral trout also use rising sea water temperatures as a cue for spawning (> 24 °C on the GBR; Samoilys 1997) and so under climate change scenarios of increasing water temperatures are likely to avoid the critical thermal thresholds that negatively affect larval development described above resulting in earlier spawning.

Coral trout appear to have preferred micro-habitat, particularly at the juvenile stage, which may be important for early survival (Wen et al. 2012), although they do inhabit a variety of micro-habitats. The predicted climate change impacts on coral reef habitats (Bell et al. 2011a, Pratchett et al. 2011) could therefore indirectly influence coral trout population replenishment and exacerbate the effects of more direct impacts such as temperature and water chemistry. General conclusions have also been made about coral reef fish, stating that warmer water temperatures are likely to increase larval development thereby reducing the planktonic larval stage, which in turn will reduce dispersal capabilities and alter spatial scales of connectivity (Munday et al. 2009).

Sea cucumber

Fishery characteristics

In the Torres Strait historically there have been at least 22 different species targeted however in recent years there has been very little activity in the fishery due to the ban on taking some of the highest value species due to declining abundance. The sandfish (*Holothuria scabra*) has historically been the primary target species and in 1995 it was estimated that 1200-1400 t was harvested. Due to significant population declines a zero TAC for sandfish was implemented in 1998 and since then surveys indicate stocks have not yet recovered to fishable levels[5] (Murphy et al. 2011). Other species with a zero TAC are black teatfish (*H. whitmaei*) (since 2003) and deepwater redfish (*Actinopyga echinites*) (since 2003). Currently the main target species in the fishery are white teatfish (*H. fuscogilva*) which has a TAC of 15 t, and prickly redfish (*Thelenota ananas*) which has a TAC of 20 t. There is also a combined TAC of 80 t for 18 other species that are sometimes harvested (SEWPaC 2011, Woodhams et al. 2012).

The bêche-de-mer or trepang fishery has historically been concentrated more in the eastern Torres Strait due to lower abundances in the west. Collection methods are by hand only and mainly by wading in shallow waters or by divers on snorkel. The sea cucumber fishery in the Torres Strait is almost exclusively commercial and it is not known to be taken for subsistence purposes (SEWPaC 2011). Sea cucumbers are harvested primarily for the fleshy body wall which can be either dried (trepang) or cooked (bêche-de-mer). Most of the product is exported to Asia. Participation in the fishery is limited to Traditional Inhabitants who must possess a TIB licence. There is one non-Traditional licence holder who has had a long history in the fishery. Since 2008 there have been only three active fishers in the Torres Strait (two in 2011) and very little commercial catch has been reported since 2005. The total reported catch in 2010 was only 600 kg however in 2011 the total was 25.5 t comprising mostly *H. fuscogilva* and *T. ananas*. The fishery is managed by the AFMA on behalf

[5] Recovery of sandfish populations appears to have been compromised by poaching from PNG Nationals (Murphy et al. 2011).

of the PZJA and uses a combination of limited entry (TIB only), vessel and gear restrictions, size limits and TACs (Woodhams et al. 2012).

Life cycle

Life history information documented here is generalised for all sea cucumbers unless individual species are indicated. It is acknowledged however that the species-specific biology and ecology can be highly variable (Welch in review).

Sea cucumbers are benthic animals found mostly on soft substrates such as sand and mud however they are usually associated with seagrass, algae and corals. Tropical sea cucumbers are primarily broadcast spawners with fertilisation taking place in the water column however some species exhibit asexual reproduction by transverse fission (Uthicke 2001a). Broadcast spawning is generally annual or bi-annual. Though some species (e.g. *H. scabra*) are capable of spawning year-round in warmer waters such as the Torres Strait (Morgan 2000a), and asexual reproduction occurs in early winter (Uthicke 2001a). Temperature appears to be the main cue to spawning though there may be other exogenous cues and is often linked to lunar cycles. Spawning seasons are generally Spring-Summer and can vary by species and spatially (Morgan 2000a) with a few species preferring to spawn during winter (e.g. black teatfish, *H. whitmaei*; Shiell and Uthicke 2006). *H. scabra* is currently the only tropical sea cucumber that can be mass reared in hatcheries, although recent developments suggest that broad-scale culture of white teatfish and curryfish (*Stichopus* spp.) may also be possible (Hamel et al. 2001, Purcell et al. 2009, Hu et al. 2010). Holothurian broodstock are induced to spawn generally by raising the tank water by 3-5 °C (Morgan 2000b), however the introduction of micro-algae into tank water has also been shown to trigger spawning in a number of holothurians species (Battaglene 1999).

Egg development in holothurians is generally short (24 hrs) and the planktonic larval duration varies among species and for some of the key harvested species ranges from 12 – 22 days (Ramofafia et al. 2003). In cultured situations for *H. scabra* temperatures are kept between 26 °C and 29 °C during larval development. Larvae feed on different species of micro-algae and successful metamorphosis has been shown to be dependent on the algal species consumed. One of the better algal species, *Chaetoceros muelleri*, is very tolerant of high temperatures (Battaglene 1999). Larvae develop through the feeding stage auricularia, the non-feeding doliolaria, and the pentactula stage which develops tentacles and settles (Figure 22; Ramofafia et al. 2003). Preferred habitat type for settlement appears to be on seagrass leaves for *H. scabra* (Mercier et al. 2000a) with cues including the presence of particular food types such as diatoms and certain bacteria (Battaglene 1999). Very little is known of the larval movement and settlement processes of *H. scabra* in the wild (Conand 2006).

Growth rates of sea cucumbers are also poorly understood but are generally believed to be slow with low overall productivity (Uthicke et al. 2004). Hu et al (2010) were able to grow curryfish (*Stichopus* sp.) juveniles to approximately 20 cm within seven months in a hatchery. Aging of holothurians in the wild has not been possible however modelling by Uthicke et al. (2004) suggested that *H. whitmaei* are long-lived (potentially several decades). Modelling by Uthicke et al. (2004) also suggested that *H. whitmaei* recruitment is low and sporadic due to the apparent slow rate of population recovery after overfishing. A study of *H. scabra* in the Solomon Islands found monthly recruitment of newly-settled juveniles (Mercier et al. 2000b).

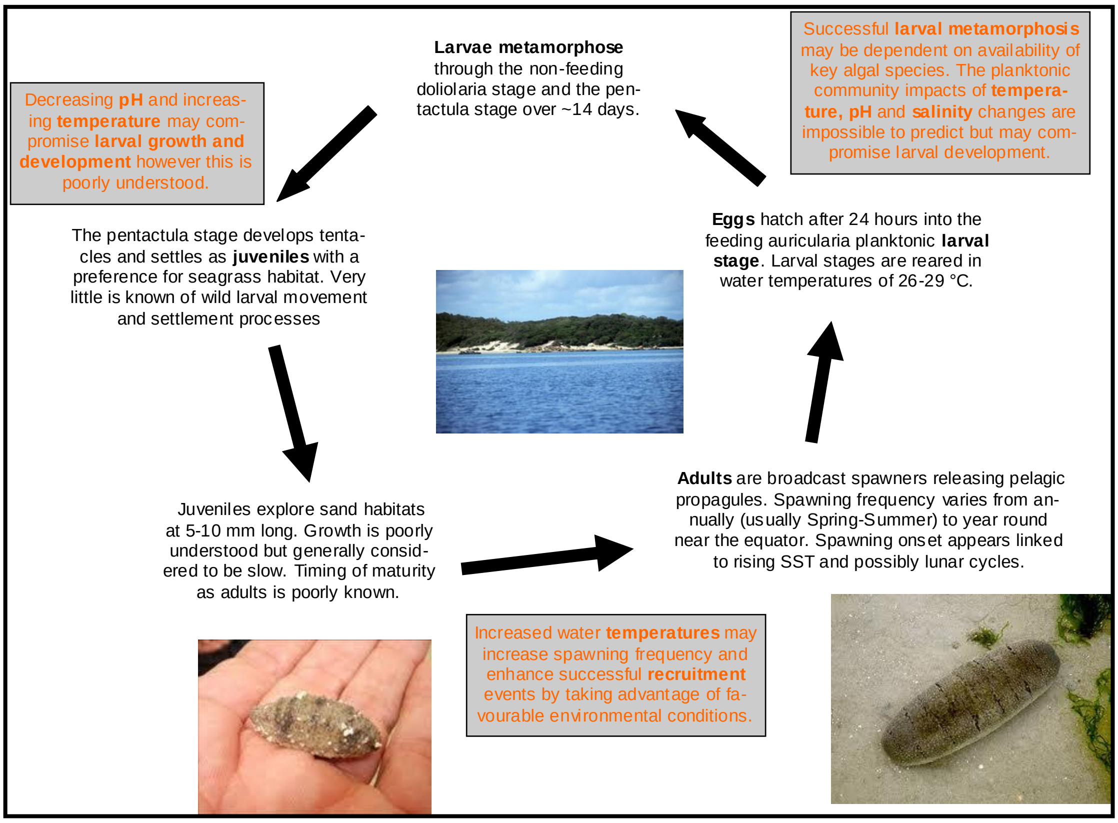

Figure 22. Generalised life cycle of the sandfish, *Holothuria scabra*. Source: Welch, in review.

Climate sensitivity

Rearing of sea cucumbers for restocking and/or to supplement over-fished wild stocks has elucidated optimal conditions for rearing larvae of some tropical sea cucumber species. These include *H. scabra*, *A. echinites* and *H. atra* and optimum temperature ranges for these species is between 27 °C and 30 °C (Chen and Chian 1990, Ramofafia et al. 1995, Battaglene 1999). In a study of a tropical sea cucumber commercially harvested in India until the fishery collapsed in 2001, the effects of temperature, pH and salinity on growth and survival of *H. spinifera* larvae were experimentally determined (Asha and Muthiah 2005). When comparing the temperatures 20, 25, 28 and 32 °C they found that growth and survival was far greatest at 32 °C, however this also reduced the time to settlement and therefore is likely to reduce dispersal capabilities. Growth was significantly affected by salinity with 35 ppt the best salinity when compared with 15, 20, 25, 30 and 40 ppt. Comparing pH of 6.5, 7.0, 7.5, 7.8, 8.0, 8.5 and 9.0 they found that survival was significantly enhanced at 7.8 (83% survival), at 9.0 there was 0% survival. At all other pH regimes survival ranged between 47 and 60%. Comparisons of growth however, could not be carried out since deformities occurred in larvae in all pH regimes except for 7.8 (Asha and Muthiah 2005).

The major holothurians targeted by tropical fisheries possess microscopic components in their body wall called spicules which form the internal skeleton. These spicules are calcareous as is the peripharyngeal ring (Conand 2006). The effects that ocean acidification may have on the development in these species is unknown. Experimental studies on different species of the Phylum

Echinodermata, of which sea cucumbers are part of, to changes in seawater pH had varying results and included reduced fertilisation rates and reduced larval sizes (sea urchin, *Echinometra mathaei*; Kurihara and Shirayama 2004) and reduced survival and larval size (sea urchin, *Tripneustes gratilla*; Clark et al. 2009). Given species-specific responses to changes in pH and other environmental variables, potential impacts on sea cucumbers will remain highly uncertain without studies on the species of interest however (Welch, in review).

