Implications of climate change impacts on fisheries resources of northern Australia

Part 1: Vulnerability assessment and adaptation options



David J. Welch, Thor Saunders, Julie Robins, Alastair Harry, Johanna Johnson, Jeffrey Maynard, Richard Saunders, Gretta Pecl, Bill Sawynok and Andrew Tobin

Project No. 2010/565

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Cover photos: Torres Strait fishing boat with dory (J. Johnson); Recreational fishers with red emperor (Tippo); Seagrass meadows (GBRMPA).

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1 NON TECHNICAL SUMMARY

2010/565	Implications of climate change impacts on fisheries resources of northern Australia.

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OBJECTIVES:

1. Describe the projected climate-driven changes that are relevant to northern Australian fisheries resources.
2. Assess the potential impacts of climate change on key fisheries and species in northern Australia.
3. Identify approaches that are adaptive to potential climate change scenarios.

OUTCOMES ACHIEVED TO DATE

Provision of scenario-driven recommendations of adaptive management approaches that provide for the sustainability of northern Australia fisheries in a changing climate.

- The final project workshops worked with stakeholders to identify adaptation options based on likely future fishery scenarios. Scenarios were based on the reviews of species biology and ecology, as well as future localised climate projections, and described the likely response of key species to climate change. For example, the abundance of barramundi on the east coast is likely to decrease by 2030 due to reduced rainfall and increased water extraction, as well as habitat changes. Adaptation options across all species were grouped as: Alteration of fishing operations, Management-based options, Research and Development and Looking for Alternatives. These groupings generalise the types of adaptation that fishers and managers identified and species-specific options are also given in the report appendices. With these options stakeholders also identified the likely barriers and who is responsible for their implementation. Cost was identified as a key barrier to most options as well as political opposition. The options presented here represent an initial, but important, step towards northern Australian fisheries preparing for climate change.

Determination of the vulnerability of northern Australia's fisheries to climate change.

- A key output from the project was the development and application of vulnerability assessments of key fishery species from three key regions of northern Australia. The assessment framework developed is semi-quantitative and draws on the elements of exposure, sensitivity and adaptive capacity. The assessments are species-based and regionally targeted and he framework is a tool to assess the relative vulnerability of species to climate change, providing an objective and strategic basis for developing responses to projected changes. The framework is also transparent and provides the means for determining the appropriateness of responses. The framework can readily be adopted for similar assessments in other regions and, with modification, could also be adopted in other disciplines. The vulnerability assessments here focused on 2030, a medium-term outlook, and one considered to be more relevant to all stakeholders, although an assessment was also carried out based on the A1FI emissions scenario for 2070.

Greater understanding of the impacts of short and long term climate variability on northern Australia's key fisheries species, fisheries and regions of northern Australia, and the key environmental drivers. These include identification of priority species, fisheries and/or locations for targeted monitoring.

- The project has delivered as a major output, summary tables of the likely impacts of climate change on key northern Australian fishery species and habitats, also identifying the environmental variables of significance. This was done for three regional areas of northern Australia based on projected climate change for 2030. The key species likely to be impacted by changes predicted for 2070 (A1FI emissions scenario) were also identified. The vulnerability assessment process also prioritised species for action.

Generally, inshore species were assessed to be more likely to be affected by future climate change. The east coast was identified as a critical region given that rainfall (riverflow) is projected to decrease and many species populations are known to be positively associated with riverflow. This is amplified by the likely increase in water extraction for land-based uses, particularly on the east coast. Across all regions in northern Australia the species identified as highest priority (high vulnerability and high fishery importance) were: golden snapper, king threadfin, sandfish, black teatfish, tiger prawn, banana prawn, barramundi and mangrove jack.

Improved capacity for fisheries management agencies and industry to assess current practices and policies to optimise positioning for future predicted scenarios.

- Collectively, the key outputs of this project provide an informed basis for management and industry to assess current fisheries management against likely future scenarios. Management as well as commercial and recreational fishing interests were key participants in the project and had direct input into key outcomes providing a credible base for further extension and uptake by relevant fishery stakeholders.

NON TECHNICAL SUMMARY:

Climate change is a major environmental threat and there is a national imperative to determine likely impacts on fisheries in Australia. Northern Australia is predicted to be affected by increased water temperatures, changes in rainfall patterns and resultant increases in river flows to the marine environment, increased intensity of cyclones, ocean acidification, and altered current patterns, which will also affect habitats. These changes will directly and indirectly impact on fishery species including modified phenology and physiology, altered ranges and distributions, composition and interactions within communities, and fisheries catch rates.

For fishery sectors in northern Australia to be able to respond positively and adapt to climate-induced changes on fish stocks there is a need to determine which stocks, and where, when and how they are likely to be affected, and prioritise species for further actions. This project set out to do this using a structured approach to develop and carry out a semi-quantitative vulnerability assessment and conduct stakeholder workshops to identify adaptation options. These outputs were informed by several tasks: a descriptions of past and future climate; identify likely impacts of climate change on habitats and key fishery species; detailed species profiles to document and understand key fisheries, species life histories, and sensitivity to environmental variability (see Part 2 companion report); and analyses of existing data sets of key species to better understand sensitivity to environmental change.

Changes in climate across northern Australia are predicted to be highly variable depending on the specific region with the trend for warmer, less saline and more acidic waters, rising sea levels, more intense cyclones and changed oceanographic conditions. By 2030, north-western Australian sea surface temperature (SST) will be 0.6 – 0.9 °C warmer, the Gulf of Carpentaria will be 0.3 – 0.6 °C warmer, and both regions will have similar or slightly higher rainfall (0 – 5%)(and riverflow). Sea level is projected to rise between 10 and 20 cm and there will be a weakening of the Leeuwin current on the west coast. By 2030, east coast SST will be 0.3 – 0.6 °C warmer, there will be -10 – 0 % less rainfall (and riverflow), sea level will rise between 5 and 15 cm and the East Australian Current with strengthen. Fishery species will be directly exposed to these changes and will also be indirectly exposed to impacts on habitats.

A literature review of climate effects on habitats in northern Australia examined the key habitat types: coral reefs, seagrass meadows, mangroves, floodplains, coastal bays and estuaries. The review found that projected increases in SST will cause more coral bleaching, and ocean acidification will reduce coral growth and structural integrity, resulting in a loss of reef diversity and structure. Increased storm severity and extreme riverflow events, resulting in increased turbidity and reduced solar radiation, will reduce seagrass cover and species diversity. Sea-level rise may result in a landward migration of mangroves depending on localised barriers and, coupled with altered rainfall patterns, will change the connectivity between rivers and floodplains, resulting in the potential loss of freshwater floodplains.

To prioritise species to be potentially included in the project we consulted stakeholders and, based on a combination of fishery importance and perceived sensitivity to environmental variation, identified a total of 47 key fishery species across the three regions of northern Australia – east coast (40 species), Gulf of Carpentaria (36 species) and north-western Australia (37 species). The species that were generally ranked highest across the three regions included barramundi, mud crab, banana and tiger prawns, coral trout, golden snapper, black jewfish, Spanish mackerel and king threadfin.

Analyses of existing data sets were carried out on barramundi, red throat emperor, coral trout, saucer scallop, Spanish mackerel, and golden snapper to identify correlations between recruitment and/or catch rates with particular environmental variables. A positive correlation was found between barramundi CPUE and river height as well as rainfall in the Northern Territory, providing further evidence of the positive influence of rainfall, riverflow (and floodplain inundation) on barramundi catchability and possibly recruitment. In southeast Queensland saucer scallop recruitment was enhanced in years of cooler water. Recruitment also appeared to be positively influenced by higher local riverflow and by the presence of a cyclonic current eddy in the Capricorn region. Recruitment of Spanish mackerel on the Queensland east coast appeared to be linked to SST with cooler years positively influencing recruitment, although the causal mechanism for this relationship is unclear. Analyses of Spanish mackerel data supported the hypothesis of a single east coast stock. Analyses of the other species produced equivocal results.

Region-based ecological vulnerability assessments for climate change scenarios for 2030 were carried out for the three regions (i) north-western Australia (23 species), (ii) the Gulf of Carpentaria (21 species), and (iii) the Queensland east coast (24 species). Species with the highest ecological vulnerability to climate change tended to have one or more of the following attributes: an estuarine/nearshore habitat preference during part of their life cycle; poor mobility; reliance on habitat types predicted to be most impacted by climate change; low productivity (i.e., slow growth/late maturing/low fecundity); known to be affected by environmental drivers; and fully or overfished. Based on the combination of ecological vulnerability to climate change and fishery importance, the highest priority species were identified as: golden snapper, king threadfin, sandfish, black teatfish, tiger prawn, banana prawn, barramundi, white teatfish and mangrove jack.

In the medium-term (2030), the most common impact identified across all species was reduced size of populations due mainly to lower rainfall and riverflow, which affects primary productivity and therefore survival of early life history stages. The indirect effects of habitat degradation on key life history stages and increasing SST were also likely to impact some species by 2030. In the longer-term (2070), changes in rainfall/riverflow, SST and habitats will continue to impact species, with ocean acidification and salinity likely to increasingly become factors that impact species through disruption of early life history development (e.g. coral trout) and habitat effects (particularly coral reefs). Some species in some regions, for example banana prawns in the Gulf of Carpentaria, may experience higher population sizes due to projected increases in rainfall. Individual species and the likely impacts on them as a consequence of changed climate are discussed in detail in the report.

Rainfall and riverflow are key environmental drivers for many fisheries populations in northern Australia through enhancement of local primary productivity and larval/juvenile survival, and by connecting key habitats such as estuaries and floodplains. The Queensland east coast in particular is a key area for concern due to projected lower rainfall and more extreme (i.e., longer) wet and dry periods, coupled with the expected increase in water extraction for land-based use. Many fishery species of northern Australia use estuarine, floodplain and nearshore habitats and so are likely to be impacted by changed hydrological conditions, particularly barramundi that use all habitats during various stages of their life history. For example, longer periods of wet and dry will result in higher variability in the size of barramundi populations. The project found there was a high level of uncertainty in how individual species, particularly their early life history stages, will be affected by changed SST, pH and salinity.

Based on priority species for each region and the likely impacts on these species, we presented future scenarios to stakeholders at workshops conducted in Darwin and Townsville. Through discussion these stakeholders identified a range of potential adaptation options. We were able to group the options identified into four categories: (1) Alteration of fishing operations, (2) Management-based options, (3) Research and Development, and (4) Looking for alternatives. Examples of the types of options stakeholders identified include: modification of target species and/or gears, revised size/catch limits, habitat protection, targeted monitoring of species, codes of conduct, restocking and habitat restoration. Most of the adaptation options identified involved regulatory changes and/or policy decision-making (Management-based options). Stakeholders also identified that major barriers to adaptation for northern Australian fisheries were likely to be costs, political opposition and bureaucracy. In terms of responsibility for taking actions, it was acknowledged that all stakeholders will need to play a role, however government will need to need to be a lead player in this process.

Due to the number of fishery species assessed across a vast area, this project took a broad approach to determining the relative vulnerability of key fishery species in northern Australia. Despite this, the project developed a process to prioritise these species to identify likely impacts on key species based on the best available knowledge, and to also engage stakeholders in identifying the range of potential adaptation responses that would mitigate consequences both environmentally and on the fisheries and its participants. To further develop adaptation options we suggest the need for a regional focus with strong representation of all relevant stakeholder groups and multiple workshops that consider: priority species and likely impacts identified in this project (as well as the underlying mechanisms behind the impacts), and current management and government policy. There is also a need to rigorously prioritise adaptation options, identify complementarity among regions and species, and to identify clear pathways for adoption. Building a solid business case for each option that articulates costs and tangible benefits will maximise the likelihood of the commitment of the associated resources required for successful adoption.

KEYWORDS: Climate change, fisheries, northern Australia, life history, life cycle, environmental drivers, vulnerability assessment, adaptation, habitats, stakeholders.

2 ACKNOWLEDGEMENTS

We would like to thank many who contributed during the course of project: Sue Helmke and Jo Atfield of the QDAFF Long Term Monitoring Program in Cairns were very helpful in providing monitoring data and also in helping us in understanding that data; several individuals who attended project workshops and provided valuable guidance and expertise and included David Mayer (QDAFF), Tony Courtney (QDAFF), Marco Kienzle (QDAFF), Colin Simpfendorfer (JCU), Steve Newman (Department of Fisheries, WA), as well as several fisheries managers and representatives from the fishing industry in Queensland and the Northern Territory. We would like to acknowledge the input of several key stakeholders throughout the project in particular Randall Owens (GBRMPA), Eric Perez and Scott Wiseman (QSIA), and at key points at the beginning of the project input from Mark Lightowler, John Robertson and Anthony Roelofs (QDAFF). Several other key experts, who are acknowledged elsewhere, contributed to specific sections including observed and projected climate change (Dr Janice Lough, AIMS), habitat reviews, the species reviews and the vulnerability assessments. Thanks also to Colin Simpfendorfer in helping to facilitate the administration of the project. This project was supported by funding from the FRDC – DCCEE on behalf of the Australian Government.

3 STRUCTURE OF THIS REPORT

There are two parts of this report. Part 1: Vulnerability assessment and adaptation options, and Part 2: Species profiles. Part 1 (this report) represents the main body of the project reporting on the approach taken in carrying out the vulnerability assessments, the results and discussion of these results. The project was structured into multiple tasks that lead to the identification of the types of adaptation options that northern Australian fisheries may need to adopt in the future under current climate change projections and potential impacts on species (see Figure 7.2). Part 1 outlines the detail of each of these tasks except for the reviews of key northern Australian fisheries species, which are presented in a separate volume; Part 2. Part 2 describes in detail the fisheries, biology, ecology and life cycle, and sensitivity to environmental variability for 23 different species/species groups; 8 invertebrates and 15 finfish and sharks. These species profiles provide much of the information that supports the project vulnerability assessments, the identification of likely impacts on species, and adaptation options. Part 2 also represents a valuable stand-alone resource for any fishery stakeholder.

4 BACKGROUND

This application for this project was developed through consultation and in conjunction with industry (Queensland Seafood Industry Association, Sunfish, Amateur Fishermans Association of the Northern Territory, Northern Territory Seafood Council), oceanographic scientists and modelers (Craig Steinberg & Richard Brinkman, Australian Institute of Marine Science), research scientists with relevant experience (Julie Robins, QDAFF; Andrew Tobin, JCU; Thor Saunders, NT Department of Primary Industries and Fisheries; Stewart Frusher, Tasmanian Aquaculture and Fisheries Institute; Bill Sawynok, Recfishing Research/Capreef; Nick Caputi, WA Department of Fisheries), and resource managers from Queensland and the Northern Territory (Mark Lightowler, John Robertson & Warwick Nash, QDAFF; Randall Owens, Rachel Pears, GBRMPA; Julia Playford, DSITTA; Steven Matthews and Andria Handley, NT DPIF). Several of these key scientists and end-users were co-investigators on the project.

During this project there was ongoing consultation and collaboration with similar projects in South-eastern Australia (PI's Gretta Pecl and Tim Ward; FRDC SE climate change adaptation project) and Western Australia (PI Nick Caputi; FRDC WA climate change adaptation project) to facilitate ongoing learning that will optimise and standardise the approaches taken across all projects. We also maintained contact with concurrent research projects to use results as relevant: coral trout, Professor Morgan Pratchett; barramundi, Professor Dean Jerry. Also, the results from this project provided valuable input into the FRDC project assessing socio-economic impacts of climate change on fisheries across Australia (PI Stewart Frusher).

This project relates directly to several other completed projects. These include the recently completed AFMA project (2013/0014) ‘Assessing the vulnerability of Torres Strait fisheries and supporting habitats to climate change’ (Welch and Johnson, 2013), the Great Barrier Reef climate change vulnerability assessment (Johnson and Marshall, 2007) and the Pacific climate change vulnerability assessment of fisheries (Bell et al, 2011), and several FRDC projects including: (2008/103) 'Adapting to change: minimising uncertainty about the effects of rapidly-changing environmental conditions on the Queensland coral reef finfish fishery' (Tobin et al. 2010); (2001/022) 'Environmental flows for sub-tropical estuaries: understanding the freshwater needs of estuaries for sustainable fisheries production and assessing the impacts of water regulation' (Halliday and Robins 2007), and the recently completed QDEEDI/QDNR/QCCCE/JCU project that examined short- and long-term climate variability on barramundi fisheries. Each of these studies provided important case studies and templates for analytical approaches adopted during the current project, and provided a solid basis from which to extend understanding of the phenology of selected key species and to examine potential future impacts under climate change scenarios. The project drew on many data sets collected over many years from past research projects and on-going monitoring programs including fisheries-related and environmental-related data sets.

5 NEED

Climate variability has always been an influence on fisheries productivity however the current trends and rates of change predicted under climate change scenarios has resulted in a national imperative to establish likely impacts on fisheries in Australia. Northern Australia is predicted to be affected by changes in rainfall patterns and resultant changes in river flows to the marine environment, increased intensity of cyclones, increased water temperatures, increases in ocean acidification, and altered current patterns (CSIRO 2007). These changes in the marine environment will directly impact on fisheries including modified phenology and physiology, altered ranges and distributions, composition and interactions within communities, and fisheries catch rates (Hobday et al 2008, Munday et al 2008, Halliday et al, 2008, Balston 2009). Critically, most fisheries in northern Australia are deemed to be not well prepared at all for future climate impacts (Hobday et al 2008). For fishery sectors in northern Australia to be able to respond positively and adapt to climate-induced changes on fish stocks there is a need to determine which stocks, and where, when and how they are likely to be affected. Current fisheries management in northern Australia is jurisdiction-based. There is a need for a co-operative approach to developing management policy that can deal with future climate change scenarios. Development of such policy requires consultation with all stakeholder groups. This addresses one of the NCCARP high priority research needs for commercial and recreational fishing, two of FRDC's Strategic Priority R&D Areas (Themes 3 & 4), and priorities for Qld and NT management agencies.

There exists extensive northern Australia biophysical and fisheries data for regional assessment of likely climate change impacts. Data include temperature, salinity, pH, wind, rainfall, upwelling events and river flows. There is a critical need for the collation of existing data sets to determine and document the key environmental drivers for northern Australian fisheries; a key research priority for national, Qld and NT agencies.

6 OBJECTIVES

1. Describe the projected climate-driven changes that are relevant to northern Australian fisheries resources.
2. Assess the potential impacts of climate change on key fisheries and species in northern Australia.
3. Assess current management to identify approaches that are adaptive to potential climate change scenarios.

7 METHODS

7.1 Overview

This project used a structured approach to achieve the ultimate objective of identifying adaptation options for northern Australian fisheries in response to projected climate change. The key underlying framework for this work was the Vulnerability Assessment framework followed by the Inter-Governmental Panel for Climate Change in their global assessment process (Figure 7.1) (Schroter et al. 2004). This framework provided an intuitive and structured approach for determining the potential impacts of climate change on fisheries species (and systems) and their relative level of vulnerability. The framework also provides transparency to stakeholders by incorporating adaptive capacity thereby informing the development of appropriate responses for relevant fisheries stakeholder groups to consider.

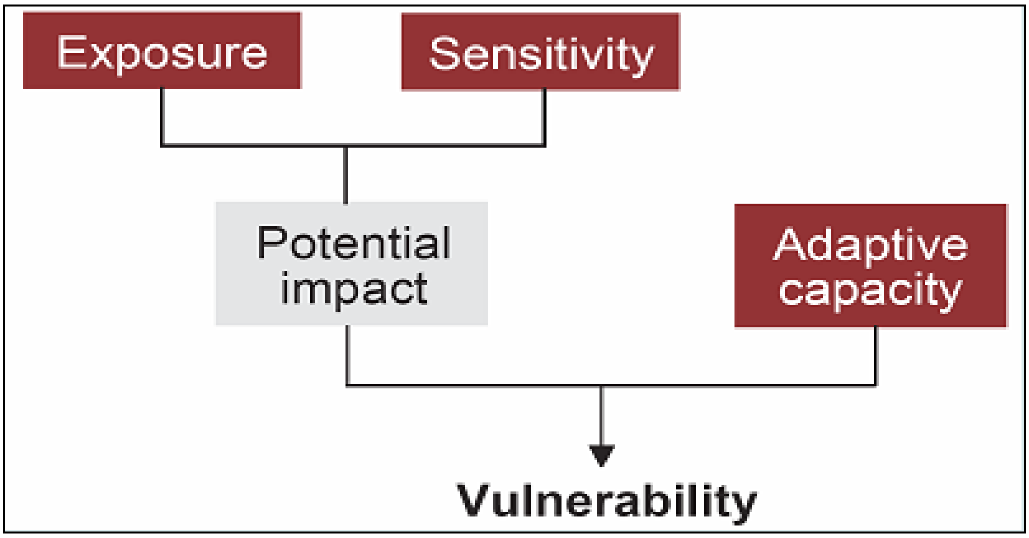

Figure 7.1 Vulnerability assessment framework adopted by the IPCC (Schroter et al. 2004).

For each of the major assessment elements used in this report definitions are as follows:

Exposure:

The nature and degree to which a system or species is exposed to significant climate variations. In a climate change context, it captures the important weather events and patterns that affect the system. Exposure represents the background climate conditions against which a species or system operates, and any changes in those conditions.

Sensitivity:

The degree to which a system or species is affected, either adversely or beneficially, by climate-related stimuli. Climate related stimuli, include mean (i.e. average) climate characteristics, climate variability and the frequency and magnitude of extremes. Sensitive species and systems are highly responsive to climate and can be significantly affected by small changes. Understanding a species or system's sensitivity also requires an understanding of the thresholds at which it begins to exhibit changes in response to climatic influences, whether these adjustments are likely to be 'step changes' or gradual, and the degree to which these changes are reversible. The effect may be direct (eg coral bleaching in response to elevated sea surface temperatures) or indirect (eg loss of suitable habitat for important fisheries species due to changes in sea temperature, ocean chemistry and storm intensity).

Adaptive Capacity:

The potential for a species or system (natural or social) to adapt to climate change (including changes in variability and extremes) so as to maximise fitness, to moderate potential damages, to take advantage of opportunities or to cope with consequences.

Vulnerability:
The degree to which a system or species is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system or species is exposed, its sensitivity, and its adaptive capacity.

The project followed a number of iterative steps to comprehensively address each of the elements of the assessment framework, while also adopting a stakeholder inclusive approach where appropriate to ensure outputs that were relevant and achievable. These steps were key to meeting the major project objectives, which address several of the framework elements (Exposure, Sensitivity, Adaptive Capacity). The steps taken as part of each of the assessment framework elements are summarised as a flow diagram in Figure 7.2. This flow diagram reveals the overall process followed by the project while the details of each of the tasks follow in subsequent sections of this chapter.

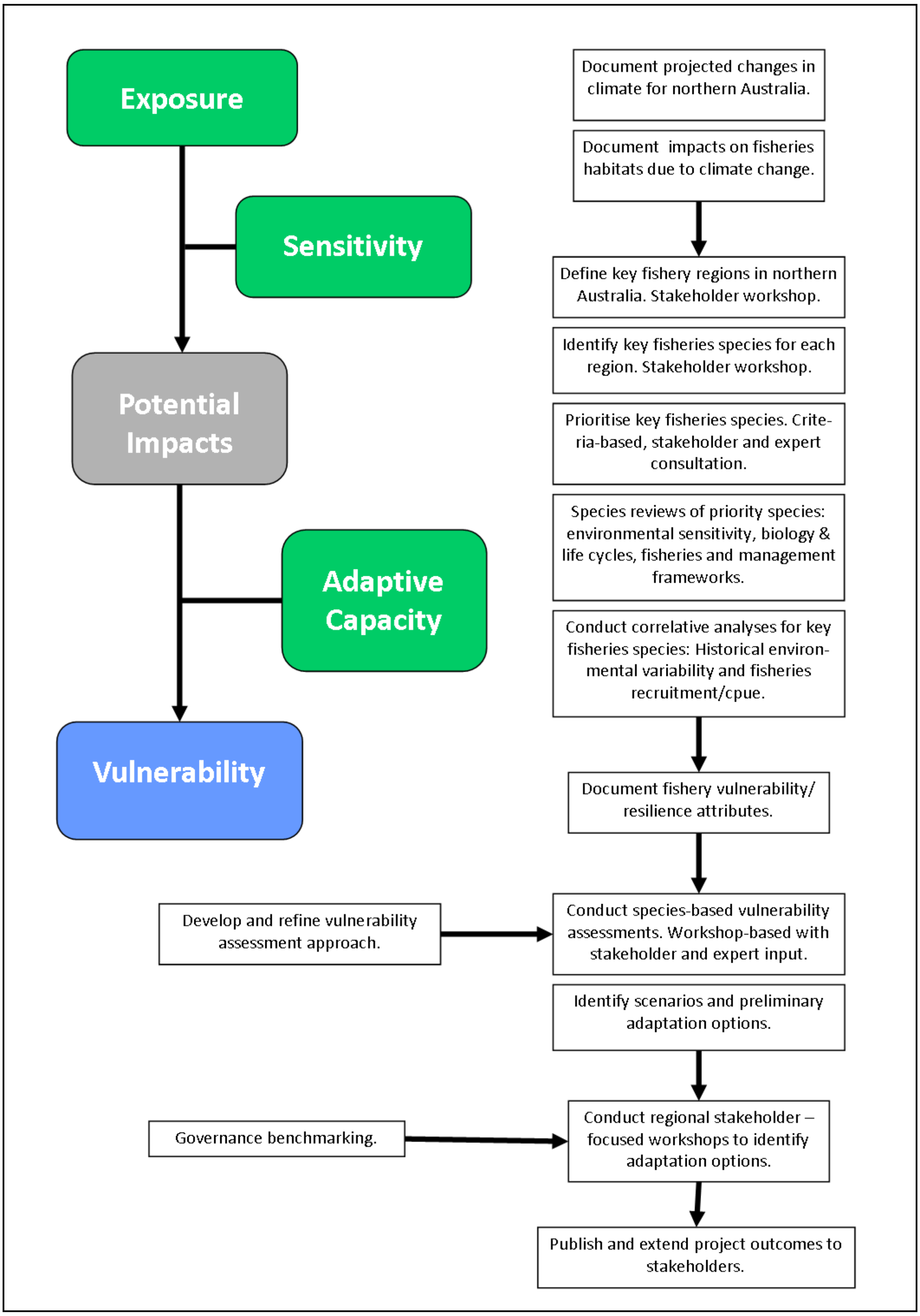

Figure 7.2 Flow diagram of key project tasks carried out in addressing the respective elements of the vulnerability assessment framework.

7.2 Defining geographic scale

The project was focused on fisheries across northern Australia covering a vast area over three jurisdictions. Given the vastness of the total area and the fact that the fisheries and species of importance across this area varies markedly, for the purposes of this project we decided it was appropriate to divide northern Australia into three major fishery regions. The three key regions were: north-western Australia (northern Western Australia and north-western Northern Territory; NWA), the Gulf of Carpentaria (GoC), and the Queensland east coast (EC) (Figure 7.3). The geographic limit of interest on the east and west coasts was determined primarily by the usual ranges of key species with some species extending into New South Wales due to seasonal migrations, with the notable example being Spanish mackerel (*Scomberomorus commerson*).

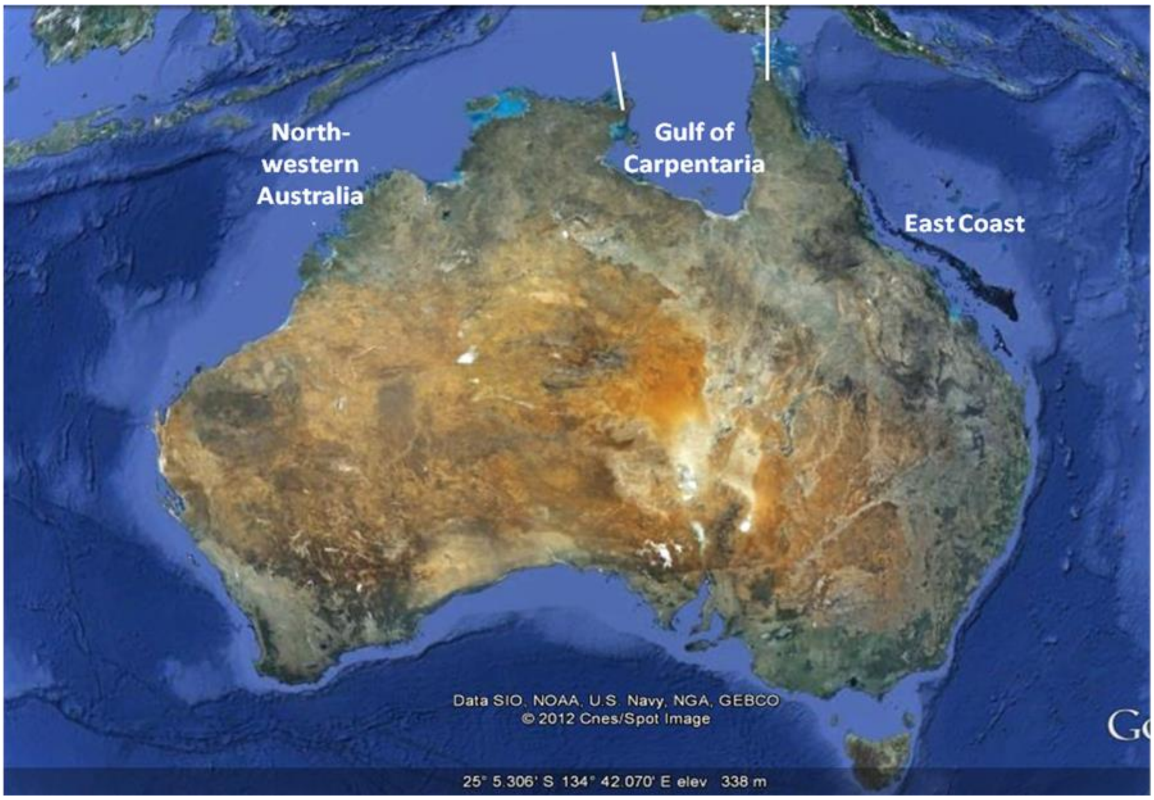

Figure 7.3 Australian map indicating the key spatial regions adopted for identifying the key northern Australian fisheries species.

7.3 Species identification

To assess the potential impacts on the different fisheries of northern Australia we focused on key species and assessed each species independently. Identification of the key species of interest was initiated at the first project workshop in Brisbane in April, 2011, where the project team in attendance comprised of stakeholders from Queensland and Northern Territory and included scientists, fisheries and conservation managers, commercial fishing interests, and recreational fishing interests. A full list of participants is provided in Appendix 3. At this workshop we conducted a 'brainstorming' session to list key species and based our species selection on three criteria: fisheries importance (social value, economic value, level of catch), potential sensitivity to climate change and, to a lesser extent, data availability. This initial list was then sent out to a wider reach of stakeholders for comment and addition of new species if necessary. Western Australian fisheries interests were consulted at this time for input into the species list for the NWA region. Once feedback had been received from all stakeholders a final list of key northern species was collated for each of the three regions.

7.4 Species prioritisation

Given the large number of species and the limited time available it was not possible to include all the listed species in the data analyses or, potentially, the project vulnerability assessment stage. Therefore we prioritised species lists for each region using a semi-quantitative framework. This was not intended to produce a definitive ranking of the importance of northern Australian fisheries species, although the final lists would likely be indicative of this. It was however, intended to provide guidance to the project of the species that should receive our focus, and the order in which we would proceed through the list of species in order to provide an assessment of as many northern Australian fisheries species as possible.

The framework was comprised of two "groups" of criteria relating to attributes of each species: Group 1. Fisheries/ecological attributes; and, Group 2. Climate change sensitivity attributes. The criteria used for the Group 1 attributes and their definitions are given in Table 7.1. For each region, project members and other "expert" stakeholders subjectively scored against the criteria for each species for Group 1 using relative scores of 3 (high importance), 2 (medium), and 1 (low). Scorers were chosen based on their expert knowledge of species biology and ecology, and fisheries for the respective regions. For each species, the individual scores for each criterion were summed to give a total Group 1 score. The final Group 1 score for each species was taken as the average score for that species across all scorers.

Group 2 criteria for climate change sensitivity were based on those developed by Pecl et al (2011) in their ecological risk assessment for south-eastern Australian fishery species. Although there are differences in the tropics compared to south-eastern Australia (eg. dramatic episodic disturbances such as cyclones and floods), many of the criteria used in the Pecl et al (2011a) framework capture these issues in some way. These criteria and how they were scored are detailed in Table 7.2. For the Group 2 criteria scientific experts were used for scoring each species and, given the lack of knowledge of species sensitivity to environmental variation, were asked to use their "professional judgement" in scoring and in some cases this meant using "educated guesses". For each species, the mean score of each of the attributes (Abundance, Distribution and Phenology), were summed to give a total Group 2 score for the individual scoring. The final Group 2 score for each species was taken as the average score across all scorers for that species.

Table 7.1 Criterion used for fisheries/ecological attributes of each species in the semi-quantitative framework used to prioritise species from each region for further analysis.

Criterion	Guiding definitions
Social/cultural importance	Species historically targeted due to popularity as a sportfish, edible qualities, large size, or other historical significance
Economic importance	Dollar value mostly as a commercial target species or through high recreational effort and/or tourism attraction
Catch	Volume of catch
Ecological importance	Considers trophic level and interactions

The final score used for ranking individual species in order of priority was the sum of the mean Group 1 score and the mean Group 2 score. The scoring process described here and above are summarised in Figure 7.4 using east coast barramundi and mud crab as examples.

Table 7.2 Criterion used for climate change sensitivity attributes of each species in the semi-quantitative framework used to prioritise species from each region for further analysis (Pecl et al 2011a).

Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		
		High sensitivity (3), low capacity to respond	Medium (2)	Low sensitivity (1), high capacity to respond
Abundance	Fecundity – egg production	<100 eggs per year	100 - 20,000 eggs per year	>20,000 eggs per year
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Highly episodic recruitment event	Occasional and variable recruitment period	Consistent recruitment events every 1-2 years
	Average age at maturity	>10 years	2-10 years	≤2 years
	Generalist vs. Specialist – food and habitat	Reliance on both habitat and prey	Reliance on either habitat or prey	Reliance on neither habitat or prey
Distribution	Capacity for larval dispersal or larval duration – hatching to settlement (benthic species), hatching to yolk sac re-adsorption (pelagic species)	<2 weeks or no larval stage	2 – 8 weeks	>2 months
	Capacity for adult/juvenile movement – lifetime range post-larval stage	<10 km	10 – 1000 km	>1000 km
	Physiological tolerance – latitudinal coverage of adult species as a proxy of environmental tolerance	<10° latitude	10 - 20° latitude	>20° latitude
	Spatial availability of unoccupied habitat for most critical life stage – ability to shift distributional range	No unoccupied habitat; 0 - 2° latitude or longitude	Limited unoccupied habitat; 2 - 6° latitude or longitude	Substantial unoccupied habitat; >6° latitude or longitude
Phenology	Environmental variable as a phenological cue for spawning or breeding – cues include salinity, temperature, currents and freshwater flows	Strong correlation of spawning to environmental variable	Weak correlation of spawning to environmental variable	No apparent correlation of spawning to environmental variable
	Environmental variable as a phenological cue for settlement or metamorphosis	Strong correlation to environmental variable	Weak correlation to environmental variable	No apparent correlation to environmental variable
	Temporal mismatches of life cycle events – duration of spawning, breeding or moulting season	Brief duration; <2 months	Wide duration; 2 – 4 months	Continuous duration; >4 months
	Migration (seasonal or spawning)	Migration is common for the whole population	Migration is common for some of the population	No migration

Group 1	Mud crab	Barramundi
social/cultural importance	3	3
economic importance (GVP)	2	3
catch (net volume)	2	3
ecological importance	3	2
SUM:	10	11

Group 2	Sensitivity attribute	Mud crab	Barramundi
Abundance	Fecundity	2	1
	Recruitment period	3	3
	Average age at maturity	2	2
	Generalist vs Specialist	2	2
	Ave:	2.25	2.00
Distribution	Larval dispersal/duration	1	2
	Adult/juvenile movement	3	2
	Physiological tolerance	2	2
	Spatial availability of unoccupied habitat	2	3
	Ave:	2.00	2.25
Phenology	Environmental spawning cue correlation	3	3
	Environmental settlement cue correlation	2	1
	During of spawning season	2	3
	Migration	1	1
	Ave:	2.00	2.00
	TOTAL:	6.25	6.25

Group 1 criteria	Scorers						
Species	1	2	3	4	5	6	AVE:
Barramundi	10	10	12	12	11	11	**11.00**
Mud crab	10	12	11	12	11	10	**11.00**

Group 2 criteria	Scorers				
Species	1	2	3	4	AVE:
Barramundi	6.25	5.25	6	6.25	**5.94**
Mud crab		4.75	7	6.25	**6.00**

FINAL RANKINGS:			
Species	Group 1	Group 2	Score
Mud crab	11.00	6.00	**17.00**
Barramundi	11.00	5.94	**16.94**

Figure 7.4 Summary of the scoring framework used for prioritisation of each species within each region. In this example we used east coast barramundi and mud crab. The two top spreadsheet screen captures show Group scores from an individual expert with the following screen captures showing how all individual scores are collated.

