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Climate change implications for Torres Strait fisheries: assessing vulnerability to inform adaptation

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Abstract Climate change impacts on marine fisheries are being observed in tropical regions, including northern Australia and the Pacific. In the Torres Strait, Islanders have a long association with their sea country that holds significant cultural, social and economic importance. Future impacts of climate change on marine fisheries stocks and supporting habitats will affect Torres Strait Islander communities. We assessed the relative vulnerability of 15 key fishery species in Torres Strait using a semi-quantitative framework modified from the Intergovernmental Panel on Climate Change that integrated both ecological and social indicators of exposure, sensitivity and adaptive capacity. The assessment identified species with high, medium and low vulnerability to projected climate change in 2030. The species assessed as having the highest vulnerability were: *Holothuria whitmaei* (black teatfish), *Pinctada margaritifera* (black-lipped pearl oyster), *Dugong dugon* (dugong), and *Trochus niloticus* (trochus). A separate prioritisation process that considered the cultural and economic value of species identified three high priority species for future management focus: *D. dugon*, marine turtles (principally *Chelonia mydas*) and *Panulirus ornatus* (tropical rock lobster). These results can inform fishers and managers to prepare for the effects of climate change and minimise impacts. The relatively healthy condition of most fisheries in the Torres Strait is likely to assist successful adaptation.

1 Introduction

The Torres Strait is a region dominated by open seas (91.2 %) with significant areas of coral reefs and seagrass meadows that support important marine fisheries (Welch and Johnson 2013).

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The region has one of the highest proportions of Indigenous people in Australia, many of whom have strong affiliations with their land and sea, and depend on their marine resources for food, livelihoods and cultural practices. Torres Strait 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 MacFarlane 1991) from local seafood, being higher than in mainland Australia and neighbouring Melanesian countries (e.g. Papua New Guinea, Solomon Islands; see Bell et al. 2011a). Fisheries in the region are exploited for food security (e.g. coral reef fish, Spanish mackerel, tropical rock lobster), local livelihoods by both Traditional Inhabitant and non-Indigenous sectors (e.g. tropical rock lobster, finfish, prawn), and traditional hunting (marine turtles and dugong). Commercial fishing is one of the most economically important activities in the Torres Strait and provides significant opportunities for financial independence for the traditional inhabitants of the region.

Climate change is a major environmental threat to wild fisheries, compounding existing pressures from overfishing and pollution (Brander 2010; Holbrook and Johnson 2014). In the Torres Strait, fisheries impacts are likely to manifest in changes to stock structure, phenology, distribution, and indirectly through habitat changes (Welch and Johnson 2013). Any impacts of climate change on marine fisheries will affect Torres Strait communities and potentially influence the accessibility of target species, reducing fisheries sustainability and food security. Therefore, there is an imperative to understand what climate change impacts are likely to affect fisheries resources, which fisheries are expected to be the most vulnerable, and how to use this information to prepare for, and cope with, the negative effects.

Previous single-species risk assessments identified climate change implications for specific high value fisheries (e.g. Norman-López et al. 2013 for tropical rock lobsters, Plagányi et al. 2013 for sea cucumbers), however, did not consider the range of fisheries species important in the Torres Strait. Understanding the relative vulnerability to climate change of multiple fisheries species in the region, the source of this vulnerability and what impacts are likely to manifest will provide targets for management and adaptation. Climate change multi-species vulnerability assessments have been conducted for analogous ecosystems and species to the south in the Great Barrier Reef (Johnson and Marshall 2007), and to the north in Papua New Guinea (PNG; Bell et al. 2011a) that shares a border with the Torres Strait and has access to jointly managed fisheries resources. Fish stocks move between the Torres Strait and adjacent regions to the north and south, and this assessment 'fills the gap' with a comparable assessment.