Spawning seasons of many sea cucumbers are during Spring-Summer and with forecast temperature increases this may cause spawning to begin earlier or spawning may even become year round as seen in *H. scabra* close to the equator (Morgan 2000a). Reproductive success in species that spawn during winter (e.g. *H. whitmaei*) may be compromised and any such impacts will be evident earlier in warmer regions, such as the Torres Strait. Upper thermal limits for spawning and larval growth and development are not known however cultured holothurian larval stages are currently raised in 26 – 29 °C water (Battaglene 1999).

Dugong

Fishery characteristics

The Torres Strait Dugong fishery is a traditional subsistence fishery limited to Traditional Inhabitants of the Torres Strait. The dugong, *Dugong dugon*, has been hunted in the region for thousands of years and is an important part of the traditional way of life and livelihood of Torres Strait Islanders. They are a very important source of protein in the diet of Torres Strait Islanders, predominantly through the use of dugong meat and oil. In fact, dugong meat is ranked the highest of all traditional foods in the region, and the practice of hunting dugong and the prowess attached to it represent important Aboriginal and Islander traditions (Marsh et al. 2004). Dugong may only be taken as part of traditional fishing and can only be used for traditional purposes.

Although harvest levels of dugong have always been uncertain, annual harvest estimates obtained from a number of different surveys between 1976/77 and 2000/01 varied between approximately 110 – 1,010 animals (Skewes et al. 2002, Marsh et al. 2004). Most of this harvest came from the western Torres Strait with Badu and Mabuiag Islands being important hunting areas. Due to limited data on current harvest levels, dugong movements and population sizes, there is uncertainty in determining sustainable harvest levels for the Torres Strait (Grayson et al. 2006). Using a combination of estimation methods several earlier studies concluded that the recent estimates of dugong harvest in the Torres Strait were unsustainable (Heinsohn et al. 2004, Marsh et al. 1997, 2004). Despite this, a recent report analysing the time series of aerial surveys of dugong population in Torres Strait note that there is no significant decline in numbers detected since the mid-1980s and that the TS dugong population exceeds 12,000 animals and the population is genetically healthy (Marsh et al. 2011). These authors also note that there are several lines of evidence that suggest dugong are vulnerable to overexploitation or may be showing signs of this already occurring and, given the uncertainty concerning their sustainability, planning for management of dugong fisheries in TS should proceed as the highest priority.

The fishery is protected by the Torres Strait Treaty between Australia and PNG, which preserves the right of Traditional Inhabitants to harvest dugong for traditional purposes (Marsh and Kwan 2008).

Recently, community-based Turtle and Dugong Management Plans have been developed by individual Torres Strait Islander communities and are being implemented on a voluntary basis throughout the Torres Strait with the assistance of the Torres Strait Regional Authority (e.g. TSRA 2011b). Each management plan includes a range of culturally-based management arrangements that have been agreed to by each respective community[6]. The main regulations currently implemented in the Torres Strait dugong fishery include: harvest by Traditional Inhabitants only; can only be taken using traditional spear (wap); cannot be taken from or carried in commercial fishing vessels greater than 6 m; and hunting is banned in the Dugong Sanctuary in the western Torres Strait, noting that this sanctuary is not enforced (Kwan et al. 2006).

Life cycle

The dugong occurs across most of northern Australia from Shark Bay in Western Australia to Moreton Bay in Queensland. The Torres Strait supports the largest population of dugongs in Australian and probably the world (Marsh et al. 1997, 2011). Most (89 %) of the high and very high density dugong habitat is located outside of the major hunting grounds for dugong (Marsh et al. 2011). It has a panmictic genetic population structure and some individuals move large distances; up to hundreds of kilometres. Therefore the abundance of dugongs is highly variable spatially and temporally (Grayson et al. 2006).

As mammals, adult dugong have separate sexes with females growing slightly longer than males and males showing tusks at a much smaller size and younger age than females (Marsh et al. 1984). Animal autopsies have shown that reproductive activity is not continuous throughout the year and mating activity takes place more in the latter half the year from about May to October. The gestation period is 13-15 months and the size of neonates can be quite variable, between 1.0 – 1.3 m long and 20 – 35 kg in weight. Dugongs usually give birth to only one live young and can lactate for at least 1.5 years even though young dugong begin eating seagrass soon after birth. The rate of pregnancy is thought to be very low with females giving birth every 3 – 7 years (Marsh et al. 1984). Male and female dugongs are estimated to reach maturity at 9 – 10 years old or older and at a size of between 2.2 – 2.5 m (Figure 23). Males with protruding tusks are assumed to be sexually mature. Dugongs are long-lived and thought to have a lifespan of at least 50 – 60 years (Marsh et al. 1984). Population modelling based on these life history traits suggest that population maintenance would require low mortality rates.

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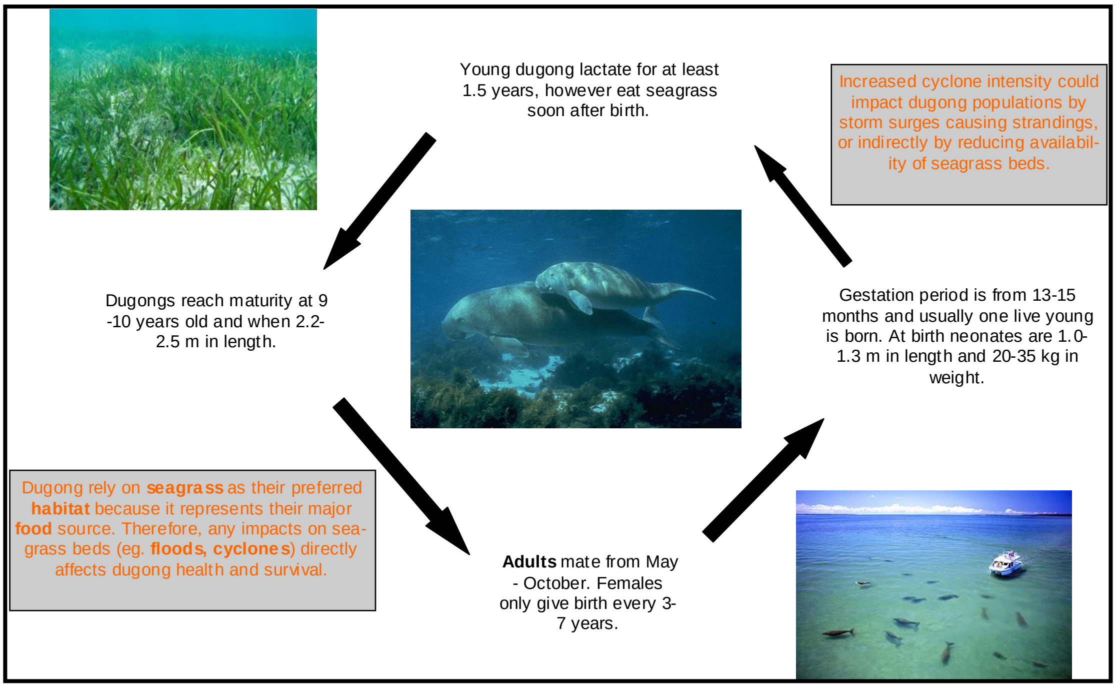

Figure 23. Generalised life cycle diagram of dugong in the Torres Strait.

Climate sensitivity

Information is limited on the influence of environmental variability on dugong. There is however strong evidence of the dependence of dugong on the availability of seagrass, their major food source (Lawler et al. 2007). In fact, the extensive seagrass meadows in Torres Strait are likely to be the reason why the Torres Strait is such a globally important region for dugong. These seagrass communities have been shown to experience natural episodic diebacks which have resulted in decreases in dugong abundance, as well as having negative effects on dugong condition and female reproductive rate (Marsh and Kwan 2008). Aerial survey population estimates of dugong in the Torres Strait from 1987–2001 found considerable temporal variability in the size of the dugong population, further supporting that dugongs undertake large-scale movements associated with temporal and spatial changes in the distribution of seagrass (Marsh et al. 2004).

High dugong mortality in Queensland after the 2011 floods was recorded with 168 reported deaths between January and October 2011, compared to 73 in 2010, 47 in 2009, and 35 in 2008 (Meager and Limpus 2011). Following this, targeted surveys from 2011 to 2013 documented a decline from >2000 to ~600 individuals (Sobtzick et al. 2012). These results are believed to be due mainly to starvation associated with the loss of seagrass meadows (Bell and Ariel 2011). In another study in Western Australia, dramatic changes in dugong abundance at three locations was concluded to be largely driven by a southerly migration of northern animals in response to seagrass foraging grounds being negatively impacted by the passing of a cyclone (Gales et al. 2004).

Episodic diebacks of seagrass communities in Torres Strait are most likely caused by light deprivation resulting from sediment re-suspension brought about by prolonged periods of monsoon winds and/or extreme weather events such as cyclones (Marsh and Kwan 2008).

Strong storm surges have also been documented to cause significant strandings of dugong likely resulting in their mortality (Limpus and Reed 1985). Dugongs are a naturally low productivity species and are currently listed as vulnerable to extinction at a global scale by the IUCN (Marsh et al. 2004).

Turtle (principally *Chelonia mydas*)

Fishery characteristics

The Torres Strait turtle fishery is a traditional subsistence fishery limited to Traditional Inhabitants of the Torres Strait. Turtles have been hunted in the region for thousands of years and are an important part of the traditional way of life and livelihoods for Torres Strait Islanders (Grayson et al. 2006). Turtles may only be taken as part of traditional fishing and can only be used for traditional purposes. The Torres Strait turtle fishery is comprised of two components: the harvesting of animals for meat and the harvesting of eggs. The most common turtle species in the Torres Strait is the green turtle (*Chelonia mydas*) which is harvested for meat and eggs and is the dominant harvest species (Harris 1997). The other two species targeted in the turtle fishery are hawksbill (*Eretmochelys imbricate*) and flatback turtles (*Natator depressus*) but generally only for their eggs. Both turtle meat and eggs are harvested for subsistence and not for sale. The three other marine turtle species found in the Torres Strait are loggerhead, leatherback and olive ridley turtles all of which are relatively uncommon and rarely hunted. There is no known nesting of these species in the Torres Strait (DEWR 2007).

Green turtles are caught on all islands throughout the year however catches peak in the mating season from September to January. Green turtles are known to nest in the north-eastern Torres Strait on Bramble Cay, the Murray Islands and Tudu Island. Hawksbill turtles are the second most-common species found in the Torres Strait, usually in the inner islands. Flatback turtles are rarely hunted in the Torres Strait because Islanders do not like their taste. They are known to nest in the north-western areas of the Torres Strait as well as on Crab Island in the southern Torres Strait, which is the largest known nesting site for flatback turtles in the world.

Surveys between 1996 and 2001 estimated the annual total harvest of green turtles in the Torres Strait to be 1,896, 1,097, 1,507, and 1,619 annually for 1996, 1998, 1999 and 2000/01, respectively. The level of annual harvest of eggs of all species is unknown (Skewes et al. 2002). Although turtles are caught throughout the Torres Strait most are taken in the western and central regions with Warraber Island being particularly important.

There are no population estimates for turtle stocks in the Torres Strait due to difficulties in estimation, however recent monitoring of key turtle nesting sites in Queensland has raised concerns with respect to green and hawksbill turtle stocks. With no estimate of turtle population size, and no accurate estimates of the traditional harvest of turtles, it is not known what level of annual turtle catch in the Torres Strait would be sustainable.