7.5 Species reviews

Based on the prioritised list of fishery species pooled across the three northern Australian regions, we produced detailed species profiles. These profiles were based on the species reviews done by Pecl et al (2011b) and so were comprised of information about the fisheries, their management, biology and life history, as well as documenting known and inferred information about species sensitivity to environmental change. These reviews not only serve as a useful stand-alone resource for all fishery practitioners, now and into the future, but they also provide the necessary baseline information for this project to (i) carry out further species sensitivity analyses, (ii) conduct the species-based vulnerability assessments, and (iii) identify appropriate adaptation options and barriers. A total of 23 species reviews were compiled and are collated into a companion publication (Part 2) to this vulnerability assessment report.

7.6 Observed and projected climate for northern Australia

7.6.1 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 the sensitivity analysis conducted at the project workshop in December 2011. The information was drawn from a range of sources, particularly the Australian Bureau of Meteorology, CSIRO (CSIRO and BoM 2007) and the Queensland Government as well as key literature, particularly Lough and Hobday 2011, Church et al. 2009 (for sea level) and Lough 2007 (for detailed information on the Great Barrier Reef). Further detailed information for other project regions (e.g. Gulf of Carpentaria, northwest WA) were sourced from state and regional datasets. The summary of observed climate covered historic temporal periods when the data are most reliable.

7.6.2 Climate Projections

The climate projections for this project were compiled from a range of sources including Climate Change in Australia (CSIRO and BoM 2007), OzClim using the CSIRO Mk3.5 model, and SPC 2011 (Table 7.3).

Table 7.3 Climate variables selected for climate projections and data sources.

Variable	Data source
SST	OzClim
Ocean temp 250 m	CSIRO and BoM 2007
Rainfall	CSIRO and BoM 2007
Riverflow	CSIRO and BoM 2007
Ocean pH	SPC 2011
Storms & Cyclones	Ozclim
Sea level	CSIRO and BoM 2007
Ocean circulation	Ozclim

Ultimately, the projections 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 historical emissions and using observed natural forcing (e.g. changes in solar radiation, volcanic eruptions). At the end of the 20th century, projection simulations were carried out based on predefined 'plausible' future emission trajectories.

For this project, we focused on two of these trajectories, corresponding to low (B1) and high 'business as usual' (A1FI) emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES) (IPCC 2007). These emissions scenarios consider a range of possible future global conditions, including economics, population (growth and distribution), energy technologies, and cultural and social interactions. The models can then simulate the atmosphere and ocean based on these possible futures, and in this project we used projections for the near-term (2030) and long-term (2070).

Some of these models are now available as web-based online tools for generating climate change projections, such as the CSIRO-developed OzClim[1]. OzClim provides an Australian-specific model for 12 variables, eight emission scenarios, three climatic sensitivities and 23 global climate models. This allows users to generate projections of annual, seasonal or monthly average changes in climate for the years 2020 – 2100 (in 5-year increments). This model was selected as it is one of the more recent CSIRO climate models developed for Australia and has reasonable 'skill' in capturing present and past states of the Australian climate system to make projections of what the future might hold.

7.7 Climate change implications for habitats that support northern Australian fisheries

We conducted a literature review to summarise information on documented habitat types and extent in the three regions of northern Australia – EC, GoC and NWA – based on published reports, grey literature and online GIS mapping tools (OzCoasts, Geoscience Australia). The review also documented known sensitivities of these habitats to climate drivers, including results from related projects in adjacent regions (Welch and Johnson 2013, Bell et al. 2011a).

The vulnerability of northern Australian habitats to projected climate change was based largely on a review and synthesis of available vulnerability assessment results. The habitats considered in this project – floodplains, coastal bays and estuaries, seagrass meadows, mangroves and coral reefs – have been assessed in tropical 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 habitat

[1] http://www.csiro.au/ozclim/home.do

vulnerability assessments conducted for habitats in the GBR (Johnson and Marshall 2007), Torres Strait (Welch and Johnson 2013) and the Pacific region (Bell et al. 2011a), particularly nearby Melanesian nations. The assessment of vulnerability was tailored to the three regions of northern Australia, taking into consideration observed and projected climate for the regions, the extent and distribution of habitats, and the scale of the regions.

7.8 Sensitivity data analyses

7.8.1 Identifying species and key variables

Although the species reviews document their sensitivity to particular environmental variables, very little of this information is from published studies and so much of what we "know" about species sensitivity is inferred based on expert knowledge and/or studies on similar species. This project was an opportunity to potentially fill some of these information gaps by investigating the quality and quantity of existing relevant fisheries data, and where suitable, examine data on key tropical fisheries species for correlation with historical environmental data.

It was acknowledged from the outset that, given the often-coarse nature of fisheries and environmental data, identifying strong signals that would signify important relationships would be difficult to achieve. To maximise the likelihood that any data analyses conducted would be able to detect significant relationships if they existed, we adopted a hypothesis-driven approach whereby the most plausible drivers of population dynamics were examined for key aspects of the species life history. This process also considered the quantity and quality of data available and the ranking of each species from the prioritisation process.

To help define the hypotheses of interest for the priority species, we used a semi-quantitative approach for determining the environmental drivers most likely to affect each of the particular species. Drawing on known sensitivity and expert opinion, the framework estimated the likely sensitivity of key aspects of each species life history characteristics to particular environmental variables. The approach used was for experts to assign a "1" for each species characteristic thought likely to be sensitive to changes in each of the particular environmental variable. A "0" was assigned if it was thought to be not sensitive. For each environmental variable these scores were summed to give a value ranging from 0 – 4. The relative level of impact of each environmental variable on each species was determined based on the scores and definitions given in Table 7.4. The species characteristics examined were recruitment, growth, distribution and catchability, while the environmental variables examined were Sea Surface Temperature (SST), rainfall, ocean pH, sea level, salinity, upwelling, nutrients, wind/current, and riverflow. An example of this framework and how it was used is given below in Table 7.5 using Spanish mackerel, while the results for this process for all species examined is provided in Appendix 6.

Table 7.4 Derivation of the estimated level of impact of environmental variables on key species.

Impact level	Impact description	Score
High	Substantial effect	3 - 4
Medium	Some effect	2
Low	No effect or unknown	0 - 1

Table 7.5 Framework for identifying likely environmental drivers of interest for each species where Impact is High (H), Medium (M), or Low (L). Aspects of the species are scored 1 or 0 based on their likely sensitivity to each environmental variable and the likely impact derived as described in Table 6.4. The example shown is for Spanish mackerel.

Spanish mackerel	Recruitment	Growth	Distribution	Catchability	Impact
SST	1	1	1	0	**H**
rainfall	1	1	0	0	**M**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	0	0	**L**
upwelling	1	1	0	0	**M**
nutrients	1	1	0	0	**M**
wind/current	1	0	1	0	**M**
riverflow	1	1	0	0	**M**

In the example given, this framework helped to identify that SST was a likely key driver of Spanish mackerel population dynamics (eg. recruitment and distribution) and therefore presented plausible hypotheses that may warrant testing through analyses of data. For our priority species we also assessed the availability of fisheries-dependent and fisheries-independent data, evidence of previous research, and the capacity for the project team to carry out the analyses. Through this process species for analysis were identified and relevant hypotheses were developed.

7.8.2 Data analyses

Based on biological aspects of individual fish species and key drivers of fisheries production, as well as the type of data available, there were two main data analysis approaches used. These were: the examination of recruitment dynamics which directly influences fishery production; and fishery catch rate, which can be influenced by past conditions (recruitment and growth), but can also be influenced by current local environmental conditions (catchability). Selection of explanatory environmental variables for inclusion in the global model was based on an integrative approach suggested by Robins *et al.* (2005). This involved carrying out a detailed review of the life history and life cycle of the species of interest in order to systematically identify a subset of biologically plausible environmental variables and the lag at which they would most likely affect different life stages (see species reviews in the companion report). This reduced the possibility of obtaining statistically significant correlations without any causal relationship (i.e. Type 1 error); the risk of this was potentially high given the often-large size of the datasets available for analysis.

Environmental data used in the respective analyses are described in each section for the relevant species and their sources. Satellite-derived Sea Surface Temperature (SST) data was sourced from NOAA/NASA Pathfinder version 5.2 with data weekly at 4km resolution aggregated across selected fishery grids or sites. Chlorophyll a. data was median monthly data for selected spatial grids and were sourced from NOAA/NASA and CSIRO Land and Water.

Catch rate analyses

Catch and effort data were obtained from the daily commercial fisheries logbooks submitted to the QDAFF and DPIF. These data were obtained from the specific location for each analysis and were aggregated into annual totals to investigate the correlation of inter-annual trends with environmental factors over the same temporal period. All data were transformed ($\log_{10}(x+1)$) prior to analysis to normalise variances. Correlation analyses and all sub-sets general linear models (GLM, Genstat 2008) were used to explore the potential relationships between catch and effort data and environmental variables. The GLM provided a relative contribution of variables individually or grouped to the variation explained by the model terms.

Year Class Strength analyses

To examine for the influence of environmental factors on recruitment success we used Year Class Strength (YCS) analysis following the methods described by Maceina (1997). To undertake these analyses a time series of age structure data was obtained for each species, where possible, from annual collections of otolith samples. Catch curves were generated for each year of data by taking a weighted linear regression of the natural log of abundance against age for the descending part of the curve. This approach uses positive and negative residuals associated with the linear catch curve as being strong and weak year classes respectively (Maceina 1997). Based on hypotheses for each species, environmental variables can then be examined as predictors of YCS. The relationship between YCS and environmental variables was investigated by correlation analysis and all sub-sets general linear modelling (GenStat 2008) with year-class strength as the response variable, and age and sample year as forced variables because the abundance of individual age-classes is not comparable between years (Staunton Smith et al. 2004).

Both analysis types were investigated for the degree of auto-correlation amongst residuals and, where significant, the degrees of freedom were adjusted to account for serial auto-correlation (Pyper and Peterman 1998).

7.8.2.1 Barramundi

Author: Thor Saunders

The analyses for this species was conducted on data collected from the Daly River, located approximately 200 km to the south of Darwin in the Northern Territory (NT). This river has one of the largest catchments in the NT and is an important area for both commercial and recreational fishers (for a detailed description see Halliday et al. 2012). The specific hypotheses investigated in these analyses were:

1. That increases in river height and rainfall as a proxy for flood plain inundation will increase barramundi catch.
2. That increases in river height and rainfall as a proxy for flood plain inundation will increase larval/early juvenile growth and survival.

Catch Data Analysis

Fishery catch and effort data were obtained from daily logbook records submitted to the Fisheries Division of the NT Department of Primary Industry and Fisheries by both commercial and Fishing Tour Operators (FTOs). Catch was aggregated into annual totals to investigate inter-year trends. Data was available during the periods 1983-2012 and 1994-2012 for the commercial sector and FTO sectors respectively. Catch rate was obtained by dividing annual catch by annual effort and the environmental variables included annual water year (e.g. October 2009 to September 2010 = 2010 water year) rainfall (mm) from Katherine (termed 'rainfall') (Bureau of Meteorology) and river height data in number of days above 10m at the Daly River crossing (termed 'river height') (NT Department of Land Resource Management) over the same period as the catch and effort data.

Correlation coefficients were calculated between annual CPUE and river height and rainfall variables. An all sub-sets general linear model (GLM, Genstat 2008) was used to more thoroughly explore potential relationships between catch and the environmental parameters. Instead of using CPUE as the dependant variable, catch was used and effort and sampling year were forced into the model so that the variation in catch attributed by variation in these variables could be quantified separately. To investigate the temporal influence of river height and rainfall, lags were included as independent variables 1, 2 and 3 years (termed 'river height 1, 2 and 3' and 'rainfall 1, 2 and 3') before the current water year.

Year class strength analysis

The age-structure of the Daly River barramundi population was determined by carrying out opportunistic sampling on commercial and recreational fisher catches throughout each sample year (2007-2011). Each sample had the total body length measured and otoliths were retained for ageing. Because of the selectivity of commercial and recreational gear types it was assumed that only the 3-8 year age classes were sampled representatively. This allowed the YCS analysis to be conducted during 2001-2009. The environmental variables used were the same as for the correlation analysis above. However, the seasonal influence of rain on catch was investigated by including seasonal (summer, autumn, winter and spring) rainfall as independent variables. River height data was not separated seasonally as flooding events were very consistent in late summer and early autumn each year and so was well represented by the annual total. Age was forced into the model, as was sampling year, because the abundance of individual age-classes is not comparable between years (Staunton Smith et al. 2004).

7.8.2.2 Coral trout

Authors: Andrew J. Tobin, Alastair V. Harry, Richard Saunders and Jeffrey Maynard
In an attempt to begin to better understand some of the processes that may drive the variable recruitment of *P. leopardus* that has been described historically, analyses were conducted to investigate – firstly, the presence of significantly variable year class strength (YCS) throughout a time series of age structure data; and secondly, where significant fluctuations in YCS are detected can these patterns be correlated with environmental variables? Based on a working group and the species review for coral trout, the following environment recruitment hypotheses were proposed and investigated in this analysis:

1. SST may affect recruitment by its influence on timing and duration of spawning and by increasing larval/early juvenile growth rates and thus survival
2. High rainfall in coastal catchments as a proxy for primary productivity may have an influence on larval/early juvenile growth and thus survival
3. Fluctuations in the SOI may affect recruitment indirectly through its influence on SST, rainfall and coastal productivity

Year class strength analysis
Age structure data collected by the CRC Reef Effects of Line Fishing Project were utilised for the analysis of year class strength. This data set incorporated 11 consecutive years of fisheries-independent age data from 1995-2005 for three regions (Storm Cay, Mackay and Townsville) from within the GBR Marine Park (GBRMP). Including region as a factor in the initial YCS analyses was paramount as *P. leopardus* are known to vary in both biology and local abundance throughout the GBRMP (Adams et al 2000; Tobin et al 2013). Details of the ELF project sampling protocols and age estimation procedures are available in Mapstone et al. (2004).

This age structure data were used to derive YCS estimates. This data was derived for each year of sampling, *i,* by using the Studentized residuals from a linear regression of $\log(N_i) = a + bx_i$ to provide replicate estimates of relative abundance in the year, $i - x$. Only fish aged 4-11 were included in the analysis since 0-3 year old fish were not fully recruited to the sampling gear, and fish > 11 years were also excluded because they were relatively rare. To avoid the confounding effects fishing can have on YCS signals (see Russ et al. 1996) only data from unfished reefs were analysed.

For each region, year class strength estimates were correlated against environmental variables hypothesised to possibly impact recruitment processes (Table 7.6). Again as *P. leopardus* is known to vary in both biology and local abundance throughout the GBRMP, SST data for the correlation analysis was localised to spatial grids corresponding to the reefs sampled in each region (Townsville, Mackay, Storm Cay). In addition, SST data were restricted to the Spring spawning period, also the timing of fish sampling. As the timing of *P. leopardus* spawning varies within latitude, the period of Sep-Nov was chosen for Townsville and the period Oct-Dec for Mackay and Storm Cay. The mechanistic impact of the Southern Oscillation Index (SOI) on year class strength is likely to be very broad, thus SOI was considered as an annual mean.

Data from major river catchments close to the sampled regions were selected as proxies for regional rainfall and catchment inundation. The catchment chosen for Townsville was the Burdekin, and for both Mackay and Storm Cay the Fitzroy River was chosen. These are the largest and most representative of river discharge into the GBRMP within these regions. The final river-flow index was the log-transformed sum of river discharge over the Spring period (Sep-Nov) as well as the Spring and Summer period (Sep-Feb). This time-period encompassed the key spawning period and the following wet-season period across northern Australia.

Each YCS vs environmental variable correlation was examined at three different time steps. Correlations were fitted to the year of interest (e.g. year of recruitment or year of catch) as well as the years immediately prior (one year lag; -1) and the year immediately after (one year in advance; +1) in order to help establish whether environmental correlations had a causal basis.

Table 7.6 Description of environmental predictors investigated for analysis of year-class strength environment-recruitment relationships.

Variable	Description
SST	Annual means for each region (Storm Cay, Mackay, Townsville)
	Spawning period means for each region (Storm Cay, Mackay, Townsville)
SOI annual	Annual mean for the Coral Sea
River flow	Burdekin flow annual total, log transformed (for Townsville)
	Fitzroy flow wet season flow, log transformed (for Mackay and Storm Cay)

7.8.2.3 Golden snapper

Author: Bill Sawynok

Tagging data was used to determine if there has been any shift in the range of golden snapper at the southern end of their range on the east coast of Australia, and assess whether it may be attributable to local estimates of sea surface temperature.

The tagging data was provided from the Suntag program, managed by Infofish Australia, and included all golden snapper tagged since the mid 1980s. Tagging was carried out voluntarily as part of normal fishing trips and data collected included tag number, date, total length and location. Locations are recorded within the database using Suntag Grid Maps that have either 1 or 2km^2 grids. This provided fine scale resolution of where fish were tagged and the opportunity to examine whether this had changed over time. Locations where golden snapper were tagged were examined for the period 1985-2013 and data were aggregated over each 5-year period. Data were also aggregated by latitude within half-degree zones from 22^o-26^o S as shown in Figure 7.5. Tagging data were further constrained to estuary and nearshore habitats; the habitats that golden snapper mostly use.

In addition, Captag, an ANSAQ club in Rockhampton, with approval from the Department of Defence, tagged fish in the creeks at the southern end of Shoalwater Bay from 2000-2012. Tagging was undertaken on trips involving a maximum of 10 boats for 2-3 days each trip and involved the capture and tagging of many golden snapper (Sawynok 2013). Catch and effort details were collected on all trips making this a consistent dataset. As this effort was significantly different from the normal tagging effort the data were analysed separately. The percentage of golden snapper tagged in the catch for Shoalwater Bay trips was calculated along with the CPUE.

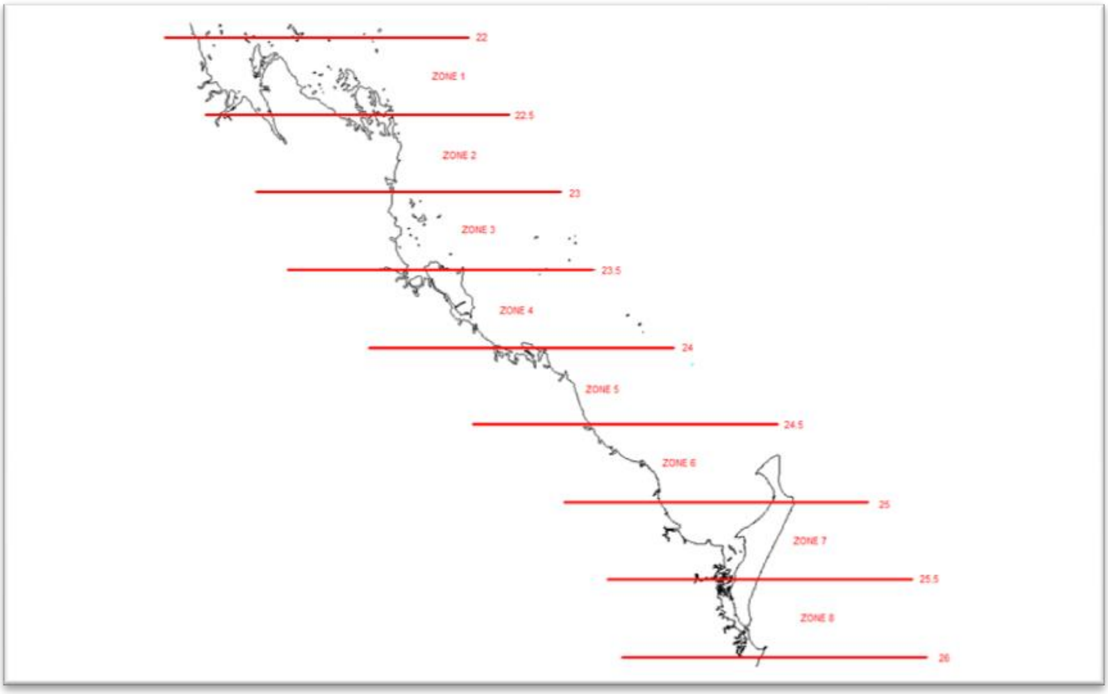

Figure 7.5 Map showing half degrees zones from 22°-26°S on east Australia coast used to analyse golden snapper data.

For each of the eight half degree zones from 22°-26°S the total tagging effort was calculated as the number of days on which fish were tagged in each 5-year period. For each zone and each period the percentage of golden snapper tagged compared with the total fish tagged was calculated. For each zone and each time period the percentage of golden snapper compared with the total tagging effort (number of days on which fish were tagged) was also calculated. Recaptures of golden snapper were examined for the direction of movement and whether movement could be related to season.

It was considered that temperature tolerance levels may be a factor in limiting the range of golden snapper and that any range change may be correlated with any temperature change. Sea surface temperature (SST) data were obtained from NOAA/NASA Pathfinder version 5.2 data at 4 km resolution (nearshore grids only) aggregated across each zone on a seasonal basis from 1985-2009. From that data the mean SST for each zone and each season were calculated.

7.8.2.4 Red throat emperor

Authors: Richard Saunders, Alastair V. Harry, Andrew J. Tobin and Jeffrey Maynard

These analyses focused on the Queensland east coast red throat emperor population and used age structure data collected during the CRC Reef Effects of Line Fishing (ELF) Project (Mapstone et al. 2004). During this project red throat emperor were sampled using commercial fishing gear using fishery-independent methods from three regions on the Great Barrier Reef (Storm Cay, Mackay and Townsville) over a period of eleven years (1995-2005). This provided the basis for a time series of age structures to be constructed for each region. Details of the ELF project sampling protocols and age estimation procedures are available in Mapstone et al. (2004). Based on a working group and the species review for red throat emperor (see Part 2 companion report), the following environment recruitment hypotheses were proposed and investigated in this analysis:

1. SST may affect recruitment by its influence on timing and duration of spawning and by increasing larval/early juvenile growth rates and thus survival
2. High rainfall in coastal catchments as a proxy for primary productivity may have an influence on larval/early juvenile growth and thus survival
3. Fluctuations in the SOI may affect recruitment indirectly through its influence on SST, rainfall and coastal productivity

Year class strength analysis

Age structures were provided from the ELF data sets (Mapstone et al. 2004). This data set was used to estimate year class strength estimates using the methods of Maciena (1997). These estimates were derived for each year of sampling, *i,* by using the Studentized residuals from a linear regression of $\log(N_i) = a+bx_i$ to provide replicate estimates of relative abundance in the year, $i - x$. Only fish aged 6-12 were included in the analysis since 0-5 year old fish were not fully selected by the sampling gear, and fish > 12 years were excluded as they were relatively rare. To avoid the confounding effects fishing can have on YCS signals only data from sanctuary zones (unfished) were considered in these analyses.

The final data treatment necessitated pooling data across regions and providing year class strength estimates for the Queensland east coast (see results and discussion) and correlating these estimates to environmental variables that are likely to act on a broad spatial scale (Table 7.7). Thus, SST data for the correlation analysis was the Coral Sea mean. The SST data were restricted to Spring (Sep-Nov) when spawning activity peaks (Williams et al. 2006), Spring and Summer (Sep to Feb) (for cumulative impact across different life stages), and an annual average. The mechanistic impact of the Southern Oscillation Index on year class strength is likely to be very broad, thus SOI was considered as an annual mean.

River flow data from a major river catchment close to the sampling locations were selected as a proxy for regional rainfall and catchment inundation. The catchment chosen was the Burdekin as the largest and most representative of river discharge to the Great Barrier Reef. The final river-flow index was the log-transformed sum of river discharge over the Spring period (Sep-Nov) as well as the Spring and Summer period (Sep-Feb). This time-period encompassed the key spawning period and the following wet-season period across northern Australia.

Similar to analyses for coral trout, each YCS vs environmental variable correlation was examined at three different time steps. Correlations were fitted to the year of interest (e.g. year of recruitment or year of catch) as well as the years immediately prior (one year lag) and the year immediately after (one year in advance) in order to help establish whether environmental correlations had a causal basis.

Table 7.7 Description of environmental predictors investigated for analysis of year-class strength environment-recruitment relationships.

Variable	Description
SST	Coral Sea mean for full calendar year
	Coral Sea mean for spring period
	Coral Sea mean for Spring and summer period
SOI annual	Annual mean
River flow	Burdekin flow annual total, log transformed
	Burdekin flow wet season flow, log transformed

7.8.2.5 Saucer scallops

Author: Julie Robins

The analyses were conducted in the area between 22°30’ S, 151° E and 26° S, 153°30’ E on the Queensland east coast where the majority of saucer scallops (*Amusium japonicum balloti*) are harvested in Queensland. It includes the inner shelf of the Great Barrier Reef on the Capricorn Coast approximately from Cape Clinton southwards to Hervey Bay. Waters in this area are generally less than 50 m deep and have a high sand content (Pitcher et al. 2007). The area is southwest of the Capricorn Channel and west of the Capricorn Bunker Group of coral cay islands. In the Capricorn region, these islands separate the inner shelf of the GBR from deeper (>200m) waters (Burrage et al. 1996). Mesoscale eddies of the East Australian Current have been reported in the area (Burrage et al. 1996) and are usually cold core cyclonic eddies. The study area also includes the relatively nearshore areas immediately east of Fraser Island, which intermittently have significant catches of saucer scallops.

From the species profile of the saucer scallop and its fishery (see species reviews in the companion report) the following environment recruitment hypotheses were proposed:

1. Water temperature may affect recruitment by its influence on gonad size and subsequent gamete production (in February and March) by benthic mature scallops.
2. Water temperatures may affect recruitment by its influence on mortality during pelagic larval phases between June and November.
3. Chlorophyll-a., as a proxy for food availability, may influence the larval growth and thus survival between June and November, subsequently affecting spatfall and recruitment. Timing of larval phase is between June and November.
4. Chlorophyll-a., as a proxy for food availability, may affect the growth and survival of benthic juvenile saucer scallops. The benthic juvenile phase occurs between September and December, with the duration of the juvenile phase is likely to vary depending on growth rates, which may also be linked to water temperatures.
5. Hydrographic features, such as cold core eddies, in the area between 22° S and 25° S, may have an influence on the distribution of larvae (June to November) and subsequently affect spatfall by entraining larvae to "optimum" areas.
6. Water temperatures (between September and December) may affect the growth rates of juvenile scallops and therefore the timing of scallop recruitment to the fishery at the legal size limit.
7. Large discharge from adjacent coastal rivers may impact negatively on scallop "recruitment" (Morison and Pears 2012) through reduced salinities or increased turbidity.

Spatial Recruitment Index

Indices of scallop abundance were provided by Dr Alex Campbell from the Queensland Department of Agriculture, Fisheries and Forestry (QDAFF). These indices represent the average scallop density of 0+ and 1+ year old scallops in 43 spatial cells across the study area, based on the scallop fishery independent surveys conducted annually in October between 1997 and 2006. For further details see Campbell *et al.* (2011). The spatial recruitment index data is standardised for sampling and fishing power differences over the duration of the LTMP scallop surveys. Data were available for 43 spatial cells, but only spatial cells where sampling occurred for ≥7 years were included in the analysis. This provided 26 spatial cells with a time series of fishery-independent abundance between 1997 and 2006 (i.e., cells 2-9 occurring within CFISH Grid V32; cells 10-18 occurring within CFISH grid T30; cells 21-28 occurring within CFISH Grid S28, and cell 43 occurring within CFISH Grid R28).

Commercial catch data

Commercial scallop catch and effort data were obtained from Queensland Department of Agriculture, Fisheries and Forestry (QDAFF). A subset of the commercial catch data was used in the analysis as an index of scallop abundance. The subset included detailed information on effort creep parameters that are not available for the full commercial catch dataset and focuses on the area between 22°30’ S, 151° E and 26° S i.e., the main scallop grounds. This subset data is updated annually and used by QDAFF in the catch rate standardisation procedure and fishing power analysis for Queensland saucer scallops. For further details see O’Neill and Leigh (2006) and Campbell *et al*. (2010). The data included daily catch weight (standardised in baskets) and effort (hours trawled) per boat per CFISH grid. Additional effort creep information included: otterboards, presence of a BRD and or TED; presence of a GPS; engine horse power; lunar phase and lunar phase advanced; net size; presence of a kortz nozzle; catch weight (kg) of prawns; presence of sonar devices; trawling speed; and presence of a try net. Commercial catch and effort data were available from 01/01/1988 to the 31/12/2011 and provided 102,355 daily records of catch per boat. The data was filtered to remove records where: (i) hours trawled per day exceeded 24 (i.e., bulk data); and (ii) prawn catch exceed 50 kg (i.e., not targeting scallops); thus providing ~91,000 daily records of catch and effort information. Queensland scallop data were aggregated into fishing years, reflecting biological characteristics of the species and operational characteristics of the fishery (O’Neill and Leigh 2006). For Queensland saucer scallop the fishing year is November (in the preceding year) to October i.e., FishYear 1989 = November 1988 to October 1989.

Environmental factors included in the analysis were selected on the basis that they: (i) were ecologically relevant; (ii) had available data; and (iii) were as close to the biological process/hypothesis as possible (Dormann et al. 2013).

SST data was used as a weekly median SST per 30’ x 30’ CFISH grids for the time series between January 1986 and December 2011. SST data were explored to investigate the most appropriate ways of aggregating SST data to capture its potential influence on the life history of saucer scallops. These included:

(i) the median seasonal weekly SST per grid for Summer (Dec to Feb: SST Sum), Autumn (Mar to May: SST Aut), Winter (Jun to Aug: SST Win) and Spring (Sep to Nov:SST Spr);

(ii) the number of days (wks x 7) per year when the weekly SST across all grids in the study area was <25°C (SST Days25 May to Nov);

(iii) the median weekly SST across all grids between May and November inclusive (SST May to Nov);

(iv) the median weekly SST across all grids, when SST was <25°C (Median SST 25);

(v) the minimum weekly median SST across all grids between May and November (Min SST Nov to May); and

(vi) the average winter (June to August) weekly median SST across all grids (SST Win all grids).

Although numerous measures of SST were explored (e.g. mean annual), further analyses used the median seasonal SST per grid to encompass spatial and temporal variability that matched commercial catch.

Chlorophyll a was included as median monthly interpretations of Chlorophyll a per CFISH grid were derived from NOAA with CSIRO corrections for GBR waters and were available as a time series between July 2002 and June 2012. Further analyses used the median seasonal SST per grid for Summer (Dec to Feb: Chla Sum), Autumn (Mar to May: Chla Aut), Winter (Jun to Aug: Chla Win) and Spring (Sep to Nov: Chla Spr).

River discharge from the following rivers was assumed to influence the following CFISH spatial grids:

- Fitzroy River – S28, S29;
- Boyne + Calliope River – S30;
- Kolan + Burnett Rivers – U31, U32, T30, T31;
- Mary River – V32, W32;
- Brisbane River – W33, W34, W35: and
- No associated river (i.e., offshore) – T28, T29, U30, V31.

For some areas, the discharge of two rivers was combined because of the close proximity of their estuaries and an inability to separate the area influenced by each river. The discharge of the Burnett and Kolan Rivers were pooled, as was the discharge of the Boyne and Calliope Rivers. Daily river discharge varies by several orders of magnitude between rivers, reflecting the catchment area of each river. Therefore, river discharge was standardised by the respective catchment area (upstream of the gauging station) to make the discharge volumes comparable.

River discharge (i.e., ML day^{-1}) was collated for the most downstream gauging station (GS) between January 1985 and September 2012, available from the Queensland Government Water Monitoring Portal (http://watermonitoring.derm.qld.gov.au/host.htm) for the following rivers:

- Fitzroy River (GS13005A @ The Gap; -23.08897222° S, 150.10713889° S; catchment area = 135,800 km^2).
- Calliope River (132001A @ Castlehope; -23.98498333° S, 151.09756389° E; catchment area = 1,288 km^2);
- Boyne River (GS133005A @ Awoonga Dam Headwater; -24.07008611° S, 151.32162528° E; catchment area = 2,258 km^2);
- Kolan River (GS 135002A @ Springfield; -24.75334711° S, 151.58717235° E; catchment area = 551 km^2);
- Burnett River (GS136001 B @ Walla; -25.13617187° S, 151.98222776° E till February 1998 then adjusted flow from GS136007A @ Figtree; -25.28507017° E, 151.9894613° S;

adjustment based on linear regression of flow at GS136007A with flow at GS136001B between January 1997 to February 1998 as recommended by R. Maynard Supervising Hydrographer, DNRM; catchment area = 32,070 km²);

- Mary River (GS 138014A @ Home Park; -25.76832547° S, 152.5273595° E; catchment area = 4,755 km²); and the
- Brisbane River (GS 143001C @ Savages Crossing; -27.43916667° S 152.6686° E; catchment area = 10,170 km²).

Discharge data were aggregated to reflect potential flow impacts on various aspects of scallop biology: January to May for impacts on gonad development (Flow Gonads); June to October for impacts on spawning (Flow Spawn); July to November for impacts on Spatfall (Flow Spat) and November to May for impacts on juvenile growth (Flow Juv).

There has long been anecdotal speculation that oceanographic eddies in the Capricorn area play a key role in influencing saucer scallop abundance. In this area of the Queensland east coast (i.e., between 22° S and 25° S in waters < 500 m deep), mesoscale eddies form as the East Australian Current passes the Swains Reef complex and Capricorn Channel (Weeks et al. 2010). These cyclonic eddies may influence the distribution of pelagic scallop larvae (June to November) and affect the distribution of spatfall and therefore successful recruitment to "optimum" habitat. While the intermittent presence of a cyclonic eddy in the Capricorn area has been documented (Griffin *et al.* 1987; Burrage *et al.* 1996; Weeks *et al.* 2010), no time-series of eddy presence is available. Further quantitative work on the longitudinal duration, spatial extent and intensity of cyclonic eddies in the Capricorn region, particularly when SST are less than 25°C, would be useful in understanding the environmental drivers of Queensland saucer scallop populations. In the absence of detailed longitudinal studies of the oceanography of the Capricorn area, and with advice from Richard Brinkman (AIMS), a surrogate of eddy presence was derived using the available data on the IMOS Ocean Current webpage (http://oceancurrent.imos.org.au/). The daily presence or absence (coded as 1 or 0 respectively) of a cyclonic eddy in the Capricorn area was visually assessed using the available maps of "sea level, geostrophic current and 3-day average SST 1993-now" for the North East (NE) region" (http://oceancurrent.imos.org.au/NE/). Where available, daily eddy presence was confirmed against images in "geostrophic current, snapshot SST + radar 2004-now" for the Southern Great Barrier Reef region (SGBR) (http://oceancurrent.imos.org.au/SGBR/) and Brisbane region (http://oceancurrent.imos.org.au/Brisbane/).

Daily counts of eddy presence between October 1993 and October 2011 were computed into the total number of days per year a cyclonic eddy was visibly present in the Capricorn area (i.e., north west of Sandy Cape) between the months of May and October inclusive. Annual counts were split into two groups: (i) May to July and (ii) August to October to investigate whether the timing of eddy presence had an influence on early or late spawning respectively.

Analysis of data

Data were transformed (ln(X+1)) prior to analysis to normalise the variances. Correlation coefficients were calculated between environmental factors. Then, all sub-sets generalized linear models (GLM's) were used to explore potential relationships between scallop abundance and environmental factors (GenStat 2011). All-subsets General Linear Model (GLM) will identify the model that explains the greatest amount of variance (as per step-forward GLM) but also calculates all possible combinations of forced and independent factors to identify a number of alternative regression models that can be evaluated by their explanatory power (adjusted R^2) and biological plausibility.