We applied an established structured framework to assess vulnerability that integrates exposure, sensitivity and adaptive capacity elements (adapted from Schneider et al. 2007). This framework has been modified to include indicators for each element and a semi-quantitative approach for fisheries assessments (Johnson and Welch 2010; Pecl et al. 2014), an explicit step for assessing social vulnerability (Marshall et al. 2010), and has been variably applied to assess climate change vulnerability of bird, amphibian and coral species (Foden et al. 2013), and coral reef fisheries in east Africa (Cinner et al. 2013). The approach reported here is novel in that it integrates both ecological and social indicators to score each element, with results providing a relative ranking of multiple fisheries species vulnerability. The assessment identifies sources of vulnerability and traits that confer high adaptive capacity for each fishery. An additional prioritisation step that considered economic and cultural values was included to identify fisheries for future management focus. Ultimately, the results can be used by fishers and managers to target effort and implement effective adaptations in the face of climate change.

2 Materials and methods

A selection process was conducted to identify the Torres Strait fisheries species to be assessed involving consultations with local fisheries managers and the Torres Strait Regional Authority (TSRA). The selection considered current levels of harvest, economic value, and cultural and social importance. The 15 species chosen for the assessment represent a range of marine taxonomic groups with contrasting biology and ecology, and are exploited to varying degrees by different fishery sectors (Table 1). We conducted reviews of each species selected with a particular focus on their sensitivity to climate drivers and ability of the fishery to adapt to change. The reviews synthesized existing literature and unpublished work and were comprised of three sections: fisheries characteristics, species life cycle characteristics, and known or inferred sensitivity to environmental drivers (see Welch and Johnson 2013 for details).

We collated data of observed ocean and surface climate for variables that tropical fisheries are most likely to respond to based on known sensitivities (see Johnson and Marshall 2007; Bell et al. 2013; Welch and Johnson 2013; Welch et al. 2014). The data were gathered from recent climate modelling for the Torres Strait (Suppiah et al. 2010), the Pacific region ([Australian] BoM and CSIRO 2011, Ganachaud et al. 2011; Lough et al. 2011) and other key studies (e.g. Puotinen 2007; Lough and Hobday 2011 (for tropical cyclones); TSRA 2011 (for sea level); Climate Commission 2013 (for extreme events)). The synthesis of observed climate included historic temporal periods where the data are most reliable.

The climate projections used for the assessment were based on the IPCC-AR4 global climate model outputs (IPCC 2007) downscaled for the Torres Strait and PNG (Suppiah et al. 2010; [Australian] BoM and CSIRO 2011, Ganachaud et al. 2011; Lough et al. 2011) for 2030

Table 1 The 15 Torres Strait fishery species assessed for vulnerability to climate change, and their fishery sectors. Where: Commercial – licenced (Indigenous and non-Indigenous) fishery that sells catch for profit; Subsistence – local fishery targeting species for food and/or traditional cultural occasions; Recreational – non-Indigenous local fishery targeting species for sport

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

under the B1 (low emissions), and A1FI (high emissions) IPCC Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart 2000). The project was conducted before the release of the IPCC-AR5 (2013) however the climate projections from CMIP3 (coupled model inter-comparison project) and CMIP5 do not differ greatly (IPCC 2013, Knutti and Sedlâĉek 2013). Emissions scenarios are comparable, with the high emissions SRES A1F1 scenario being similar to RCP8.5 and the moderate emissions SRES A1B/A2 scenarios similar to the RCP6. The assessment focused on 2030 as a medium-term timeframe and the A1FI emissions scenario since this most closely represents current trajectories.

We assessed the vulnerability of habitats that support fisheries in the Torres Strait based on published literature; summarising the extent and status of estuarine, seagrass, mangrove and coral reef habitats in the Torres Strait, and known sensitivities of these habitats to climate drivers. The vulnerability of these habitats has been assessed in adjacent comparable regions using the same framework (Johnson and Marshall 2007; Bell et al. 2011b), and those results were used for this study (see Welch and Johnson 2013).