The fishery is protected by the Torres Strait Treaty between Australia and PNG which preserves the right of Traditional Inhabitants to harvest turtle for traditional purposes (Marsh and Kwan 2008). Recently, community-based Turtle and Dugong Management Plans have been developed by individual Torres Strait Islander communities and are being implemented on a voluntary basis throughout the Torres Strait with the assistance of the Torres Strait Regional Authority (e.g. TSRA 2011b). Each management plan includes a range of culturally-based management arrangements that have been agreed to by each respective community[7]. The main regulations currently implemented in the TS turtle fishery include: harvest by Traditional Inhabitants only and prohibition of take from or carried in commercial fishing vessels greater than 6 m.

Life cycle

All marine turtle species generally have a similar life cycle. Marine turtles show strong site fidelity to particular areas for foraging, and migrate every few years for breeding, sometimes for hundreds or thousands of kilometres, although migration distances can vary greatly (Plotkin 2003, Kennett et al. 2004). Once mature and breeding each turtle are thought to return to the beach from which they hatched as their preferred nesting beach (Meylan et al. 1990).

Mating generally occurs in early summer and takes place offshore from breeding beaches a month or two before the female's first nesting attempt for the season. During a breeding season a female green turtle can lay up to six clutches of eggs at about 14 day intervals, each with approximately 100 eggs. This is possible because the female has a sperm store to fertilise each subsequent egg clutch. Fecundity varies slightly between species. Once females begin laying eggs the males generally make the return trip back to foraging grounds (Harris et al. 2000, Arthur et al. 2008).

When the female is ready to lay eggs she crawls up the nesting beach and, once she finds a suitable location, will excavate a hole in the sand about 30 to 60 cm deep in which she will lay her eggs. She will then bury the eggs with sand and crawl back to the sea. The eggs vary in size among species and are generally between 4 and 7 cm in diameter. This whole process takes 1-2 hours and is physically very demanding on the turtle. The female will then prepare her next egg clutch in adjacent waters, and after laying the last clutch will return to the foraging grounds. Females only migrate to breed once every two to eight years.

The temperature of the nest during incubation is a critical determinant of hatchling gender. In warmer dark sand mostly females are hatched, while in cooler white sand mostly males are hatched. Males also tend to take longer to hatch. Hatching occurs 7-12 weeks after laying and it can take hatchlings two or more days to reach the sand surface. Hatchlings from each clutch tend to emerge from the sand at the same time and generally at night. They then crawl their way to the sea, generally by orienting themselves towards the brightest light, and, using a combination of environmental cues such as waves, currents and magnetic fields, then swim to deeper offshore areas. Crossing the beach and swimming away is believed to imprint the hatchlings with the cues necessary to find their way back when they are ready to breed. It is believed that most of the mortality in the first year of green turtles is caused by predation while crossing the reef crest in the first hour after entering the sea (Gyuris 1994).

Once in deeper water it is thought that hatchlings associate with floating seaweed and other flotsam caught up in ocean currents where they drift and have an omnivorous diet (Musick and Limpus 1997). The following period of their life is least known as they are rarely seen again until, for green turtle, their carapace length is approximately 44 cm when they return to inshore foraging grounds. In the Torres Strait, mature turtles returning to inshore foraging grounds will change their diet to be

[7] www.pzja.gov.au

herbivorous eating mainly seagrasses and macroalgae (Andre´ et al. 2005). This may be 5-10 years after hatching (Arthur et al. 2008). Turtles are very slow to grow and depending on the species can take 30-50 years to mature into breeding adults. Once mature they begin to undertake migrations to breeding locations (Figure 24).

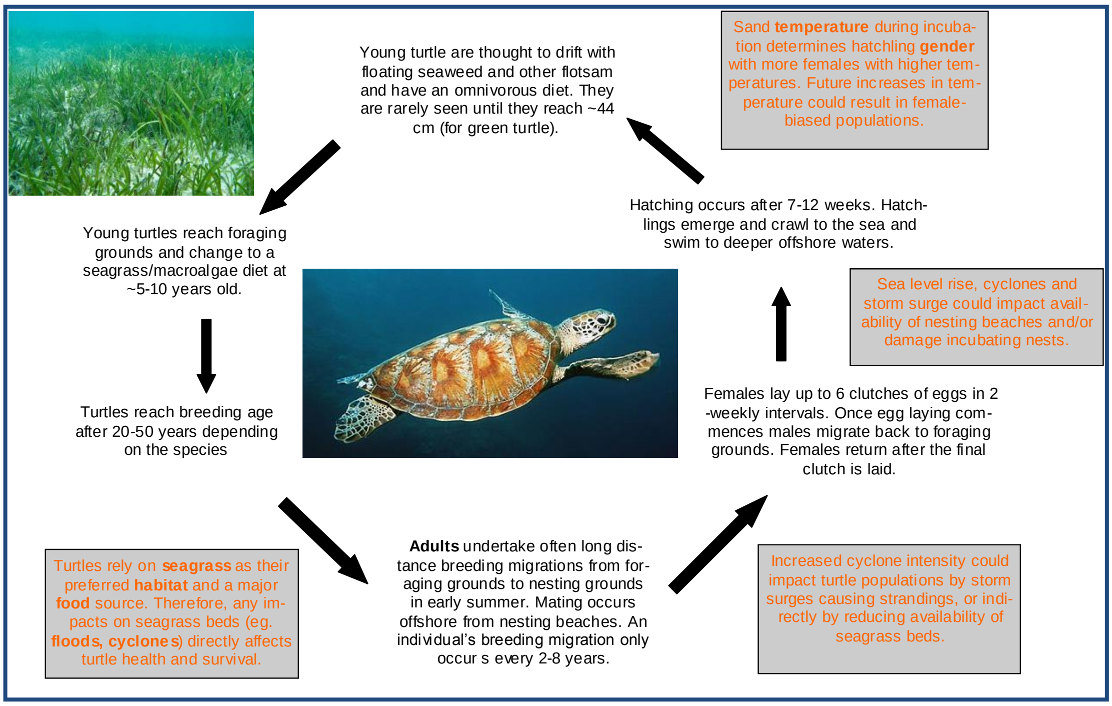

Figure 24. Generalised life cycle diagram for turtles in the Torres Strait.

Climate sensitivity

Turtles are ectotherms and as such their life history traits, behaviour and physiology are influenced by temperature (Hamann et al. 2007). It is well documented that the sand temperature during incubation of egg clutches is critical in determining the gender of hatchlings with low temperatures producing males and high temperatures producing females (Yntema and Mrosovsky 1982). The preferred temperature range for successful incubation is between 25 – 35 °C and the pivotal temperature for gender determination appears to be between 28 and 31 ° C (Hawkes et al. 2009). Increasing surface temperatures are predicted to produce a highly female biased population in the future, however, it may also increase the availability of thermally suitable beach areas for nesting that are currently not used (Hawkes et al. 2009). Local rainfall patterns may also alter the successful incubation of eggs and gender ratios of hatchlings with higher rainfall lowering sand temperatures.

Turtles rely on suitable beach zones for nesting and there are a number of environmental variables that can affect this. Sea-level rise has the potential to compromise the availability of nesting sites, particularly where coastal development exists or beaches are narrow (Hawkes et al. 2009, Fuentes et al. 2010). Cyclones and storm surges can also impact on these sites and the success of breeding. Storm surges have been shown to decrease the number of nests that develop to hatching stage and the number of hatchlings per clutch through inundation, although this may vary among species depending on their attachment to nesting sites and the timing of their nesting. The green turtle may be the turtle species most at risk to cyclone related inundation as their nesting occurs during the height of the tropical cyclone season (Pike and Stiner 2007).

Climate-related impacts have already been observed for green turtles in regions adjacent to Torres Strait. Storm surge from TC Kathy during 1984 in the Gulf of Carpentaria is documented to have physically thrown large numbers of green turtles up on the shoreline with an estimated 500 animals left stranded, some up to 9 km inland (Limpus and Reed 1985). Despite an extensive rescue effort it was estimated that at least 20% of stranded turtles died. During the extreme flooding in Queensland in 2011, approximately 1,100 turtles (mostly green turtles) were reported as stranded on the coast, compared with 624 in the same period in 2010, 715 in 2009, and 645 in 2008 (Meager and Limpus 2011).

Turtles have a varied diet including green turtle populations, however they are assumed to be herbivorous once they move to inshore foraging grounds and so they have a dependence on seagrass beds, algal beds and mangrove growth. There is data from the Torres Strait that suggests that any impact on seagrass beds results in turtles in poorer condition (Marsh and Kwan 2008). Also, inter-nesting intervals have been shown to be shorter when sea temperatures are warmer (Hays et al. 2002).

All turtle species have naturally low productivity and are listed internationally as either endangered or critically endangered. From an Australian perspective, all marine turtles are protected in Commonwealth waters/territory by the Environment Protection and Biodiversity Conservation Act (2000). Under this act the loggerhead and olive ridley turtles are listed as ‘endangered’ and green, leatherback and hawksbill turtles are declared ‘vulnerable’.

Overview of potential impacts based on species reviews

Based on the literature searches for climate sensitivity of the key species reviewed, and on interviews conducted with TS Islanders (see section below), Table 10 presents a summary of the potential impacts on each species by 2030.

Table 10. Summary of the potential impacts on key TS fishery species based on literature searches and interviews with TS Islanders.

Species	Key potential impacts of climate change (based on 2030 projections)	Source
Coral trout – common/barcheek/ passionfruit	Increases in intense storm activity may reduce the catchability of coral trout. Increased water temperatures may reduce survival and development of egg and larval stages resulting in lower population sizes. Adults may also move south or to deeper water. Changes to coral reef habitat may affect juvenile survival.	Tobin et al. 2010 Pratchett et al. 2013 Wen et al. 2012
Dugong	Projected declines in sea grass will likely negatively affect dugong populations due to their strong association with sea grass beds as their preferred habitat and their primary food source. More intense storms may also directly increase dugong mortality through strandings.	Bell and Ariel 2011; Gales et al. 2004; Marsh and Kwan 2008 Limpus and Reed 1985
Blue endeavour prawn	Predicted negative impacts on sea grass beds may decrease juvenile growth and survival. Increases in temperature may compromise growth and survival due to being near their northern range limit and Torres Strait is assumed to be a single stock.	Coles et al. 1987 O'Brien 1994
Brown tiger prawn	Predicted negative impacts on sea grass beds may decrease juvenile growth and survival. Increases in temperature may compromise growth and survival due to being near their northern range limit and Torres Strait is assumed to be a single stock.	Young and Carpenter 1977; Staples et al. 1985; Coles et al. 1987 O'Brien 1994
Turtle	Increasing air temperatures are likely to result in strongly female biased populations due to thermal influence on gender during incubation. Sea level rise, more intense storms and extremes in rainfall are likely to decrease available nesting sites and disrupt successful nesting through inundation. More intense storms may also increase mortality of local populations through strandings. Predicted negative impacts on sea grass beds may impact on turtle growth and survival.	Yntema and Mrosovsky 1982 Fuentes et al. 2010; Hawkes et al. 2009; Pike and Steiner 2007 Limpus and Reed 1985 Marsh and Kwan 2008
Trochus	Unknown and previously assessed as minor.	Bell et al. 2011a
Sandfish	Generally unknown.	
Black teatfish	Reproductive success may be compromised with an increase in water temperatures since they spawn during winter.	Shiell and Uthicke 2006
Tropical rock lobster	Increases in water temperature may promote faster growth and higher larval supply, but may decrease juvenile survival. The net result may be a reduction in spawning biomass. Adults may move to deeper water with increases in water temperature. Changes in currents in the northwest Coral Sea may impact on settlement areas and recruitment rates.	Norman-Lopez et al. 2012; Plaganyi et al. 2011 TS Islanders Pitcher et al. 2005
Mud crab	Higher temperatures may result in higher catch rates. Projected increases in (overall) rainfall and rainfall extremes may increase mud crab populations.	Meynecke et al. 2012; Williams and Hill 1982 Loneragan and Bunn 1999;