7.8.2.6 Spanish mackerel

Authors: Alastair V. Harry, David J. Welch, Andrew J. Tobin, Sue Helmke, Jo Langstreth and Jeffrey Maynard

Introduction

Many characteristics of narrow-barred Spanish mackerel and their fisheries are known to be closely associated with environmental conditions, potentially suggestive of a high sensitivity to climate change in this species (Welch *et al* this publication). From an ecological perspective, temperature is thought to be an important cue for spawning in Spanish mackerel. Additionally, larval transport from outer-shelf spawning reefs to suitable settlement areas in estuaries may be affected by currents and prevailing winds. Importantly, early-life history and survival are also presumed to be influenced by the conditions in estuaries where larvae settle and spend the first few months of life before they begin to disperse offshore.

Reflecting their apparent sensitivity to temperature, commercial fisheries for Spanish mackerel are highly seasonal. For instance, off eastern Australia Spanish mackerel occur over a 20° latitudinal gradient between the Torres Straits (10°S) and Coffs Harbour (30°S). Temporal peaks in landings vary regionally and have anecdotally been associated with the location of the 24°C sea surface temperature (SST) isotherm which is thought to influence the longshore movement and migration of older fish. The majority of the landings in the eastern Australia fishery are from fishers targeting spawning aggregations of Spanish mackerel between Lizard Island and Townsville, thus the timing and duration of these fisheries each year is directly linked to spawning behaviour which is influenced by temperature. These life history traits of Spanish mackerel led McPherson (1981) to speculate that fluctuations in fishery landings may be attributed to the effects of the el

Nino-Southern Oscillation (ENSO), and that this could provide a major challenge for managing the fishery.

Despite considerable interest and speculation there has been little formal investigation of the environment-recruitment links in Spanish mackerel. A clearer understanding of these could be beneficial to management of this commercially and recreationally importance species since, to date, there has been little explicit consideration of environmental variation in stock-assessments. Understanding how environmental variability affects the fishery may help in adapting to future climate-driven changes and in the interpretation of historical change in the fishery. We compared and contrasted the relationships between four key environmental variables (sea surface temperature (SST), Southern Oscillation Index (SOI), coastal rainfall, and primary productivity (Chl-a)) and two indices of abundance (year-class-strength and standardised catch per unit effort) on Queensland east coast *S. commerson*.

Study species and area

This analysis focused on the Queensland east coast Spanish mackerel population and the commercial line fishery that targets the species (Welch *et al* this publication). The stock structure of Spanish mackerel across northern Australia has been well-studied and fish on the east coast, which form a distinct genetic stock, are treated as a single unit for management purposes (Buckworth, Newman *et al.* 2007). While there is considerable genetic homogeneity within the east coast population, inferences from both parasites and otolith microchemistry provide strong evidence of subdivision within stocks and much finer-scale population structure (Moore *et al.* 2003; Newman *et al.* 2009). This seems to indicate that adults are relatively sedentary and exhibit little mixing on scales of 100-300km. Buckworth *et al.* (2007) suggests a metapopulation model as the most likely form of stock structuring. Nonetheless, a proportion of fish migrate longer distances, and on the east coast larger fish appear to migrate seasonally into northern NSW waters. Although fishing occurs around the entire Queensland coast, the majority of Spanish mackerel on the east coast is landed during Spring (Sep-Nov) around the outer-shelf reefs north of Townsville where fish aggregate to spawn (Figure 7.6). Although fish are thought to spawn all along the east coast, the extent to which the Townsville region is the dominant or sole area important for spawning is not known. Historical reports of the fishery indicated that similar spawning aggregations may have previously extended much further north to Lizard Island.
For stock assessment purposes the fishery is divided into five nominal regions; North, Townsville, Mackay, Rockhampton and South (Figure 7.6) (Campbell et al. 2012). These regions were adopted in this study.

Abundance indicators

Two indicators of abundance were used in the present study; catch curve-based year class strength (YCS) and standardised annual catch-per-unit-effort (CPUE).

Year class strength

YCS was determined from annual monitoring of commercial and recreational landings of *S. commerson* by the Queensland Government Department of Agriculture Fisheries and Forestry (QDAFF) from 2001-2011. Representative data on the length structure of fisheries landings were collected from 11 geographic regions on the east coast of Queensland. A subsample of measured fish were then aged, and an age length key (ALK) generated and used to convert the resulting length structure to age.

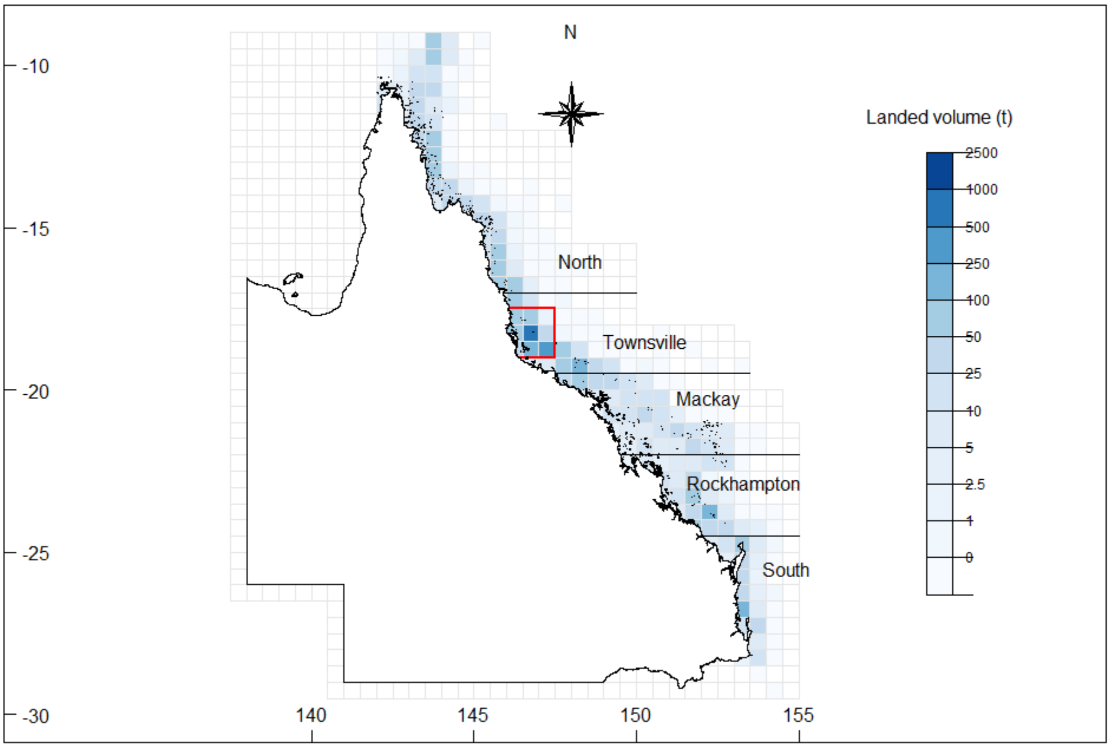

Figure 7.6 Landed-volume (t) of Spanish mackerel, *Scomberomorus commerson*, in east coast Queensland waters 1988–2012 in 0.5×0.5° grids. Five nominal stock assessment regions referred to in the YCS analysis are denoted by the solid black line. The red box denotes the spatial grids used in the CPUE analysis.

The age of subsampled fish was determined by counting growth increments visible on the otolith and based on the otolith edge classification. Because of the highly seasonal nature of the fishery and rapid growth of *S. commerson* a number of age and length adjustments were made prior to constructing the ALK. This was done to ensure that the lengths of fish were comparable throughout the year, and so that fish from the same cohort were kept together. The birth-date for east coast *S. commerson* was assumed to be 1st October with growth bands formed in winter. Individuals sampled between April and August with a 'new' edge classification had one year subtracted to keep them in the previous years' cohort. Individuals with an intermediate or wide edge type between June and October had one year added. Length adjustments were made based on the time between the assigned birth date and capture. The growth expected during this period of time was added (or subtracted) to the measured length. Length adjustments were based on male and female specific growth models, or a combined model if sex was not determined. The resultant whole age and adjusted length were used to generate ALKs for each sampling year, with both sexes combined (Isermann and Knight 2005).

YCS was measured retrospectively from the resulting age-structure using the catch curve residual method of Maceina (1997). For each year of sampling, *i*, the Studentized residuals from a multiple linear regression of abundance, *N* against age, *x,* and sample year, *i;*

$$\ln(N_i) = a + bx_i + ci$$

were used to provide replicate estimates of relative abundance of recruits in the year, *i* - *x*. Individuals younger than two were excluded from the analysis as they were not fully recruited into the fishery and fish older than 11 were excluded because they were relatively rare (Figure 7.7). Linear regression was weighted by sample size (*N*) to minimise the effect of outliers on the analysis (Maceina 1997). For the first year of sampling the residual from the oldest cohort was not used since there was only a single replicate for that year based on only a small number of fish. The coefficient of determination, r^2, from the above regression model was used as a measure of the relative variability in recruitment, with lower values indicative of less stable recruitment (Maceina 1997).

Catch per unit effort

Analysis of CPUE was based on logbook data collected from commercial fishers, who are required to record daily catch of *S. commerson* (weight in kg, or numbers of fish then converted to weight), allocated to a 0.5° spatial grid (Figure 7.6). Although data are collected by fishers along the entire coast, analysis of CPUE was restricted to data collected from the 3×3 array of spatial grids encompassing the principle spawning reefs near Townsville where the majority of fishing occurs in Spring and Summer: $(i, j, k)^T \cdot (18,19,20)$ (Figure 7.6). The data were then limited to a further set of 50 fishers that had landed >25 tonnes of Spanish mackerel since logbook reporting began and who had an average catch >20kg.day^{-1}. These criteria were chosen to limit logbook data to fishers with a long history of specifically targeting Spanish mackerel.

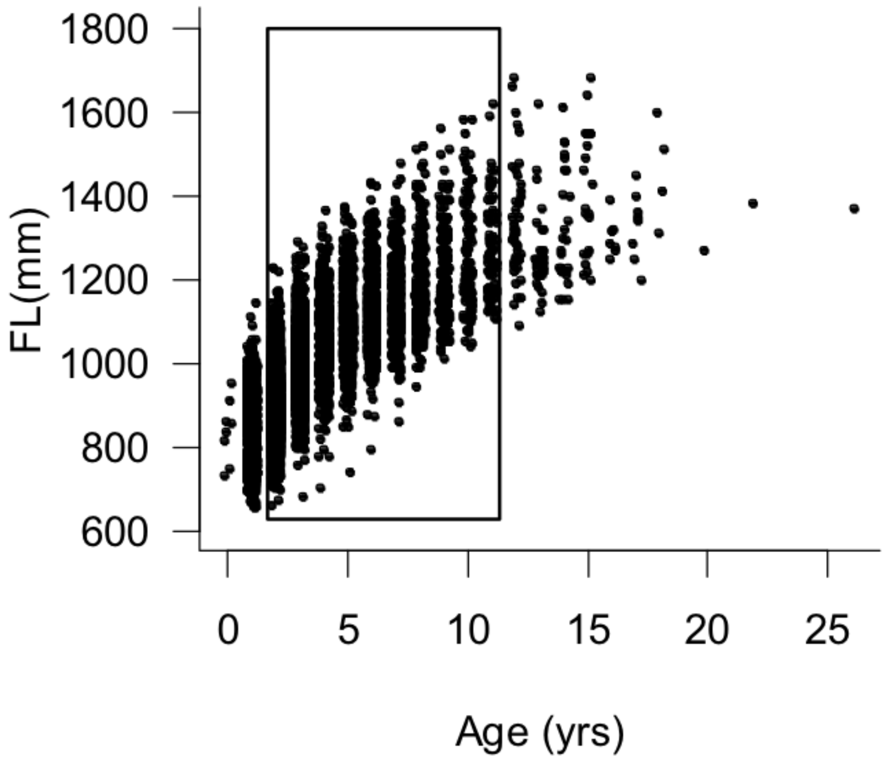

Figure 7.7 Length-at-age data (jittered) available for *S. commerson*. Black box shows ages included in the year-class-strength analysis.

Linear mixed-models were used to standardise logbook data (Maunder and Punt 2004) and followed a similar approach to previous standardisations of Queensland *S. commerson* CPUE data (Begg et al. 2006, Campbell et al. 2012). CPUE standardisation was carried out using a linear mixed effects model and the nlme package in R. The fundamental assumption of this analysis is that the observed catch, *C,* is proportional to the product of effort, *E*, abundance, *N,* and catchability, *q,* (Maunder and Punt 2004), $C = qEN$, such that $\ln\left(\frac{C}{E}\right) = \ln(q) + \ln(N)$, where *q* is a product of fixed and random variables estimated using a mixed effects model (Pinheiro and bates 2000). Financial year (July-June), month, lunar phase and statistical reporting grid were included as fixed variables, and vessel ID was included as a random variable (see Appendix 9) (Begg et al. 2006, Campbell et al. 2012). The estimated year coefficients were extracted and used as the annual index of abundance as $\exp\left(\hat{\alpha}_t + \frac{\hat{\sigma}_t}{2}\right)$, where $\hat{\alpha}_t$ is the estimate of the year coefficient for year *t* and $\hat{\sigma}_t$ is the standard error of $\hat{\alpha}_t$ (Maunder and Punt 2004). Finally standardised year coefficients were divided by the first year of sampling, $\hat{\alpha}_0$.

Interpretation and comparison of abundance indices

The catch-curve residual YCS approach of Maceina (1997) estimates the strength of an individual year class based on the residual of the catch curve corresponding to that year. Because a single year provides an estimate of YCS for many cohorts, multiple years of sampling can be used to refine estimates. Importantly though, the method only provides a relative index of recruitment and does not reflect the true magnitude of variation in recruitment, overestimating the strength of weak year classes and underestimating the strength of strong year classes (Catlano et al. 2009). Catch-curve derived estimates of YCS are likely to provide a reasonable proxy for YCS providing that recruitment variation exceeds 50-80%, however below this level any variation is likely to be obscured by many factors (Catlano et al. 2009, Tetzlaff et al. 2011). The method is also particularly sensitive to changes in fishing mortality (Catlano et al. 2009).

CPUE was interpreted as index of abundance of mature biomass. The minimum commercial size limit for *S. commerson* in Queensland waters is 75cm, below the length at maturity of this species (~88cm). However, full recruitment to the commercial line fishery typically occurs at age 2, which corresponds to the age at maturity of *S. commerson,* thus the vast majority of fish captured are adults (Figure 7.7).

The two indices of abundance used here are both indirect and representative of different quantities; one is a measure of recruitment and the abundance. To assess their similarity to each other YCS and CPUE (lagged 2 years to account for time to recruit to the fishery) were compared using Pearson's correlation coefficient.

Environmental correlations with recruitment, stock abundance and catchability
Based on an expert working group and the species review (see Part 2 companion report), the following hypotheses were investigated in this analysis:

1. SST may influence on timing and duration of spawning and increasing larval/early juvenile growth rates and thus survival (recruitment). SST may increase feeding activity (catchability) and increasing growth of individuals and population biomass (abundance).
2. Chlorophyll-a as a proxy for primary productivity may have an influence on larval/early juvenile growth and thus survival in estuarine and coastal areas by increasing food availability (recruitment).
3. High rainfall in coastal catchments as a proxy for primary productivity may have an influence on larval/early juvenile growth and thus survival in estuarine and coastal areas by increasing food availability (recruitment).
4. Fluctuations in the SOI are related to changes in SST, rainfall and coastal productivity (recruitment and abundance). SOI may have a general effect on weather conditions (catchability).

The above hypotheses were tested using linear regression analysis; YCS was to investigate environment-recruitment hypotheses and CPUE to investigate stock abundance and catchability hypotheses. YCS data were pooled to match stock assessment regions and were available from each of the broad-scale regions except North (Figure 7.6). In each of the four regions, SST data for the correlation analysis were selected from a spatial grid in the region of highest catch, or in the Mackay region when that data was not available from an adjacent grid (Table 7.8, Figure 7.8). SST data were restricted to Spring (Sep-Nov) when spawning activity peaks. Any effect of Chl-a was thought to be related to increases in primary productivity of the coastal and estuarine areas important to juveniles. For Townsville and Rockhampton, where key catch grids were further offshore, an adjacent inshore grid was selected for Chl-a. These data were unavailable for Mackay, so the closest adjacent grid was selected. In the South, the highest catch occurred in a coastal grid, so this was also selected for Chl-a. In each region, data from a major river catchment close to the key catch grids was selected as a proxy for regional rainfall and catchment inundation. Catchments chosen were Herbert (Townsville), Burdekin (Mackay), Fitzroy (Rockhampton) and the Brisbane (South). The final river-flow index was the log-transformed sum of river discharge over the Spring and Summer period (Sep-Feb). This time-period encompassed the key spawning period and the following wet-season period across northern Australia.

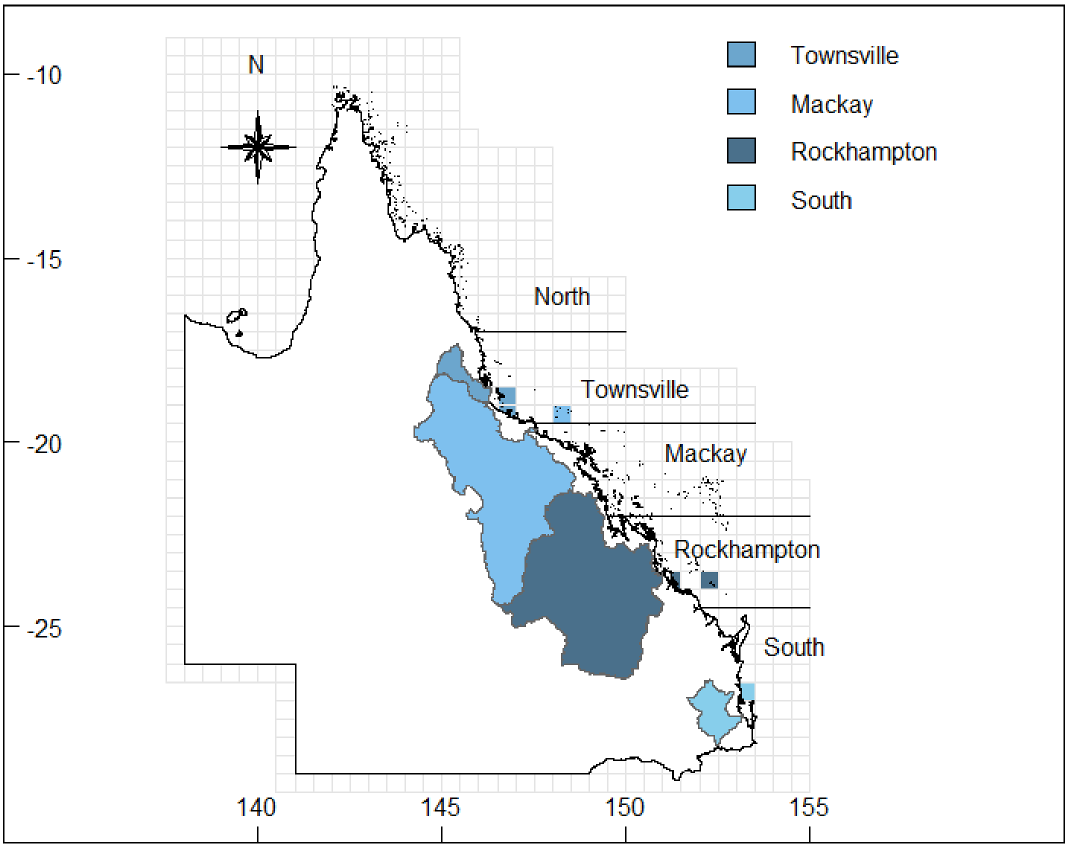

Figure 7.8 Map of the study area indicating regions used in the year-class-strength analysis and catch grids where SST and Chl-a data were sourced. River catchments used in analyses are also highlighted.

It was not immediately possible to separate stock-abundance and catchability hypotheses which were tested simultaneously using CPUE data. Since CPUE data also came from the Townsville region (Figure 7.6), similar environmental data were used, although Chl-a data was from an offshore grid rather than an inshore grid reflecting differences in the stock-abundance hypothesis (Table 7.9).

Standard bivariate linear regression models were used for all analyses, although a range of models were initially trialled in the YCS analyses. Mixed effects models including a random intercept term and both a random slope and intercept term were also trialled however did not change the results substantially. Correlations were fitted to the year of interest (e.g. year of recruitment or year of catch) as well as the years immediately prior (one year lag) and the year immediately after (one year in advance) in order to help establish whether environmental correlations had a causal basis.

Table 7.8 Description of environmental predictors investigated in each region for analysis of year-class-strength environment-recruitment relationships.

Variable	Townsville	Mackay	Rockhampton	South
SST	Spring mean, J20 (146.75°E, 18.75°S)	Spring mean, M21 (148.25°E, 19.25°S)	Spring mean, U30 (152.25°E, 23.75°S)	Spring mean, W36 (153.25°E, 26.75°S)
SOI	Annual mean	Annual mean	Annual mean	Annual mean
Chl-a	Spring mean in adjacent inshore areas, J21 (146.75°E, 19.25°S)	Spring mean offshore (inshore not available), M21 (148.25°E, 19.25°S)	Spring mean in adjacent inshore area, S30 (151.25°E, 23.75°S)	Spring mean, inshore grid, W36 (153.25°E, 26.75°S)
River flow	Spring and Summer flow, Herbert River, log transformed	Spring and Summer flow, Burdekin River, log transformed	Sum of Spring and Summer flow, Fitzroy, log transformed	Sum of Spring and Summer flow, Brisbane River, log transformed

Table 7.9 Description of environmental predictors investigated for analysis of environment-stock abundance and -catchability relationships

Variable	Description
SST	Spring mean, J20 (146.75°E, 18.75°S)
SOI	Annual mean
Chl-a	Spring mean at spawning aggregation, J20 (146.75°E, 18.75°S)
River flow	Spring and Summer flow, Herbert River, log transformed

7.8.2.7 Summary of analyses

Table 7.10 Summary of the species analysed, the analyses conducted and for which regions, the environmental variables used in each analysis, and sources of all potential data.

Species	Analyses	Regions	Environmental Variables	Data sources
Barramundi	YCS	NT	Rainfall, River height	NT Fisheries, NT DLRM
	Catch rate	NT	Rainfall, river height	NT Fisheries, NT DLRM
Coral trout	YCS	EC; Townsville, Mackay, Storm Cay	SST, SOI, river flow	ELF, CSIRO, NOAA, DERM
Golden snapper	Range shift	Rockhampton	SST	Infofish Australia; NOAA/NASA
Red throat emperor	YCS	EC; Townsville, Mackay, Storm Cay	SST, SOI, river flow	ELF, CSIRO, NOAA, DERM
Saucer scallop	Recruitment	SE Queensland	SST, Chl a., river discharge, eddy currents	NOAA, NASA, CSIRO, QDAFF, IMOS, DERM
	Catch rate	SE Queensland	SST, Chl a., river discharge, eddy currents	NOAA, NASA, CSIRO, QDAFF, IMOS, DERM
Spanish mackerel	YCS	East coast	SST, Chl. a, river flow, SOI	Qld LTMP; CSIRO, BoM, DSITIA
	Catch rate	East coast	SST, Chl. a, river flow, SOI	Qld LTMP; CSIRO, BoM, DSITIA

*YCS = year Class Strength; NT = Northern Territory; GoC = Gulf of Carpentaria; EC = east coast; SST = Sea Surface Temperature; Chl.a = Chlorophyll a; LTMP = Long Term Monitoring Program; DSITIA = Department of Science, Information Technology, Innovation & the Arts; DERM = Department of Environment & Resource Management; ELF = Effects of Line Fishing Project; EAC = East Australian Current.

7.9 Vulnerability assessment

7.9.1 Assessment indicators and criteria

We developed a semi-quantitative approach to be used for the vulnerability assessments that used indicators for each of the elements Exposure, Sensitivity and Adaptive Capacity (Johnson and Welch 2010; Welch and Johnson 2013). ***Exposure*** indicators were developed based on the specific environmental variables predicted to be important for northern Australian fishery species and the criteria for these were developed to reflect the environment the particular species lives in; for example, whether they were predominantly an estuarine or pelagic species. For each future scenario (e.g. 2030 A1FI, 2070 A1B, etc.) the exposure indicators were specific to the model projections that corresponded to that particular scenario. The indicators used for exposure for 2030 (A1FI & A1B), and their criteria, are shown in Table 7.11. Exposure indicators used for alternate future climate scenarios are provided based on those presented in Table 8.12 (Section 8.2).

The indicators and their criteria for ***Sensitivity*** were adapted from those developed by Pecl et al (2011a) who provide a detailed explanation of the development of these criteria. 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 7.12.

The indicators for ***Adaptive Capacity*** were developed based on previous assessments and research (Allison et al. 2009; Johnson and Welch 2010; Marshall and Marshall 2007; Marshall et al. 2007; Pecl et al 2011a; Welch and Johnson 2013). Adaptive capacity can fall in two categories: the ability of the species to cope with changes (ecological), or the ability of participants in the industry (fishery) to cope with changes (socio-economic). We developed indicators for each of these categories, however, we only used the ecological Adaptive Capacity indicators when we applied our assessments, making these assessments ecologically-based only. We acknowledge that to truly assess the vulnerability of *fisheries* (as opposed to fishery species), the adaptive capacity of fishers and other industry members needs to be considered in the assessment process and to do this requires a dedicated consultation process, e.g. using surveys. However, it was not possible during this project to comprehensively consult with industry members in scoring the socio-economic indicators. The ecological and socio-economic indicators for Adaptive Capacity are shown in Table 7.13.

7.9.2 Assessment scoring

For each indicator, scores were assigned using Low (1), Medium (2) or High (3) and based on specified criteria (Tables 6.6 – 6.8). Pecl et al (2011a) demonstrated that this simple 3-level approach is sufficient for resolving species rankings, and for use by expert judgement while avoiding the need to determine precise rankings. For each element (e.g. Exposure) an index was calculated by dividing the total score by the number of indicators (i.e. the average score). The Potential Impact index was determined as the product of the Exposure and Sensitivity Indices (PI = E * S). Since vulnerability is defined as the *inability* to cope with changes, the potential impact measured by the framework assumes a *negative* direction, however, some consequences of high exposure and high sensitivity are positive. For example, mud crab in north-western Australia have a high exposure to changes, largely due to their shallow water estuarine/nearshore habitat requirements, as well as relatively high sensitivity. However, the consequences of being exposed to increases in rainfall (and riverflow) and higher sea surface temperatures are likely to result in enhanced recruitment and catchability, as well as higher growth rates. To capture this we incorporated a ‘Direction of impact’ component with the Potential Impact score:

- Negative consequence = +1.0
- Neutral or unknown effect = 0.0
- Positive consequence = -1.0

The overall effect of adding this step in the scoring process moderated the level of vulnerability given to a species where the impact of climate change was likely to be positive. Therefore, for mud crab in north-western Australia where the consequence was actually positive, we subtracted 1.0 from the Potential Impact.

Since Adaptive Capacity (AC) is the inverse of both Exposure and Sensitivity, the final AC Index was determined based on the following process. First, the AC score was calculated as the average of the respective (ecological) indicator scores. These scores were then standardised to 1.00 with the highest average AC score given 1.00 and all other scores expressed as a proportion of this. That is, Standardised AC = Average AC/Maximum AC. The inverse was ten taken to derive the AC index. That is, AC index = 1 - Standardised AC. The vulnerability index was then calculated by the following: Vulnerability = (Potential Impact x AC index) + 1.

7.9.3 Vulnerability assessment process

The vulnerability assessments were done in a workshop setting with all project team members in attendance as well as other relevant experts (eg. a WA Fisheries representative). The project team, which comprised of scientists, managers, commercial and recreational fishers, with the addition of some key individuals, contained sufficient expertise and experience with the relevant species to provide comprehensive and informed assessments. A full list of workshop participants and their affiliations are given in Appendix 4. The assessment framework was explained to participants and a worked example was provided for discussion and clarification of the process, including making any minor refinements and/or additions to the framework.

Vulnerability assessments were then carried out for each individual species in the order of priority for each of the key regions as determined above using three major lines of evidence: (i) information summarised from the species reviews, (ii) information derived from project data analyses, and (iii) expert opinion. Scores were decided based on consensus among workshop participants and, if necessary, the most conservative score was accepted for that indicator (i.e. for Exposure and Sensitivity the higher of the two possible scores was taken; for Adaptive Capacity the lower of the two possible scores was taken).

Table 7.11Exposure indicators and their criteria. The indicators shown are based on changes in the respective variables projected for 2030. High (A1FI) and low (A1B) emission scenarios are similar for 2030.

	Projections for 2030 (A1B & A1FI)	Low = 1	Medium = 2	High = 3
EXPOSURE	**SST increase 0.3 to 0.6 °C (EC, GoC); 0.6 to 0.9 °C (NWA)**	Adult spends <50% of time in surface (<25 m) waters	Adult spends 50-80% of time in surface (<25 m) waters	Adult spends 80-100% of time in surface (<25 m) waters
	Rainfall -10 to 0% (EC); 0 to +5% (NWA, GoC)	Spends no time in estuarine or freshwater habitats during any life history phase	Spends <50% of time in estuarine or freshwater habitats; no critical (larvae, juvenile, spawning) life history phase in these habitats	Spends >50% of time or has critical (larvae, juvenile, spawning) 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
	Salinity decline 0.1 psu	Open ocean or deep water species	Continental shelf species	Inshore or estuarine species
	Habitat changes (loss of productivity, structure or function) (nb. this incorporates sea level rise)	Species with wide habitat preferences	Species dependent on pelagic or mangrove/estuarine habitats	Species dependent on seagrass or coral reef habitats
	Altered large-scale currents: Stronger EAC; weaker Leeuwin current; GoC unknown	Live young/egg bearers or no dependence on large-scale wind/current for larval dispersal/settlement	Proximate dispersal/settlement of young not entirely dependent on large-scale wind/current dispersal	Dispersal/settlement of young 100% dependent on large-scale wind/currents
	More intense cyclones/storms (EC possibly fewer; NWA possibly more)	Deep water or highly mobile species	Shallow water (< 25 m) and moderately mobile species	Shallow water (< 25 m) or low mobility species
	Altered riverflow/nutrient supply: Reduction (EC) and potential increase linked to rainfall (NWA, GoC)	Spends no time in estuarine or freshwater habitats during any life history phase	Spends <50% of time in estuarine or freshwater habitats; no critical (larvae, juvenile, spawning) life history phase in these habitats	Spends >50% of time or has critical (larvae, juvenile, spawning) part of life cycle in estuarine or freshwater habitats

Table 7.12Sensitivity indicators and their criteria (adapted from Pecl et al 2011a). Indicators are grouped into three categories of how the organism may be affected: abundance, distribution and phenology.

			Low = 1	Medium = 2	High = 3
Sensitivity	Abundance	**Fecundity – egg production**	>20,000 eggs/year	100-20,000 eggs/year	<100 eggs/year or live young
		Average age at maturity (females)	≤2 years	3-10 years	>10 years
		Generalist v. specialist (food & habitat)	Reliance on *neither* habitat or prey for any life history stage	Reliance on *either* habitat or prey for any life history stage	Reliance on *both* habitat and prey for any life history stage
	Distribution	**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 may be exceeded	Threshold likely to be exceeded for one or more climate variable
		Capacity for larvae to disperse	<100 km	100-500 km	>500 km
	Phenology	**Reliance on environmental drivers (for spawning, breeding or settlement)**	No apparent correlation to environmental variable	Weak correlation to environmental variable	Strong correlation to environmental variable
		Potential for timing mismatch of life cycle events (duration of spawning, moulting or breeding)	Continuous duration; >4 months	Moderate duration; 2-4 months	Brief duration; <2 months

Table 7.13Adaptive capacity indicators and their criteria, grouped into ecological and socio-economic. NB. Adaptive capacity has the inverse effect compared to Exposure and Sensitivity. That is, low Sensitivity is a positive trait while low Adaptive Capacity is a negative trait.

			Low = 1	Medium = 2	High = 3
Adaptive Capacity	Ecological	**Stock status**	Overfished or on the verge of overfishing	Undefined	Sustainably fished
		Replenishment potential	Late maturing (>6 years), slow growth or few young	Matures at 3-6 years, moderate growth or moderate numbers of young	Early maturing, fast growth or many young
		Suitable alternate habitat availability	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 (eg. poor water quality, disease, incidental catch)	Some acute pressures (eg. cyclones, storms, floods)	No or minimal other pressures
	Socio-economic	**Resource dependence**	No alternate species and/or significant gear/practice modifications required to target other species	Some alternate species that could be targeted with minor gear/practice modifications	Multiple alternate target species that could be targeted without any gear/practice modifications
		Ability to change fishing practices	Not able to change	Able to change with support	Able to change without support
		Climate change awareness	Unaware	Aware and no planning steps taken	Aware and has taken preparatory action
		Governance	Inflexible or non-existent	Flexible *or* adaptive (not both)	Flexible *and* adaptive

7.9.4 Prioritising species for future 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 of species. The relative 'fishery importance' of individual species should also be taken into account. To further assist managers, scientists and other fishery end-users in taking the next steps we incorporated the fishery importance 'scores' of each species derived through stakeholder consultation at the start of the project (see Tables 8.1-8.3) with relative vulnerability to prioritise species for future action. That is, species with higher vulnerability scores and higher fishery importance scores get higher priority.

7.10 Identifying adaptation options

To identify climate change adaptation options that were relevant and appropriate for particular fisheries and regions of northern Australian, two regional stakeholder workshops were conducted. The workshops were conducted in Darwin and Townsville and involved invited stakeholders that comprised of local fisheries and conservation managers, scientists, commercial fishers, recreational fishers, charter fishers, and fishing industry representatives (see Appendix 5 for lists of workshop participants and the workshop agenda).

At each of these workshops key project members presented the project, the vulnerability assessment framework, and the outputs of the preliminary assessments for key species relevant to the workshop region. To elicit adaptation options from workshop participants, outputs from the vulnerability assessments and species reviews were used to generate a summary of the likely impacts on key fishery species. The workshop used a series of breakout group sessions for discussing and identifying potential adaptation options and barriers to each of these impacts. The workshops were conducted to facilitate stakeholders to, as much as possible, be the ones who identified the key challenges and future considerations for their respective fisheries of interest. During each workshop, we also used the opportunity to obtain stakeholder perceptions on changes they have observed.

8 RESULTS/DISCUSSION

8.1 Species identification & prioritisation

There were a total of 40 species identified for the east coast, 36 species for the Gulf of Carpentaria, and 37 species for north-western Australia. Given the overlap in species across regions this was a total of 47 species for northern Australia. The identification of species, and their prioritisation, was not intended to provide an absolute species list for northern Australia. The list was intended to identify the key fishery species for the respective regions and to rank them as a guide *for this project* in carrying out the climate change vulnerability assessments to ensure that the most important fishery species were included. Indeed, many fishery stakeholders across northern Australia had input to the whole process.

Not surprisingly given their widespread distribution, mud crab and barramundi were in the top 3 ranked species in all three regions. Other species ranked highly were banana and tiger prawns (EC and GoC), coral trout (EC), golden snapper and black jewfish (NWA), and king threadfin (GoC and NWA). The full species lists and their ranking order are provided for the east coast, the Gulf of Carpentaria, and north-western Australia in Tables 8.1, 8.2 and 8.3 respectively. Based on the fishery and ecological importance criteria for each species, which included social/cultural importance, economic importance, catch and ecological importance (see Table 7.1), the species with the five highest ranked scores from each region are shown in Tables 8.4, 8.5 and 8.6 for the east coast, the Gulf of Carpentaria and north-western Australia respectively.