We applied a semi-quantitative approach to assess multiple fisheries species vulnerability based on a framework that includes the elements of exposure, sensitivity and adaptive capacity proposed by the IPCC (adapted from Schneider et al. 2007; Fig. 1). This framework provides a structured approach for determining the potential impacts of climate change on multiple fisheries and their relative level of vulnerability. The framework also provides transparency to stakeholders by using a scoring system that integrates expert and local knowledge, and identifies factors that contribute to vulnerability.

The indicators and scoring criteria used for each element underwent a rigorous selection and expert review process. Indicators for exposure were based on climate projections for the Torres Strait, and for sensitivity and adaptive capacity were adapted from previous studies (e.g. Marshall and Marshall 2007; Johnson and Welch 2010; Pecl et al. 2014) to be tailored to the Torres Strait (Table S1). We used sensitivity indicators developed by Pecl et al. (2014) for comparable species to those assessed in this study (e.g. rock lobsters, finfish and echinoderms), who comprehensively reviewed the rationale for their use. Indicators were tailored to the tropical environment and the life history characteristics of the 15 fisheries species assessed. This step, which is not described further here, generated a set of 24 indicators for each vulnerability element (Table S1; Welch and Johnson 2013).

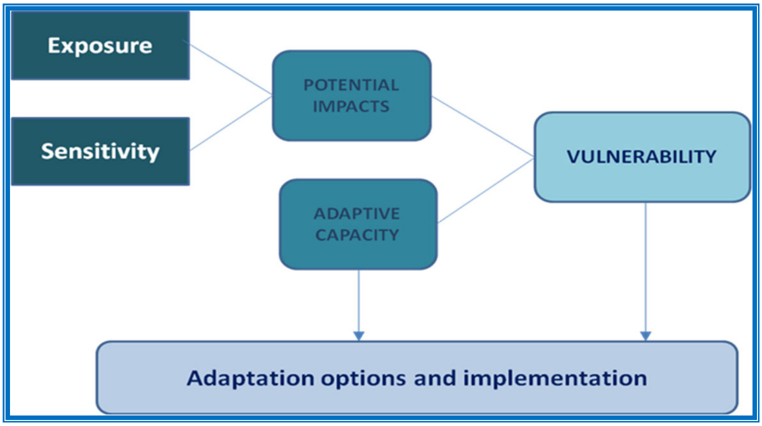

Fig. 1 Framework used to assess the vulnerability of Torres Strait fisheries to climate change that integrates socio-ecological indicators for exposure, sensitivity and adaptive capacity (adapted from Schneider et al. 2007)

Indicators for exposure and sensitivity were ecological in focus, while indicators for adaptive capacity integrated both ecological and social factors, since this is where fisher and community behaviour has an influence on vulnerability. In ecosystems, (autonomous) adaptation relates to genetic diversity, biological diversity, and heterogeneity within landscapes (Carpenter and Gunderson 2001), while in social systems, (planned and autonomous) adaptation relates to learning, managing risk, developing new knowledge and devising responses (Marshall et al. 2010). All indicators were unweighted since the relative value and interactions among the different assessment components are not well understood (Allison et al. 2009).

Indicators for each species were scored consistently and directly using: (1) available literature, (2) relevant expert assessment from a pool of 11 fisheries and biological scientists, and indirectly using (3) local Indigenous fisher knowledge (10 fishers) elicited through a structured interview process conducted by telephone or in person. There was a hierarchy of information for scoring where published literature combined with information from fishers was used to inform scientists' estimate (Table S2). Each indicator was scored as: low =1, medium = 2 or high = 3 based on the criteria outlined in Table S1. Pecl et al. (2014) 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 as the average score by dividing the total score by the number of indicators. Allison et al. (2009) showed that there is very little difference in the ranking outcomes between averaging (additive) and multiplicative approaches when estimating vulnerability using the same framework.