		Halliday and Robins 2007; Meynecke et al. 2012; Robins et al. 2005
Spanish mackerel	Possible links between water temperature and larval survival but generally unknown.	Harry et al. unpublished data
Gold-lipped pearl oyster	Increases in rainfall extremes may reduce larval growth in some years due to reduced salinity.	Doroudi et al. 1999
Black-lipped pearl oyster	Increased water temperature may result in a lower abundance due to upper thermal limits of ~32° C for adults and reduced larval growth > 29° C.	Yukihira et al. 2000; Doroudi et al. 1999

Torres Strait Islander interviews

Ten community members local to the Torres Strait were interviewed for the project and asked a series of 12 questions (Appendix 2). Respondents came from a range of islands in the region – Warraber, Horn, Thursday, Iama, Erub and Moa Islands – and represented different backgrounds and fishing experiences; summarised in Table 11. The information collected was treated in a way that makes it impossible to attribute any response to individuals. The summary of results below collates all the responses into relevant categories and no respondents have been identified.

Table 11. Summary table of respondents' background and experience.

Years fishing	Average	27.3 years
	Maximum	50 years
	Minimum	1 year
Fishing type	Predominant[8]	Commercial (6)
	Sole activity	Recreational/cultural (3)
	Other	Processing (1)
Fishing locations	Warraber Island, Warrior Reefs, Thursday Island, Iama Island, Badu Island, Mabuiag Island, Aureed Reefs, Erub Island	
Species targeted (in descending order)	Tropical rock lobster, mackerel, reef fish, turtle, dugong, trochus, pearl oyster, sandfish	

Observed changes in sea conditions and fisheries

Many questions focused on whether the respondents had noticed or experienced any changes in sea conditions, fisheries catch rates, target species size or locations of catch. These questions aimed to document whether changes were already occurring in Torres Strait, and if these might be related to climate conditions. Some respondents (n=4) reported observing changes in sea/habitat conditions and many (n=7) reported noticeable changes in fisheries catches, sizes or locations of catch. However, climate was only attributed to some of these changes, with increased fisheries management and greater fishing effort identified as key drivers of these changes. A summary of responses is provided in Table 12.

Table 12. Changes experienced to sea conditions and/or fisheries in Torres Strait.

Observed changes in sea conditions
Noticed changing tides – bigger and earlier – and rougher sea conditions in winter.
Noticed sand covering fringing reefs during king tides that affects reef fish and other reef species.
Noticed changes in wave heights (+ 0.5 m) and erosion on islands and cays because of bigger waves.

[8] All commercial fishers also fished for recreational and subsistence purposes.

Also noticed sea conditions are harder to predict and the seasons are a bit delayed.
Anecdotal evidence of higher tides each year especially on low-lying islands such as Boigu, Saibai and Warraber, that cause erosion and impact on fringing reefs.
Observed changes to fisheries
Reef fish catch rates lower at reefs with high fishing effort.
It is well-known that when the water gets warmer lobster and trout go deeper and can be harder to catch. For example, in 2005, there were no lobsters caught during a hot summer period as they moved outside the main fishing areas and into deeper waters (> 25 m) where divers couldn't collect them.
Lobster catches are improving with more and larger animals collected.
There are fewer dugong and turtle available because there is too much hunting in the region.
Lobster are a seasonal fishery with the hot summer months the worst and the cooler winter months the best season. Lobster are smaller in Oct/Nov and larger in Mar/Apr.
Technology (e.g. GPS, hookah) has made catching lobster more efficient.
When the water is hot there are sometimes fish kills with reef fish washing ashore. Saw this in 2010/11 (hot summer).
Lobster catch lower when there are lots of boats around working on hookah as they target deeper lobster (20-30 m), and commercial fishers are taking too many.
Fisheries management has changed the commercial lobster industry.
Haven't seen lobster mating in last 2-3 years while in the past you'd see them mating on the reef. More abundance in lobster in winter when water temps are noticeable cooler than usual (with big catches in 2012 winter). Has noticed big changes in last 2-3 years with higher lobster numbers.
Fewer finfish and lobster caught around islands with lots of fishing effort, and have to travel further to catch both.
Noticed big changes in catches because of management decisions and habitat loss from trawling.
Unusual species observed
Noticed more sailfish in early 2013, which is unusual as they are usually rare.
More crown-of-thorn-starfish lately, sees 1-2 adults every dive. Sailfish also noticed in early 2013 and they're normally rare.
Sailfish sometimes around but not all the time and there were more observed in early 2013.
Seen bull sharks mid-2012, which is very unusual. Doesn't know why.

Awareness of climate change

The final questions focused on the awareness of respondents about climate change as an issue for fisheries in Torres Strait, and whether they would be able and prepared to change their fishing/hunting practices if there were impacts in the future. These responses were particularly important for scoring the adaptive capacity indicators of the vulnerability assessment. Although all respondents were aware of climate change as an issue for Torres Strait communities and fisheries, and many (n=7) had considered what the impacts might be for fisheries, none had taken any preparatory actions (i.e. developed future plans) to address the issue (summarised in Table 13).

Table 13. Summary of responses on climate change awareness.

Possible climate change impacts on fisheries
Warmer waters due to climate change will affect the lobster fishery as they move into deeper water and become harder to catch but the lobster won’t die.
Saltier water will affect corals and there will also be more coral bleaching (like in 2010). Changes in coral reefs will affect the fish targeted. Warmer waters will also affect the fish directly.
Climate change will affect lobster but hopefully not too much because they are the most important fishery in Torres Strait.
Climate change is too far in the future but expects target species will become smaller, there will be more storms moving sand and coastal vegetation, loss of some species, and higher king tides that will inundate low-lying islands.
Reduced availability of lobster product will affect the seafood processing industry, and ultimately, reduce industry viability.
Hasn’t thought about climate change much but thinks the abundance of lobster would be lower and there would be changes to currents that will affect lobster in deeper reefs. Lobster go deeper in hot water so would be harder to collect under climate change. Also, more pollution might be likely and this would affect commercial fisheries.
Global warming will affect fisheries catches as more waves and wind cause erosion and sand to cover fringing reefs, also higher water temperatures will cause coral bleaching, as seen in 2010. Reefs that bleached in 2010 are still not recovering and fisheries catches are low in these locations.
Lobster move in warmer water conditions but this is not a major issue for recreational fishers.
Climate change will have a big impact on lobster stock and the location you can collect them. Lobster are very sensitive to tides, water temperature, water clarity and availability of food. Knows of examples where lobster have moved to cooler waters during hot periods.
Capacity to change target species or fishing practices
Small commercial lobster fishers won’t be able to travel further distances as fuel is too expensive and boats are too small, and can’t dive deeper to collect lobster.

Lobster fishers can't target different species as they are set up for collection using hookah and there aren't any alternatives. Mackerel aren't abundant enough to catch commercially in large quantities, prawns require special vessels and are processed on-board and local fishers don't target reef fish commercially (just for subsistence).
Prepared to travel further from the island to catch fish but this will depend on weather conditions and the cost of fuel. Alternatively, they can buy fish to eat.
Hotter summers with changing tides will affect lobster catch (they go deeper in hot water >25 m) making them harder to collect.
Willing to change target species and catch whatever was available to eat.
Might consider *beche de mer* but unlikely to be successful because there are none available. Not many other options and most fisheries are specialised so can't change gear easily.
Willing to consider targeting trochus instead of lobster and perhaps *beche de mer* but only some reefs are open now for fishing.
Depends on market demand and what the processing plants are prepared to buy. Willing to target different species but doesn't think the processing plants would have the infrastructure to cope. Sandfish are profitable but they've now crashed.
Willing to target other species and travel further but depends on the cost of fuel.
Need for preparatory actions
There are no short-term business plans to deal with climate change issues because it's too far into the future.
Not sure what to expect from climate change and would like more information.
Management has been ill-conceived and not based on good data or traditional knowledge so doesn't believe it is effective or could allow for adaptation – too inflexible. Other pressures – increasing population, mining – are also impacting on fisheries and need to be considered in future actions.

All respondents felt their experiences and the changes they had noticed were the same or similar to experiences of other fishers, family members and friends who fished in Torres Strait.

Vulnerability assessment of Torres Strait fishery species

Fifteen fisheries species in the Torres Strait were assessed for their vulnerability to climate change by scoring the criteria for each of the framework indicators of Exposure, Sensitivity and Adaptive Capacity. The results table for all species is provided in Appendix 3.

Overall vulnerability

Species were grouped as high, moderate or low relative vulnerability to climate change based on their overall vulnerability scores (Figure 25). The species that showed the highest vulnerability was the black teatfish. Currently the fishery for black teatfish is closed and has been since 2003. Black-lipped pearl oyster was assessed as the second most vulnerable. Although the cultured pearl industry is of high economic value, pearl oyster harvest is currently thought to be very low in the Torres Strait and the black-lipped pearl oyster is the least common and of lesser importance compared to the gold-lipped pearl oyster. Dugong was also assessed as having high relative vulnerability to climate change. The traditional fishery for dugong has very important cultural significance to Torres Strait Islanders and is an important subsistence species. Similarly, turtle are also highly important culturally as well as for subsistence, and they were assessed as having moderate relative vulnerability (fifth highest overall). The other species assessed as having a high relative vulnerability was trochus. The trochus fishery has had very low harvest in recent times and does not rank highly in terms of economic value or quantity. All four species assessed to have a high relative vulnerability have important social and cultural values but are not economically important commercial species in the Torres Strait.