Table 8.1 Species list and final rankings for fishery species identified for the east coast **based on total scores derived from scores for 'Fishery Importance' criteria (FI), and 'Climate change sensitivity' criteria (CC).**

Common name	Species name	FI	CC	Score
Coral trout	*Plectropomus* spp.	11.67	6.13	**17.79**
Mud crab	*Scylla serrata*	11.00	6.00	**17.00**
Barramundi	*Lates calcarifer*	11.00	5.94	**16.94**
Banana prawn	*Penaeus merguiensis*	10.67	6.25	**16.92**
Eastern king prawn	*Melicertus plebejus*	10.80	6.00	**16.80**
Tropical lobster	*Panulirus ornatus*	9.33	7.25	**16.58**
Tiger prawn	*Penaeus esculentus/P. semisulcatus*	10.40	6.17	**16.57**
Spanish mackerel	*Scomberomorus commerson*	11.17	5.33	**16.50**
Red spot king prawn	*Penaeus longistylus*	10.00	6.17	**16.17**
Blacktip sharks	*Carcharhinus limbatus/C. tilstoni*	9.17	6.50	**15.67**
Red throat emperor	*Lethrinus miniatus*	9.00	6.38	**15.38**
Spot tail shark	*Carcharhinus sorrah*	8.75	6.50	**15.25**
Billfish (Black marlin)	*Istiompax indica*	10.00	5.13	**15.13**
Moreton Bay bug	*Thenus orientalis*	9.17	5.92	**15.08**
Red emperor	*Lutjanus sebae*	9.17	5.92	**15.08**
Grey mackerel	*Scomberomorus semifasciatus*	9.00	5.92	**14.92**
Sand fish	*Holothuria scabra*	7.50	7.38	**14.88**
Pigeye shark	*Carcharhinus*	8.25	6.63	**14.88**
Saucer scallop	*Amusium japonicum*	8.83	5.92	**14.75**
Spotted mackerel	*Scomberomorus munroi*	8.67	5.69	**14.36**
King threadfin	*Polydactylus macrochir*	8.00	6.25	**14.25**
Spanner crab	*Ranina ranina*	8.17	5.92	**14.08**
Blue threadfin	*Eleutheronema tetradactylum*	7.83	6.08	**13.92**
Scalloped hammerhead	*Spyhrna lewini*	7.25	6.63	**13.88**
Whiting	*Sillago ciliata*	8.00	5.50	**13.50**
Barred javelin	*Pomadasys kaakan*	7.67	5.78	**13.44**
Mangrove jack	*Lutjanus argentimaculatus*	7.33	5.67	**13.00**
Pikey bream	*Acanthopagrus berda*	7.17	5.83	**13.00**
Golden snapper	*Lutjanus johnii*	7.17	5.75	**12.92**
Dusky flathead	*Platycephalus fuscus*	7.17	5.67	**12.83**
Crimson snapper	*Lutjanus erythropterus*	6.60	5.75	**12.35**
Saddle tail snapper	*Lutjanus malabaricus*	6.60	5.75	**12.35**
School mackerel	*Scomberomorus*	6.00	6.25	**12.25**
Black jewfish	*Protonibea diacanthus*	6.33	5.83	**12.17**
Grass emperor	*Lethrinus laticaudis*	6.17	5.92	**12.08**
Spangled emperor	*Lethrinus nebulosus*	5.83	5.92	**11.75**
Goldband snapper	*Pristipomoides*	5.75	5.63	**11.38**
Black spot cod	*Epinephelus malabaricus*	5.00	5.88	**10.88**
Gold spot cod	*Epinephelus coiodes*	5.00	5.88	**10.88**
Blue swimmer crab	*Portunus pelagicus*	5.00	5.00	**10.00**

Table 8.2 Species list and final rankings for fishery species identified for the Gulf of Carpentaria **based on total scores derived from scores for 'Fishery Importance' criteria (FI), and 'Climate change sensitivity' criteria (CC).**

Common name	Species name	FI	CC	Score
Banana prawn	*Penaeus merguiensis*	10.67	6.00	**16.67**
Mud crab	*Scylla serrata*	10.75	5.75	**16.50**
Barramundi	*Lates calcarifer*	10.75	5.67	**16.42**
Tiger prawn	*Penaeus esculentus/P. semisulcatus*	10.33	5.92	**16.25**
King threadfin	*Polydactylus macrochir*	10.00	6.13	**16.13**
Grey mackerel	*Scomberomorus semifasciatus*	10.00	5.38	**15.38**
Tropical lobster	*Panulirus ornatus*	8.00	6.63	**14.63**
Billfish (Sailfish)	*Istiophorus platypterus*	8.00	6.38	**14.38**
Blacktip sharks	*Carcharhinus limbatus/C. tilstoni*	9.50	4.88	**14.38**
Spanish mackerel	*Scomberomorus commerson*	9.25	4.75	**14.00**
Golden snapper	*Lutjanus johnii*	7.00	6.50	**13.50**
Scalloped hammerhead	*Sphyrna lewini*	8.00	5.38	**13.38**
Blue threadfin	*Eleutheronema tetradactylum*	7.75	5.50	**13.25**
Mullet	*Liza vaigiensis*	8.00	5.25	**13.25**
Spot tail shark	*Carcharhinus sorrah*	8.33	4.88	**13.21**
Pigeye shark	*Carcharhinus amboinensis*	7.50	5.38	**12.88**
Red emperor	*Lutjanus sebae*	6.33	6.38	**12.71**
Sand fish	*Holothuria scabra*	5.67	7.00	**12.67**
Mangrove jack	*Lutjanus argentimaculatus*	6.25	6.38	**12.63**
Black jewfish	*Protonibea diacanthus*	6.25	6.00	**12.25**
Garfish	*Hyporamphus* spp.	7.00	5.25	**12.25**
Grass emperor	*Lethrinus laticaudis*	5.67	6.38	**12.04**
Barred javelin	*Pomadasys kaakan*	7.75	4.00	**11.75**
Sardines/herring	Family Clupeidae	6.00	5.75	**11.75**
Coral trout	*Plectropomus* spp.	5.33	6.13	**11.46**
Spangled emperor	*Lethrinus nebulosus*	5.00	6.38	**11.38**
Bugs	*Thenus orientalis*	5.67	5.50	**11.17**
Crimson snapper	*Lutjanus erythropterus*	5.00	5.88	**10.88**
Saddle tail snapper	*Lutjanus malabaricus*	5.00	5.88	**10.88**
Saucer scallops	*Amusium japonicum*	5.00	5.75	**10.75**
Goldband snapper	*Pristipomoides multidens*	4.67	5.75	**10.42**
Pikey bream	*Acanthopagrus berda*	6.00	4.00	**10.00**
Dusky flathead	*Platycephalus fuscus*	4.50	4.75	**9.25**
Spotted mackerel	*Scomberomorus munroi*	4.67	4.50	**9.17**
Longtail tuna	*Thunnus tonggol*	5.00	4.00	**9.00**
Whiting	*Sillago ciliata*	5.00	3.88	**8.88**

Table 8.3 Species list and final rankings for fishery species identified for north-western Australia **based on total scores derived from scores for 'Fishery Importance' criteria (FI), and 'Climate change sensitivity' criteria (CC).**

Common name	Species name	FI	CC	Score
Barramundi	*Lates calcarifer*	11.50	5.63	**17.13**
Mud crab	*Scylla serrata*	11.00	6.13	**17.13**
Black jewfish	*Protonibea diacanthus*	10.50	6.13	**16.63**
Golden snapper	*Lutjanus johnii*	10.00	6.63	**16.63**
King threadfin	*Polydactylus macrochir*	10.00	6.00	**16.00**
Spanish mackerel	*Scomberomorus commerson*	11.00	4.88	**15.88**
Sand fish	*Holothuria scabra*	8.50	7.13	**15.63**
Billfish (Sailfish)	*Istiophorus platypterus*	8.00	7.50	**15.50**
Grey mackerel	*Scomberomorus semifasciatus*	9.50	5.50	**15.00**
Scalloped hammerhead	*Sphyrna lewini*	9.50	5.50	**15.00**
Red emperor	*Lutjanus sebae*	8.00	6.50	**14.50**
Goldband snapper	*Pristipomoides multidens*	8.50	5.88	**14.38**
Blacktip sharks	*Carcharhinus limbatus/C. tilstoni*	9.00	5.00	**14.00**
Pigeye shark	*Carcharhinus amboinensis*	8.50	5.50	**14.00**
Spot tail shark	*Carcharhinus sorrah*	9.00	5.00	**14.00**
Crimson snapper	*Lutjanus erythropterus*	7.50	6.00	**13.50**
Mangrove jack	*Lutjanus argentimaculatus*	7.00	6.50	**13.50**
Saddle tail snapper	*Lutjanus malabaricus*	7.50	6.00	**13.50**
Mullet	*Liza vaigiensis*	8.00	5.25	**13.25**
Blue threadfin	*Eleutheronema tetradactylum*	7.50	5.63	**13.13**
Coral trout	*Plectropomus* spp.	6.50	6.25	**12.75**
Tropical lobster	*Panulirus ornatus*	6.00	6.75	**12.75**
Grass emperor	*Lethrinus laticaudis*	6.00	6.38	**12.38**
Barred javelin	*Pomadasys kaakan*	8.00	4.25	**12.25**
Garfish	*Hyporamphus* spp.	7.00	5.25	**12.25**
Sardines/Herrings	Family Clupeidae	6.00	5.75	**11.75**
Bugs	*Thenus orientalis*	5.00	6.25	**11.25**
Saucer scallops	*Amusium japonicum*	5.00	6.25	**11.25**
Banana prawn	*Penaeus merguiensis*	5.00	6.00	**11.00**
Spangled emperor	*Lethrinus nebulosus*	4.50	6.50	**11.00**
Tiger prawn	*Penaeus esculentus/P. semisulcatus*	5.00	6.00	**11.00**
Giant trevally	*Caranx ignobilis*	6.00	4.75	**10.75**
Golden trevally	*Gnathodon*	5.00	5.00	**10.00**
Spotted mackerel	*Scomberomorus munroi*	5.00	4.63	**9.63**
Dusky flathead	*Platycephalus fuscus*	4.00	5.25	**9.25**
Pikey bream	*Acanthopagrus berda*	5.00	4.25	**9.25**
Whiting	*Sillago ciliata*	4.50	4.13	**8.63**

Table 8.4 Fishery species with the five highest ranked scores for the east coast based only on the fishery/ecological importance attributes.

Common name	Species name	FI
Coral trout	*Plectropomus* spp.	11.67
Spanish mackerel	*Scomberomorus commerson*	11.17
Mud crab	*Scylla serrata*	11.00
Barramundi	*Lates calcarifer*	11.00
Eastern king prawn	*Melicertus plebejus*	10.80
Banana prawn	*Penaeus merguiensis*	10.67

Table 8.5 Fishery species with the five highest ranked scores for the Gulf of Carpentaria based only on the fishery/ecological importance attributes.

Common name	Species name	FI
Mud crab	*Scylla serrata*	10.75
Barramundi	*Lates calcarifer*	10.75
Banana prawn	*Penaeus merguiensis*	10.67
Tiger prawn	*Penaeus esculentus/semisulcatus*	10.33
King threadfin	*Polydactylus macrochir*	10.00
Grey mackerel	*Scomberomorus semifasciatus*	10.00
Blacktip sharks	*Carcharhinus limbatus/tilstoni*	9.50

Table 8.6 Fishery species with the five highest ranked scores for north-western Australia based only on the fishery/ecological importance attributes.

Common name	Species name	FI
Barramundi	*Lates calcarifer*	11.50
Mud crab	*Scylla serrata*	11.00
Spanish mackerel	*Scomberomorus commerson*	11.00
Black jewfish	*Protonibea diacanthus*	10.50
Golden snapper	*Lutjanus johnii*	10.00
King threadfin	*Polydactylus macrochir*	10.00
Grey mackerel	*Scomberomorus semifasciatus*	9.50
Scalloped hammerhead	*Sphyrna lewini*	9.50

8.2 Observed and projected climate for northern Australia

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8.2.1 Northern Australia's observed climate and recent trends

The natural ecosystems that northern Australian fisheries rely on have evolved to operate within a specific range of prevailing local climatic conditions – the coping range (Jones and Mearns 2005). Any changes in these specific climate conditions will influence fisheries resources – stocks, species, populations and communities – and the habitats that support them. Therefore understanding the observed climate is important when seeking to assess how these resources are likely to respond under future climate change. Known sensitivities provide insight into potential impacts and ultimately the sustainability of fisheries over this century. The information aims to provide a picture of the observed ocean climate that fisheries species (prioritised for this study) have experienced, focusing on the variables that they are most likely to be sensitive to, and future projections for these variables. The projections focus on the three project regions: the East Coast (EC), Gulf of Carpentaria (GoC) and northwest Australia (NWA). Table 8.7 summarises the variables, expected fisheries sensitivities, level of confidence in the data and data sources.

Table 8.7 Data considerations for different climate variables

Variable	Expected fisheries sensitivity	Level of confidence	Source	Spatial coverage
SST	Low – Very high	High	CSIRO/BoM/NOAA	EC; GoC; NWA
Ocean temp at >10 m	Low – Very high	Low	BoM/UCSD	EC; GoC; NWA
Rainfall	Low – High	High	BoM/QDNRM	EC; GoC; NWA
Riverflow/nutrient supply	Low – High	Mod – High	QDNRM	By catchment
Ocean pH	Moderate*	High	CSIRO/NOAA/NCAR	EC; GoC; NWA
Storms & cyclones	Moderate*	High	CSIRO/BoM	By region
Sea level	Low	High	BoM/NASA	EC; GoC; NWA
Ocean circulation	Moderate*	Low	CSIRO	EC; GoC; NWA

The information was drawn from a range of sources, particularly climate modelling for Australia (CSIRO and BoM 2007, Poloczanska et al. 2012), as well as relevant key literature (e.g. BoM and CSIRO 2011, Church and White 2011, Lough and Hobday 2011). Observed climate data was used to conduct the climate-response analyses for priority fisheries species, with an example of the variables that are likely to be prioritised for analyses for different fisheries provided in Table 7.5 (and see Appendix 6 for all species examined). These results will provide an indication of how fisheries species are likely to respond to future climate projections and how this might influence fisheries activities and management.

8.2.2 Observed climate trends

Average seasonal surface climate in northern Australia is dominated by large-scale global circulation systems, such as the south-easterly trade winds and the Australian summer monsoon westerly circulation. These effectively divide the year into a warm summer wet season (October to March) and a cooler winter dry season (April to September). Tropical cyclones are also an important feature of the summer monsoon and occur mainly between November and May (Lough 2007).

Sea surface temperatures
Monthly mean air and sea surface temperatures (SST) in northern Australia show a similar spatial distribution, however SST varies more slowly than air temperatures due to the heat capacity of water. As such, SST lag air temperatures on a seasonal timescale by about 1 month. The annual maxima are usually observed in February/March and the minima are usually observed in August/September. Greatest seasonal warming of SST occurs from September to October (+1.4 to 1.7°C) and greatest seasonal cooling from May to June (-1.1 to 1.8°C). SST tends to be warmer than air temperatures throughout the year, the difference being greater in winter than in summer.

On the tropical east coast, monthly mean SST range from 26 – 30.5 °C (from south to north) in the summer monsoon and 21 – 27 °C (from south to north) in the winter dry season. In the Gulf of Carpentaria SST range from 30 – 32 °C in the summer and are around 26 °C in winter. In northern WA the range is 29.4 – 30.5 °C (from south to north) in the summer monsoon and 24.8 – 26.6 °C (from south to north) in the winter dry season (Table 8.8). SST in NWA is also influenced by the warm Indonesian Throughflow from the western Pacific and northern Australian region, which eventually forms the Leeuwin Current along the WA coast.

The annual range of SST is approximately 4°C in the northern tropics and approximately 6°C in the southern tropics. However, these data are based on large-scale averages and the range of SST variability observed at a particular site can be much greater. For example, at the offshore Myrmidon Reef in the Great Barrier Reef (GBR), the average diurnal SST range is 1°C and average daily SST vary between a minimum of 24°C in late August to a maximum of 29°C in early February (4.8°C range; Lough and Hobday 2011). These large-scale averages also disguise the tendency for SST in nearshore shallow waters to be warmer in summer and cooler in winter compared to offshore deeper waters (Lough 2007).

Table 8.8 Average SST, maxima and minima (°C) for representative stations within the three project regions (Source: Bureau of Meteorology).

Region	SST mean (°C)	SST maximum (°C)	SST minimum (°C)
***East coast*:** GBR (Cairns[1])	26.3	29 (28.7)	22 (24)
***Gulf of Carpentaria*:** Groote Eylandt (Weipa[2])	29.4 (28.3)	31.8 (30)	26.2 (26.3)
***Northwest Australia*:** Melville Island (Broome[1])	28.4 (26.8)	30.1 (29)	26.4 (23.4)

Significant warming is already evident in Australia's oceans (Lough 2009, Lough et al. 2012) with warming greatest off southeast Australia and in the Indian Ocean off southwest Australia, as well as substantial warming of the tropical Pacific Ocean over recent decades (BoM and CSIRO 2011). The recent warming of Australian waters has seen average SST increase above early 20th century records (1910–1929) by +0.68 °C. The rate of temperature rise in Australian waters has accelerated since the mid-20th century; from 0.08 °C per decade in 1910-2011 to 0.11 °C per decade from 1950-2011 (Lough et al. 2012)(Figure 8.1). The evidence for significant ocean warming both at the surface and through the water column is supported by global SST compilations, and continuous *in situ* coastal observations (e.g. Ridgway 2007, Caputi et al. 2009, Lough et al. 2010). This warming has been accompanied by increasing sea-surface salinity (Pearce and Feng 2007, Thompson et al. 2009) and changes in 'climate zones'. In Australia's coastal waters between 10.5° S and 29.5° S, warming has resulted in southward shifts of climate zones by ~200 km along the east coast and ~100 km along the west coast over the period 1950-2007 (Lough 2008).

Rainfall and river flow

Australia has a high degree of inter-annual and decadal rainfall variability, making understanding the significance of rainfall extremes and changes in averages difficult to detect (CSIRO and BoM 2007, Gallant et al. 2007, Hennessy et al. 2008). In the northern tropics, the summer monsoon circulation brings the majority of the annual rainfall with approximately 80% of the annual total occurring in the wet season. On the EC, rainfall typically occurs on only 30% of days in summer and only 14% of days in winter. The GoC is in

[2] http://www.metoc.gov.au/products/data/aussst.php

the wet-dry tropics and experiences high rainfall, for example Weipa has a mean annual rainfall of 1768 mm, the majority of which falls between November and April. The Kimberley coast region of NWA has both arid and wet tropical environments with annual average rainfall varying between <200 mm and >1000 mm, respectively.

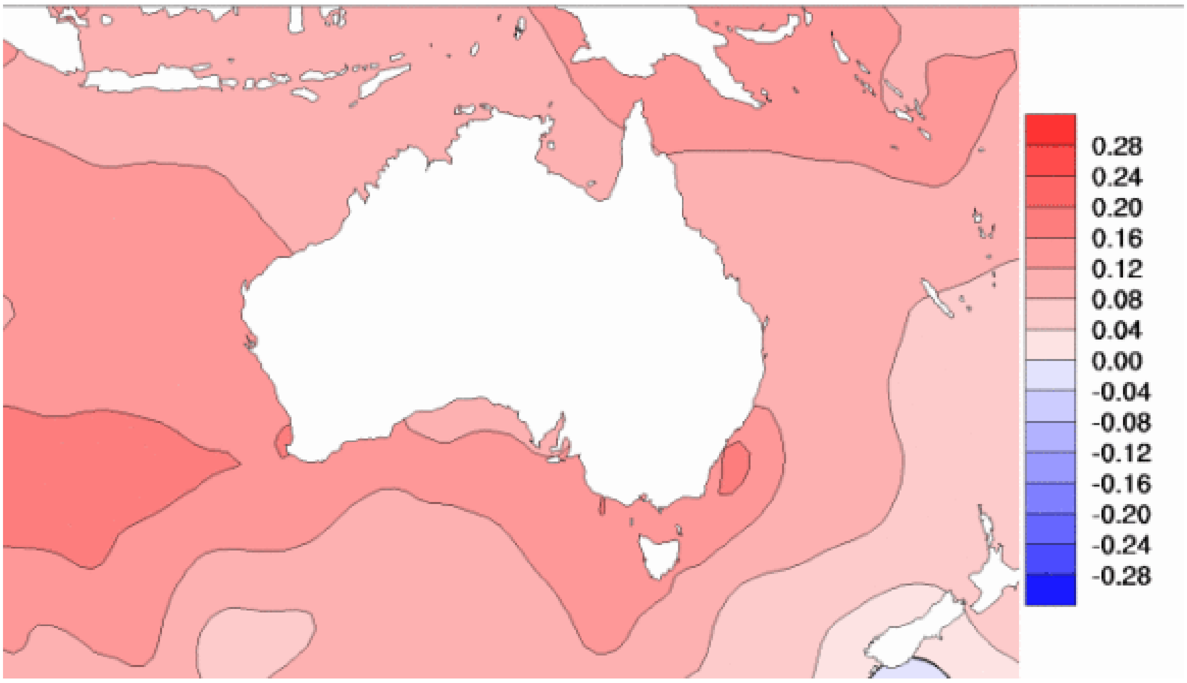

Figure 8.1 Trend in SST for the Australia region (°C/10yr) from 1950 – 2012 (Source: Bureau of Meteorology).

Due to the high spatial and temporal variability of rainfall in tropical Australia, the long-term average is not a good guide to the amount of rain that can be expected. The median is more appropriate as it is not influenced by extreme high and low values that are common. All coastal rainfall sites show maximum rainfall and greatest variability during the summer monsoon from about December to March (Table 8.9)(Lough and Hobday 2011).

The highly seasonal and variable rainfall regime of northern Australia also results in highly variable river flows. For example, the majority (~ 80%) of total river flow into EC coastal waters occurs between 17° S and 23° S with greatest annual flow in March, after the rainfall maxima. High rainfall variability results in Australian river flows being among the most variable in the world (Finlayson and McMahon 1988; Ward et al 2010). The larger rivers emptying into the GoC are the Wenlock, Archer, Holroyd, Mitchell, Staaten, and Gilbert, and again highly variable rainfall influences river flow, with greatest flows at the end of the wet season. The landscape of northwest WA has a comprehensive network of large river systems that have highly variable river flows that peak during the late wet season with tropical cyclones being a primary driver of significant rainfall and hence river flows (Lavender and Abbs 2013). The Pilbara region has the Ashburton, De Grey, Robe and Fortesque Rivers.

Major rivers in the Kimberley include the Ord River in the east and the Fitzroy River spans ~750 km and is said to be the largest river in Australia when in flood. The meeting of five river systems near Wyndham causes significant flows out to Cambridge Gulf during the wet season. These highly variable river flows regulate many processes in freshwater and coastal environments and shape ecosystem dynamics (e.g. Leigh et al. 2010, Puckridge et al. 2010).

Table 8.9 Average monthly rainfall (mm) for representative stations within the three project regions based on available records to date (e.g. 1941 for Broome, 1914 for Weipa). Bold cells show wettest months.

Region	J	F	M	A	M	J	J	A	S	O	N	D
East coast (Lockhart River[2])	**396**	**391**	**452**	297	107	58	44	29	16	29	72	208
East coast (Gladstone[2])	**153**	**146**	90	48	59	38	35	33	27	60	72	**132**
Gulf of Carpentaria: (Weipa[3])	**456**	**441**	**349**	109	16	4	2	3	6	27	103	265
Gulf of Carpentaria: (Nhulunbuy[2])	**228**	**234**	**268**	**233**	83	17	13	4	4	11	26	**194**
Northwest Australia (Broome[2])	**179**	**180**	**102**	26	27	20	7	2	1	1	9	56

Seasonal, inter-annual and longer-term rainfall variability across Australia is largely controlled by external factors, for example, El Niño-Southern Oscillation (ENSO) events have long been recognised as the primary source of inter-annual variability across much of the eastern part of the country (e.g. Troup 1965, Allan et al. 1996), although effects vary across seasons and region (Risbey et al. 2009). Over eastern Australia this high rainfall variability associated with ENSO also results in river discharge being highly sensitive to ENSO (Ward et al. 2010).

Documented trends of wetter summer conditions in northwest Australia (Shi et al. 2008, Smith et al. 2008) appear to be part of significant changes in large-scale atmospheric circulation patterns, including a more intense subtropical ridge along the east coast (Larsen and Nicholls 2009, Nicholls 2010). The east coast has experienced substantial rainfall declines since 1950, partly reflecting a very wet period around the 1950s, and recent years that have been unusually dry. However, this trend has changed in recent years, with the

[3] http://www.bom.gov.au/jsp/ncc/cdio/weatherData

2010/11 and 2012/13 wet seasons having extreme rainfall and flood events that dominated the Queensland summer under a climate system that is warmer and moister (Climate Commission 2013). In contrast, northwest Australia has experienced a consistent increase in rainfall since the 1970s (CSIRO and BoM 2007)(Figure 8.2).

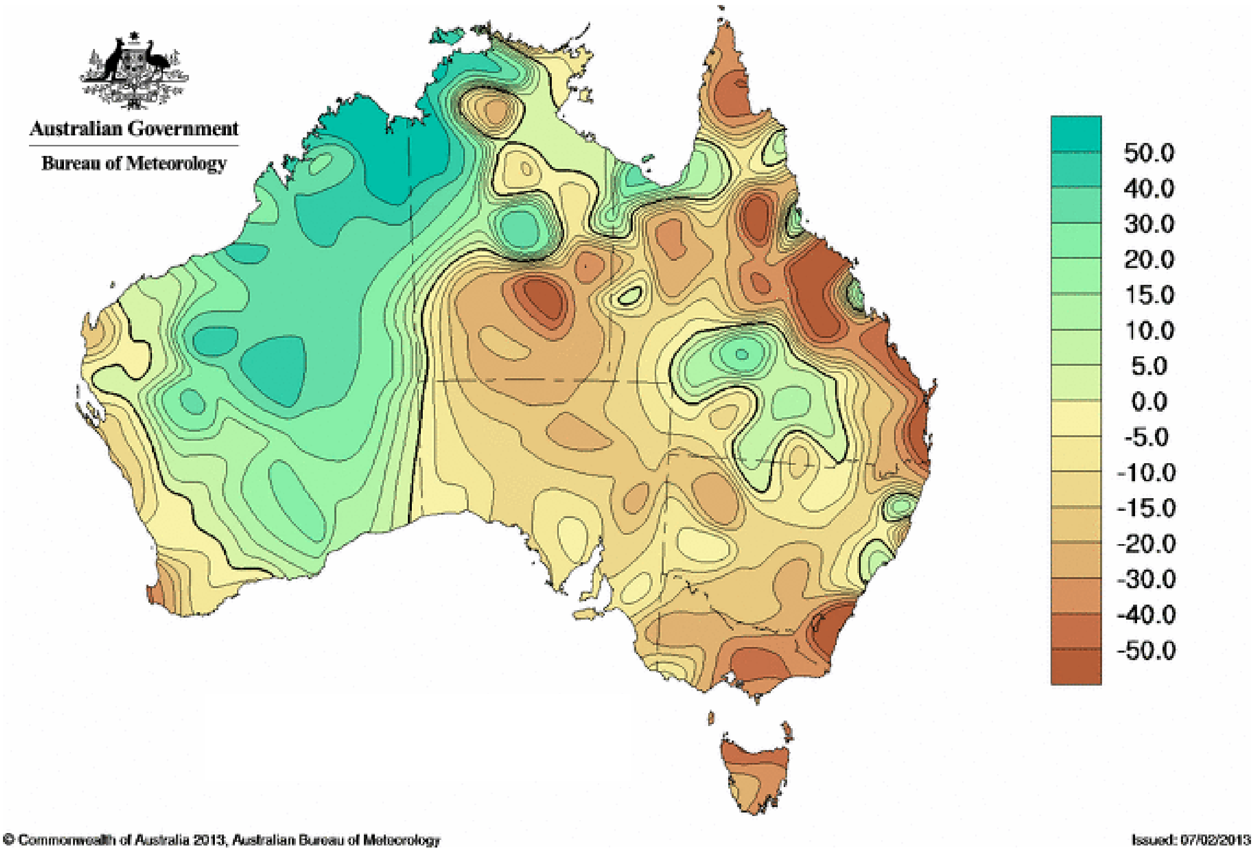

Figure 8.2 Trend in annual total rainfall 1970 – 2012 (mm/10yr) with green representing an increase in rainfall and brown a decrease over time (Source: Bureau of Meteorology).

Trends in extreme daily rainfall across Australia show that from 1970 to 2012, there have been increases in north-western and central Australia, but decreases along the EC. Trends in most extreme rainfall events are rising faster than trends in the mean. Since the start of the 20th century, the period with the lowest rainfall was from the 1930s to the early 1940s. In addition, recent Australian droughts have been accompanied by higher surface temperatures due to global warming, which may have exacerbated the impact of drought in regions where warming increases water demand and surface evaporation (Lough and Hobday 2011).

Although clear evidence is now emerging for a recent acceleration in the global hydrological cycle (Helm et al. 2010), assessing the magnitude and significance of observed rainfall and river flow changes across Australia is hindered by the high inter-annual rainfall variability (Lough and Hobday 2011).

Ocean chemistry

The oceans absorb carbon dioxide (CO2) from the atmosphere and are estimated to have absorbed about a third of the excess CO_2 released into the atmosphere by human activities in the past 200 years (Doney et al 2009). Global estimates of changes in ocean chemistry are used as very little is known about baseline conditions, and any variation in Australian waters is complex and variable both spatially and temporally (e.g. Gagliano et al. 2010). In addition, most measurements have been made for open-ocean waters, which are not representative of coastal or nearshore waters (e.g. McNeil 2010) and especially coral reefs, which modify their own water chemistry (Anthony et al. 2011).

Changes in water chemistry are the result of CO_2 absorption, with about half of this anthropogenic CO_2 remaining in the upper 10% of oceans (less than 1,000 m depth) due to slow ocean mixing processes. This absorbed CO_2 is resulting in chemical changes in the ocean, causing an estimated 0.1 decrease in oceanic pH since 1750, representing a 30% increase in hydrogen ion (acid) concentration (Ganachaud et al. 2011, Howard et al. 2012). Although this pH change is not uniform for all Australian waters, there is not high enough data resolution to provide spatially refined estimates.

Sea level

As global climate warms, sea level rises due to thermal expansion of the oceans and the contribution of additional water through the melting of glaciers and continental ice sheets. As a result, global sea level appears to be rising at a rate of 1 to 2 mm per year. A recent reconstruction of global mean sea level from 1870 indicates that between January 1870 and December 2004, global sea level rose by 195 mm (Figure 8.3). There is also observational evidence (matching climate model simulations) of a significant acceleration in the rate of global sea level rise of 0.13 ± 0.006 mm per year (Church and White 2006).

Globally, average sea level has risen 20 cm since the late 19^{th} century, largely as a result of thermal expansion, with a relatively minor contribution, so far, from melting land ice (Bindoff et al. 2007). The average rate between 1950 and 2000 was 1.8 ±0.3 mm per year, but for the period when satellite data are available (i.e. from 1993), the rate increased to 3 mm per year. Since 1990, the observed rate of global sea level rise corresponds to the upper limit of IPCC projections (IPCC 2007). For the period 1993 to 2011, sea level rose at all of the Australian coastal sites monitored, with substantial variability in trends from location to location (Figure 8.4). Over the period 1920 to 2000 the estimated average relative sea level rise around Australia was 1.2 mm per year (Lough and Hobday 2011).

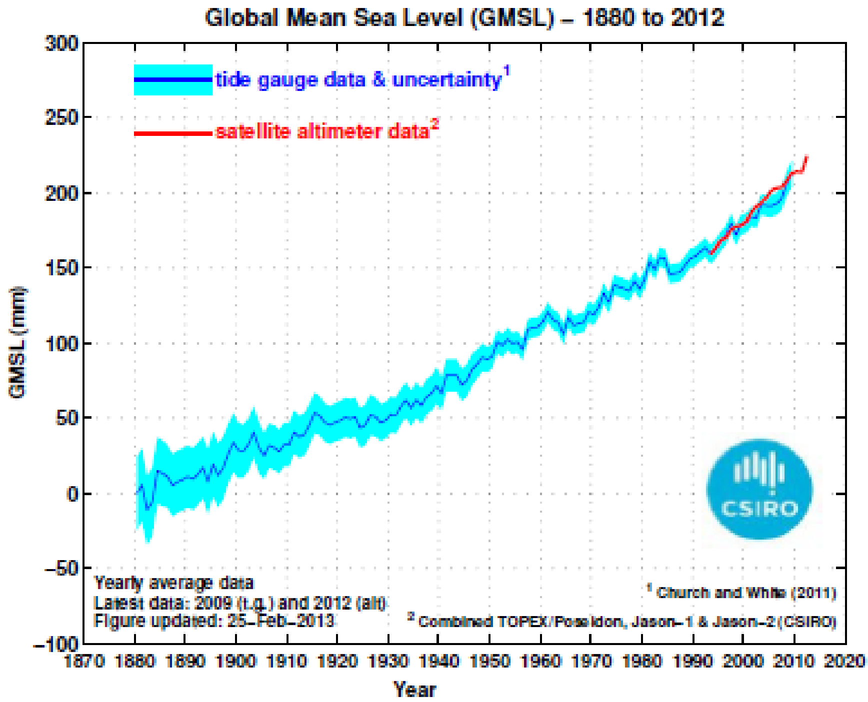

Figure 8.3 Global mean sea level 1880 – 2012 (Source: CSIRO, Church and White 2011).

Sea levels are rising around Australia, with fastest rates currently in northern Australia. Rising sea level also affects the frequency of high sea-level events (e.g. storm surge inundation) on annual to decadal timescales and these have increased by a factor of three during the 20th century (Church et al. 2012). This regional variation in the magnitude of sea-level rise is linked with inter-annual climate variability (e.g. ENSO), and changes in ocean circulation (e.g. increased southward penetration of the East Australian Current) and atmospheric circulation dynamics (Church et al. 2009). Sea-level rise is, therefore, not uniform in either the Indian or Pacific Oceans (Han et al. 2010).

Tropical cyclones

Tropical cyclones occur during the summer monsoon season and are destructive weather systems that affect tropical Australia (Figure 8.5). Conditions suitable for tropical cyclone development occur from November through May on the EC, GoC and NWA, with highest numbers usually experienced in January and February. In NWA the chance of experiencing an intense cyclone (category 4 or 5) is highest in March and April. The northwest WA coastline between Broome and Exmouth is the most cyclone-prone region of the Australian coastline, having the highest frequency of coastal crossings and the highest incidence of cyclones in the southern hemisphere (Lough 1998, BoM 2013). On average about five tropical cyclones occur during each tropical cyclone season over the warm ocean waters off the northwest coast between 105°E and 125°E (BoM 2013). Tropical cyclones occur most frequently between latitudes 16° S to 18° S and less often between latitudes 10° S to 12° S. Tropical cyclones bring destructive winds and waves and, when making landfall, can cause elevated sea levels and destructive storm waves (storm surge) as well as heavy rainfall and rapid increases in river flows (Lough 2007).

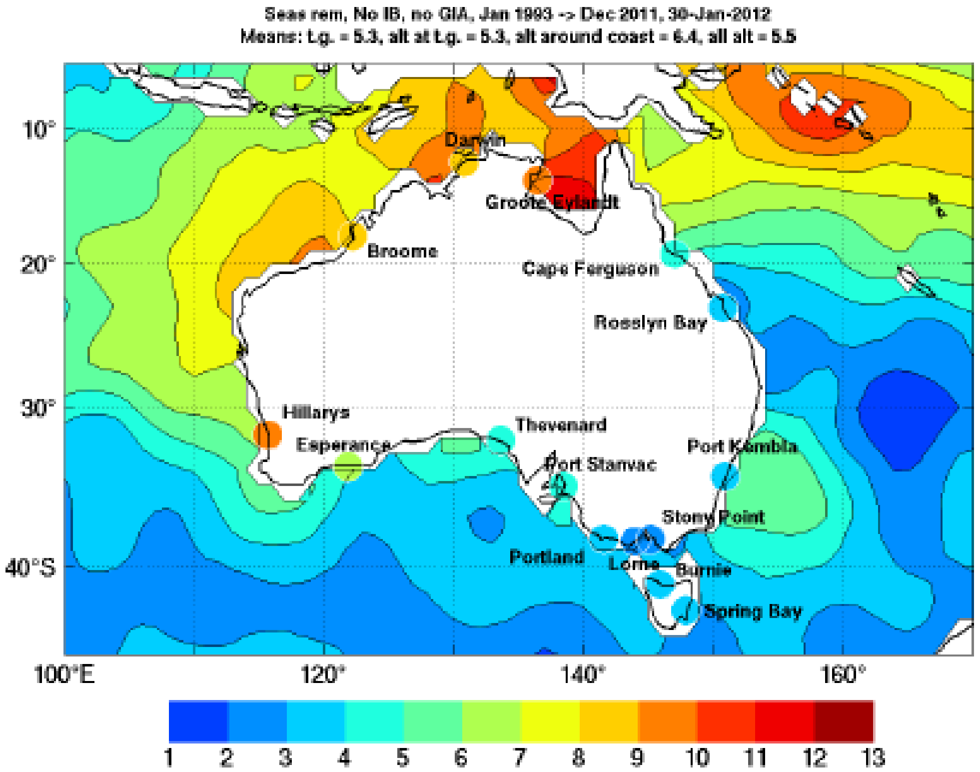

Figure 8.4 Australian sea-level trend (mm/yr) from 1993 – 2011 (Source: Church et al. 2012).