The potential impact index (PI) was calculated as the product of exposure (E) and sensitivity (S) indices. However, since the scoring framework does not accommodate direction of impact (i.e. positive or negative), the final PI index was derived by incorporating a "direction of impact" (DI) value. The DI value was: negative =1, unknown or neutral =0, or positive = −1. The PI index was calculated using:

$$\mathrm{PI} = (\mathrm{E} * \mathrm{S}) + \mathrm{DI}$$

Since adaptive capacity (AC) confers resilience to change (or tempers vulnerability) it is the inverse of the other elements, and accordingly the AC Index was standardized to a value between 0.0 and 1.0 (by dividing by the maximum score), and then inverted using 1 – AC to calculate relative vulnerability for each species. Vulnerability (V) was calculated using the following equation:

$$\mathrm{V} = \mathrm{PI} * (1 - \mathrm{AC\ standardized}) + 1$$

Due to the effect of standardization, 1 was added to avoid zero values, which may imply a species has no vulnerability. Therefore, the species with the lowest relative vulnerability had a score of 1.00. Full assessment results are provided in Table S3.

Prioritisation for fisheries management used the relative 'importance' of individual species to Torres Strait fishers and communities based on their economic and cultural values (Georgeson et al. 2014). To determine the level of fishery 'importance' we derived an index based on the current documented fishery dollar value and the estimated cultural value using high =3, medium =2, low =1 and negligible =0 (see Table S4 for details). Economic value was scored based on the mean dollar value of each commercial fishery in 2011/12 and 2012/13.

Cultural value was scored based on whether the species is harvested for subsistence and the level of use for cultural activities based on available literature and local interviews. Cultural value was assigned a higher weighting due to the local emphasis on traditional cultural activities in the region (Kwan et al. 2006; van Putten et al. 2013) and feedback received during the structured interviews. A score of "zero" was given if there was no economic value or subsistence catch.

The fishery importance (FI) index was calculated for each species using:

$$\mathrm{FI\ index} = \mathrm{Ec} + (2\mathrm{xC})$$

Where *Ec* is the economic value score and *C* is the cultural value score. Combining the FI index with the relative vulnerability score identified species with highest importance and highest relative vulnerability that should be prioritised for further research, management and/or community consultation.

To provide a sound basis for choosing species for priority action, we further calculated Euclidean distances for each species data point from the uppermost right corner of the plot (highest combination of scores) and identified the 20th, 40th, 60th, and 80th percentiles.

3 Results

3.1 Vulnerability assessment

Our findings were that by 2030, marine fisheries species in the Torres Strait are expected to respond to changes in the marine environment due to climate drivers:

- Increased sea surface temperatures between +0.62 and +1.27 °C (Suppiah et al. 2010) likely resulting in more frequent coral bleaching, redistribution of fishery species, and possible changes to the timing of spawning for some species.
- More intense cyclones with an increase in maximum wind speeds (Knutson et al. 2010) that will physically damage habitats, such as coral reefs, seagrass meadows and mangroves.
- More extreme rainfall and a slight increase in annual average rainfall of +1.2 % (Suppiah et al. 2010) that will deliver pulses of terrestrial pollutants to the marine environment, particularly in the northern Torres Strait that is influenced by the Fly River, PNG.
- Sea-level rise of between 5 and 15 cm ([Australian] BoM and CSIRO 2011) that will affect mangrove habitats, important nursery grounds for some fisheries species.
- Ocean stratification, upwelling and currents are likely to change ([Australian] BoM and CSIRO 2011) with consequences for fisheries productivity, however the nature of these changes is uncertain.
- Decreased salinity of 0.1 psu (on the practical salinity scale) ([Australian] BoM and CSIRO 2011) that may influence life cycle stages of some species.
- Ocean acidification impacts may be significant in the future, however projected changes by 2030 are small and unlikely to be a key factor in the short-term (Bell et al. 2011b).