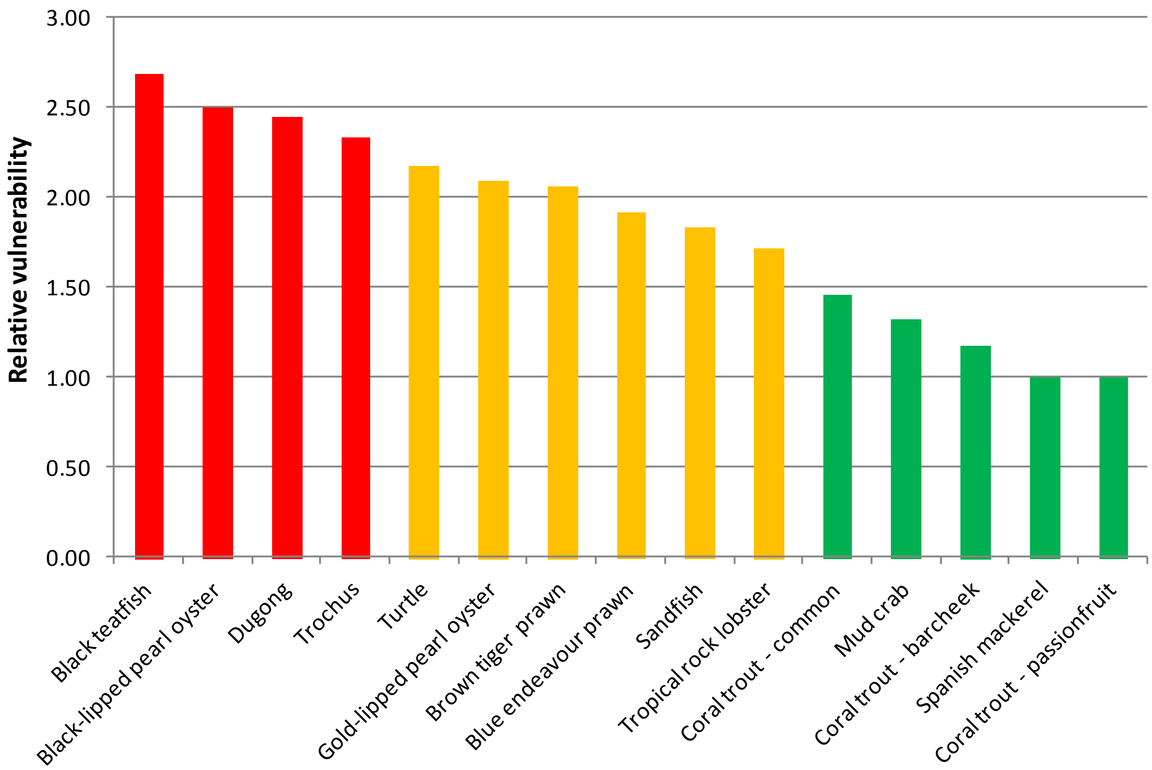

Figure 25. Relative vulnerability of key Torres Strait fisheries species. Each species has been nominally grouped as high (red), moderate (orange) or low (green) vulnerability.

Species assessed as having moderate relative vulnerability were turtle, gold-lipped pearl oyster, the two key commercial prawn species, sandfish and tropical rock lobster. All the finfish assessed were in the low relative vulnerability category along with mud crab (Figure 25).

Overall exposure, sensitivity and adaptive capacity

To identify the factors that determine the vulnerability of individual species, particularly those that are assessed as high relative vulnerability, it is useful to examine the individual elements of the framework and their indicators separately. The two species with the highest exposure scores were mud crab and tropical rock lobster, despite both species having an overall vulnerability that was low to medium (Figure 26). The species that had the lowest exposure score was dugong. Based on the scoring of exposure criteria for each species, the critical climate-related changes for the Torres Straits fisheries by 2030 will be increases in SST, changes in key habitats and more severe storms.

The species that had the highest sensitivity score was turtle followed by dugong (Figure 27). The sensitivity scores for the remaining species were relatively lower and generally similar. Based on the scoring of sensitivity criteria for each species, the sensitivity of Torres Strait fisheries species to climate change is largely due to a high reliance on environmental cues for reproductive activity and settlement as well as physiological thresholds either unknown or likely to be exceeded by 2030.

The species with the highest adaptive capacity scores were all the finfish species as well as mud crab and tropical rock lobster (Figure 28). Overall, based on the adaptive capacity criteria scores for all species, lower adaptive capacity was due to social and fishery governance factors rather than biological factors. It should be noted that scoring for most of the social indicators were based on the limited interviews conducted with TS Islanders and their general perceptions overall and were not specific to individual species/fisheries. This meant that the same scores were (mostly) given to all species for: ‘willingness of fishers to change targeting practices’, ‘climate change awareness of fishers’, and ‘governance’. The exception was for dugong and turtle that were assessed as having management arrangements that were flexible due to the voluntary restrictions on harvest and hunting practices, but were not necessarily adaptive. Further information on adaptive capacity indicators would need to be obtained using a dedicated survey that was stratified by fishery/species targeted and included TS Islander fishers, non-Islander fishers and managers to provide accurate and species-specific data.

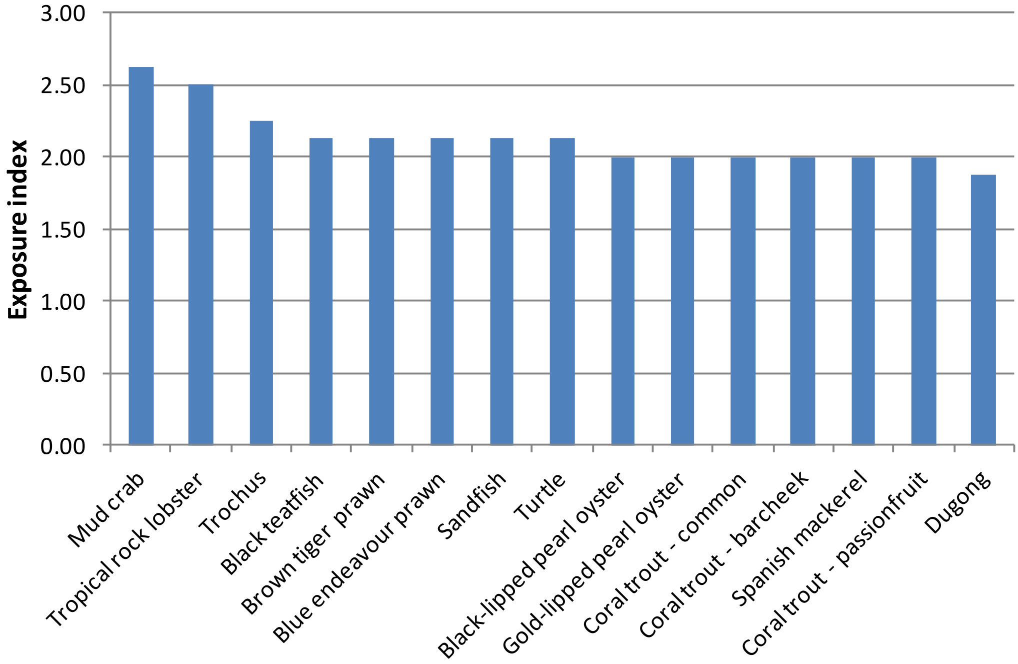

Figure 26. Exposure index for each of the key Torres Strait fisheries species assessed.

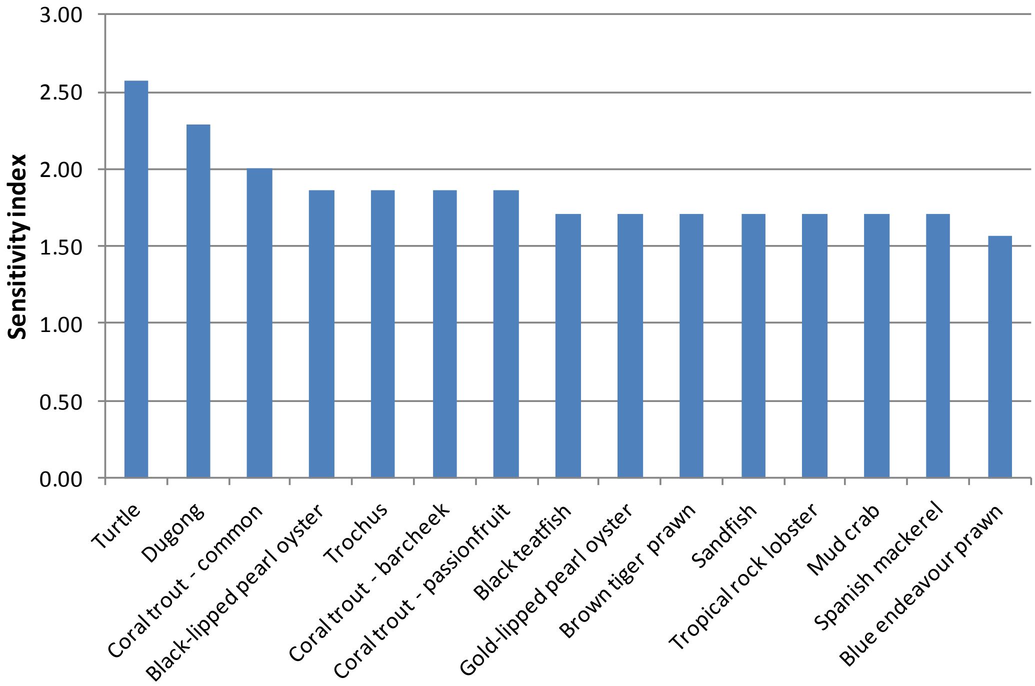

Figure 27. Sensitivity index for each of the key Torres Strait fisheries species assessed.

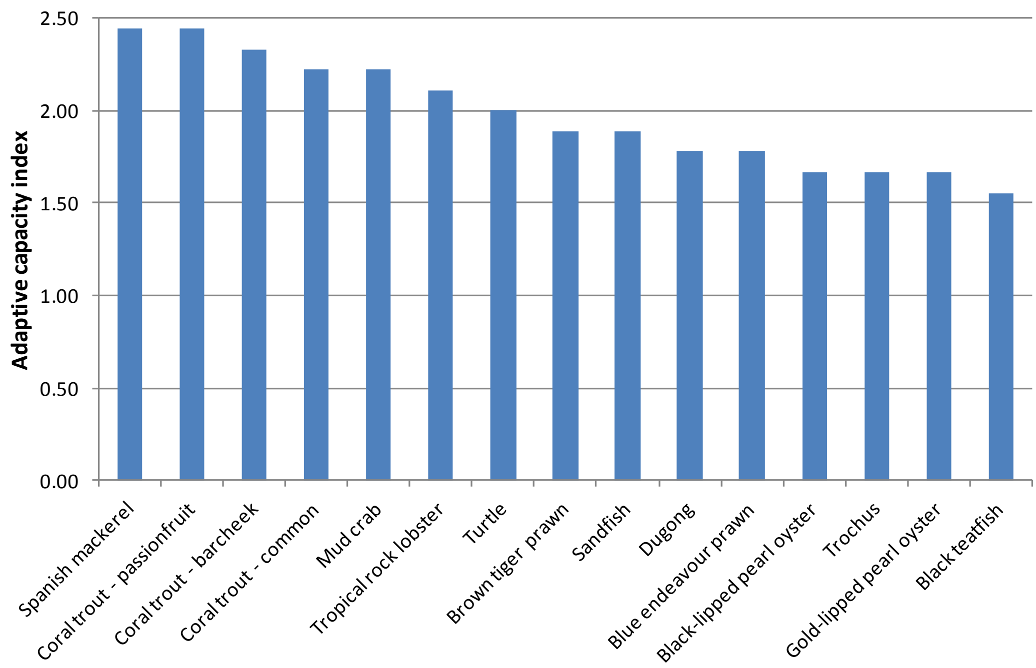

Figure 28. Adaptive capacity index for each of the key Torres Strait fisheries species assessed.

Individual species vulnerability

Sea cucumbers

Black teatfish had the highest vulnerability to climate change. This was because it will be highly exposed to changes projected to occur by 2030 and, although only moderately sensitive to those changes, was assessed as likely to experience negative impacts. Importantly, black teatfish were assessed as having low adaptive capacity mainly because of their low reproductive potential and as a winter spawning species any rise in water temperature is likely to restrict or even prevent spawning in the TS. Despite being a highly valuable fishery resource economically, the Torres Strait fishery for black teatfish has been closed since 2003. Further, with no subsistence targeting and multiple other sea cucumber species available, any realised negative impacts on this species are not likely to greatly affect Torres Strait fisheries.