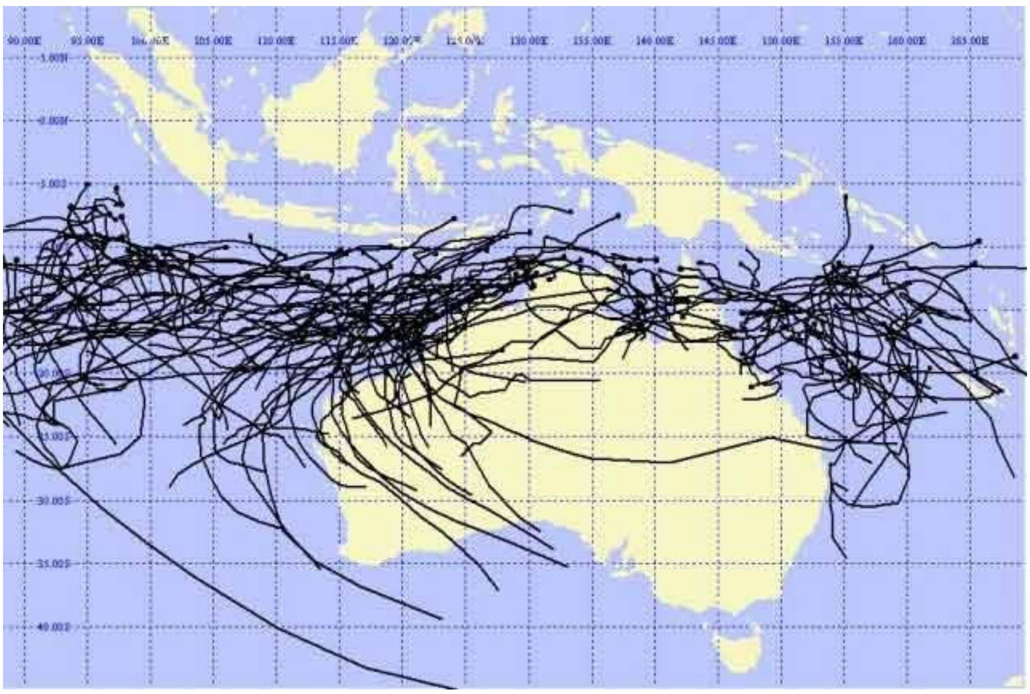

Figure 8.5 Tropical cyclone tracks in the Australian region from 1989/90 to 2002/03 (Source: Bureau of Meteorology).

Detecting trends in tropical cyclone frequency and intensity is difficult due to the high natural variability in their occurrence and that it is probably only since the advent of satellites that all tropical cyclones have been identified (Knutson et al. 2010). Nicholls et al. (1998) provided evidence of an apparent decline in the number of weak tropical cyclones and a slight increasing trend of more intense tropical cyclones in the Australian region over the period from 1969–1970 to 1995–1996 based on satellite observations. This trend has been attributed, in part, to improved distinction of tropical cyclones from other tropical storms. Hassim and Walsh (2008) compared eastern and western Australian tropical-cyclone regions from 1969–1970 to 2004–2005 and found evidence that the number, duration and maximum intensity of severe tropical cyclones off NWA have been increasing since the 1980s. However, on the EC, the number has decreased, with no obvious trend in either intensity or duration. There has been no observed change in the latitudinal distribution of tropical-cyclone activity. The GBR on the EC has however experienced six severe tropical cyclones between 2005 and 2011 (GBRMPA 2011).

El Niño – Southern Oscillation

A major source of inter-annual climate variability in northeast Australia (affecting the EC and GoC) is the El Niño – Southern Oscillation (ENSO) phenomenon (Lough and Hobday 2011). ENSO describes the aperiodic variations in the ocean-atmosphere climate of the tropical Pacific, which causes climate anomalies in many parts of the tropics and extra-tropics. ENSO has two phases:

1) El Niño events when the eastern equatorial Pacific is unusually warm, and
2) La Niña events when the eastern equatorial Pacific is unusually cold.

Events typically evolve over 12 to 18 months and, once initiated, their development is somewhat predictable with distinct climate anomalies occurring in northeast Australia. During typical El Niño events, the summer monsoon circulation is weaker than normal associated with higher sea level pressure and more south-easterly winds. Cloud cover is reduced increasing radiation, and rainfall and river flows are considerably lower than normal. In typical La Niña events, the summer monsoon circulation is stronger than normal with lower sea level pressure and more north-westerly winds. Cloud cover, rainfall and river flows are higher than average. SST anomalies are more marked during El Niño than La Niña events, with warmer than average SST occurring during the summer wet season. The differences in the strength of the summer monsoon circulation with ENSO also results in marked differences in the occurrence of tropical cyclones with much less activity during El Niño years. Overall, the level of disturbance is greater during La Niña events when the more vigorous summer monsoon circulation and heightened tropical cyclone activity causes enhanced rainfall and river flow. This can lead to reduced salinity and higher turbidity of nearshore waters and increased levels of physical disturbance. Suppression of the summer monsoon and tropical cyclone activity during El Niño events is associated with reduced rainfall and river flow and maintenance of more winter-like conditions (Lough 2007).

Instrumental and palaeo-climate records show large variations in the frequency and intensity of ENSO, and the impact of ENSO on Australia has varied from decade to decade. This is partly driven by the Pacific Decadal Oscillation (PDO, Mantua et al 1997; Power et al 1999). While there has been an apparent increase in the frequency of El Niño events in recent years, there is no consensus amongst global climate models that climate change should cause such an increase; the increase might therefore reflect natural variability. The relationship between the SOI and Australian temperatures and rainfall has changed. For example, Australia-wide rainfall and temperatures since the mid-1970s have been higher for any given value of the SOI than previously (CSIRO and BoM 2007).

Although El Niño or La Niña events show some common features, no two evolve in exactly the same way (Trenberth and Stepaniak 2001) and recently it has been suggested that ENSO events have shifted from those dominated by warming or cooling centred in the eastern equatorial Pacific to events characterised by warming or cooling in the central equatorial Pacific (Ashok et al. 2007). Whether this is a signal of global warming is not clear yet (Lough and Hobday 2011).

Wind and ocean currents

The prevailing wind conditions that influence the east coast of Australia are the southeast trade winds. The impact of the trade winds is greatest from April to September with winds of 45 to 55 km/h often observed north of Cooktown. Trade winds are at their strongest when a slow-moving high pressure system is located off the east coast of Australia in the Tasman Sea[4].

In the GoC, the prevailing winds are south-easterly during the dry season and north-westerly during the wet season. These trade winds are driven by the sub-tropical ridge; an extensive area of high pressure that lies across southern Australia in winter, and further south in summer. The trade winds tend to be strongest in winter when high-pressure systems are more intense (April to September), directing cool south-easterly winds towards northern Australia[5]. Mid-latitude westerly winds appear to have decreased in most seasons from 1979 to the late 1990s and there has been a 20% reduction in the strength of the subtropical jet over Australia (CSIRO and BoM 2007). In NWA the prevailing wind conditions are westerly/north-westerly during the summer and more variable in winter[6].

[4] http://www.climatekelpie.com.au/understand-climate/weather-and-climate-drivers/queensland#TradeWinds

[5] http://climatekelpie.com.au/understand-climate/weather-and-climate-drivers/northern-territory#tropical_systems

[6] http://www.bom.gov.au/climate/averages/wind/selection_map.shtml

Australia is unique in having warm, poleward-flowing currents along both its east (EAC) and west (Leeuwin Current) coasts, which result in significant tropical communities along both coastlines (Lough 2008). Evidence is emerging for significant changes in the EAC which, over the period 1944–2002, has increased its southward penetration by ~350 km, bringing warmer saltier waters further south (Ridgway 2007, Hill et al. 2008). The intensification of flow and accelerated warming observed in the EAC is driven by the strengthening and contraction south of Southern Hemisphere westerly winds (Poloczanska et al. 2012). Since the mid-1970s, the Leeuwin Current has weakened due to more frequent El Niño events. However, in the past two decades, a strengthening is observed, linked to natural decadal variability and not long-term change (Poloczanska et al. 2012). The intensity of the Leeuwin Current is also significantly modulated by ENSO events, in particular La Niña events are associated with a strengthening of the current and transport of warmer waters further south, as happened in 2011 (Feng et al. 2013) resulting in significant impacts on west coast marine ecosystems (Wernberg et al. 2012).

Ocean circulation patterns are less well documented for the GoC region. In the Gulf of Carpentaria barotropic diurnal tidal currents dominate (Church and Forbes 1983). Observations also show a slow, clockwise circulation, which appears to be a permanent feature in the Gulf. Northwest monsoon winds and density-induced currents enhance the clockwise circulation. However, when the south-east trade-winds build at neap tides they drive a counter-clockwise circulation, and at spring tides, a weak clockwise circulation (Forbes and Church 1983).

8.2.3 Climate projections

The climate projections presented here are based on the IPCC-AR4 CMIP3 global climate model outputs downscaled for Australia (CSIRO and BoM 2007, Lough 2007) and specific regions (Bell et al. 2011a, Poloczanska et al. 2012) for 2030 and 2070 (or the nearest available projection years) for a moderate emissions scenario (SRES A1B/A2) and a high ('business-as-usual') emissions scenario (SRES A1FI) (IPCC 2007). Where available, updated projections for IPCC-AR5 based on the newly developed CMIP5 models are presented (IPCC 2013). This new generation of models operate at higher spatial resolution and include a wider range of climate processes than CMIP3.

The IPCC-AR4 assessments were based on the Special Report on Emissions Scenarios (SRES, Nakicenovik et al. 2000) which have been replaced in IPCC-AR5 with a new set of scenarios: the Representative Concentration Pathways (RCPs; Moss et al 2010). These are named after the level of radiative forcing in 2100, i.e. the change in the balance of incoming and outgoing radiation to the atmosphere due to changes in the atmospheric concentration of greenhouse gases such as CO_2. Although not directly comparable, the SRES A1F1 scenario is very similar to RCP8.5 and the moderate SRES A1B/A2 scenarios are similar to the RCP6 (see

Figure 8.6). Despite the changes in the models, however, climate projections from CMIP3 and CMIP5 do not differ greatly and the basic conclusions from previous assessments remain largely valid (Knutti and Sedláĉek 2013, IPCC 2013).

The projections do not show significant divergence by 2030 under the different SRES or RCP 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 impact on biological productivity of marine environments. Although changes in *average* climate conditions are expected to cause major impacts on tropical Australian marine environments, 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 2013).

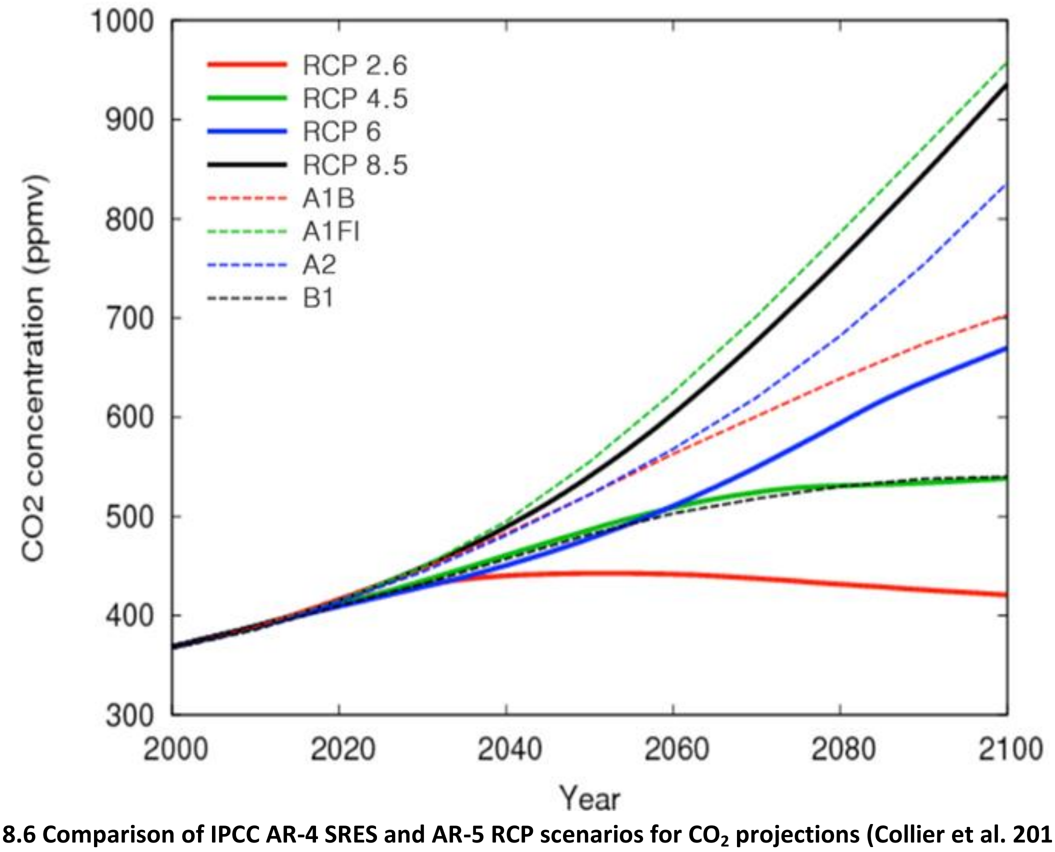

Figure 8.6 Comparison of IPCC AR-4 SRES and AR-5 RCP scenarios for CO_2 projections (Collier et al. 2011).

Sea surface temperatures

Sea surface temperatures are expected to continue warming during this century, affecting maximum, minimum and mean temperatures. The projections for sea temperature in northern Australia under the moderate A1B emissions scenario are between 0.3–0.6 °C warming (relative to 1980-1999) by 2030 for the EC and GoC, and 0.6 to 0.9 °C warming by 2030 for NWA (CSIRO and BoM 2007) (Table 8.10). The pattern of greatest SST increase in northwest WA continues to 2070 under both the moderate and high emissions scenarios (Table 8.10). Results from the newly developed CMIP5 models for the relatively high RCP8.5 emissions pathway (equivalent to A1FI) also indicate greatest tropical ocean warming off northwest Australia of ~2.5 °C by 2100 (Lough et al. 2012).

Table 8.10Projected increases in sea surface temperatures for northern Australia (CSIRO and BoM 2007).

	2030 (A1B)	2070 (A1B)	2070 (A1FI)
East coast (°C)	+0.3 to +0.6	+1.2 to +1.5	+2.2 to +2.5
Gulf of Carpentaria (°C)	+0.3 to +0.6	+1.2 to +1.5	+2.2 to +2.5
Northwest Australia (°C)	+0.6 to +0.9	+1.5 to +1.8	+2.5 to +2.8

Rainfall and River flow

Projected rainfall changes are more variable and uncertain, with both increases and decreases expected; the EC is projected to become drier while the GoC and NWA are projected to become wetter (Table 8.11). There is also still a high degree of uncertainty associated with rainfall projections for tropical northern Australia where CMIP5 models still have a lack of agreement between models and a wide spread in the simulations (Irving et al. 2012). Extreme rainfall events are projected to occur more frequently with more intense rainfall and more dry days in between (CSIRO and BoM 2007, BoM and CSIRO 2011).

Table 8.11Projected changes (%) in rainfall for northern Australia (CSIRO and BoM 2007).

	2030 (A1B & A1FI)	2070 (A1B)	2070 (A1FI)
East coast	-10 to 0	-20 to +10	-30 to +10
Gulf of Carpentaria & North-western Australia	0 to + 5	0 to +20	

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 events will most likely result in more extreme flood events (Climate Commission 2013).

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 (Collins et al. 2010, 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-annual variability in the region but super-imposed on warmer SST (Lough and Hobday 2011, Poloczanska et al. 2012).

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 northern Australia (CSIRO and BoM 2007). It is possible that the recent trend of more frequent TCs in NWA will continue. 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 CO2 are projected to lead to substantial additional acidification of the ocean, reducing the pH of the ocean by 0.2–0.3 units (under 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), jeopardising the growth of corals, shellfish and some plankton. Projections for the mid-term are that ocean pH will decline by 0.1 unit by 2035 under the A2 IPCC-AR4 emission scenario (Ganachaud et al. 2011). The aragonite saturation level is expected to decrease to 2.4 in 2100 (under A2), with severe consequences for the formation of coral reef habitats and many reef organisms (Ganachaud et al. 2011, BoM and CSIRO 2011).

Sea level

The current rate of sea-level rise (1993 to present) is about 3.1 ± 0.4 mm/yr (Church et al. 2012). To date, most of this rise has been attributed to thermal expansion as the oceans have warmed. With continued thermal expansion of the upper ocean layers and a greater contribution from melting of land-based ice, this rate is expected to accelerate. The projections from IPCC–AR4, that sea level will rise between 18 cm (under the B1 low emissions scenario) 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). It is also projected that the rate of sea-level rise will be regionally variable, with the GoC and NWA likely to experience a greater increase of 10 – 20 cm by 2030 (Church et al. 2012). Even the lower estimates would mean a profound change for coastal habitats. Confidence in IPCC-AR5 projections of sea-level rise has increased since IPCC-AR4 due to improved understanding and modelling of key processes. IPCC-AR5 projections suggest sea levels at the end of the 21st century (2081-

2100) relative to 1986-2005 are likely to be in the range of 33 to 63 cm for RCP6.0 and 45-82 cm for RCP 8.5 (IPCC 2013).

Rising sea level influences the frequency of extreme high sea-level events (e.g. king tides) that occur on annual to decadal timescales, which has increased by a factor of about three during the 20th century (Church et al. 2012). Higher sea levels would also increase the magnitude and destructive capacity of storm surges associated with tropical cyclones crossing the coast.

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) by 26% by 2100 under A2 (Ganachaud et al. 2011) – will have potential implications for currents, stratification and productivity on the EC and possibly GoC. Changes in the variable and complex tidal regimes of tropical Australia will have implications for species life cycles, and larval and nutrient exchange. 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).

The EAC along the EC is projected to increase in flow off southeast Australia with a compensating decrease off north-east Australia (Ridgeway and Hill 2012). The Leeuwin Current along northwest WA is predicted to weaken over this century. Despite this, warming will continue to drive southward range shifts in marine biota and there will be more frequent extreme temperature events (Ridgeway and Hill 2012).

Ocean salinity and Solar radiation

Other ocean climate variables that are expected to influence fisheries in northern Australia 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.

A reduction in salinity, or freshening, has been observed over recent decades in the western tropical Pacific Ocean (Cravatte et al. 2009, Durack et al. 2012). 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-AR4 scenario (BoM and CSIRO 2011). Solar radiation is projected to undergo minor changes of -1% to +2% by 2030, with larger changes projected for 2070 however, there is high uncertainty (CSIRO and BoM 2007).

8.2.4 Summary of climate projections

A summary of the climate projections for 2030 and 2070 under the moderate and high SRES emissions scenarios (A2/A1B and A1FI) for key variables is provided in Table 8.12.

Table 8.12 Summary of climate projections for northern (tropical) Australia for 2030 and 2070 under the A2/A1B and A1FI emissions scenarios.

Variable	2030	2070	
	A1B/A1FI	**A2/A1B**	**A1FI**
SST (°C)	+0.3 to +0.6 (EC, GoC); +0.6 to +0.9 (NWA)	+1.2 to +1.5 (EC, GoC); +1.5 to +1.8 (NWA)	+2.2 to +2.5 (EC, GoC); +2.5 to +2.8 (NWA)
Ocean temp >250 m (°C)	0 to +0.6[a]	+0.6 to +1.5	+0.6 to +2.4[b]
Rainfall change (%)	-10 to 0 (EC); 0 to +5 (GoC, NWA)	-20 to +10 (EC); 0 to +20 (GoC, NWA)	-30 to +10 (EC); 0 to +20 (GoC, NWA)
Riverflow/nutrient supply	1:4 reduction	Region specific[c]	
ENSO	Continued source of interannual climate variability		
Storms & cyclones[d]	-9 to -44% number[e]; +3 to +21% intensity		
Ocean pH	~7.98	~7.81	
Sea level (cm)	+5 to +15 (EC); +10 to +20 (GoC, NWA)	+20 to +60 (by 2090)	
Ocean circulation	Strengthening of EAC; weakening of Leeuwin current		
Sea surface salinity (psu)	-0.1	-0.34 (by 2100)	

(a) n/a for GoC; (b) northern EC the warmest; (c) linked to rainfall changes; (d) by 2100; (e) possibly more frequent TCs in NWA.

Sources: Climate Change in Australia, OzClim, CSIRO and BoM 2007, Cravatte et al. 2009, Knutson et al. 2010, Bell et al. 2011b, BoM and CSIRO 2011, Lough and Hobday 2011, Church et al. 2012, Lough et al. 2012, Poloczanska et al. 2012.

8.3 Climate change implications for habitats that support northern Australian tropical fisheries

8.3.1 Overview

The natural ecosystems that northern Australian fisheries rely on have evolved to operate within a specific range of prevailing local climatic conditions – a tolerance range (e.g. Jones and Mearns 2005, Hoegh-Guldberg et al. 2007). Changes beyond these specific conditions will influence the habitats that support fisheries, as well as fisheries stocks, species, populations and communities themselves. Tropical fisheries that target species with strong ecological relationships to specific microhabitats or a combination of seasonally-available habitat patches are most likely to be influenced by climate related impacts (Badjeck et al. 2010, MacNeil et al. 2010, Donnelly 2011, Pratchett et al. 2011, Bell et al. 2013).

Understanding how climate change is likely to influence a range of key habitats – coral reefs, seagrass meadows, mangroves, estuaries and floodplains (Figure 8.7) – is critical to assessing fisheries changes under future climate scenarios. The aim of this chapter is to review the range of potential climate change impacts on key fisheries habitats across northern Australia. The project is focused on fisheries across northern Australia covering a vast area over three regions: north-western Australia (northern Western Australia and north-western Northern Territory; NWA), the Gulf of Carpentaria (GoC), and the Queensland east coast (EC). Our review considers the vulnerability of fisheries habitats in these three regions to climate change and what impacts might manifest in the future. Section 8.2 provides climate projections for the three regions of northern Australia for 2030 and 2070 under the IPCC SRES A1B/A2 (moderate emissions reductions) and A1FI ('business-as-usual') scenarios, which are referred to in this review.

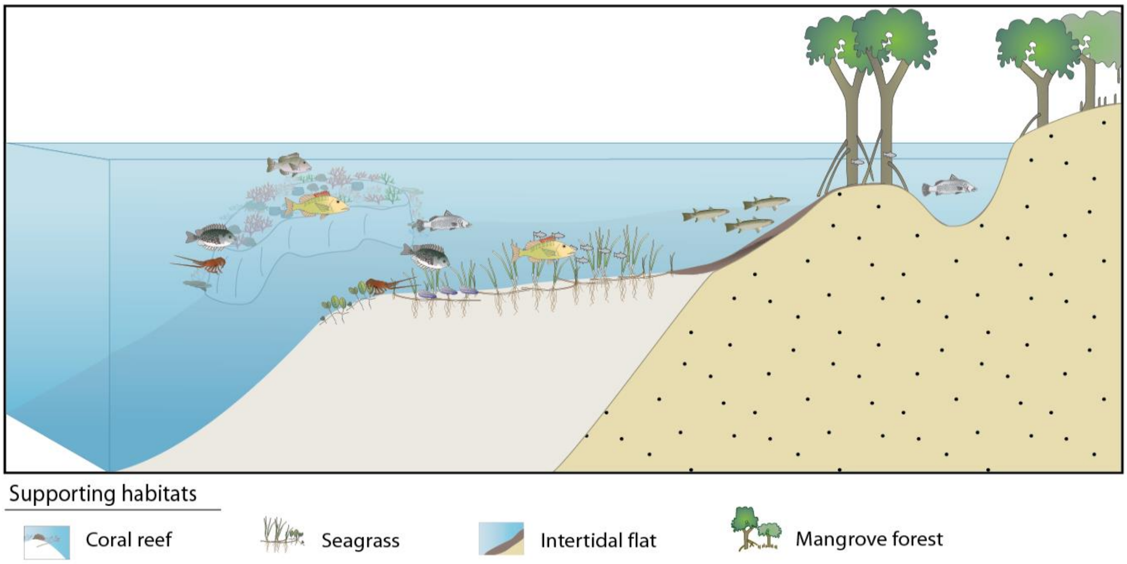

Figure 8.7 Graphic representation of tropical habitats and their connectivity.

8.3.2 Exposure of northern Australian habitats

Marine environments in northern Australia range from floodplains, coastal bays and mangrove-lined estuaries, through near-shore intertidal flats and seagrass habitats, to coral reefs, deep-water seagrass meadows, and wider continental shelf and open-ocean pelagic habitats (Poloczanska et al. 2007). These various habitats are connected by water movements that influence transport of fish larvae, sediment, nutrients and other marine organisms, as well as dynamic temperature and salinity gradients. Tropical fish species utilise these habitats during different life-history stages, and often move between habitats.

Coastal mangrove forests and intertidal flats are found throughout northern Australia, including the EC, GoC and NWA regions of this project, particularly where rivers and estuaries meet the coast (Figure 8.8a). The EC of Australia is characterised by significant coral reef areas with high coral species diversity between latitudes 10°and 25°S (Great Barrier Reef and Torres Strait). While NWA has coastal reefs between latitudes 20° and 24 °S and a concentration of offshore reefs centred around 17 °S (Rowley Shoals; Figure 8.8b).

Coral reefs on the EC are interspersed with shallow seagrass meadows, with an estimated ~35,000 km^2 representing >50% of seagrass area in Australia (McKenzie et al. 2012). In the GoC, the generally shallow and soft sediment environment supports extensive areas of seagrass in coastal and estuarine locations, however recent mapping observed low diversity and biomass[7]. The large tidal variation (1 - 11 m) in NWA causes strong tidal flows that dramatically influence coastal habitats and seagrass meadows are mostly found in sheltered intertidal bays along the southern coast of the Kimberley region, with low to moderate abundance. Seagrasses are also interspersed in coral reef environments in NWA but the high-energy environments of the northern Kimberley means seagrass are largely absent on that part of the coast[8] (Figure 8.8c).

The location of coastal habitats will determine their exposure to projected future climate change: increasing sea surface temperature (SST), ocean acidification, changing rainfall and river flow patterns, sea-level rise, more intense storms and cyclones, and changing ocean circulation. Although all three regions in northern Australia are projected to experience increases in SST, the magnitude of increase will be greatest in NWA meaning that coral reefs and mangrove forests in this region will be exposed to higher sea temperatures. Similarly, habitats in NWA and GoC will be exposed to wetter conditions with rainfall projected to increase, while habitats on the EC will be exposed to drier conditions with rainfall projected to decrease under all scenarios (see Table 8.12 for details of A1B/A2 and A1FI 2030 and 2070 projections).

[7]http://seagrasswatch.org/Napranum.html
[8]http://seagrasswatch.org/WA.html

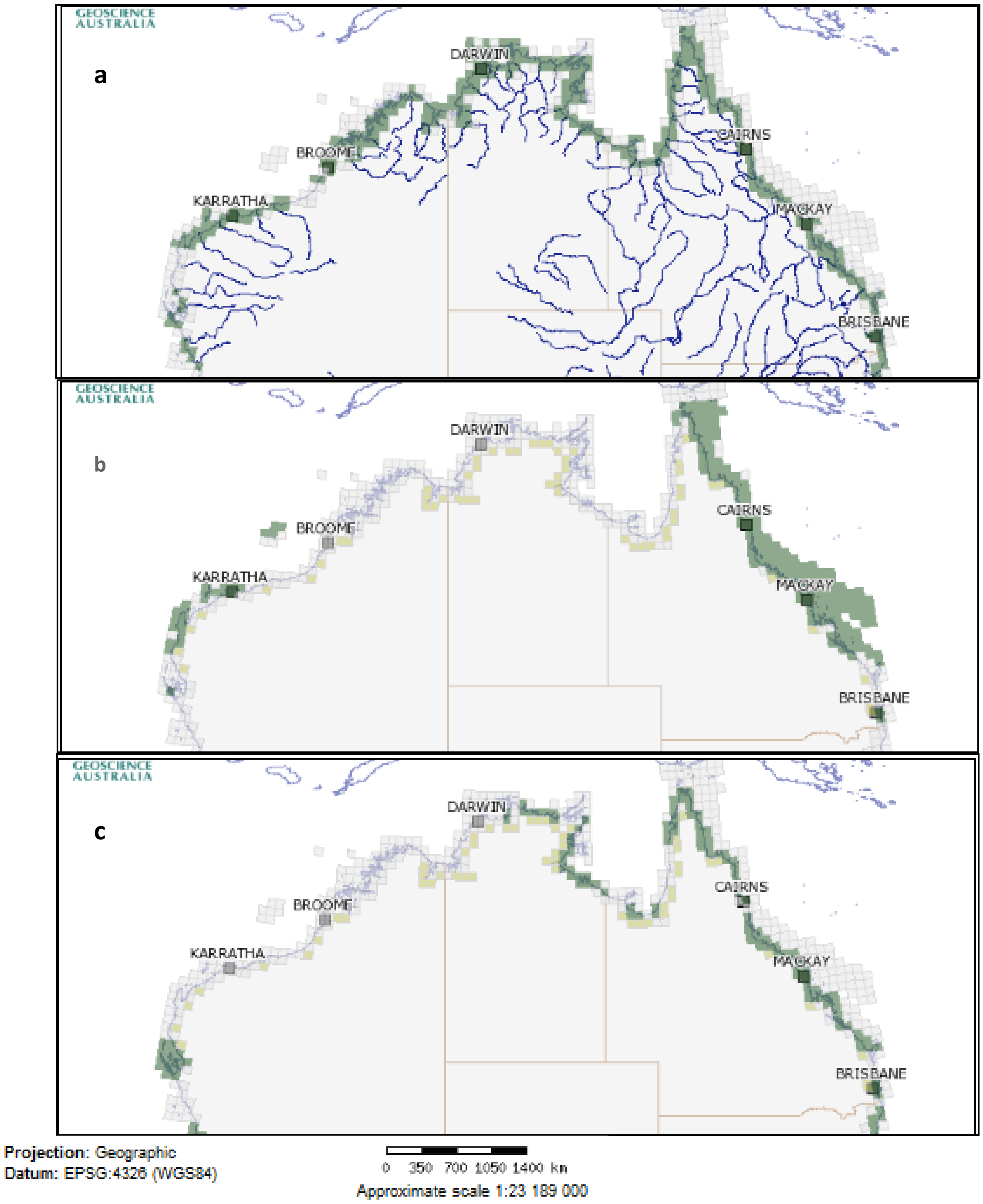

Figure 8.8 Location of marine and coastal habitats in northern Australia: (a) Rivers, estuaries and mangroves, (b) coral reefs, and (c) seagrass meadows (Source: OzCoasts, Geoscience Australia).

8.3.3 Habitat types

Floodplains

Floodplains are shallow, well-vegetated habitats adjacent to lowland river channels. Floodplain habitats are prevalent across northern Australia, occupying over one third of most river catchments. Most are largely unmodified by human impacts, but they vary in extent and nature. In NWA and GoC, floodplains become available to fish with the onset of the annual flood pulse that inundate this habitat mainly during December-February (Warfe et al. 2011). Extent and intensity of this flood pulse varies significantly across tropical Australia. For example NT Rivers generally flood for a long period of time compared to the Mitchell (GOC) and Fitzroy (EC) Rivers that flood for a shorter period (typically a few days) due to having less extensive catchments (Warfe et al. 2011). During the dry season, as water depth and water quality parameters decline in floodplain waters, the availability and quality of floodplains as fish habitat becomes limited, and fish kills in isolated and drying wetlands are common.

Floodplains provide an array of rich food resources for fish, driven by local algal production. This food supply includes vegetation, insects, crustaceans and juvenile fish, and supports marine fisheries production both directly and indirectly (e.g. as a source of material for downstream habitats). For example, Jardine et al. (2012) examined food web structure in floodplain habitats of the Mitchell River using stable isotopes. They found that floodplain food sources accounted for the majority of the diet of large-bodied fishes captured on the floodplain in the wet season, including barramundi, and for gonadal tissues of a common herbivorous fish (gizzard shad, *Nematalosa come*), the latter suggesting that critical reproductive phases are fuelled by floodplain production. They also found that floodplain food sources subsidised barramundi from the recreational fishery in adjacent coastal and estuarine areas. This increased food, in conjunction with providing shelter from predators, means that floodplains also provide an important nursery habitat for a wide range of fish and invertebrate species (Bunn and Arthrington 2002). This relationship is a key driver for the productivity of important tropical species such as barramundi with recruitment success being driven by floodplain inundation (Robins et al. 2005).

Floodplain ecosystems are sensitive to changes in river-flow regimes that affect the hydrological features of the flood pulse (Bunn and Arthington 2002). Consequently, floodplain habitats are likely to be affected by changes to the climate system that affects timing, duration and magnitude of inundation events, including interactions between rainfall, river discharge and sea level. While there is inherent uncertainty in predicting the ecological effects of such changes on fisheries, previous reviews (principally Pusey and Kennard 2009) have consistently identified two key drivers of change in northern floodplain systems: sea-level rise and changing rainfall patterns.

Sea-levelrise is predicted to increase by 0.6 m by 2090 (BoM and CSIRO 2011). Many northern wetlands are located only minimally above sea level and are at extreme risk from sea-level rise (Low 2011, Pusey and Kennard 2009). Finlayson et al. (2002) predicted that the Alligator Rivers region (NWA) will lose existing mangrove forests, followed by an upstream change in their distribution, with a concomitant loss of Melaleuca wetlands and a transformation of existing freshwater wetlands to saline flats. These impacts may be amplified by increased severity of monsoonal storms and associated storm surges, with the present 1 in 100 year event potentially occurring more than once a year by 2100 (Church et al. 2008). Modelling of such scenarios indicates that the frequency of saltwater inundation of the Kakadu floodplain (NWA) will increase by 60% in 2030 and 500% in 2070 (BMT WBM 2010).

Changing rainfall patterns (particularly greater variability of rainfall and more extreme events) are expected to have pronounced effects on floodplains through alterations to hydrological regimes (Day et al. 2008). On the EC lower rainfall is likely to result in fewer flood events that will mean shorter inundation periods that may not enable sufficient exchange of biota and materials between habitats. Alternatively the rainfall predicted in the GOC and NW will potentially increase the flood period inundation allowing for greater productivity of biota in catchments in these areas. Increased temperatures are likely to result in increased production and decomposition rates in floodplains (Gehrke et al. 2011). Evaporation rates will also increase significantly as atmospheric temperatures rise and this may impact on both persistence and water quality (e.g. dissolved oxygen concentration) on floodplains. Such changes would impact greatly on species that are obligate floodplain dwellers or use floodplains at critical phases of their life history (e.g. many species of estuarine and freshwater fish; Pusey and Kennard 2009). Overall, the important roles that coastal floodplains play as nursery habitats and for water purification are likely to be compromised, ultimately affecting downstream fisheries.

Coastal bays and estuaries

Coastal bays and estuaries form a transition zone between river 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 both the water column and sediment, making estuaries among the most dynamic and productive natural habitats in the world. At the interface between land and sea, estuaries will be highly exposed to changing rainfall patterns and river flows, intense storms and cyclones, changes in ocean chemistry, highly variable SST and sea-level rise. However, they are accustomed to large variability in environmental conditions, which may in fact make them less sensitive to changing climate conditions. The potential impacts of climate change, and ultimately the vulnerability of estuaries, will depend on the dominant habitat, since they can be comprised of a range of different habitats, including mangroves, shallow seagrass meadows and intertidal flats.

Estuaries dominated by seagrasses, adjacent to rivers and heavily exposed to increased terrestrial runoff, are likely to have high vulnerability to future changes in rainfall and pollutant runoff, surface temperatures, and physical disturbance from cyclones and storms. While estuaries with mangrove habitats will be vulnerable to more intense storms and cyclones, changing rainfall patterns 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 seagrass meadows and mangroves to future climate change are provided below.

Intertidal estuarine habitats will be particularly exposed to rising SST as they experience periods when peak daytime temperatures coincide with low spring tide exposure, resulting in possible losses of intertidal organisms despite the high stress-tolerance of many species (Brierley and Kingsford 2009). This will be particularly pronounced in NWA estuaries, where the greatest SST increases are projected. Increased temperature is expected to potentially inhibit intertidal primary productivity in estuaries (Gehrke et al. 2011).