The three species that were assessed as having the highest vulnerability to these projected changes were: *H. whitmaei* (black teatfish), *P. margaritifera* (black-lipped pearl oyster) and *D. dugon*. The traditional fishery for *D. dugon* has cultural significance to Torres Strait Islanders and is an important subsistence species. Similarly, marine turtle are important culturally as well as for subsistence, and were assessed as having moderate relative vulnerability (fifth highest overall). The other species assessed as high relative vulnerability was *T. niloticus* (fourth highest). The sources of vulnerability for the five most vulnerable species are discussed below, and further details on less vulnerable species are available in Welch and Johnson (2013).

3.1.1 Sea cucumbers

H. whitmaei (black teatfish) was assessed as the most vulnerable species to climate change due to high exposure to projected changes and, although only moderately sensitive to those changes, was assessed as having low adaptive capacity. This was mainly due to their low reproductive potential (Uthicke et al. 2004) and as a winter spawning species (Shiell and Uthicke 2006) any rise in water temperature is likely to restrict or prevent spawning in Torres Strait. They also have very low adult mobility, which limits their capacity to relocate if environmental conditions become unfavourable. Although ocean acidification could be a significant factor affecting spicule development in the longer term, especially in juvenile sea cucumbers, this remains a significant knowledge gap (Byrne 2011). Despite being a highly valuable fishery economically, the *H. whitmaei* fishery has been closed since 2003, although in late 2014 a trial re-opening allowed the take of 15 tonnes by Traditional Inhabitants. With no subsistence targeting and other sea cucumber species available, any realised negative impacts on this species are unlikely to greatly affect Torres Strait fisheries. However, in the event that the fishery is re-opened, a re-assessment of vulnerability incorporating catch limits and fishery importance estimates should be conducted.

H. scabra (sandfish) was assessed as moderately vulnerable mainly due to their current overfished status with evidence of very slow recovery (Murphy et al. 2011), as well as their low productivity, low mobility and the importance of seagrass beds for juveniles (Mercier et al. 2000). Although this has historically been an important fishery in the Torres Strait with high economic value, the fishery has been closed since 1998 and subsistence harvest is minimal (Georgeson et al. 2014).

3.1.2 Pearl oysters

Although the cultured pearl industry is of high economic value, pearl oyster wild harvest is currently very low in the Torres Strait (Torres Strait Fisheries Assessment Group 1999). *P. margaritifera* (black-lipped pearl oyster) is the least common and of lesser importance compared to *P. maxima* (gold-lipped pearl oyster). *P. margaritifera* was assessed as having high relative vulnerability primarily due to their low mobility (Gervis and Sims 1992) and naturally low abundance in the region, probably because Torres Strait is near their northern limit and they are more common in higher latitudes (Zhao et al. 2003). *P. maxima* was assessed as moderately vulnerable due to their low mobility, their stock status 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. Pearl oysters were also assessed as vulnerable due to the effects of ocean acidification on shell growth and spat survival (Welladsen et al. 2010). However, ocean acidification impacts on marine invertebrates, although potentially significant and complex due to the interacting effects with other climate variables (e.g. temperature), remain a key knowledge gap (Byrne 2011).

3.1.3 Dugong

D. dugon was assessed as having high relative vulnerability to climate change. Although they had the lowest score for exposure, they had high sensitivity because of their low productivity and very strong dependence on seagrass meadows as a preferred habitat and primary food source (Marsh and Kwan 2008). Seagrass meadows are prolific in the western Torres Strait (McKenzie et al. 2010) and are predicted to be impacted by rising water temperatures, reduced light and increased storm intensity (Waycott et al. 2011), which is projected to have flow-on negative effects on dugong populations. The reliance of *D. dugon* on seagrass has been documented in Torres Strait and other tropical regions, with reduced dugong survival and health correlated with decreases in seagrasses due to storm activity and natural episodic die-backs (Marsh and Kwan 2008; Bell and Ariel 2011). As a significant cultural fishery targeted by traditional hunters and used for ceremonies, the high vulnerability of dugong is a concern.