Sandfish were assessed as being moderately vulnerable to climate change. Some of the important factors for this were that they are currently considered overfished with evidence of very slow recovery and therefore productivity is low, they have low mobility and the importance of seagrass beds for juveniles. Although this has historically been an important fishery in the Torres Strait and when available are economically valuable, the fishery has been closed since 1998 and harvest for subsistence is very low.

Dugong

Dugong had the equal highest relative vulnerability to climate change. Although they had the lowest score for exposure, they were assessed as having high sensitivity because of their low productivity and their very strong attachment to seagrass meadows as a preferred habitat and primary food source. Seagrass meadows are prolific in the western Torres Strait and are predicted to be negatively impacted by rising water temperatures, reduced light and increased storm intensity in particular, which is projected to have flow-on negative impacts on dugong populations. The reliance of dugong on seagrass has been documented before in the Torres Straits and elsewhere with reduced dugong survival and health correlated with decreases in seagrasses due to storm activity and natural episodic die-backs (Gales et al. 2004, Marsh and Kwan 2008, Bell and Ariel 2011, Department of Environment and Resource Management 2011). Further, it is highly uncertain as to whether current dugong harvest in the Torres Strait is sustainable (Heinsohn et al. 2004, Marsh et al. 1997, 2004, 2011). Although not a commercial species dugong are caught by subsistence fishing and are a highly important cultural species for TS Islanders.

Pearl oysters

Black-lipped pearl oyster was assessed as having a high relative vulnerability to climate change. This was primarily due to their low mobility and their naturally low abundance in the region, probably because the Torres Strait is near their northern limit and they are more common in higher latitudes. Being naturally uncommon in the Torres Strait they are the less important of the two pearl oyster species harvested. The gold-lipped pearl oyster was assessed as being moderately vulnerable to climate change due to their low mobility, their stock status assessed as nearing overexploitation despite low fishing effort, and the fact that there are no other species in the Torres Strait that could be harvested as a substitute. Total harvest and therefore the commercial importance of pearl oyster in Torres Strait is low.

Trochus

Trochus were also assessed as having a high relative vulnerability to climate change due to a combination of generally high exposure and low adaptive capacity. The underlying cause of this was their low mobility and their very short larval duration, which collectively limit their avoidance and dispersal capabilities. Despite this, the Torres Strait fishery for trochus is characterised by variable but generally very low effort and, although there is a small level of subsistence harvest, they are one of the relatively less important fishery species in Torres Strait.

Turtle

Turtle were assessed as having moderate relative vulnerability to climate change in the Torres Strait. This was despite being assessed as being the most sensitive to changes in climate variables. This sensitivity has already been observed through direct effects on turtles as well as indirect effects on nesting success, and there is a high level of confidence in the prediction of future impacts. These include stranding due to storms, storm surge inundation on nesting grounds, the influence of temperature on hatchling gender, and the potential loss of important food resources associated with seagrass meadows as foraging grounds. Although, green turtles in particular are opportunistic foragers and may be able to switch to other abundant marine plants, such as algae, as seagrass decline.

Prawns

The two main target species of prawns were both assessed as being moderately vulnerable to climate change. One of the influencing factors for both prawn species is that they are endemic to Australia and as such the Torres Strait represents almost the northern limit of their distribution (Turnbull and Williams 2000). Therefore, increasing water temperatures may cause a southerly contraction of populations. The brown tiger prawn was assessed with a slightly higher vulnerability than the blue endeavour prawn due to their strong association with seagrass meadows during the juvenile phase.

Tropical rock lobster

Tropical rock lobster was assessed as having a moderate relative vulnerability to climate change. They were one of the species most highly exposed to climate change however sensitivity was relatively low overall, except for their sensitivity to increases in water temperature. Based on the assessment, and the overwhelming feedback from TS Islander interviews, tropical rock lobster already show a response to warm ocean conditions by moving into deeper water. Although this is not a negative consequence from a population perspective, moving into deeper water make them less accessible for the dive-based fishery and so fishery consequences may be highly negative. This warrants further investigation because tropical rock lobster is the most important fishery in the Torres Strait from a commercial and economic perspective, both for Islander and non-Islander fishers, as well as being important for subsistence. Importantly, there are no comparable alternative species given the market price and demand for rock lobster and the high degree of gear and fishing technique specialisation.

Coral trout

All the three species of coral trout were assessed as having a low relative vulnerability to climate change. This was largely because they all had high adaptive capacity being highly productive species that are targeted as part of a multi-species fishery with potentially many alternative species. Notwithstanding this, recent evidence of a thermal tolerance threshold at 28 °C for larval development and the known importance of temperature as a spawning cue (common coral trout: Samoilys 1997, Pratchett et al. 2013) means projections of SST increases for the Torres Strait that will exceed this threshold are of concern. Also, the documented importance of particular coral reef habitat for juveniles (barcheek coral trout: Wen et al. 2012) infers some sensitivity to environmental change for coral trout species in the Torres Strait.

Mud crab

Mud crab, along with tropical rock lobster, had the highest exposure to climate change however overall both were assessed as having low relative vulnerability to climate change. Although mud crab are known to be influenced by environmental variables such as river flow and temperature, they also occupy a wide range of habitats across a large distributional range and so are a species exposed to a wide range of environmental conditions. Further, in the Torres Strait the commercial harvest is very low although they are mainly caught for subsistence.

Spanish mackerel

Spanish mackerel were assessed as having low relative vulnerability to climate change. This was due to their high mobility and productivity resulting in low scores for exposure and sensitivity, while also having the highest adaptive capacity score. Temperature is known to be a potential cue for spawning and may be important in the longer term especially as they are thought to be a separate stock in the Torres Strait. However, more data is needed to determine whether they are in fact a separate stock and the temperature threshold for optimum spawning activity.

Prioritising species for action

The vulnerability assessment provides a robust basis for identifying species of highest concern and therefore priority species and fisheries for future action and/or further investigation, particularly for climate change adaptation. Relative vulnerability however should not be the only consideration for prioritisation. The relative 'importance' of individual species to TS fishers and communities should also be taken into account and could include a combination of factors. For the purpose of further assisting managers and other stakeholders in clearly identifying the Torres Strait species of highest priority we have incorporated importance of each species based on their economic value and their cultural value. To do this for each species we used the current documented fishery dollar value and an estimated cultural value based on whether they are harvested for subsistence purposes, as well as the level of use for cultural activities. We acknowledge that to estimate accurately the cultural and social value of Torres Strait species requires input from TS Islanders, as well as some consideration of the cost (monetary and social) of accessing alternative protein sources. Given that this assessment was to provide a relative measure for prioritising management, we have estimated the species cultural value based on the species literature searches and the interviews conducted with TS Islanders. The method is provided below and could readily be revised with further review and input.

To determine the level of fishery 'importance' we derived an index based on arbitrary levels of the economic value of the fishery and on the estimated cultural value using high = 3, medium = 2, low = 1 (further details are provided in Appendix 4). A score of "zero" was given if there was no economic value or no subsistence catch. The fishery importance index was obtained by summing the scores given to the economic and cultural values for each species; however greater weighting was given to cultural values by doubling the cultural value score. This gave an index that, when used in conjunction with the relative vulnerability score, clearly identified species that should be given highest priority for further research and/or action, including education (Figure 29).

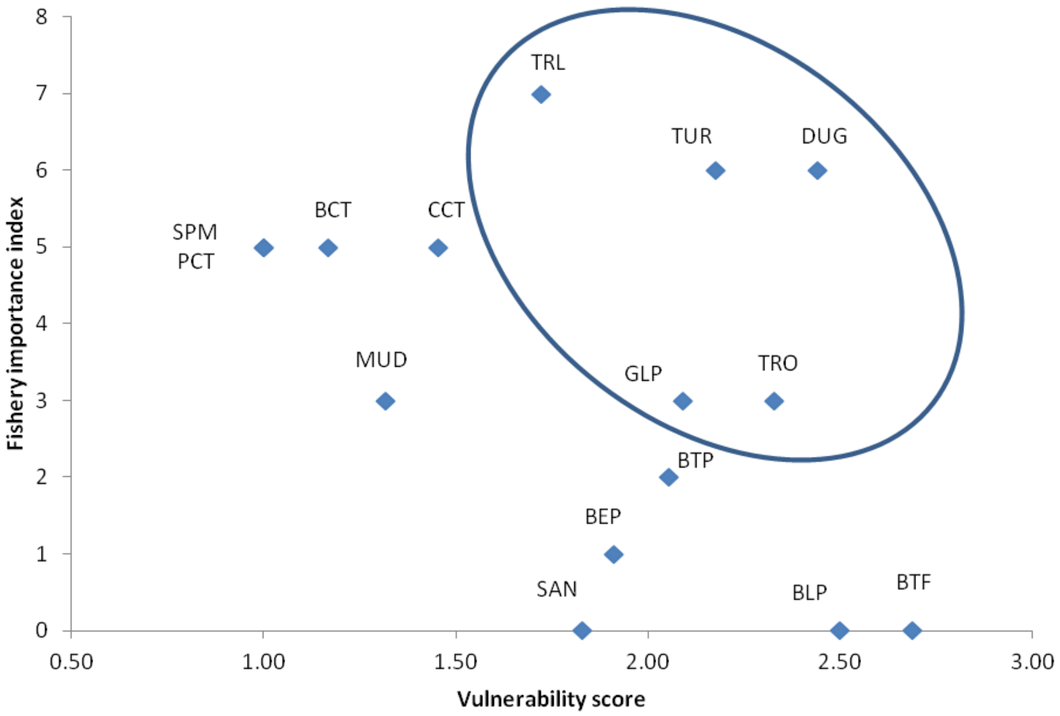

Figure 29. Relative vulnerability plotted against an index of fishery importance to assist in prioritising the species for further research and/or action. Species are indicated by three letter codes as: BTF – black teatfish, BLP – black-lipped pearl oyster, DUG – dugong, TRO – trochus, TUR – turtle, GLP – gold-lipped pearl oyster, BTP – brown tiger prawn, BEP – blue endeavour prawn, SAN – sandfish, TRL – tropical rock lobster, CCT – common coral trout, MUD – mud crab, BCT – bar-cheek coral trout, SPM – Spanish mackerel, and PCT – passionfruit coral trout.

The species with the combination of high importance and high vulnerability (top right of graph), and therefore the highest priority species for further research and action, are indicated in the circled area. These are: dugong, turtle, tropical rock lobster, trochus and gold-lipped pearl oyster.

7. Benefits and Management outcomes

This project has completed a number of key activities that will provide resources for managers and stakeholders in Torres Strait, and inform responses of fisheries to climate change. This report provides a concise compendium of all this information relevant to Torres Strait fisheries and climate change.

1. Summary of the observed climate in Torres Strait and projected changes for key climate variables relevant to marine fisheries and supporting habitats.
2. Review of the key habitats important for marine fishery species and how they are likely to be affected by climate change.
3. Species reviews of 10 key fisheries groups that are important in Torres Strait. The species reviews describe the main fisheries in the Torres Strait, including species life cycle characteristics and known and inferred information on the sensitivity and response of species to changes in climate variables.
4. Relative vulnerability assessment of 15 key TS fishery species to climate change by 2030, a medium-term time frame that has relevance to stakeholders and management planning timeframes in the Torres Strait.