Estuaries are highly variable habitats and their fauna and flora have evolved to deal with environmental variability. For example, recorded pH in the Fitzroy River estuary (EC; a primary habitat of barramundi) can vary between 8.6 and 6.8 (Robins, unpublished data). The potential impacts of projected pH reductions under climate-change scenarios (0.5 unit decline; Gillanders et al. 2011) are likely to be relatively minor when compared to this natural variation (Meynecke et al. 2013).

Estuaries in low-lying areas are likely to expand inland with rising sea levels, as inundation by freshwater inflows increases during high rainfall periods. Tidal movements and salinity will extend further inland. These effects will be accentuated by storm surges during any cyclones of higher intensity (Gehrke et al. 2011).

Changes to estuarine habitats will have implications for the fisheries they support. For example, examination of NSW commercial fisheries data has shown that catch-per-unit-effort (CPUE) increased in proportion to freshwater flow for four commercial estuary species (dusky flathead, luderick, sand whiting and sea mullet) and decreased during drought (Gillson et al. 2009). Booth et al. (2011) found similar correlations, with increases in overall CPUE of the EC northern mud crab fishery interpreted as a response to SST increases. Barramundi landings have been correlated to an index of climate variability (Balston 2009a), and nursery habitat productivity (Balston 2009b) in estuarine habitats.

Seagrass meadows

Seagrasses provide nursery areas for many commonly harvested fish and invertebrates (e.g. tiger prawns, sandfish and red emperor), and feeding grounds for many species of prey and adult demersal fish targeted by fisheries (e.g. barramundi and black jew). Seagrasses (and intertidal flats) are also permanent habitats for a wide range of invertebrates, such as sea cucumbers.

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, Grech et al. 2011). Changes to nutrient dynamics and light penetration in coastal waters have been documented to impact on seagrass extent and condition with continued declines recorded on the EC since 2005 (McKenzie et al. 2012). 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).

Tropical seagrasses require water temperatures of 25 - 35°C and when SST rises to 35 - 40°C, photosynthesis declines due to the breakdown of photosynthetic enzymes (Ralph 1998) and can result in reduced growth rates (Waycott et al. 2011). Although temperature tolerance varies between species and seasons (Campbell et al. 2006, Perez and Romero 1992), overall seagrass can only survive temperatures >40°C for short periods, and prolonged exposure leads to the 'burning' of leaves or plant mortality (Waycott et al. 2011). Although seagrass meadows in NWA are not an extensive habitat, they will be exposed to a projected SST increase of 2.5 to 2.8 °C by 2070, and may therefore experience earlier or greater impacts.

Severe cyclones and storms physically damage seagrass meadows, particularly in shallow locations (Waycott et al. 2011, McKenzie et al. 2012). For example, seagrass meadows on the EC were impacted by Tropical Cyclone Yasi and associated flooding during the 2010/11 wet season, with 98% of the intertidal seagrass area lost as a consequence of the destructive winds (McKenzie et al. 2012). Although seagrass meadows in northern Australia have been impacted by cyclones for hundreds of years, the projected increase in intensity of these events is particularly concerning, as greater impacts coupled with shortened return intervals are likely to hinder the natural recovery cycle. Therefore, seagrasses are predicted to be moderately to highly vulnerable to future projections of changing rainfall patterns and more severe cyclones and storms.

Overall, tropical seagrasses are expected to be vulnerable to increasing SST (particularly in NWA), reduced light penetration (due to increased turbidity or lower solar radiation), changes to rainfall and increases in cyclone intensity (Table 8.13).

The vulnerability of seagrasses to increasing SST, decreasing light penetration, changing rainfall patterns and possible increases in cyclone intensity is projected to reduce seagrass area, with declines expected under both the B1 and A1FI scenarios in the medium- (2030) and long-term (2070)(Waycott et al. 2011). For the tropical Pacific, declines in seagrass area have been predicted of between 5 and 20 % by 2030 (Waycott et al. 2011), and similar predictions are expected for tropical northern Australia.

Table 8.13 Vulnerability of seagrasses to projected changes in surface and ocean climate (adapted from Bell et al. 2011a).

	Sea surface temperature	Solar radiation	Ocean chemistry	Cyclones & storms	Rainfall patterns	Sea level	Nutrient supply
2030 B1/A1FI	Moderate	Moderate	Very low	Moderate	Moderate	Low	Low
2070 B1	Moderate	Moderate	Very low	Moderate	Moderate	Moderate	Low
2070 A1FI	High	High	Very low	High	High	Moderate	Moderate

Mangroves

Mangroves 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. emperors, snappers, barramundi, mud crab and prawns). Mangroves have evolved to not only tolerate but to depend on tidal inundation by saltwater. However, they are unable to tolerate complete submersion, and as the frequency and duration of inundation increases, growth of trees will decline and forests may retreat landward unless they are able to migrate onto higher ground (Waycott et al. 2011). Thus areas in northern Australia with low tidal ranges, low rainfall and limited sediment supply are more likely to experience retreat of seaward fringing mangroves as sea-level rises. Compared to areas with high tidal ranges, high rainfall and high sediment supply, which are conditions where mangrove expansion is likely to occur (Lovelock et al. 2007, Steffen et al. 2009, Waycott et al. 2011). This has already been observed in other tropical regions, with the gradual retreat of mangroves in southern Papua New Guinea (PNG) in response to rates of sea-level rise similar to those projected (Valiela et al. 2001), and in Micronesia, where mangrove sediments are not keeping pace with current sea-level rise (Wolanksi et al. 2001).

Landward migration of mangroves is only possible if landward barriers, such as roads, levee banks and developments, don’t inhibit movement. Under the B1 and A1FI emissions scenarios in 2030 and 2070, mangroves are projected to be most vulnerable to sea-level rise (depending on the rate of increase), and to a lesser extent increasing cyclone intensity and changes to rainfall (Table 8.14). Ultimately, the vulnerability of mangroves to climate change is projected to reduce mangrove area, with declines becoming greater over time.

Mangroves support significant fisheries resources in northern Australia, with production estimates for fish of 20 - 290 kg per ha, and for prawns 450 - 1,000 kg per ha per year (Lovelock et al. 2007). Along the Queensland coast, as in other locations, mangrove cover is positively correlated with fisheries landings (Blaber 2002, Manson et al. 2005). Therefore, any decline in mangrove area, or loss of connectivity with other critical fish and invertebrate habitats, such as floodplains likely to result in reduced fisheries catches.

Table 8.14 Vulnerability of mangroves to projected changes in surface and ocean climate (adapted from Bell et al. 2011a).

	Sea surface temperature	Surface salinity	Ocean chemistry	Cyclones & storms	Rainfall patterns	Sea level	Nutrient supply
2030 B1/A1FI	Very low	Low	Very low	Moderate	Low	High	Low
2070 B1	Very low	Low	Very low	Moderate	Moderate	Very high	Low
2070 A1FI	Very low	Low	Very low	Moderate	Moderate	Very high	Low

Coral reefs

Coral reefs are an important coastal and offshore habitat in the NWA and EC regions of northern Australia, with thousands of fish and invertebrate species associated with the structures created by corals, several of which have been identified as priority species for this project. Coral reefs support important fisheries for demersal fish (e.g. coral trout, red throat emperor), some near shore pelagic fish (e.g. species of mackerel, sharks), and invertebrates targeted for export and recreation (e.g. tropical lobster, black teatfish). Maintaining the structural complexity of reef frameworks is vitally important to the continuation of these fisheries.

Ultimately, coral reefs are most vulnerable to increasing SST and ocean acidification. Coral reefs are highly vulnerable to further increases in SST due to coral sensitivity to thermal stress, with coral bleaching impacts already 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 projected increase in SST in northern Australia will influence the structure and function of coral reefs, particularly in NWA where SST increases of 2.5 to 2.8 °C by 2070 are projected (Lough et al. 2012) and isolated offshore reefs can take decades to recover (Smith 2008). Effects will be evident by 2030, with annual bleaching conditions associated with atmospheric CO_2 equivalent concentrations of 510 ppm (under RCP6.0 equivalent to A1FI). Bleaching also shows a latitudinal gradient with higher latitude reefs projected to experience bleaching conditions later under RCP6.0 (equivalent to SRES A1FI)(van Hooidonk et al. 2013).

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. 2011a). A decline in coral calcification on the GBR was documented by De'ath et al. (2009) and postulated to be due to increasing temperature stress and a declining saturation state of seawater aragonite, with a tipping point reached in the late 20th century. Further, studies in natural 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 by 2100 if atmospheric CO_2 concentrations increase from 390 to 750 ppm). 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.

Under the B1 and A1FI emissions scenarios in 2030 and 2070, coral reefs are projected to be vulnerable to increasing SST, ocean acidification, and cyclone intensity, as well as ocean circulation and upwelling (Hoegh-Guldberg et al. 2011). The vulnerability of coral reefs to the projected changes in climate is summarised in Table 8.15.

Table 8.15 Vulnerability of coral reefs to projected changes in surface and ocean climate (adapted from Bell et al. 2011a).

	Sea surface temperature	Ocean chemistry	Cyclones and storms	Rainfall patterns	Sea level*	Ocean circulation
2030 B1/A1FI	High	High	Moderate	Moderate	Low	Moderate
2070 B1	Very high	Very high	High	High	Low – Moderate	Moderate
2070 A1FI	Very high	Very high	High	High	Low – Moderate	Moderate

* Range of vulnerability reflects the significant uncertainty regarding the rate of sea-level rise.

The range of potential impacts resulting from future climate change means that coral reef habitats are projected to change, with coral cover expected to decline under both 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). Recent modelling showed that at CO_2 levels above ~600 ppm there is a regime shift to alternate coral-algal states, leading to macroalgal dominance at the highest CO_2 level (Anthony et al. 2011). And a long-term study in the Indian Ocean detected declines in reef fishery catches consistent with lagged impacts of habitat disturbance (Pistorius and Taylor 2009). These examples demonstrate the dynamic nature of coral reefs, and how declining reef cover and diversity is likely to have significant implications for fisheries.

Coral reef fisheries are also likely to be affected by predicted reductions in population connectivity due to the effects of climate change on reproduction, larval dispersal and habitat fragmentation, potentially affecting catch rates and species availability as reef fish community composition changes (Munday et al. 2009).

8.3.4 Conclusions

In northern tropical Australia there is growing evidence of ecosystem and species vulnerability to climate change that has implications for fisheries. Responses to increasing sea surface temperatures (e.g. coral bleaching and mortality, Veron et al.2009), ocean acidification (e.g. reduced coral calcification, De'ath et al.2009; altered reef community structure, Fabricius et al. 2011) and indirect climate effects provide examples of how tropical habitats might change in the future.

Tropical marine and coastal habitats that are subject to local pressures are likely to be more vulnerable to increasing climate change impacts in the future (Veron et al. 2009, Waycott et al. 2009, Anthony et al. 2011, Bell et al. 2011b). Conservation of these habitats (e.g. coral reefs, mangroves and seagrass) has therefore been identified as important to protect important fish species, create natural barriers against sea-level rise and storms, and effective catchment management to minimise impacts from terrestrial runoff on coastal habitats that support coastal fisheries species (e.g. barramundi, prawns)(Holbrook and Johnson 2012, Bell et al. 2011b, Bell et al. 2013).

Table 8.16 Summary table of potential impacts of climate change on northern Australian fisheries habitats by 2030 under the A1B/A1FI emissions scenarios.

Habitat	Region/s	Key potential impacts of climate change	Source
Floodplains	NWA, GoC, EC	Increased temperatures may increase productivity and decomposition rates (+); Changes to rainfall patterns likely to result in more variability in river-floodplain connectivity (+/-); Sea-level rise and storm surge likely to increase salinity inundation and loss of freshwater floodplain habitat area (-)	Gehrke et al. 2011; BMT WBM 2010
Coastal bays and estuaries	NWA, GoC, EC	Increased SST may inhibit intertidal primary productivity (-); Changing rainfall patterns and storm inundation may result in inland area expansions (+); More intense storms and cyclones may alter habitat dynamics and connectivity (+/-)	Gehrke et al. 2011
Seagrass meadows	GoC, EC (small extent NWA)	Increased cyclone intensity and extreme riverflow events may cause extensive localised damage to seagrass beds (-); Reduced solar radiation combined with turbidity from river runoff and storm events is likely to reduce seagrass area available as shelter and food (-) and species diversity (-)	McKenzie et al. 2012; Waycott et al. 2011
Coral reefs	NWA, EC	Increasing SST and SST extremes will likely cause more coral bleaching events resulting in more algal-dominated reef areas (-); Ocean acidification will reduce coral growth and structural integrity and when combined with more intense storms, significant coral loss (-); Combined impacts will result in loss of reef diversity & structure (-)	Veron et al. 2009; Hoegh-Guldberg et al. 2011; van Hooidonk et al. 2012
Mangroves	NWA, GoC, EC	Sea-level rise will result in retreat of seaward fringing mangroves and possible area reductions particularly where there are barriers for mangrove landward migration (e.g. coastal development, sea walls) (+/-); Loss of coastal mangroves combined with more intense storms will result in reduced coastal protection (-)	Ellison et al. 2011; Lovelock et al. 2007

8.4 Sensitivity data analyses

8.4.1 Species and likely environmental driver scoping

For the species-specific data analyses the initial step was to determine the likely drivers of influence for key species. The specific results for each species examined are provided in Appendix 6, while the summary for all species examined is given in Table 8.17 below. The species examined were based on the prioritised lists developed for each region however were also limited to those species that researchers thought potentially had sufficient data for analyses. This process used the published knowledge collated during the individual species reviews, however was largely 'expert' based meaning that most of the results are inferred based on experts knowledge of the particular species and/or knowledge of other species with comparable life histories and habitat preferences. In fact, this process highlighted the complete lack of published knowledge on the sensitivity to climate variability and environmental variables of the vast majority of key fishery species in northern Australia (see Appendix 6).

Due the nature of the framework used, the species judged to be affected the most, and the environmental variables deemed to have the most influence, was largely a reflection of the focus of past research. Although this process is not very conservative (i.e. the sensitivity scores, e.g. SST vs. recruitment, tend to be lower when effects are unknown), it nevertheless provided a basis for further analysis where the certainty in a potential impact on a species is highest. The species chosen for analyses were based on this process including, along with the species reviews, the hypotheses to be tested for each respective species. Across the 19 species examined in this process, changes in SST were considered most likely to have an impact, while nutrients were also important.

Table 8.17 Summary table of the inferred effects of changes in key environmental variables on selected northern Australian fishery species. This was an initial screening process for determining the species for further data analyses and the possible hypotheses for testing. The likely effects of each variable on each species are described as high (H), Medium (M) and Low (L) based on scoring described in Section 6.8.

Common name	SST	rainfall	riverflow	salinity (surf.)	nutrients	upwelling	wind/ currents	pH	sea level
Grey mackerel	H	M	M	M	H	M	L	L	L
Tropical lobster	H	L	L	M	M	M	M	L	L
Coral trout	H	L	L	L	H	M	M	L	L
Spanish mackerel	H	M	M	L	M	M	M	L	L
Red throat emperor	H	L	L	L	H	M	L	L	L
Barramundi	H	H	H	H	H	H	L	L	M
Banana prawn	H	H	H	H	H	H	H	L	M
Scallops	M	L	L	L	L	L	M	L	L
Mud crab	H	H	H	H	M	H	M	L	M
Eastern king prawn	M	L	M	H	L	L	M	L	L
Tiger prawn	H	M	H	H	L	L	L	L	L
Goldband snapper	L	L	L	L	M	M	L	L	L
Red spot king prawn	M	L	L	L	M	M	L	L	L
Sandfish	M	L	L	H	H	L	L	M	L
King threadfin	M	M	M	L	M	L	L	L	L
Golden snapper	L	M	M	L	M	L	L	L	L
Black jew	L	M	M	L	M	L	L	L	L
Scalloped hammerhead	M	L	L	L	L	L	L	L	L
Blacktip sharks	M	L	L	L	L	L	L	L	L

8.4.2 Barramundi

8.4.2.1 Catch data analysis

Both commercial and FTO CPUE was significantly correlated to the number of days that river height was greater than 10m and water year rainfall (Table 8.18, Figure 8.9).

Table 8.18 Pearson correlation coefficient (r) and significance (p) values for annual CPUE for commercial and FTO sectors plotted against annual river height and rainfall environmental variables.

Sector	Environmental variable	r	p
Commercial	River height	0.55	<0.02
Commercial	Rainfall	0.46	<0.05
FTO	River height	0.67	<0.01
FTO	Rainfall	0.55	<0.02

The GLM for the commercial catch showed that fishing effort explained 21.7% of the variation in the catch. The catch adjusted for effort was significantly correlated with the river height and river height 1 variables (Table 8.19). This model explained an additional 27.5% to the base model (total of 49.2% explained). A similar analysis of the FTO catch showed that effort explained a significant proportion (75.6%) of the variation in the catch (r= 0.77, p<0.01). The catch adjusted for effort was significantly correlated with river height (Table 8.19). This model only explained an additional 11.7% to the base model (total of 87.3% explained) indicating that while this was a better model than for the commercial catch the environmental variables were less important in explaining variations in catch.

Table 8.19 Best all sub-sets regression for annual barramundi catch for commercial and FTO sectors and annual river height and rainfall environmental variables.

Sector	Regression model	Percentage variation accounted for (adjusted R^2)
Commercial	River height, River height 1	49.2
FTO	River height	87.3

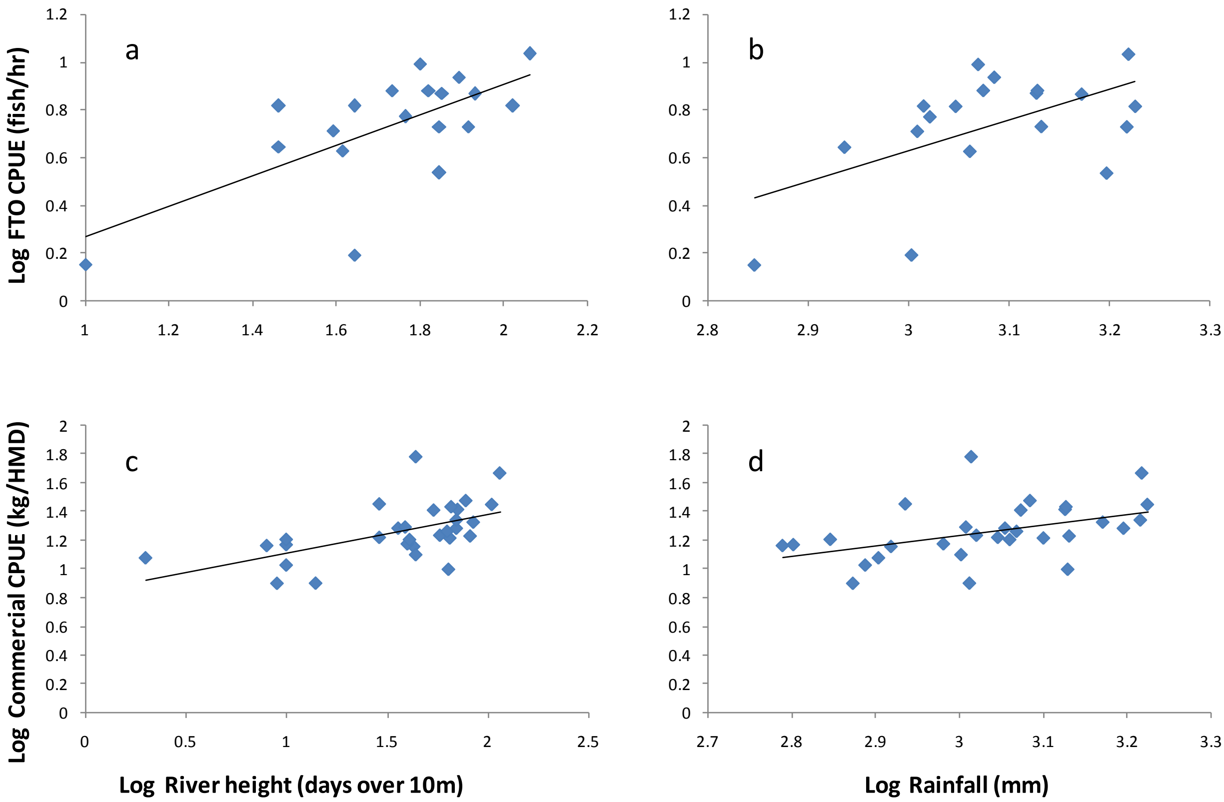

Figure 8.9 Plot of log CPUE against log river height for FTOs (a) and the commercial sector (b) and log rainfall for FTOs (c) and the commercial sector (d).

8.4.2.2 Year Class Strength analysis

Barramundi in the Daly River showed two separate cohorts with a systematic change in their age structure from three to six year olds between 2007 and 2010, and two to five year olds between 2008 and 2011 (Figure 8.10).

The average YCS showed positive residuals for year-classes 'born' in 2004 and 2006 indicating 'stronger' recruitment (Figure 8.11). However there were no large, negative residuals (i.e., <-0.5) indicative of 'weak' barramundi recruitment in the Daly River for the time series examined, and in fact all other years had relatively even residuals (i.e., between +0.8 and -0.4) and thus could not be classified as either 'strong' or 'weak' (Figure 8.11). While the data suggests that river height better explained variability in year class strength (Figure 8.11a) compared to rainfall (Figure 8.11b), neither environmental variable consistently matched the YCS for all years. Consequently, the GLM indicated that neither of these variables explained a significant proportion of variation in YCS ($r=0.19$, $p>0.05$).

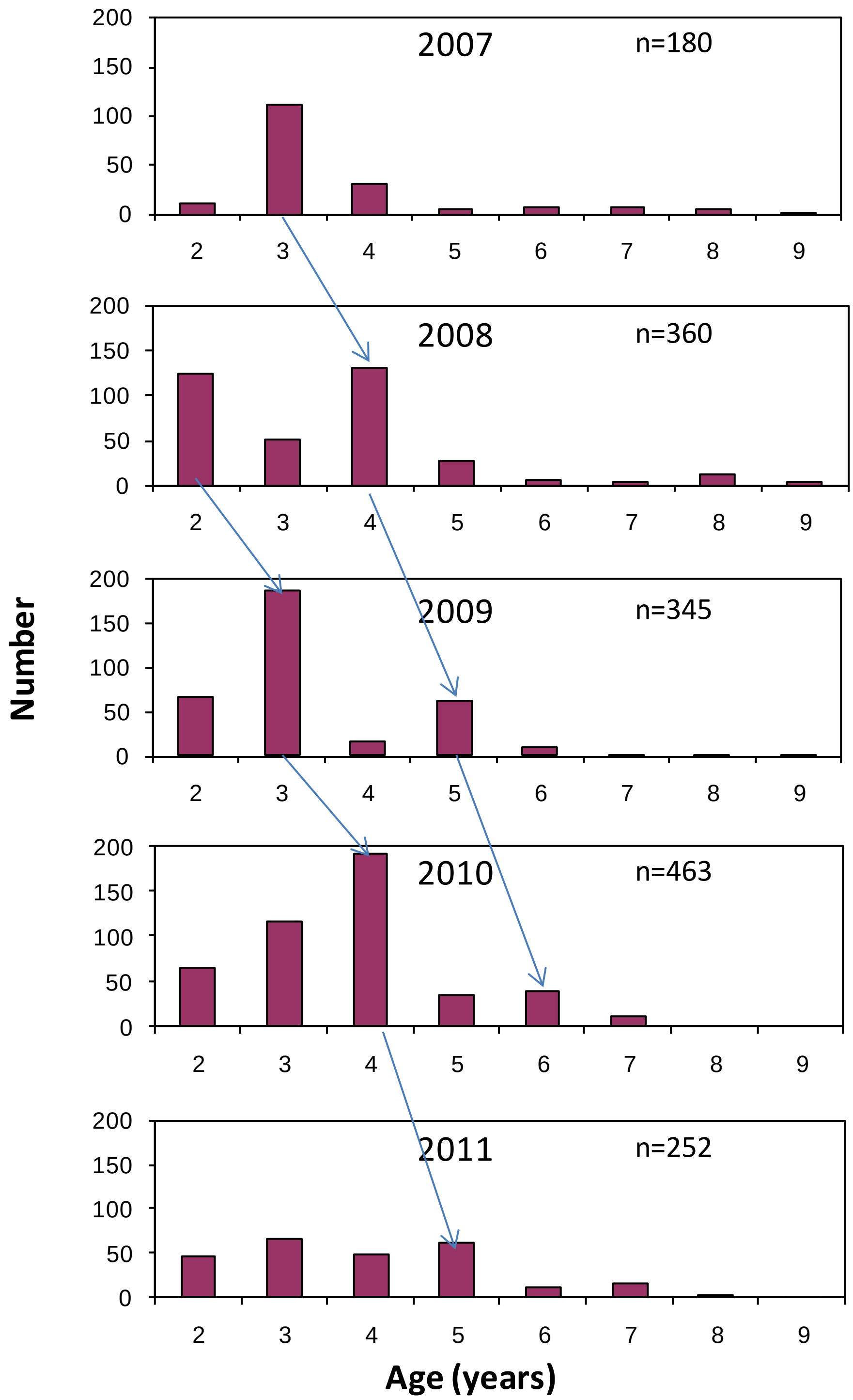

Figure 8.10 Annual age structures of barramundi in the Daly River.

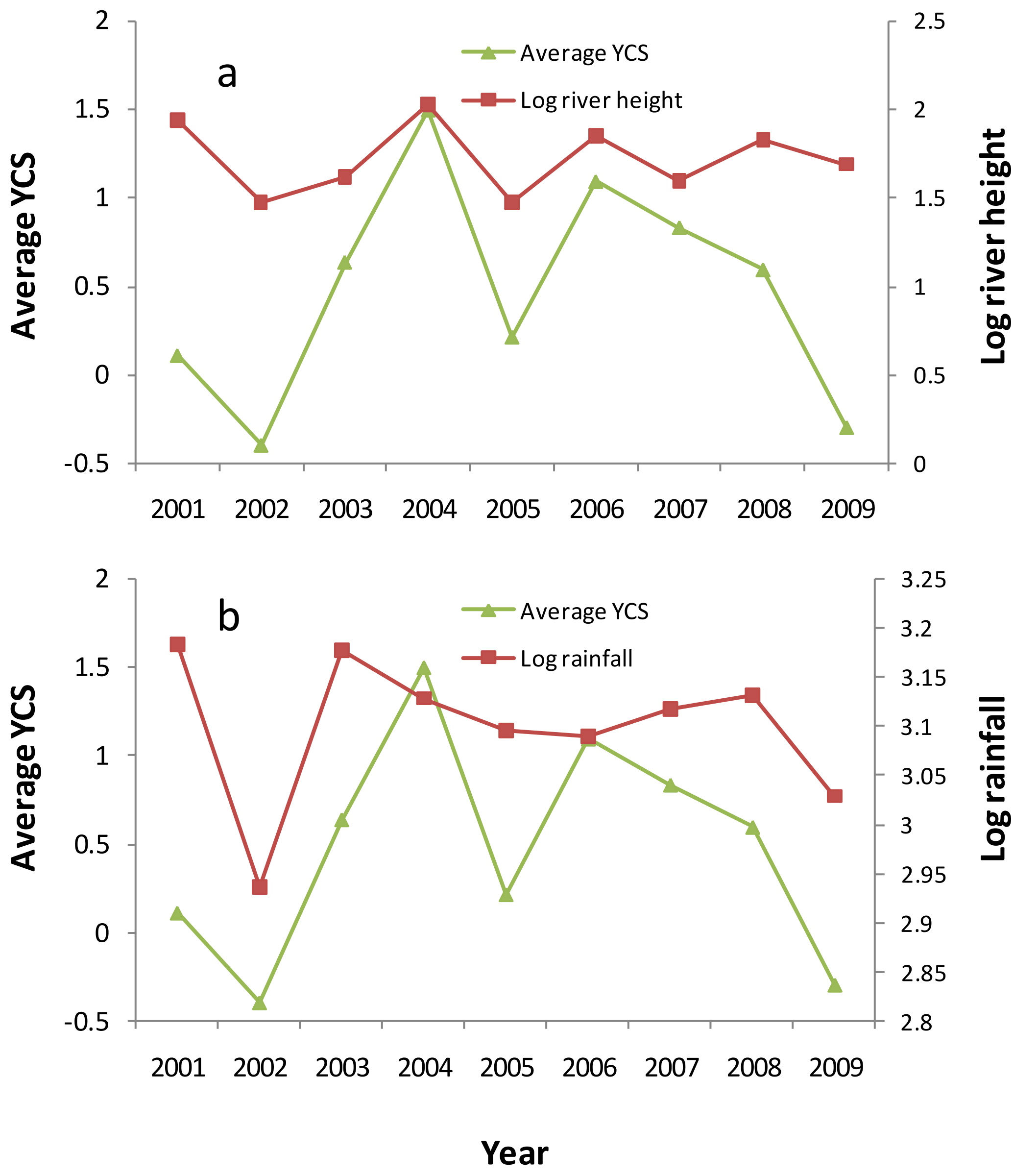

Figure 8.11 Average YCS plotted against (a) log river height and (b) log rainfall during 2001-2009.

8.4.2.3 Discussion

Variations in barramundi CPUE were significantly correlated to variations in both river height and rainfall on the Daly River and this was consistent for both the commercial and FTO sectors. However river height data had a better correlation and the GLM suggested that only river height significantly influenced variations in catch. The reason for this better explanation by river height is that it is more likely to be correlated to flood plain inundation compared to rainfall. The reasons for flood plain inundation increasing barramundi catch have been well documented in other studies (e.g. Robins et al. 2005; Meynecke et al. 2011, Halliday et al. 2012). Briefly, flood plain inundation promotes production of large volumes of prey items which barramundi aggregate to feed on at the mouth of the river and associated tributaries. These aggregations are easier to target by fishers, which in turn, results in higher catches. The one-year lag in river height that was included in the commercial catch data model suggests that the previous year's productivity on the flood plain has increased growth of barramundi allowing for the total tonnage to increase in the following year. If this was related to recruitment the lags would be at least two years prior to the current year as barramundi only become susceptible to commercial gillnets at between 2-3 years of age (NT Government 2012). It was also interesting that the data suggested that FTO catch had a much higher proportion of its variation explained by effort compared to the commercial catch. This result can probably be explained by the fact that FTOs tend to target 'good fishing' periods during the good wet season years to take clients out, whereas commercial fishers are more likely to fish most of the time during any given year as they rely on catch as income.

Variation in river height and rainfall variables showed some correlation between average YCS, however these relationships were not significant. Significant relationships between barramundi YCS and rainfall and river flow have been found in numerous catchments across northern Australia (Staunton-Smith et al. 2004; Halliday et al. 2011) including the Daly River (Halliday et al. 2012). The lack of a significant correlation between these variables in the current results is probably related to the fact there has been very little contrast in the YCS over the study period with most years having neither strong nor weak recruitment. Where there were significant positive recruitment years there were concurrent increases in the environmental variables suggesting that more years of data would reveal a significant relationship when there is better contrast in the model. Again, the reasons for rainfall and flow variables driving YCS are well explained in the references above. Briefly, increases in these variables are thought to increase recruitment by enhancing the access of larvae and post-larvae to suitable nursery habitats providing increased food availability through higher production of prey items.

Although the results in this particular study were not as equivocal as other recent similar studies regarding environmental influences on recruitment, the results found that higher river height correlated to higher fishery catches. This further adds to the compelling evidence across numerous studies, that barramundi populations and fisheries of northern Australian are significantly influenced by local hydrological characteristics of coastal systems.

8.4.3 Coral trout

8.4.3.1 Year class strength analysis

Age at recruitment to the sampling gear (standard commercial fishing gear) was clearly consistent among regions at age 4 (Figure 8.12) and population age structures are provided in Table 8.20. Close examination of the age frequency distributions by region suggests that *P. leopardus* in the Mackay region may experience higher rates of natural mortality than those populations within either Townsville to the north or Storm Cay to the south. The modal peak at age 4 is strongest for Mackay and the relative strength of progressively older age classes in Mackay decreases faster than either Townsville or Mackay. In addition, the age structure data also contains some evidence of strong year class dominating progressive age classes through consecutive sampling years. For example, in Townsville fish aged 3 dominated the sample in 1997, fish aged 4 dominated the sample in 1998, and fish aged 5 dominated the sample in 1999 (Table 8.20). Notably, no similar trend was observed in either Mackay or Storm Cay. Although weak evidence, these differences in age structure among regions may be reflective of YCS patterns that vary regionally. Thus regional treatment of age structure data was maintained for analysis of year class strength.

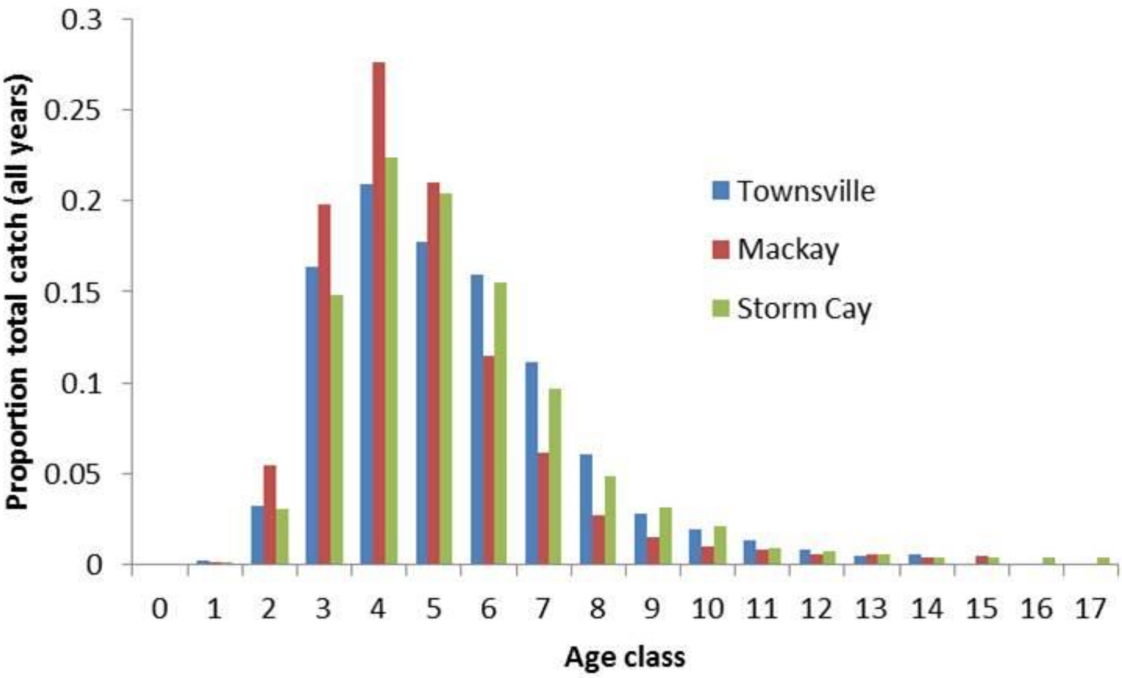

Figure 8.12 Regional age structure of *P. leopardus* demonstrates a consistent age of recruitment to the fishery among the three sampled regions. Age data is pooled across all years.

It was possible to reconstruct the relative year class strength of *P. leopardus* over a 17-year period 1985-2001 (Figure 8.13). Inter-year variability was significant for all regions (ANOVA; F= 3.15, df= 17206, p< 0.001) implying that recruitment was not constant over time. As YCS was found to be significantly variable through time for each region, analysis of the correlations that may be present between YCS and environmental factors was justified.

The linear mixed-effect models regressing single environmental variables against YCS were mostly statistically non-significant (*p*<0.01) (Table 8.21). In the most southern region of Storm Cay, no significant effect was present for any of the variables tested. Although annual and wet season flows were significantly correlated with YCS in both Townsville and Mackay regions, the effects were not consistent among the in-built lag factors. For example wet season flow from the Burdekin River was significantly correlated with YCS in the Townsville region lagged by one year. In the Mackay region there was a significant correlation between wet season flow from the Fitzroy River and YCS advanced one year. Similar inconsistencies were observed for SST and SOI with both environmental factors detected to be significant in only Townsville (with a 1 year lag) and Mackay (no lag) respectively.