3.1.4 Trochus

T. niloticus was assessed as having high relative vulnerability due to a combination of high exposure and low adaptive capacity. The underlying source of this was their low mobility and very short larval duration (Bertram 1998) that collectively limit their avoidance and dispersal capabilities. The Torres Strait fishery for *T. niloticus* is characterised by variable but generally very low effort (SEWPaC 2012, Woodhams et al. 2012) and, although there is a small level of subsistence harvest, the low harvest in recent years means it does not rank highly in terms of economic value or catch quantity.

3.1.5 Marine turtles

Marine turtles (principally *C. mydas*) are culturally important in Torres Strait (Grayson et al. 2006) and were assessed as having moderate relative vulnerability to climate change, despite being assessed as 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 (Fuentes et al. 2010), and there is a high level of confidence in the projection of future impacts. These impacts include stranding due to storms (Meager and Limpus 2012), storm surge inundation of nesting grounds (Pike and Stiner 2007), the influence of temperature on hatchling gender (Hawkes et al. 2009), and the potential loss of important food resources associated with seagrass meadows (Marsh and Kwan 2008). Although, *C. mydas* are opportunistic foragers and may be able to switch to other abundant marine plants, such as algae, as seagrass decline (M. Hamann, pers comm).

3.2 Sources of vulnerability

Each element of the framework (exposure, sensitivity and adaptive capacity) and their indicators were examined to identify the factors that drive vulnerability of individual species. The two species with the highest exposure scores were *Scylla serrata* (mud crab) and *P. ornatus*, despite both species being assessed with an overall vulnerability that was low to moderate. The species that had the lowest exposure score was *D. dugon*. Based on the scoring of exposure criteria for each species, the factors expected to have the greatest effects on Torres

Strait fisheries by 2030 will be increases in sea surface temperature, changes in supporting habitats and more severe storms.

The species that had the highest sensitivity scores were marine turtles and *D. dugon*. Based on the scoring of sensitivity criteria, the sensitivity of Torres Strait fisheries species to climate change is largely due to a high reliance on environmental drivers for reproduction and settlement. Species also scored high sensitivities due to the fact that many are at the northern extent of their range and therefore have physiological thresholds that are likely to be exceeded by 2030 under the A1FI emissions scenario, particularly in relation to sea temperature.

The species with the highest adaptive capacity scores were all finfish species as well as *S. serrata* and *P. ornatus*. Overall, based on the adaptive capacity criteria scores for all species, lower adaptive capacity was due to social and fishery governance factors rather than ecological factors. Species assessed as having management arrangements that were flexible (e.g. voluntary restrictions on harvest or hunting practices) were conferred the highest adaptive capacity. A sensitivity analysis of all assessment indicators found that adaptive capacity had the greatest influence on vulnerability, which was expected given its importance in moderating impacts. However, despite a range of indicators influencing vulnerability scores, only two had an effect on the ranking of the top 5 (most vulnerable) species (stock status and replenishment potential), and no indicators affected the species' that were ranked as the least vulnerable, providing confidence in the assessment results in terms of informing management.

3.3 Prioritising species for action

The species assessed as having higher relative vulnerability to climate change (Fig. 2) generally have social and cultural importance but are not currently the most economically important commercial species in the Torres Strait. Therefore, the prioritisation process was central to effectively target fisheries management. The 'fishery importance' of each species (based on economic and cultural values) identified a mostly different suite of species for further research and management action (see Table S4 for rankings). Plotting 'importance' against relative vulnerability highlighted that the highest priority species (in the 20th percentile) were: *P. ornatus*, *D. dugon*, and marine turtles (Fig. 3). These species all have high economic and/or cultural values and were assessed as being moderately to highly vulnerable to climate change. Two coral trout species also ranked relatively high (20-40th percentile) due to their local importance as a commercial fishery and as a regular part of Traditional Inhabitant catches (mostly subsistence).