The vulnerability assessment results identified: (i) species that are highly vulnerable to projected climate change, and (ii) species that because of their economic and/or cultural importance in the region should be given a higher priority for action by managers and future research. The results also provide valuable information that will be of interest to Torres Strait Islanders and can be the basis of climate change education and communication activities.

The main outcomes for managers and key stakeholders are:

- *Improved understanding of the climate-related changes predictions for the TS region.* The project has documented the most up-to-date climate projections for the Torres Strait that are relevant to marine fisheries and supporting habitats, such as coral reefs and seagrass meadows.
- *A greater understanding of the potential consequences of climate change on Torres Strait fishery species and supporting habitats.* The current and potential impacts of projected changes in climate variables on key fisheries species and habitats have been identified based on the best available scientific and local knowledge.
- *A clear understanding of which fisheries and which species are most vulnerable to climate change and the source of vulnerability.* The assessment framework determined the relative vulnerability of key fisheries and identified four species that had the highest relative vulnerability in TS – black teatfish, black-lipped pearl oyster, dugong and trochus.
- *A preliminary consideration of fishery importance to prioritise actions and research.* The correlation between fishery vulnerability and importance (as measured using economic and cultural values) identified five species for priority focus – dugong, turtle, tropical rock lobster, trochus and gold-lipped pearl oyster.
- *An improved understanding of important information gaps and where future research should be directed.* The species reviews and vulnerability assessment highlighted key knowledge gaps, and in particular, where there is high uncertainty in the input information, thereby enabling prioritisation of future research investment.

- *Improved capacity of TS Island communities and management to prepare for and respond to potential impacts (positive and negative) of climate change.* Knowledge of the potential impacts on fisheries species/habitats and dependent stakeholders provides information about how livelihoods and traditional practices will be influenced. An improved understanding of climate change and potential impacts is essential to enable proactive planning, and to inform management on the efficacy of current management and potentially where to target management actions under future scenarios.

These project outcomes should be of benefit to all stakeholders in Torres Strait and provides a strong basis upon which to engage Torres Strait Islanders about climate change and its implications for communities and fisheries. Climate change awareness raising and information was highlighted as a desired need for communities during interviews with TS Islanders. Identification of the most vulnerable fisheries to climate change in the region, and the causal mechanisms provides the basis for planning next steps including the selection of appropriate management and/or adaptation strategies and long-term planning for the future sustainability of fisheries (e.g. incorporate species-specific responses into stock assessments).

8. Conclusions

There are several key conclusions that can be made based on the species reviews and the completed vulnerability assessment.

By 2030 the Torres Strait can expect to experience changes to the marine environment that will have an effect on local habitats and fishery species. The key changes that are expected to have the greatest influence on TS fisheries and supporting habitats are:

- An increase in sea surface temperature of between +0.62 and +1.27 °C resulting in more coral bleaching, movement of fishery species and possible changes to the timing of spawning of some species.
- Fewer but more intense cyclones that will physically damage critical habitats (coral reefs, seagrass meadows, mangrove forests) and island communities.
- More extreme rainfall events (projections of mean annual rainfall changes are uncertain) that will deliver terrestrial pollutants to the marine environment, particularly in the northern TS that is influenced by the Fly River, PNG.
- Sea level will rise between 5 and 15 cm which would affect mangrove habitats and further inundate low-lying communities – Saibai, Boigu, Masig, Warraber and Iama Islands.
- Ocean stratification, upwelling and currents are likely to change with consequences for TS productivity levels however the nature of these changes is uncertain.
- Decreased salinity that may influence life cycle stages of some fishery species.

Of the key fisheries habitats in Torres Strait, coral reefs and seagrass meadows are predicted to be at highest risk of deleterious impacts by 2030 mainly due to increases in sea surface temperature, more extremes in rainfall and storms, and ocean acidification.

Based on the key fishery species assessed, the environmental changes most likely to affect fisheries in Torres Strait by 2030 are increases in sea surface temperature, increasing storm severity, and habitat degradation.

The interviews conducted with TS Islanders regarding climate change influences on local fisheries were extremely informative and proved an effective means of informing the assessment process. Local knowledge of fisheries and ocean conditions is important for informing future planning.

The species in Torres Strait assessed as having high relative vulnerability to climate change are black teatfish, black-lipped pearl oyster, dugong and trochus. By taking into account cultural and economic values with the relative vulnerability scores, the species identified as the highest priority for management and/or research action are dugong, turtle, tropical rock lobster, trochus and gold-lipped pearl oyster.

Of the high priority species, the key factors contributing to their vulnerability were: lack of mobility; Torres Strait near their northern distributional limits; strong habitat associations particularly for species reliant on seagrass; close to upper limit of preferred thermal range; high dependence of the fishery on a single species; and inflexible or non-adaptive management regimes.

The relatively healthy condition of most fisheries in the Torres Strait will aid in the success of any adaptation options implemented. Adaptations that focus on sustainable management of stocks, habitat preservation (coral reefs and seagrass) and diversification of fisheries species hold the most promise for fisheries under climate change. Strong local governance is also important in an uncertain and changing future.

Recommendations

The results of this project have highlighted a number of future activities and research priorities that should be considered for fisheries in TS facing future climate change. These recommendations can be divided into three themes: (1) improving assessment accuracy, (2) extension of results to communities and decision-makers, and (3) research to address key knowledge gaps.

Improving assessment accuracy

1. We recommend that the vulnerability assessment results be reviewed and if necessary, revised, based on expert comments and consultation with TS Islanders, potentially through a series of local workshops. Further, we recommend that prior to these workshops that a comprehensive survey be conducted with TS Islanders that builds on the interviews conducted during this project, to better investigate TS Islander adaptive capacity traits for specific fisheries/target species.
2. Benchmarking of Torres Strait fisheries governance should also be done as this has been identified as a key driver of low adaptive capacity to future climate change. Together, these activities would inform the vulnerability assessment outcomes and improve the accuracy of the results so they can inform the selection of effective adaptation options for TS. They would need to be undertaken as the next step to operationalising the assessment results and attempting to address climate change implications for fisheries in Torres Strait.

Extension of results

3. The stakeholder workshops would allow ground-truthing of the assessment results, facilitate increased education and awareness raising about climate change and the implications for

communities and fisheries, and begin the process of identifying appropriate priority adaptation strategies to support fisheries in the face of inevitable change.

Importantly, adaptation planning is an established process for identifying appropriate and effective adaptation options based on vulnerability assessment results. It requires the participation of fisheries managers and stakeholders as well as other sectors (e.g. catchment and land use managers), an analysis of the key sources of vulnerability, and integration of all available management strategies to address these, including barriers to implementation and supporting policy needs.

Research to address knowledge gaps

The benefit of a structured and semi-quantitative assessment approach is that it can identify where information is lacking, and where future research should focus. Through the species reviews and vulnerability assessment, a number of key knowledge gaps emerged that if addressed would not only improve the certainty of the assessment but also inform adaptation planning.

4. The indirect impacts of habitat loss or degradation was identified as a key source of vulnerability for many species, and while current projects in TS are investigating the distribution, diversity and bleaching thresholds for coral reefs (NERP project 2.3), mangrove wetlands (NERP project 2.2) and seagrasses (Seagrass-Watch[1]), ongoing monitoring is essential. Validation of known sensitivity thresholds for temperature, salinity and light for the TS region will inform an understanding of coral reef and seagrass resilience in the Torres Strait and likely habitat changes or declines under future climate projections. Monitoring potential changes in habitat distribution, abundance and community composition will be critical for understanding how fisheries that depend on reefs and seagrass are likely to respond. Current monitoring is relatively short-term and opportunistic and a more targeted effort needs to be funded to determine what habitat changes will occur and the implications for the highest priority fisheries species in TS – dugong, turtle, tropical rock lobster (and brown tiger prawn) – that depend on seagrass meadows, as well as for fisheries species that depend on coral reefs.
5. Another key factor that contributed to high sensitivity scores for many of the species assessed was physiological tolerance of species and reliance on temperature cues for spawning or settlement. Temperature is also a key driver of growth/metabolic rate and species distribution, yet little has been documented on critical upper temperature thresholds for fisheries species in TS. This will be particularly important for determining when such thresholds might be crossed, and the magnitude of impacts of rising SST on species growth, reproduction and distribution, and therefore how fisheries will have to adapt.
6. Although ocean chemistry is unlikely to become an issue for marine ecosystems until mid to late century, it is expected to be a pervasive threat that can undermine the structure of coral reef habitats, and the growth and survival of other calcium carbonate forming species, e.g. trochus, pearl oyster, prawns, rock lobster and mud crab. Three of these species were identified in this assessment as the highest priority fisheries in the face of climate change and therefore a better understanding of regionally-scaled acidification projections (as the TS has slow water turn-over that may influence ocean chemistry) and critical pH thresholds for

early life history stages is needed. Again, this will inform when such thresholds might be crossed and the magnitude of likely impacts for fisheries in the short- to medium-term.

7. The TS Islander interviews conducted during this project received a high number of respondents commenting on the current observed effects of 'hot' water years when tropical rock lobster move to deeper water limiting the ability for them to be caught. Further, comments also highlighted the dependence on this species as a key fishery in the Torres Strait. Research on the thermal thresholds for tropical rock lobster as well as the fishery social characteristics, particularly relating to adaptive capacity, is warranted given the impacts already being observed with a short-term view to identify and implement adaptation options for fishery participants.

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Appendices

Appendix 1 – Project community flyer

Torres Strait fisheries and climate change

Engaging with communities

Major fisheries species targeted in the Torres Strait are the focus of a pilot project that will assess their vulnerability to climate change. Communities in the Torres Strait have an intimate relationship with and knowledge of their sea country and its resources, and will be consulted as part of the project.

The project will focus on coral trout, Spanish mackerel, prawns, trochus, tropical rock lobster, mud crab, pearl oyster, sea cucumber, and traditional fisheries to better understand how they will respond to changes in climate predicted for the Torres Strait.

In May and June, researchers will contact local community members to include their knowledge in the assessment. The project findings will identify which fisheries are most likely to change, and will be provided to communities to help them start to prepare for future change. This will be done in conjunction with the Australian Fisheries Management Authority and with the support of the Torres Strait Regional Authority. If you would like to be involved or want further information please call or email.

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This project is supported by the Protected Zone Joint Authority through the Torres Strait Scientific Advisory Committee and implemented by C_2O Fisheries (2013)

Appendix 2 – TS Islander interview questions

A community questionnaire was conducted as part of the project seeking to draw on local knowledge of awareness of climate change issues for fisheries in the Torres Strait, any changes noticed, and to understand how adaptive fishers are. The questionnaire targeted community members who had a long-standing history of fishing, collecting and/or hunting in Torres Strait, both commercially and recreationally. The responses were treated confidentially and used to inform the vulnerability assessment process, in particular scoring the adaptive capacity indicators.