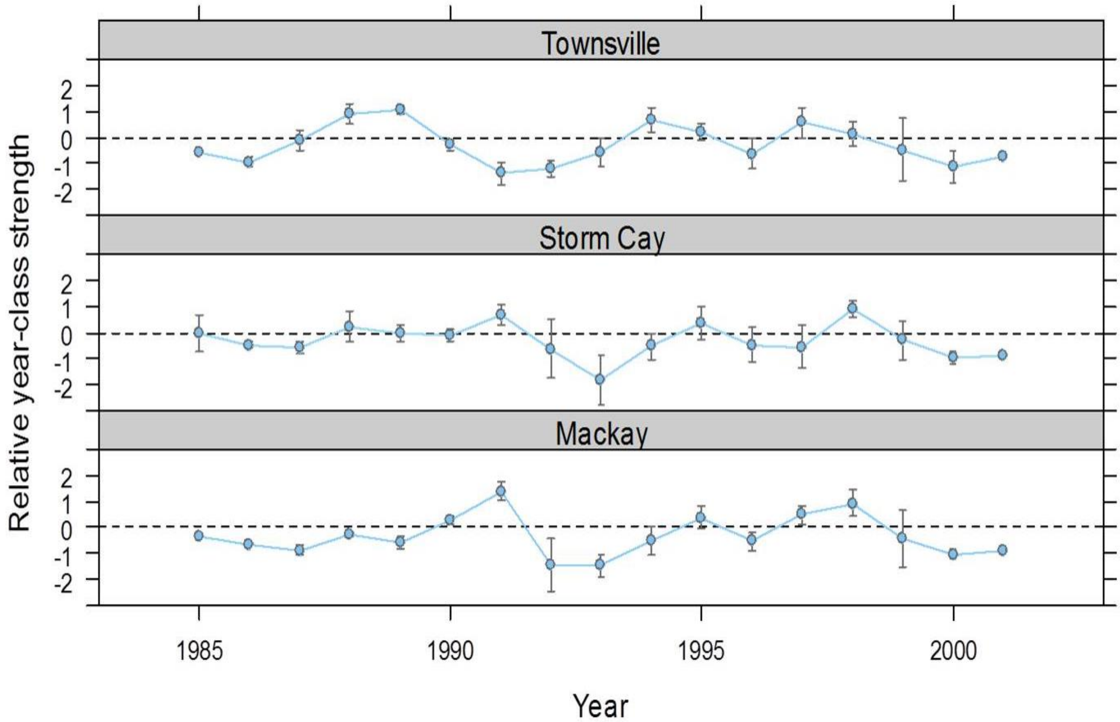

Figure 8.13 Relative year class strength of *P. leopardus* within each of the three sampled regions of the GBRMP.

Table 8.20Population age structures collected for each year for each region by the Effects of Line Fishing Project. Modal age classes for each year are in bold.

Region	Age	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
TOWNSVILLE	0	0	0	0	0	0	0	0	0	0	0	0
	1	1	0	0	1	1	0	0	1	0	0	1
	2	8	6	23	8	6	7	4	10	1	3	2
	3	25	33	**106**	83	46	26	21	21	5	15	20
	4	47	19	53	**137**	79	56	48	**43**	4	11	15
	5	39	34	27	50	**94**	**74**	42	33	7	20	13
	6	85	28	9	12	41	62	**60**	37	**9**	**23**	**21**
	7	**117**	**37**	10	4	9	12	23	23	6	15	12
	8	48	20	15	8	4	4	2	11	4	7	19
	9	13	5	10	7	1	1	1	4	3	13	3
	10	14	3	4	3	7	2	0	1	0	1	4
MACKAY	0	0	0	0	0	0	0	0	1	0	0	0
	1	1	1	1	0	1	0	0	0	1	0	1
	2	12	30	27	11	14	23	22	11	17	9	21
	3	42	56	**59**	**105**	70	62	116	**61**	28	28	**88**
	4	**229**	104	20	104	**101**	**98**	**137**	47	44	**42**	72
	5	116	**145**	34	38	54	93	110	43	**46**	36	43
	6	46	42	25	13	22	33	95	19	31	35	50
	7	30	20	10	22	18	8	23	17	16	17	35
	8	12	7	2	10	18	6	6	4	7	4	16
	9	7	2	3	4	6	6	5	1	2	4	6
	10	4	0	0	0	3	2	6	1	3	4	3
STORM CAY	0	0	0	0	0	0	0	0	0	0	0	0
	1	0	1	0	0	1	0	1	1	2	0	1
	2	4	27	12	11	13	7	19	13	5	4	9
	3	28	55	48	**91**	121	49	52	**57**	**34**	22	42
	4	**133**	100	36	73	**163**	**124**	89	56	33	30	**65**
	5	117	**138**	**80**	39	74	115	**128**	24	**34**	28	45
	6	83	77	55	63	26	67	105	18	30	**43**	55
	7	69	57	25	39	29	30	47	5	24	23	36
	8	22	22	11	12	26	14	21	6	16	16	25
	9	17	14	6	9	12	12	15	4	6	18	7
	10	16	8	5	6	5	5	10	1	1	10	11

Table 8.21 Results of mixed effect linear regression of environmental variables against recruitment for *P. leopardus* for each of the three sampled regions within the GBRMP. Offset refers to the lag (-1) or advance (+1) in regressing the time series of environmental variables against the time series of year class strength data. The +/- indicates whether the regression relationship is either a positive or negative one.

TOWNSVILLE	Offset	+ / -	F	df	p
SST annual	0	-	0.00	1,60	0.966
	-1	-	0.01	1,57	0.918
	+1	+	4.28	1,61	0.043
SST Sep-Nov (spawning season)	0	+	0.24	1,60	0.626
	-1	+	0.55	1,57	0.547
	+1	+	1.85	1,61	0.179
SOI annual	0	+	0.84	1,60	0.363
	-1	-	0.03	1,57	0.862
	+1	***+***	***10.79***	***1,61***	***0.002***
Burdekin flow annual	0	-	3.13	1,60	0.082
	-1	***-***	***8.10***	***1,57***	***0.006***
	+1	+	0.44	1,61	0.512
Burdekin flow (wet season)	0	+	0.05	1,60	0.833
	-1	-	3.95	1,57	0.052
	+1	***+***	***8.84***	***1,61***	***0.004***

MACKAY	Offset	+ / -	F	df	p
SST annual	0	+	1.31	1,62	0.257
	-1	-	0.23	1,61	0.636
	+1	+	5.03	1,63	0.028
SST Oct-Dec (spawning season)	***0***	***+***	***8.36***	***1,62***	***0.005***
	-1	-	0.11	1,61	0.737
	+1	-	0.01	1,63	0.905
SOI annual	0	-	0.00	1,62	0.950
	-1	+	0.57	1,61	0.454
	+1	+	1.13	1,63	0.293
Fitzroy flow annual	***0***	***+***	***17.13***	***1,62***	***0.001***
	-1	-	1.50	1,61	0.226
	+1	+	0.66	1,63	0.418
Fitzroy flow (wet season)	0	+	0.53	1,62	0.469
	-1	***+***	***13.28***	***1,61***	***0.001***
	+1	-	0.63	1,63	0.430

STORM CAY	Offset	+ / -	F	df	p
SST annual	0	+	2.08	1,62	0.041
	-1	-	0.58	1,61	0.447
	+1	+	0.55	1,63	0.461
SST Oct-Dec (spawning season)	0	+	5.24	1,62	0.025
	-1	+	0.33	1,61	0.565
	+1	-	0.56	1,63	0.457
Fitzroy flow (wet season)	0	+	1.10	1,62	0.298
	-1	+	0.00	1,61	0.992
	+1	+	2.39	1,63	0.127
SOI annual	0	+	4.93	1,62	0.030
	-1	+	0.05	1,61	0.819
	+1	+	0.12	1,63	0.731
Fitzroy flow annual	0	+	0.14	1,62	0.771
	-1	+	3.17	1,61	0.080
	+1	+	0.16	1,63	0.694

8.4.3.2 Discussion

The significant correlations found between YCS and environmental variables were inconsistent among areas, variables and lags in variables. Consequently, no individual variable could be confidently attributed to driving variations in YCS. A number of explanations are possible though insufficient data may be the most plausible. This statement is based upon the acknowledged presence of recruitment spikes (strong year classes) in regional populations of *P. leopardus* within the GBRMP (Ayling et al., 1992; Russ et al., 1996; Doherty et al 1996; Welch 1996). It is possible that data sets that encompass a much longer time series of both age structure and environmental variables than were available for this study are needed to explore the full influence of environmental variables on YCS and hence fisheries productivity.

P. leopardus also live in a relatively stable environment compared to more nearshore habitats (in terms of large annual variation in environmental variables). Compared with shallow coastal and estuarine waters, the water that surrounds and influences fish that live on emergent coral reefs is contrastingly stable. Further, the variation in recruitment that has been observed and described for *P. leopardus* in historical studies (Ayling et al., 1992; Russ et al., 1996; Doherty et al 1996; Welch 1996) may be driven by fine scale changes that are difficult to pin-point in relatively short data time series, or in data that are averaged across too coarse time and/or space units.

While *P. leopardus* inhabit a relatively stable environment they are exposed to cyclones, which have been demonstrated to have a significant influence on their catchability (Tobin et al. 2010). This research described significant reductions in fishery CPUE and landed catch across broad areas of the GBRMP following the passage of severe Tropical Cyclones Justin (March 1997) and Hamish (March 2009). In both events, cool water anomalies were experienced across the fishing grounds and may have been affecting catchability as well as productivity through negative disruptions on growth or mortality of juveniles spawned in the years immediately prior to TC impact. However, in this study the time series of data was too short to attempt an evaluation of infrequent events such as Tropical Cyclones on YCS. However, the impact of cyclones may be masking the effect of the other environmental variables examined due to their significant influence on *P. leopardus* catchability and productivity.

8.4.4 Golden snapper

8.4.4.1 Tagging data analyses

From 1985-2013 there were a total of 31,581 tag days and 105,826 fish tagged in estuary and nearshore habitats of the study area (zones 1-8). While the total number of fish tagged has increased since 2004, the effort expended to do this has been fairly consistent through the time series (Figure 8.14).

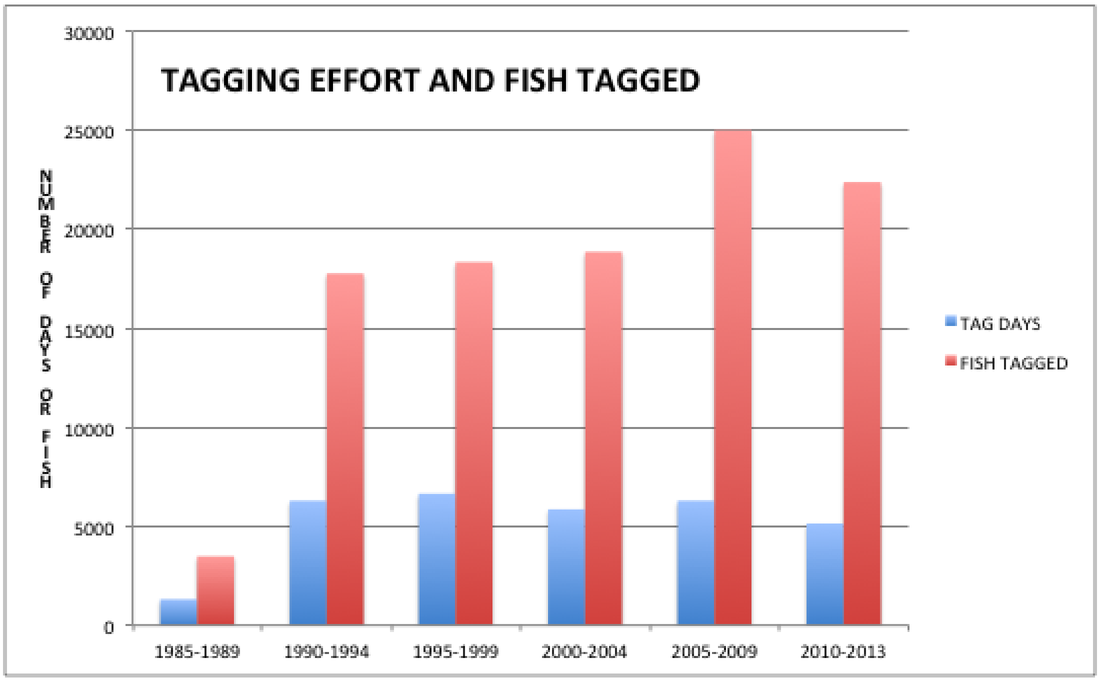

Figure 8.14 Total tag days and fish tagged each 5 years from 1985-2013 from 22°-26° S.

The number of golden snapper tagged as a percentage of the total fish tagged and tagging effort has steadily increased over time (Figure 8.15 & 8.16 respectively). No golden snapper were tagged in zones 3 or 4 until 1990 and none in zones 5 or 6 until 2000. No golden snapper were tagged in zones 7 or 8 over the entire period from 1985-2013. There was an increase in the percentage of golden snapper tagged in zones 1, 2 and 4 (Figure 8.15).

Golden snapper tend to be found in the lower parts of estuaries making the total fish tagged and tagging effort an overestimate of total tagging. However as some golden snapper have been tagged in most parts of the estuaries it was considered that all estuary tagging needed to be taken into account. A number of factors could have contributed to the changes observed. Targeting of golden snapper, and other species, with soft plastic lures has increased, particularly since 2010. However, the trend in increased percentage of golden snapper tagged, was apparent prior to that time. The result could also be a reflection of increased targeting of golden snapper. As golden snapper became more prevalent in the catch this likely resulted in increased targeting. Increased catch was also likely to have increased skills in catching golden snapper and GPS and new sounder technology have made finding the fish easier, particularly in turbid nearshore habitats.

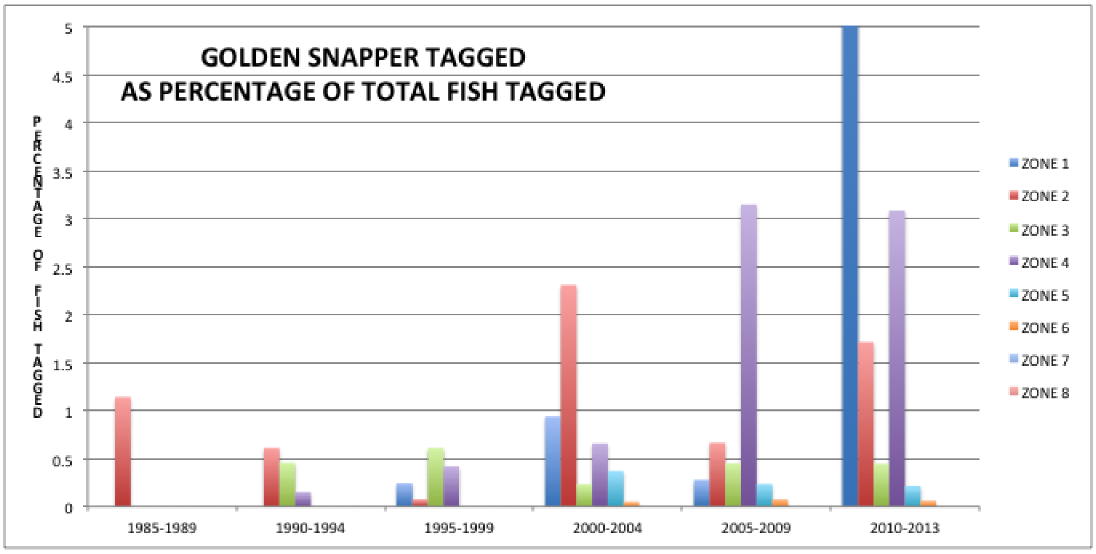

Figure 8.15 Percentage of golden snapper tagged in each zone from 1985-2013

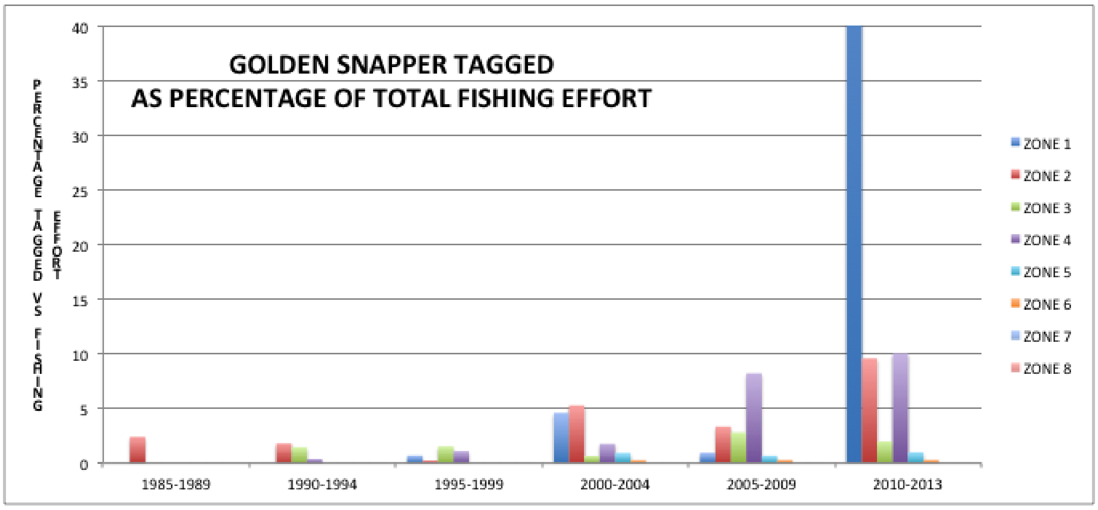

Figure 8.16 Percentage of golden snapper tagged compared with fishing effort in each zone from 1985-2013

From 2000-2012 there were a total of 27 trips to Shoalwater Bay with 10,947 hours of fishing effort and 14,083 fish caught. A total of 1,168 golden snapper were caught on these trips, which was 8.3% of the total fish caught. The area where fish were caught in Shoalwater Bay is in both zones 1 and 2. Figure 8.17 shows the percentage of golden snapper in the catch for each trip and the CPUE through the time series of Shoalwater Bay trips. These data show an increase in the number of golden snapper in the catch, similar to that in the percentage of fish tagged in zones 1 and 2 from normal tagging trips.

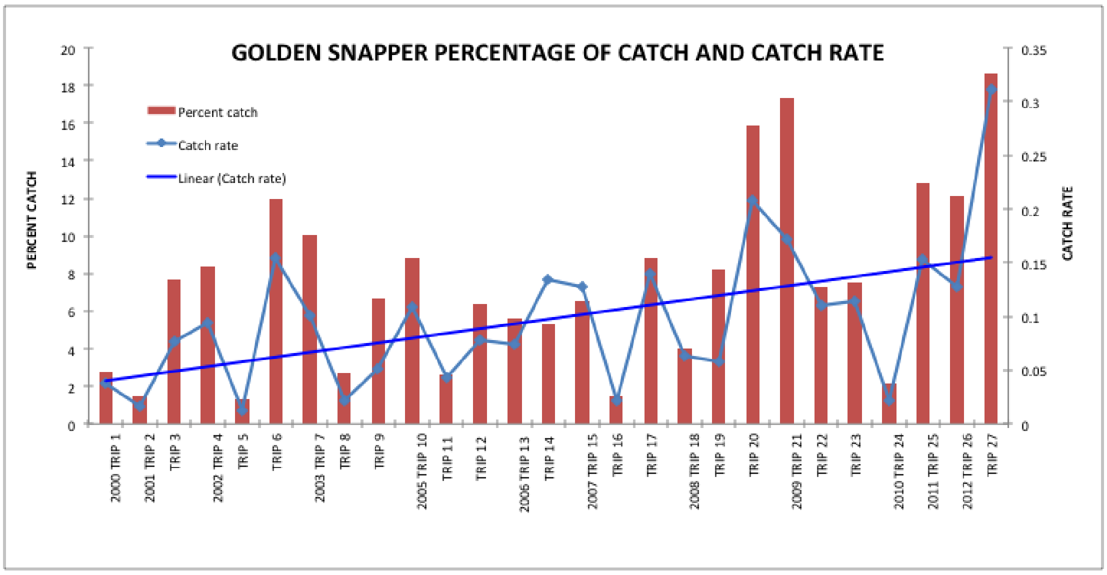

Figure 8.17 Percentage of golden snapper caught and CPUE on Shoalwater Bay trips from 2000-2012.

Of the 766 golden snapper tagged from 1985-2013 there have been 39 recaptures (5.1%), excluding fish from Shoalwater Bay trips. Of these, 35 fish were caught in the same area as tagged or within 10km in the same system. Four fish moved over 20km and were caught outside the system they were tagged in; two fish moved north and 2 fish moved south. A further fish that was presumed tagged back in 1998 (tag data missing) and recaptured over 16 years later in 2013, was also considered to have moved north (Figure 8.18). Of the recaptures, 2 fish were recaptured within approximately 6 months so that the time of movement could be attributed to the Spring/Summer season.

Figure 8.19 shows where Golden Snapper were tagged and recaptured from 1985-2013. The data can be viewed interactively at www.info-fish.net/suntag showing the number of fish tagged in each Suntag grid square over time.

There is anecdotal evidence of golden snapper aggregating in the Port Clinton area in zone 2 during periods when they are known to spawn. There have not been any reports from other areas that suggest spawning sites or aggregations although it is possible that other sites exist.

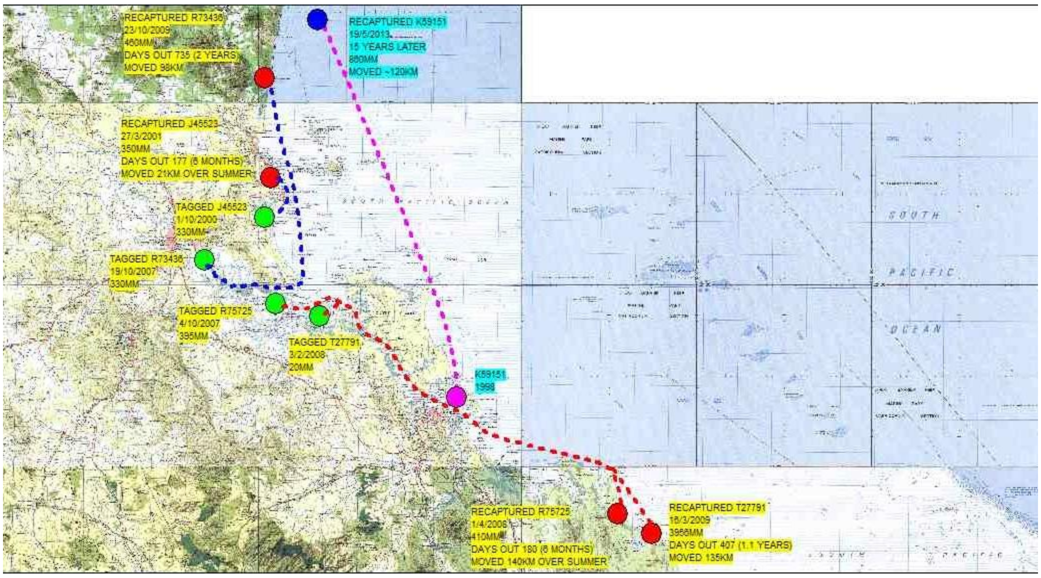

Figure 8.18 Movement of golden snapper tagged in Central Queensland that moved >10 km from the location they were tagged.

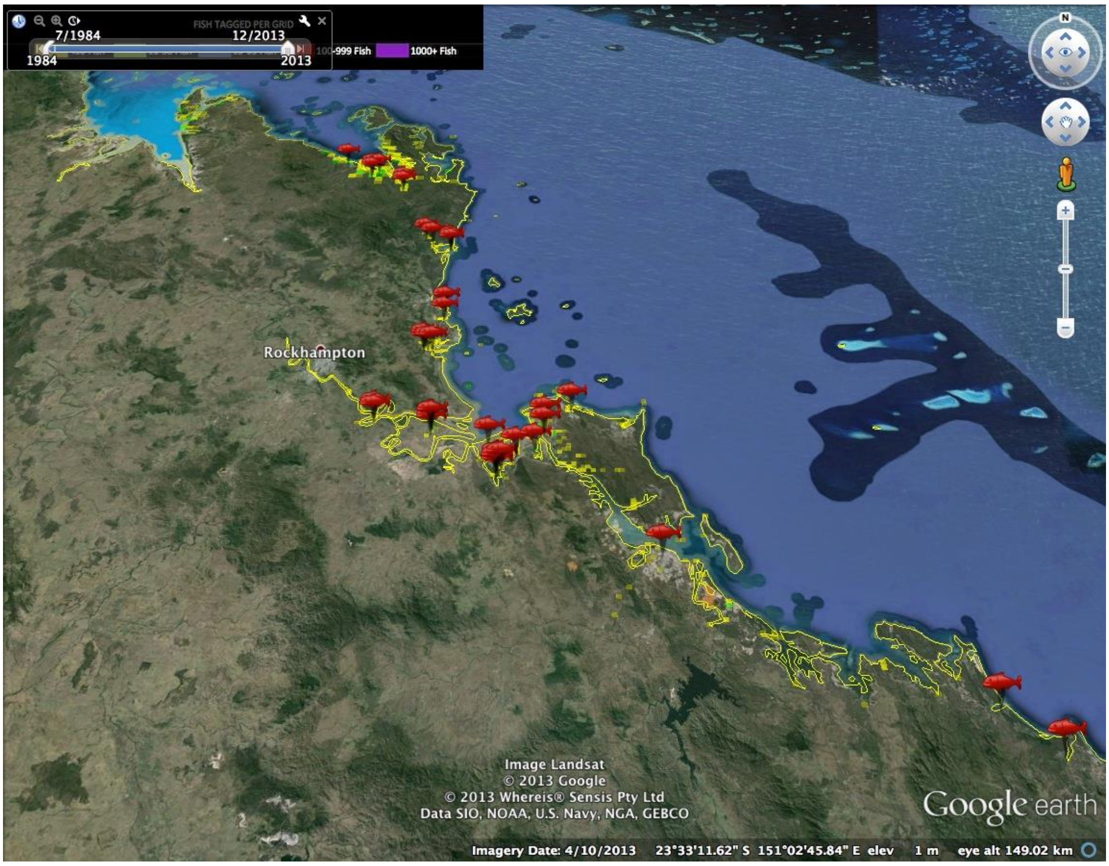

Figure 8.19 Google earth map showing where Golden Snapper were tagged and recaptured from 1985-2013.

Mean SST from 1985-2009 for nearshore areas ranged from 27.6°C at latitude 21.5° S to 25.7°C at latitude 25.5° S in summer, and from 20.9°C at latitude 21.5° S to 21.7°C at latitude 25.5° S in winter. The SST at 25.5° S was the highest winter mean and may be an anomaly due to the inherent difficulties in obtaining accurate satellite-derived SST readings in nearshore areas due to the interference of landmasses (Figure 8.20). There was little or no change in SST at each latitude band over that time (Figure 8.20). However, there was a slight rise in SST of around 0.3°C at latitudes 22.0° S and 23.5° S, but no change was noted at 25.5° S.

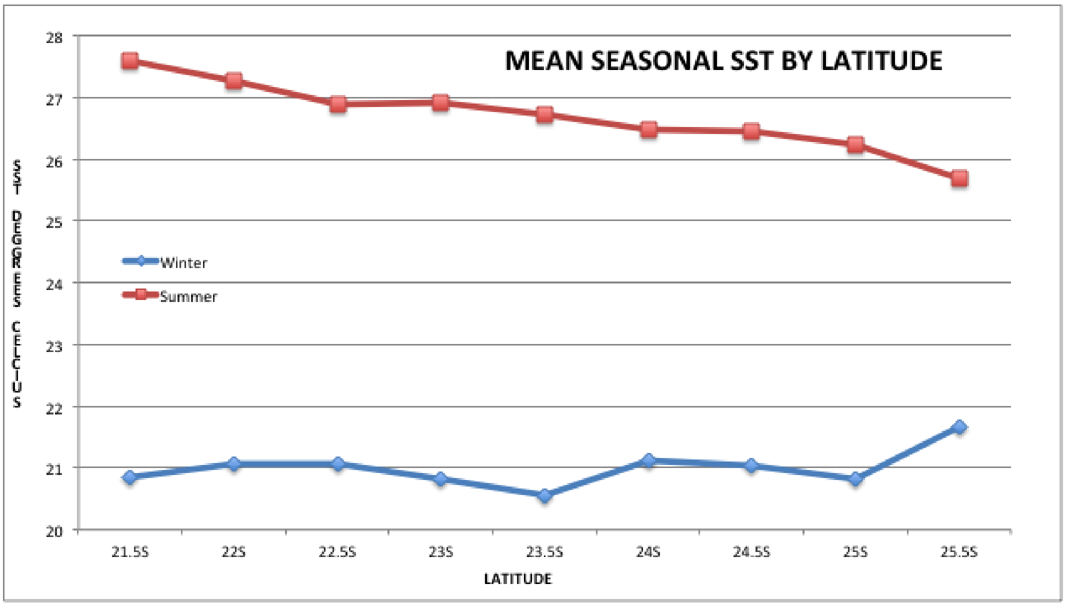

Figure 8.20 Mean summer and winter SST at each latitude from 1985-2009.

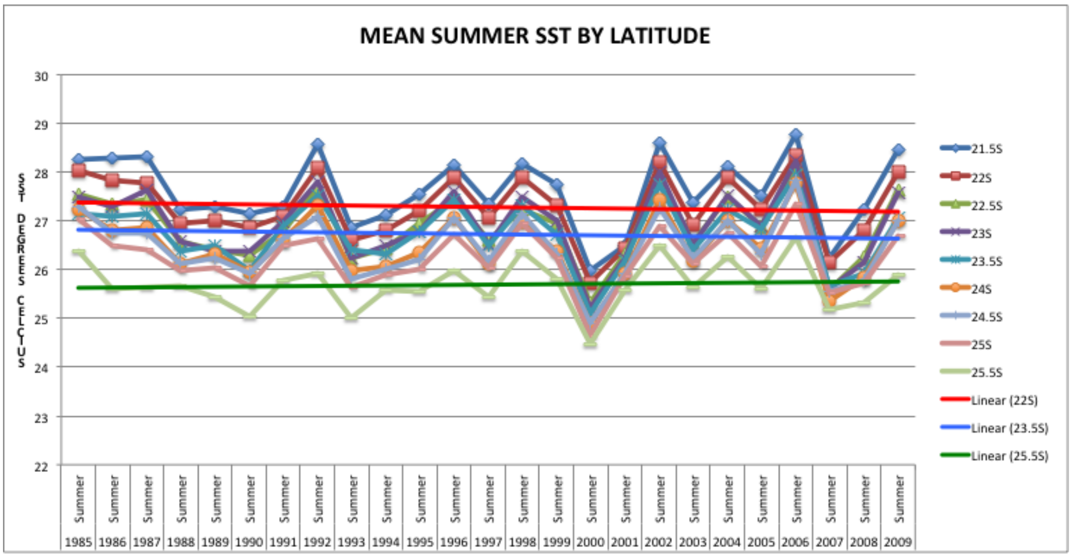

Figure 8.21 Mean summer SST from 21.5°S to 25.5°S from 1985-2009

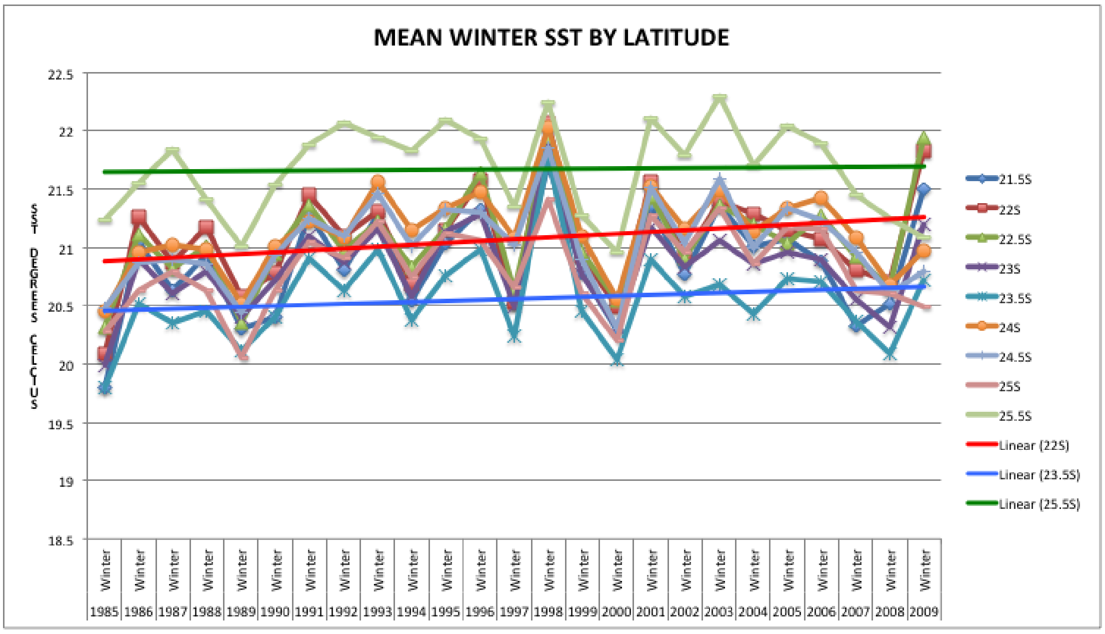

Figure 8.22 Mean winter SST from 21.5°S to 25.5°S from 1985-2009

8.4.4.2 Discussion

There are no references available for the temperature tolerance range for golden snapper. Therefore it makes it difficult to assess the impact of temperature change on the range of golden snapper. Another possibility is that a reduction in the habitat preferred by golden snapper south of Agnes Water may be a more significant barrier. While there are sufficient suitable estuaries south of Agnes Water the nearshore areas lack rocky headlands and reef that are a preferred habitat of adults. This may limit the ability of golden snapper to increase use of these areas.

There may also be some confusion with identification with Moses Snapper (*Lutjanus russelli*) as both these species are often referred to as Fingermark. This is more likely to occur in the southern zones where there are fewer recordings of golden snapper.

Based on the tagging data presented here, there is evidence that there has been an increase in the numbers of golden snapper that have been caught throughout the time series. This is supported by the separate data collected in the past 12 years of tagging effort in Shoalwater Bay. The exceptions are the two southernmost zones (zones 7 & 8) where there are no records of golden snapper being tagged throughout the time series, and in zone 3 where catches have been stable. Zone 3 represents the area immediately adjacent to the mouth of the Fitzroy River and north to Yeppoon. This area has very high accessibility and is an area where fishing effort has traditionally been high. It is therefore possible that the stable rate of capture of golden snapper in this area, compared with increases in most other areas, is due to prolonged and sustained fishing effort over time. The preferred habitat of golden snapper during the juvenile phase is estuarine and in more nearshore areas as they grow and mature, but with a preference for turbid waters near headlands and rocky reef structure and with associated sandy areas where they tend to move across and feed. This nearshore turbid habitat tends to change from around the junction of zones 5 & 6 to be clearer water more influenced by oceanic waters, and indeed very few golden snapper were caught in zone 6 during the entire time series and none in zones further south.

It is not possible from the data and these analyses to attribute increased golden snapper captures through time to increasing SST. Based on mean winter SST data there is evidence of slight increases in water temperature over time, which is consistent with broader-scale longer time series trajectories, however there are several other factors that could explain the increased incidence of golden snapper captures. Firstly, targeting of golden snapper is anecdotally known to have increased during this time period. This has led to an increase in the level of skills in catching golden snapper, and there have also been technological advances in GPS and sounders making targeting the fish easier, particularly in turbid nearshore habitats. Indeed, the tagging data since 1990 indicate a general increase in the number of all fish tagged despite tagging effort being relatively stable.

Although there is no clear evidence of a southerly shift in the range of golden snapper, there is an increased rate of capture over time in most of the zones. The recapture data also show fairly clearly that golden snapper do not tend to move very far preferring to be localised in their movements. Even though the data analysed represents a 29-year data set, it is likely that any range shift will take longer to manifest. There is therefore likely to be value in continuing the time series of tagging golden snapper, and other species. If golden snapper do in future years begin to appear in zones 7 and 8, and further south, then this may indeed represent evidence of a range shift, especially given the significant change in habitat types through this area.

8.4.5 Red throat emperor

A close examination of the age frequency distributions by region demonstrated that age at recruitment to the sampling gear differed between the regions (Figure 8.23). Furthermore, the apparent age at recruitment to the sampling gear was not consistent between years, although this is likely to be influenced by low sample sizes in many of the years sampled (Table 8.22). Differences in growth rate do not account for the temporal and regional variation in the age structures or apparent age at recruitment (Williams et al. 2007). Thus, there is evidence to suggest that young red throat emperor recruit to different locations at different ages and that the age at which they arrive at these locations is inconsistent between years. Furthermore, older age classes are not present at Mackay, suggesting either emigration from that location or, as hypothesised by Williams et al. (2007), different rates of mortality exist between regions. These factors indicate that regional treatment of the data to develop year class strength estimates is inappropriate and this should be done using pooled data across all locations. Pooling data across all regions indicated the appropriate age at recruitment to the sampling gear (standard commercial fishing gear) to be at age 6 (Figure 8.24).