Notably, although *P. ornatus* was assessed as moderately vulnerable to climate change, it is the most important commercial fishery in Torres Strait and ranked highly in the prioritisation process. The life cycle of the species (Pitcher et al. 2005) makes it highly exposed to changes in climate however sensitivity was assessed as low overall, except for their sensitivity to increases in water temperature (Norman-López et al. 2013). Plagányi 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, which had negative consequences for the profitability of the fishery and fishers who target them.

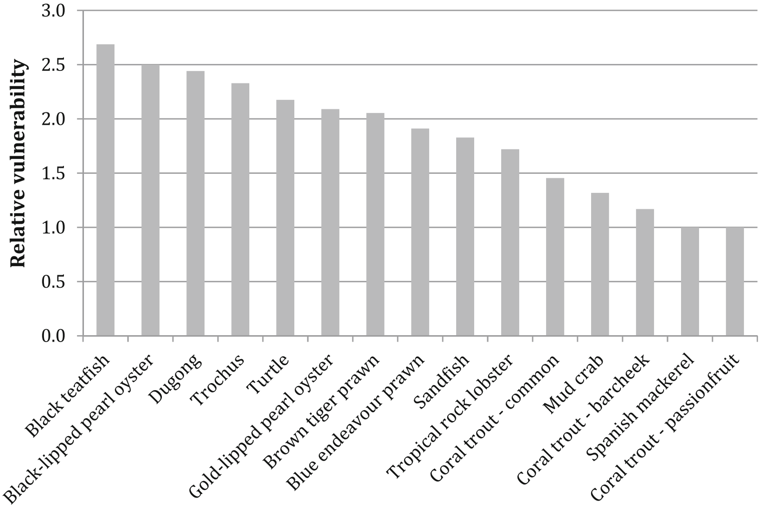

Fig. 2 Relative ranking of the vulnerability of 15 Torres Strait fisheries species to climate change

P. ornatus already show a response to warm ocean conditions by moving into deeper water. Although this is not necessarily a negative consequence from an ecological perspective, moving into deeper water makes them less accessible for the dive-based fishery, particularly Islander divers who, despite increasing interest in hookah, still use breath-hold diving (AFMA 2013; van Putten et al. 2013), and so fishery consequences may be highly negative. This warrants management focus due to the fisheries importance to both Traditional Inhabitant and non-Indigenous fishers, as well as for subsistence. Importantly, there are no comparable alternative species given the market price and demand for rock lobster relative to other species in Torres Strait and the high degree of gear and fishing technique specialisation (Georgeson et al. 2014).

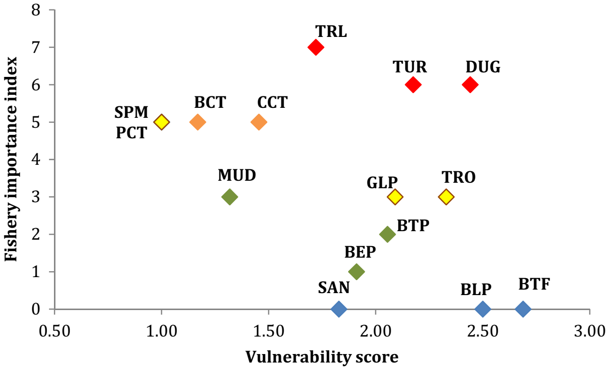

Fig. 3 Prioritisation plot showing the 15 fisheries species assessed and their relative vulnerability against an index of fishery importance to prioritise species for further research and/or action. To highlight priority species we calculated Euclidean distances for each data point from the uppermost top right corner of the two axes, and colour coded them based on their percentile group: <20th percentile -◆; 20th percentile -◆; 40th percentile -◆; 60th percentile -◆; 80th percentile -◆. 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