Questions:

1. Do you fish/hunt in Torres Strait, and if so, what are the main fish or animals you target?
2. How long have you been fishing/hunting in the Torres Strait?
3. Do you use the fish and animals you catch for food or to sell?
4. Have you changed the fish/animals you target over this time? Do you catch lots of fish that you don’t target?
5. Have you noticed changes in the sea conditions, e.g. wind, waves, currents, temperature? If so, does this affect the fish/animals you catch or their size?
6. Have you noticed any change in where you catch these fish/animals? Do you have to travel further?
7. Have you noticed any change in when you catch these fish/animals?
8. Have you noticed any new or rare fish/animals coming into the places you fish/hunt?
9. Do you know how your fishing/hunting experiences compare with the experiences of your father, grandfathers or brothers?
10. What effects do you think that climate change will have on the Torres Strait and its fisheries?
11. Would you target different species if current preferred species were less available?
12. Is there anyone else you think we should talk to?

Appendix 3 – Vulnerability assessment individual scores

Exposure

	Exposure								
	SST+	Altered rainfall	pH decline	Salinity changes	Habitat changes (e.g. loss of productivity, structure or function)	Altered wind/ currents	More severe storms	More extreme riverflow	***Exposure index***
Black teatfish	3	1	2	2	3	2	3	1	2.13
Black-lipped pearl oyster	2	1	3	2	1	3	3	1	2.00
Dugong	3	1	2	2	3	1	2	1	1.88
Trochus	3	1	3	2	3	2	3	1	2.25
Turtle	3	2	2	2	3	1	2	2	2.13
Gold-lipped pearl oyster	2	1	3	2	1	3	3	1	2.00
Brown tiger prawn	2	1	2	2	3	2	3	2	2.13
Blue endeavour prawn	3	2	2	2	1	2	3	2	2.13
Sandfish	3	1	2	2	3	2	3	1	2.13
Tropical rock lobster	3	2	3	2	3	3	2	2	2.50
Coral trout - common	3	1	2	2	3	2	2	1	2.00
Mud crab	3	3	3	3	2	2	2	3	2.63
Coral trout - barcheek	3	1	2	2	3	2	2	1	2.00
Spanish mackerel	3	3	2	2	1	1	1	3	2.00
Coral trout - passionfruit	3	1	2	2	3	2	2	1	2.00
Average	2.80	1.47	2.33	2.07	2.40	2.00	2.40	1.53	

Sensitivity & Potential Impact

	Sensitivity							
	Fecundity (egg production)	Average age at maturity	Generalist v specialist (food & habitat)	Early development duration (dispersal capacity)	Physiological tolerance of stock	Reliance on environmental cues (for spawning, settlement)	Reliance on temporal cues (duration of spawning, breeding, moulting)	***Sensitivity index***
Black teatfish	1	2	1	2	2	2	2	1.71
Black-lipped pearl oyster	1	1	2	2	3	3	1	1.86
Dugong	3	2	3	3	2	2	1	2.29
Trochus	1	2	2	3	2	2	1	1.86
Turtle	2	3	2	3	3	3	2	2.57
Gold-lipped pearl oyster	1	1	2	2	2	3	1	1.71
Brown tiger prawn	1	1	2	2	3	2	1	1.71
Blue endeavour prawn	1	1	2	2	2	2	1	1.57
Sandfish	1	2	2	2	2	2	1	1.71
Tropical rock lobster	1	2	2	1	3	2	1	1.71
Coral trout - common	1	1	2	2	3	3	2	2.00
Mud crab	1	1	2	2	1	3	2	1.71
Coral trout - barcheek	1	1	2	2	2	3	2	1.86
Spanish mackerel	1	1	1	2	2	3	2	1.71
Coral trout - passionfruit	1	1	2	2	2	3	2	1.86
Average	1.20	1.47	1.93	2.13	2.27	2.53	1.47	

	Potential Impacts (negative)		
	PI = E * S	Direction of impact	PI Index
Black teatfish	3.64	1.00	4.64
Black-lipped pearl oyster	3.71	1.00	4.71
Dugong	4.29	1.00	5.29
Trochus	4.18	0.00	4.18
Turtle	5.46	1.00	6.46
Gold-lipped pearl oyster	3.43	0.00	3.43
Brown tiger prawn	3.64	1.00	4.64
Blue endeavour prawn	3.34	0.00	3.34
Sandfish	3.64	0.00	3.64
Tropical rock lobster	4.29	1.00	5.29
Coral trout - common	4.00	1.00	5.00
Mud crab	4.50	-1.00	3.50
Coral trout - barcheek	3.71	0.00	3.71
Spanish mackerel	3.43	0.00	3.43
Coral trout - passionfruit	3.71	0.00	3.71

Adaptive Capacity

	Adaptive Capacity											
	Stock status	Replenishment potential	Ability to range shift	Species mobility	Non-fishing pressures on stock	Resource dependence of the fishery	Willingness of fishers to change targeting practices	Climate change awareness of fishers	Governance	***Adaptive Capacity index***	**AC normalisation**	**1-AC**
Black teatfish	1	1	1	1	2	3	2	2	1	1.56	0.64	0.36
Black-lipped pearl oyster	1	3	1	1	1	3	2	2	1	1.67	0.68	0.32
Dugong	1	1	2	3	2	1	2	2	2	1.78	0.73	0.27
Trochus	2	2	2	1	2	1	2	2	1	1.67	0.68	0.32
Turtle	2	1	3	3	2	1	2	2	2	2.00	0.82	0.18
Gold-lipped pearl oyster	1	3	3	1	1	1	2	2	1	1.67	0.68	0.32
Brown tiger prawn	3	3	1	2	2	1	2	2	1	1.89	0.77	0.23
Blue endeavour prawn	3	3	1	1	2	1	2	2	1	1.78	0.73	0.27
Sandfish	1	2	3	1	2	3	2	2	1	1.89	0.77	0.23
Tropical rock lobster	3	3	3	2	2	1	2	2	1	2.11	0.86	0.14
Coral trout - common	3	3	2	2	2	3	2	2	1	2.22	0.91	0.09
Mud crab	3	3	3	2	2	2	2	2	1	2.22	0.91	0.09
Coral trout - barcheek	3	3	2	2	3	3	2	2	1	2.33	0.95	0.05
Spanish mackerel	3	3	3	3	3	2	2	2	1	2.44	1.00	0.00
Coral trout - passionfruit	3	3	3	2	3	3	2	2	1	2.44	1.00	0.00
Average	2.20	2.47	2.20	1.80	2.07	1.93	2.00	2.00	1.13			

Appendix 4 – Estimating fishery importance indices

The process for deriving the fisheries importance index is based on a combined score for economic value and cultural value, with cultural value given double the weighting of the economic value. Scoring for each of the economic and cultural values were given as: high = 3, medium = 2 and low = 1, with a zero score given if there was deemed to be no value. The economic value was subjectively based on the mean dollar value of the commercial fishery for that species over the past two years. The cultural value was based on the literature searches conducted during this project and on feedback received during the project interviews with TS Islanders. The scores and the derived fishery importance (FI) indices for each species are provided below and can readily be reviewed as required.

Species	Economic value	Cultural value	FI Index	Value $M (based on last 2 yrs)
Black teatfish	0	0	0	0
Black-lipped pearl oyster	0	0	0	0
Dugong	0	3	6	0
Trochus	1	1	3	~0
Turtle	0	3	6	0
Gold-lipped pearl oyster	1	1	3	~0
Brown tiger prawn	2	0	2	2.93
Blue endeavour prawn	1	0	1	0.58
Sandfish	0	0	0	0
Tropical rock lobster	3	2	7	19.1
Coral trout - common	1	2	5	0.45
Mud crab	1	1	3	~0
Coral trout - barcheek	1	2	5	0.45
Spanish mackerel	1	2	5	0.76
Coral trout - passionfruit	1	2	5	0.45

Appendix 5 – Final project fact sheet

Torres Strait fisheries and climate change

Future climate change is expected to affect many marine species and habitats in the Torres Strait.

Climate change is already influencing the Torres Strait, with more extreme weather events, and temperature related coral bleaching and movement of rock lobster into deeper water.

Fisheries species will be further exposed to future changes in the ocean, both directly and indirectly through changes to habitats and critical food resources.

Communities in the Torres Strait have an intimate relationship with and knowledge of their sea country and depend on a range of fisheries resources.

Fifteen local fisheries species were assessed for their responses and potential vulnerability to climate change using a structured framework, and knowledge from local fishers.

The fisheries assessed were coral trout, Spanish mackerel, prawns, trochus, tropical rock lobster, mud crab, pearl oyster, sea cucumbers, dugong and turtle.

CLIMATE DRIVERS & IMPACTS

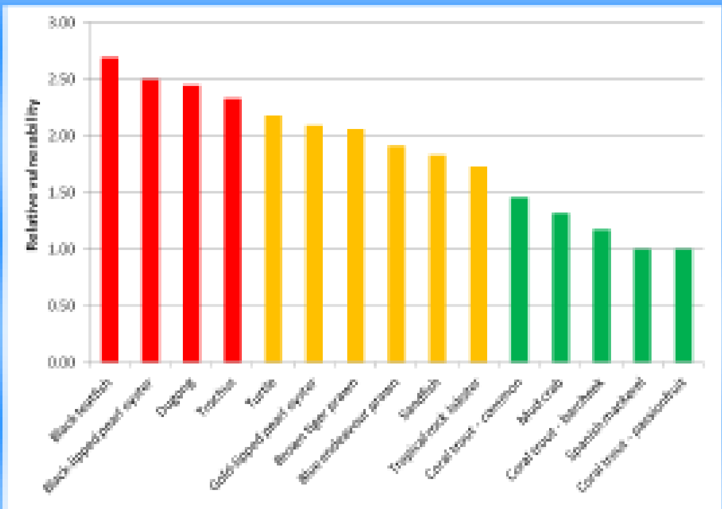
The main changes expected to occur in Torres Strait by 2030 are:

- Increases in average sea temperature of between +0.62 and +1.27 °C.
- Fewer but more intense cyclones and more extreme rainfall events.
- Sea level rise between 5 and 15 cm.
- Altered local currents and productivity (but these are less certain).

These changes are expected to impact on important fishery species and their habitats with coral reefs and seagrass habitats most at risk.

Fishery species most at risk

Black teatfish were the most vulnerable species while sandfish were moderately vulnerable



Dugong are one of the most vulnerable species mainly due to loss of seagrass habitat

Rock lobster will be vulnerable to rising sea temperature and changing currents; and the industry is very resource dependent

Vulnerability assessment results identified which species are most at risk from climate change and prioritised further action. The assessment results are shown above and group species into high (red), moderate (orange) and low (green) vulnerability. These are relative rankings among the 15 species assessed.

The two most highly vulnerable species were black teatfish and black-lipped pearl oyster, which are either not fished currently or are harvested in very low numbers. By taking into account economic and cultural value as well as vulnerability to climate change, the project identified 5 species that should be given highest management priority: **dugong, turtle, tropical rock lobster, trochus and gold-lipped pearl oyster.**

Adaptations that focus on sustainable management of stocks, habitat preservation (reefs and seagrass) and diversifying fisheries hold the best promise for fisheries under climate change. Strong local governance is also important in an uncertain and changing future. Workshops with Islanders are the recommended next step to develop appropriate actions.

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This project was funded by AFMA and supported by the Protected Zone Joint Authority through the Torres Strait Scientific Advisory Committee and implemented by C_2O Fisheries (2013)