4 Discussion and conclusions

This analysis used a semi-quantitative approach to apply the established IPCC framework to identify the most vulnerable fisheries in the Torres Strait to climate change by 2030 under two emissions scenarios. The results identified the main climate change impacts that are likely to affect locally important fisheries in the future and the sources of vulnerability, which are being used to inform management decision-making and possible adaptation strategies. By considering both ecological and human factors, and prioritising species based on cultural and economic values, we have provided a target list for fisheries management and research focus.

The results have provided insight into which fisheries species are most vulnerable to climate change and the sources of this vulnerability. The key factors contributing to fisheries' high vulnerability were: lack of species mobility; species near their northern (thermal) distributional limits; strong habitat associations particularly for species reliant on seagrass meadows; strong dependence of the fishery on a single species; and inflexible or non-adaptive management. Understanding these vulnerability sources provides specific targets for action that will promote strategies to manage future climate risks and maintain fisheries sustainability. Focusing adaptations on priority species to minimise sources of vulnerability will reduce future impacts on Torres Strait fisheries and dependent communities. For example, *D. dugon* were assessed as highly vulnerable due to their dependence on seagrass as a food resource, and possible adaptation actions need to consider effective means of conserving seagrass meadows and minimising other pressures. Ultimately, adaptation options will need to meet community imperatives for food security and livelihoods, and be selected and implemented by stakeholders, particularly Torres Strait Islanders.

The relatively healthy condition of most fisheries in the Torres Strait (Georgeson et al. 2014) may aid in the success of any future adaptations since healthy stocks are inherently more resilient and more capable of coping with change (Brander 2010). Adaptations that focus on sustainable management of stocks, habitat conservation (particularly coral reefs and seagrasses), and diversification of fisheries target species present the most promise for fisheries under climate change, which is consistent with findings of comparable assessments in PNG and the Great Barrier Reef. Strong local governance is also important in an uncertain and changing future, particularly in remote regions. The next important step involves consultation with community and managers to clearly identify and prioritise adaptation options that help mitigate climate vulnerabilities by addressing their sources.

This framework is designed as a rapid assessment tool in resource-limited (funding and data) scenarios common in many regions, and progresses previous research to develop climate change assessment tools for managers (Johnson and Welch 2010; Bell et al. 2013; Pecl et al. 2014). The framework is a cost-effective method for prioritising future research and management investment under resource constraints, providing a strategic complement to current single-species fisheries management. Despite this, there are some important considerations of the results that provide opportunities for further research or framework modifications. Empirical validation of the vulnerability indicators, particularly for climate sensitivity, would provide greater certainty for application to a broader suite of species. Validation of the assessment results based on observational data under climate variability would confirm the extent of potential impacts, and provide greater certainty. Additionally, the nominal classification of low, moderate and high vulnerability, and prioritisation groupings could be revised to meet specific criteria or management needs, and adjusted as practices change. For example, if re-opening the black teatfish fishery were to be considered, its stock status and economic value would change thereby grouping it with other high priority species for further focus. The assessment that this species is highly vulnerable to future climate change, particularly ocean warming, warrants scrutiny of quotas and practices, particularly since experience has demonstrated that the species can be easily overfished and is slow to recover (Uthicke et al. 2004; Murphy et al. 2011).

Importantly, this modified framework can be applied to other fisheries, species and ecosystems, providing appropriate indicators and criteria are developed (Johnson et al. 2015). Because the approach is transparent and consultative, it is a powerful tool for engaging with communities, and collaboratively enabling future adaptation to climate change. This framework also provides a semi-quantitative methodology that is consistent with other modified approaches (e.g. Cinner et al. 2013; Foden et al. 2013) and therefore comparisons of results could provide insight into a wider range of resource-dependent systems.

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