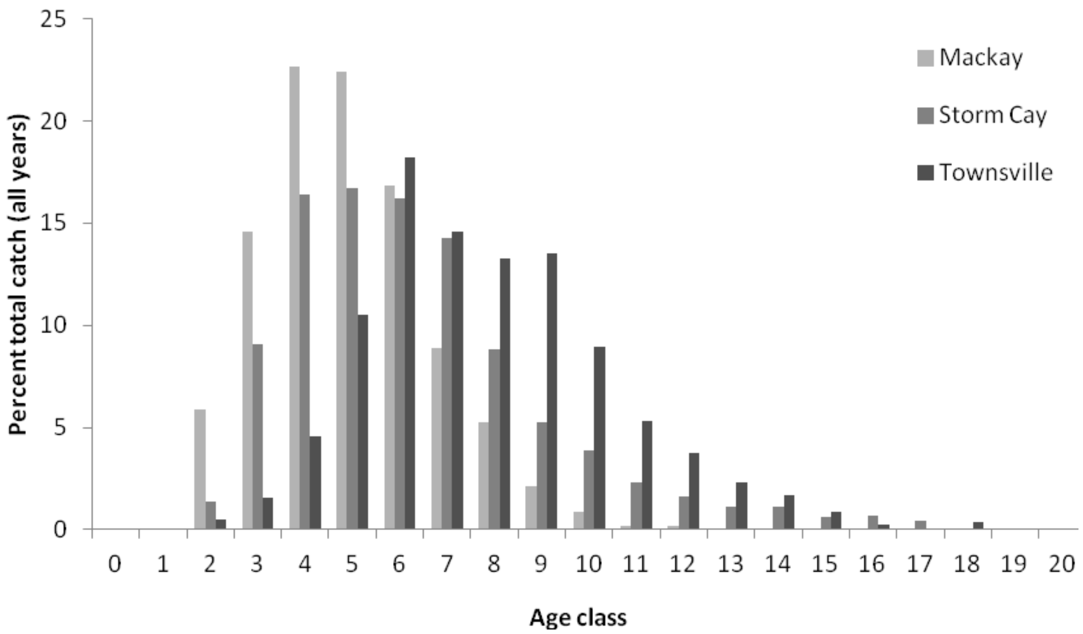

Figure 8.23 Regional age structure of *L. miniatus* pooled across all years.

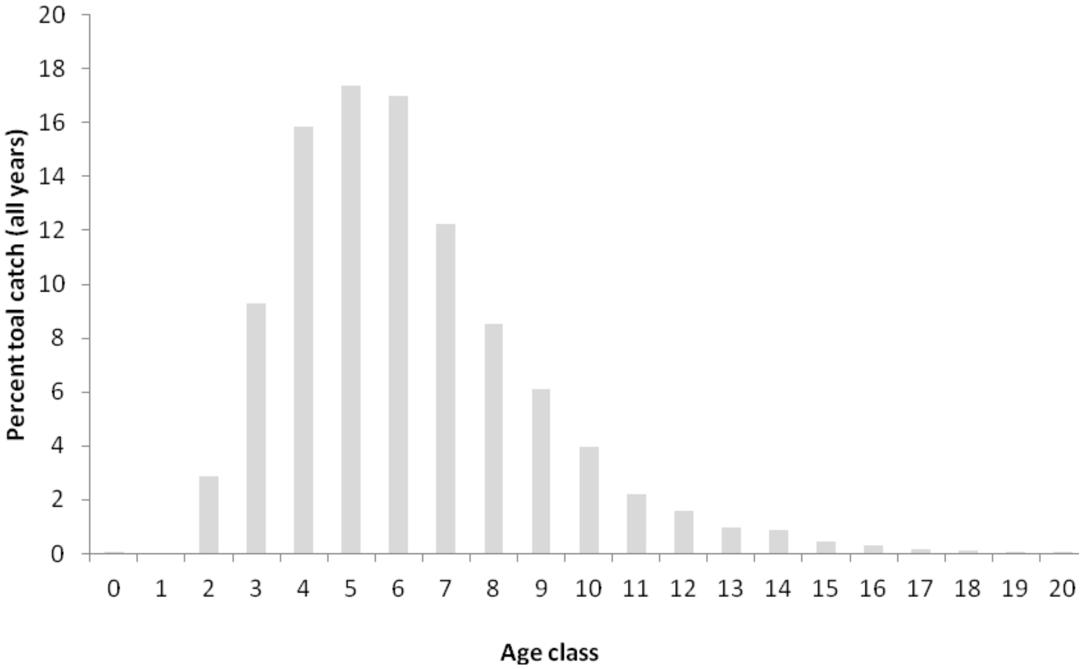

Figure 8.24 Age structure of *L. miniatus* pooled across all regions and all years.

The relative year class strength of red throat emperor over the 11-year period 1995-2005 had the 2003 sampling year excluded from the analyses as it produced a highly aberrant outlier due to the significant underrepresentation of the 1997 cohort. Inter-year variability was significant (ANOVA: F = 3.15, *d.f.* =17,206, $p < 0.001$) implying that recruitment was not constant over time (Figure 8.25). However, it is important to note that while this was significant, it was not a large inter-annual variation in year class strength with the highest and lowest values being approximately +1 and -1.

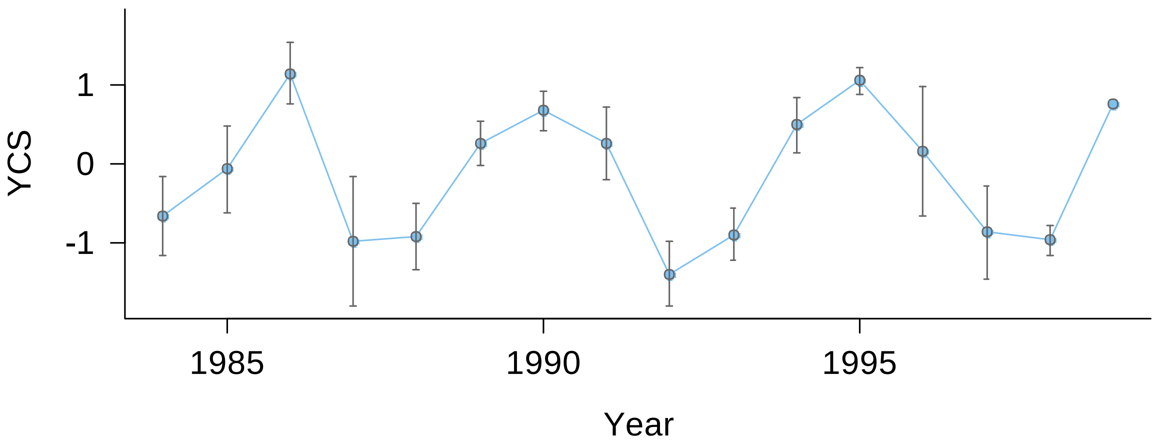

Figure 8.25 Relative year class strength of red throat emperor on the Queensland east coast.

Table 8.22 Population age structure of *L. miniatus* from eastern Australia, 1995-2005, showing numbers of fish sampled per age class.

Region	Age	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Mackay	0	0	0	0	0	0	0	0	0	1	0	0
	2	5	3	9	2	19	25	4	2	3	1	2
	3	11	13	23	18	35	26	20	14	10	6	10
	4	36	8	19	30	66	42	29	15	9	20	15
	5	48	18	6	24	46	28	19	26	3	26	42
	6	39	25	6	4	19	22	22	11	5	14	48
	7	13	25	9	6	4	7	13	11	3	10	12
	8	13	11	2	7	6	5	3	9	2	2	7
	9	6	1	0	3	4	4	0	3	1	1	4
	10	5	2	1	0	0	0	2	0	0	0	1
	11	1	0	0	0	0	0	0	1	0	0	0
	12	0	1	0	0	0	0	0	1	0	0	0
Storm Cay	0	0	0	0	0	0	0	0	0	0	0	0
	2	3	0	1	0	2	5	1	4	0	0	0
	3	12	4	17	16	15	21	4	12	2	1	3
	4	18	4	4	35	63	28	20	5	0	6	11
	5	15	10	11	17	54	38	14	9	1	13	16
	6	39	12	16	8	14	27	22	9	0	11	34
	7	26	17	18	21	15	14	17	12	0	11	18
	8	8	11	9	11	13	17	4	11	0	11	9
	9	14	1	3	7	5	11	2	5	0	5	9
	10	3	7	1	3	5	12	4	1	0	4	6
	11	0	1	1	4	3	4	5	3	0	4	2
	12	0	2	0	6	1	5	2	1	0	0	2
Townsville	0	0	0	0	0	0	0	0	0	0	0	0
	2	1	0	1	0	0	0	0	0	2	0	0
	3	0	0	3	4	0	0	0	1	5	0	0
	4	3	0	7	6	6	3	1	1	1	7	3
	5	23	5	23	4	4	2	0	2	4	6	14
	6	47	12	22	20	10	8	3	1	2	15	11
	7	30	5	16	19	9	7	2	4	9	10	10
	8	27	4	14	18	15	4	1	4	6	13	4
	9	32	3	8	17	12	8	4	1	0	15	12
	10	16	10	10	4	7	6	0	1	4	8	8
	11	5	7	6	8	4	4	1	1	1	4	3
	12	3	2	3	9	2	1	4	2	1	3	1

None of the linear mixed-effect models regressing single environmental variables against year class strength were statistically significant ($p<0.01$) (Table 8.23). While there were no significant correlation found between YCS and the environmental variables measured, the interpretation and analyses were stymied to a large extent as pooling of the age data across a broad geographic range was required. It appears likely that the population of red throat emperor are highly mobile, recruit to different regions/locations at different ages and that these patterns are not consistent between years. Indeed the dramatic low representation of the 1997 year class in the 2003 sampling may not simply be an outlier but an example of part of the population moving out of the sampling area. It is noteworthy in every year some significant recruitment was evident in that there were no missing or extremely low abundance year classes indicating that suitable conditions for recruitment occurred in every year from 1984 to 1999, a period which encompassed a wide range of different environmental conditions.

Table 8.23 Results of mixed effect linear regression of environmental variables against recruitment for *L. miniatus* for each of the three sampled regions within the GBRMP. Offset refers to the lag (-1) or advance (+1) in regressing the time series of environmental variables against the time series of year class strength data. The +/- indicates whether the regression relationship is either a positive or negative one.

Variable	Offset	+/-	*F*	*d.f.*	*p*
SST annual	0	-	0.3187755	1,53	0.5747
	-1	+	4.450333	1,49	0.04
	+1	-	1.8097152	1,56	0.184
SST Spring	0	+	0.7842664	1,53	0.3798
	-1	+	3.273444	1,49	0.0765
	+1	-	0.0939525	1,56	0.7603
SST Spring/Summer	0	+	2.9534492	1,53	0.0915
	-1	+	3.418752	1,49	0.0705
	+1	+	0.1264813	1,56	0.7234
SOI annual	0	+	2.0218331	1,53	0.1609
	-1	+	4.729922	1,49	0.0345
	+1	-	1.0735989	1,56	0.3046
Burdekin flow annual	0	+	1.8064968	1,53	0.1847
	-1	-	3.52253	1,49	0.0665
	+1	+	2.615399	1,56	0.1115
Burdekin flow Wet Season	0	+	2.547322	1,53	0.1164
	-1	+	2.01529	1,49	0.1621
	+1	+	0.3446817	1,56	0.5595

8.4.6 Saucer scallops

8.4.6.1 Characteristics of environmental data

SST fluctuated with season, although there were between year differences in the median SST per grid for any given month (Figure 8.26). Between 1986 and 2001, the greatest anomalies in SST (i.e., difference from overall median for any given month) were +2.03°C (Grid R29, January 1987) and -2.22°C (CFISH Grid R28, December 1999).

Chlorophyll *a* (Chl *a*) fluctuated seasonally, with lowest values occurring most frequently in August and September (Figure 8.27). Highest values of Chl *a* were variable between years in their timing (February through to May) as well as their values (Figure 8.27).

Discharge varied between catchments, but over the study period (1986 to 2012), all of the major rivers adjacent to the Capricorn region experienced large floods as well as periods of extended low flow (Figure 8.28). Of particular note, were the extreme (1-in-100 year) floods in January 2011 that occurred in all rivers of interest. The region has generally low river discharge coincidental to the scallop spawning season (i.e., May to October), with the greatest discharge generally occurring between January and April.

Binary classification of the presence or absence of a cyclonic eddy in the Capricorn region from satellite data provided a simple (although not validated) measure of eddy activity. This data showed considerable variation between years in the eddy activity (i.e., total count) as well as indicated variable timing of eddy presence in relation to the spawning season i.e., early – May to July; or late – August to October (Figure 8.29).

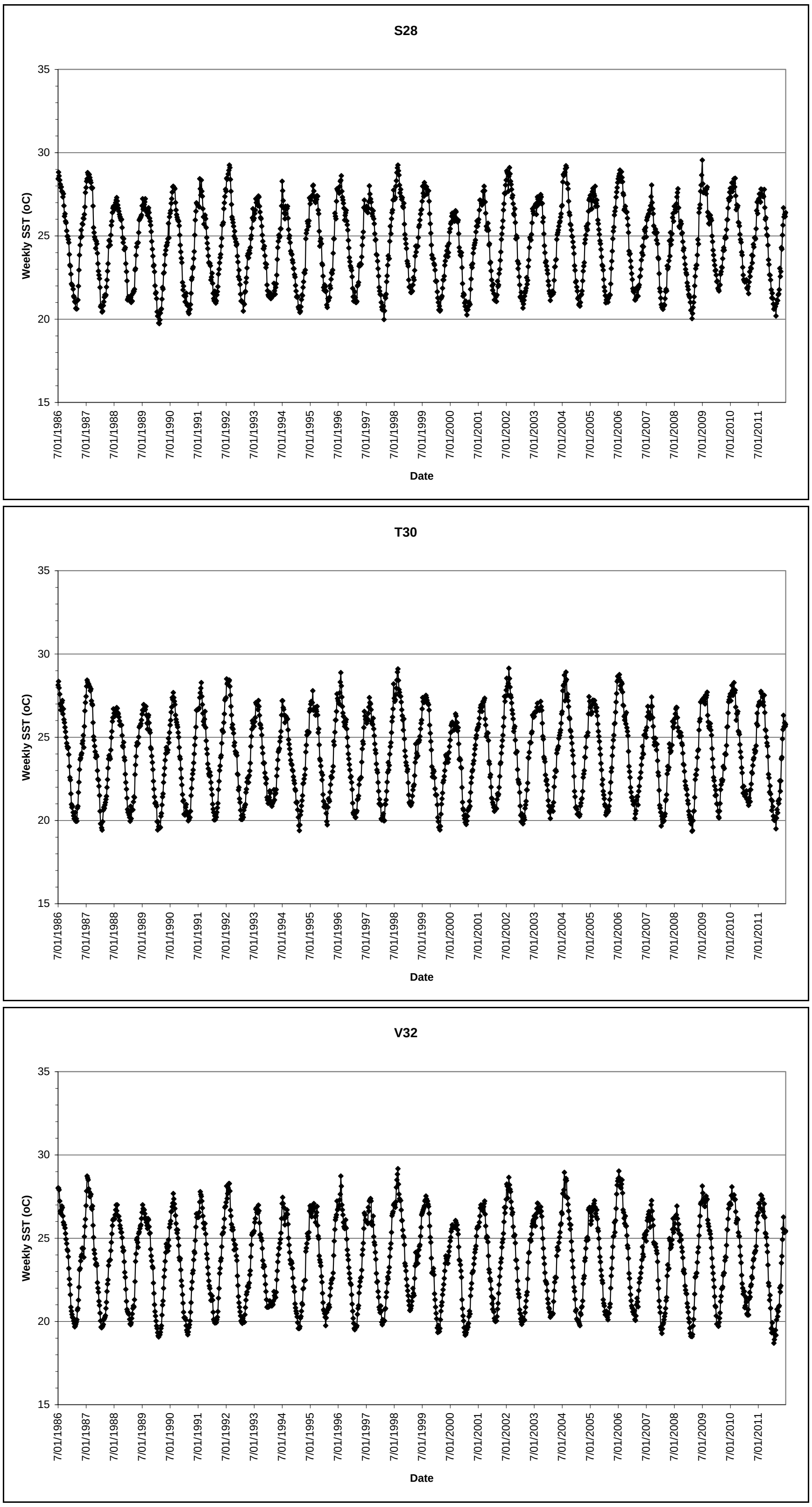

Figure 8.26 Weekly median SST between January 1986 and January 2011 for key scallop (CFISH) grids (S28, T30 and V32) in the Capricorn region of the Queensland east coast.

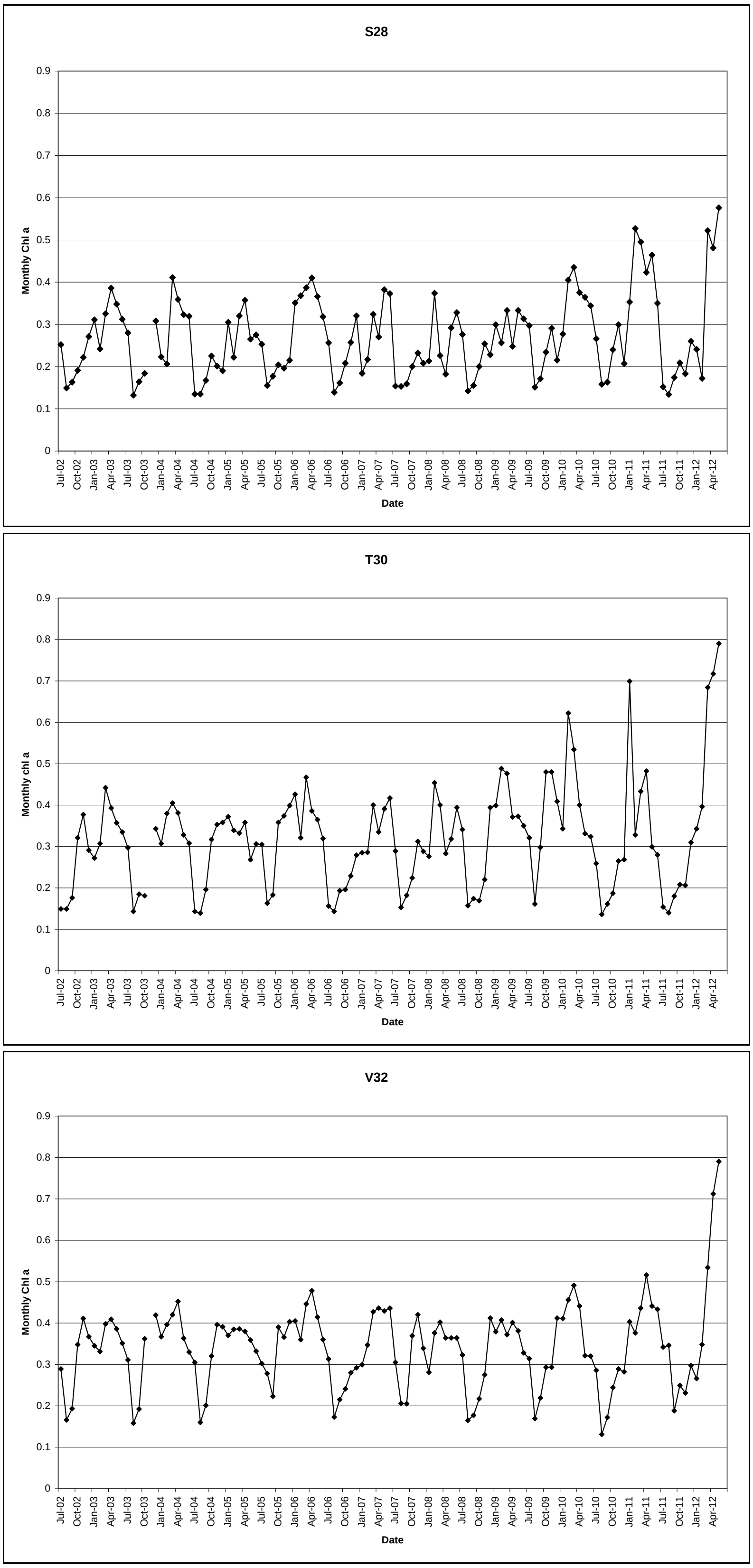

Figure 8.27 Monthly median Chlorophyll a between July 2002 and May 2012 for key scallop (CFISH) grids (S28, T30 and V32) in the Capricorn region of the Queensland east coast.

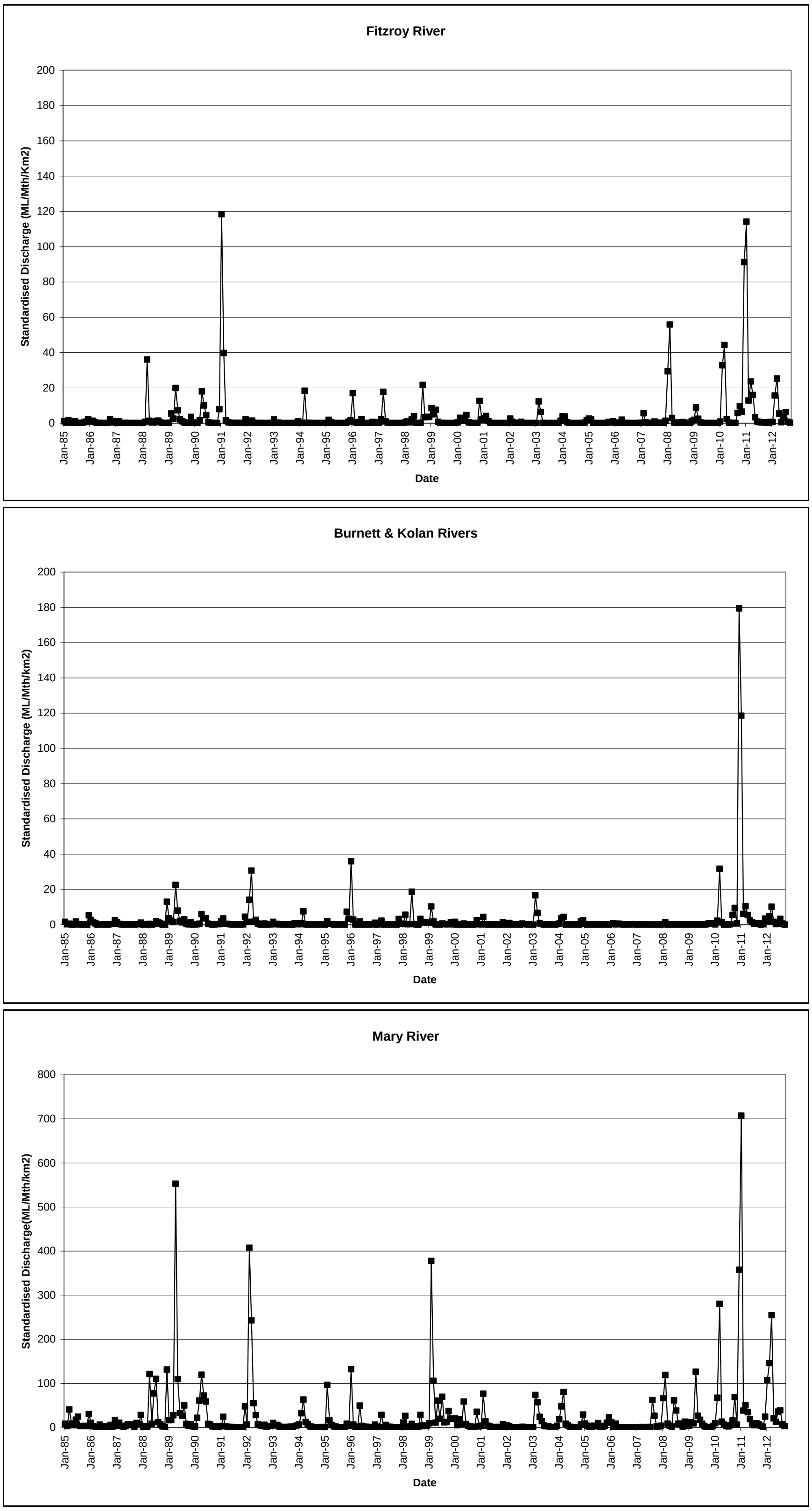

Figure 8.28 Standardised (by catchment area) monthly discharge between January 1986 and September 2012 for rivers influencing the key scallop (CFISH) grids (S28 – Fitzroy; T30 – Burnett & Kolan; and V32 – Mary River) in the Capricorn region of the Queensland east coast.

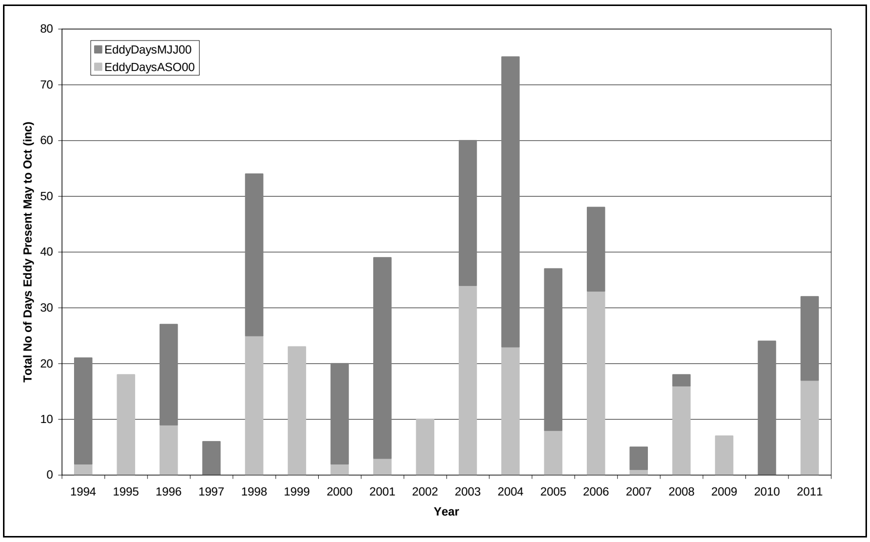

Figure 8.29 Count of the number of days in the scallop spawning season (May to October inclusive) that a cyclonic (hydrological) eddy was visibly present in the Capricorn Region between 1994 and 2011.

Many of the environmental factors in the current study were correlated, with high collinearity between some factors, i.e., r>0.7, as per collinearity diagnostic critical value (Dormann et al. 2012). Collinearity between environmental factors is a known, and almost unavoidable, problem. Some of the observed collinearity was a function of the overlap in the temporal aggregations applied to the data (e.g. Flow Juvenile and Flow Gonads). In other cases, the observed collinearity is probably a function of the interdependence between factors e.g. Chl *a* in Summer is dependent on SST and nutrient input derived from river discharge (Flow). While in other instances, the collinearity probably reflects intra-year climate patterns e.g. SST in Summer, Autumn and Winter.

8.4.6.2 Spatial Recruitment Index

The abundance of 0+ (i.e., recruitment) scallops was highly variable between years and also between cells. The annual commercial catch of scallops per CFISH grid was not significantly correlated to the abundance of 0+ or 1+ scallops. However, the abundance of 1+ scallops was significantly correlated to the abundance of 0+ scallops (r=0.435, p<0.001). Best all sub-sets regression models were used to explore relationships between the abundance of 0+ and 1+ scallops with seasonal Sea Surface Temperature (SST), seasonal and regional river discharge (Flow) and eddy presence (EddyDays). Chlorophyll *a* was not included in the analyses because these data were not available until June 2002, providing an insufficient time series.

Table 8.24 Correlation coefficients (r) environmental factors. Values of r>0.7 (bold type) are indicative of high collinearity between factors.

	Cha Sum	Chla Aut	Chla Win	Chla Spr	SST Sum	SST Aut	SST Win	SST Spr	Flow Gonads	Flow Spawn	Flow Spat	Eddy Days	Eddy Days MJJ	Eddy Days ASO	SOI 6mth Avg	SOI MovAvg06
Chla Sum	1.00															
Chla Aut	0.58	1.00														
Chla Win	-0.11	-0.19	1.00													
Chla Spr	0.16	0.03	0.04	1.00												
SST Sum	**0.72**	0.51	-0.68	0.10	1.00											
SST Aut	0.53	0.37	**-0.83**	0.24	**0.87**	1.00										
SST Win	**0.89**	0.59	-0.15	-0.10	**0.72**	0.57	1.00									
SST Spr	0.00	-0.16	0.58	**0.72**	-0.39	-0.20	-0.09	1.00								
Flow Gonads (Jan to May)	0.44	0.41	-0.59	-0.42	0.48	0.58	0.53	-0.53	1.00							
Flow Spawn (Jun to Oct)	**0.79**	0.58	0.06	-0.29	0.39	0.28	**0.88**	-0.07	0.65	1.00						
Flow Spat (Jul to Nov)	**0.76**	0.60	-0.28	-0.17	0.52	0.53	**0.79**	-0.18	**0.86**	**0.90**	1.00					
Flow Juv (Nov to May)	0.41	0.20	-0.56	-0.38	0.45	0.62	0.57	-0.37	**0.94**	0.64	**0.82**					
EddyDays	0.08	-0.20	**-0.88**	-0.17	0.58	0.69	0.11	-0.58	0.55	-0.08	0.21	1.00				
EddyDays MJJ	-0.09	-0.17	**-0.80**	-0.32	0.36	0.64	0.13	-0.45	0.65	0.04	0.29	**0.86**	1.00			
EddyDays ASO	-0.19	-0.36	-0.48	0.21	0.29	0.20	-0.40	-0.36	-0.23	-0.67	-0.48	0.58	0.16	1.00		
SOI JunNov	0.27	0.09	0.48	-0.55	-0.26	-0.31	0.42	0.04	0.37	**0.75**	0.54	-0.33	-0.07	**-0.80**	1.00	
SOI MovAvg06	0.25	0.16	0.39	-0.59	-0.20	-0.25	0.44	-0.04	0.41	**0.74**	0.54	-0.29	-0.01	**-0.79**	**0.95**	1.00

The base model of "Cell" explained ~32% of variation in the abundance of 0+ scallops (Table 8.25). All sub-sets generalised linear modelling identified several alternate models with adjusted R^2s of between 41 and 52%, depending on the number of terms in the model (i.e., model complexity). Significant factors in the complex models were the Winter sea surface temperature ($p<0.001$) in the same year as the survey (i.e., ~3 months prior), river discharge in the summer to autumn months ($p<0.001$) in the same year as the survey (i.e., ~7 months prior), and eddy presence between May to July ($p<0.001$) in the same year as the survey (i.e., ~ 4 months prior). The parameter estimate for Winter SST indicated an inverse relationship between the abundance of 0+ scallops and Winter SST i.e., 0+ scallops were more abundant when winter sea surface temperatures were lower.

The base model of "Cell" explained ~47% of variation in the abundance of 1+ scallops (Table 8.26). All sub-set generalised linear modelling identified several alternate models with adjusted R^2s of between ~50 and 58%, depending on model complexity. In the most complex 4-term models, the main significant factors were Summer sea surface temperature ($p<0.001$) in the year prior to the survey (i.e., ~20 months before the survey), eddy presence between August and October ($p<0.001$) in the year preceding the survey year (i.e., ~16 months prior), and Autumn sea surface temperature ($p<0.001$) in the year preceding the survey year (i.e., ~18 months prior). The parameter estimates indicated an inverse relationship between the abundance of 1+ scallops and SST in Summer and Autumn in the year preceding the survey i.e., 1+ scallops were more abundant when Summer and Autumn sea surface temperatures were lower when the 1+ scallops were juveniles.

8.4.6.3 Commercial catch data

The commercial catch of saucer scallops has varied dramatically over time (Figure 8.30). Fluctuations in landed catch follow the same trends across the three sub-sets of commercial catch data that were examined. These three sets were: (i) total scallop catch reported within the Queensland East Coast Otter Trawl Fishery (CFISH all data); (ii) scallop catch reported within the Capricorn region (CFISH 22.5° to 26.0° S); and (iii) scallop catch reported by boats selected within the effort standardisation sub-set (Standardisation data). As the trends were similar across data sets, the effort standardisation sub-set was used in further analyses to allow the inclusion of effort creep parameters.

Table 8.25 Best all sub-sets regression models for the abundance of 0+ scallops based on the spatial recruitment index derived by Campbell *et al.* 2011. Base Model = Cell, Adjusted R^2=32.4%.

Adj. R^2	EddyDays MJJ	EddyDays ASO	SST Sum	SST Aut	SST Win	SST Spr	Flow Gonads	Flow Juv	Flow Spat	Flow Spawn	ENSO Class	SOI 6mth Avg
1 terms												
41.3					***							
37.5							***					
36.0								***				
2 terms												
48.8					***		***					
47.4					***			***				
44.5				***	***							
3 terms												
51.2	***				***		***					
49.6	***				***			***				
4 terms												
51.8	***				***		***			*		

[A] Factors in the multiple regression are positively related to the recruitment index unless otherwise indicated in red. *** p < 0.001; ** p < 0.01; * p < 0.05.

Table 8.26 Best all sub-sets regression models for the abundance of 1+ scallops based on the spatial recruitment index derived by Campbell *et al.* 2011. Base Model = Cell, Adjusted R^2=47.3%.

Adj. R^2	EddyDays MJJ01	EddyDays ASO01	SST Sum01	SST Aut01	SST Win01	SST Spr01	Flow Gonads01	Flow Spat01	Flow Juvenile01	ENSO Class01	SOI 6 mth Avg01
1 term											
50.9			***								
49.4					***						
49.2										**	
2 terms											
54.6					***					**	
52.7	**		***								
52.0			***		*						
3 terms											
56.4		***	***	***							
55.9					***			**		**	
4 terms											
57.5	*	***	***	***							
57.1		***	***	***	*						

[A] Factors in the multiple regression are positively related to the recruitment index unless otherwise indicated in red. *** p < 0.001; ** p < 0.01; * p < 0.05.

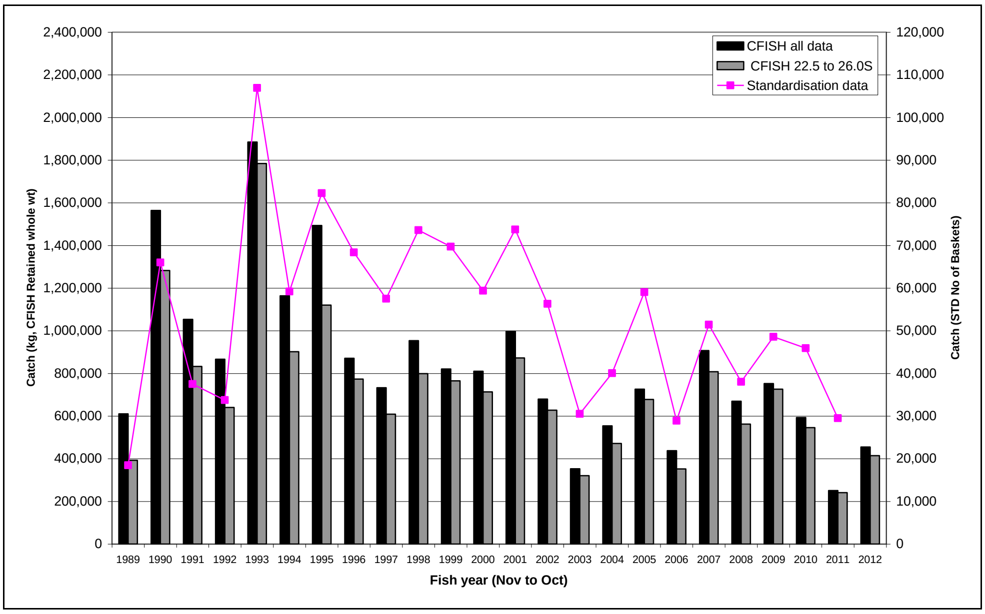

Figure 8.30 Reported catch of scallops in the commercial logbooks of the Queensland east coast otter trawl fishery.

Within the effort standardisation sub-set, total effort (i.e., days of fishing) for scallops increased up to 1997, but then declined (Figure 8.31). Annualised scallop catch per day has fluctuated from about six baskets per boat day (e.g. 1997) to as much as ~20 baskets per boat day (e.g. 1993, 2007, 2009 and 2010).

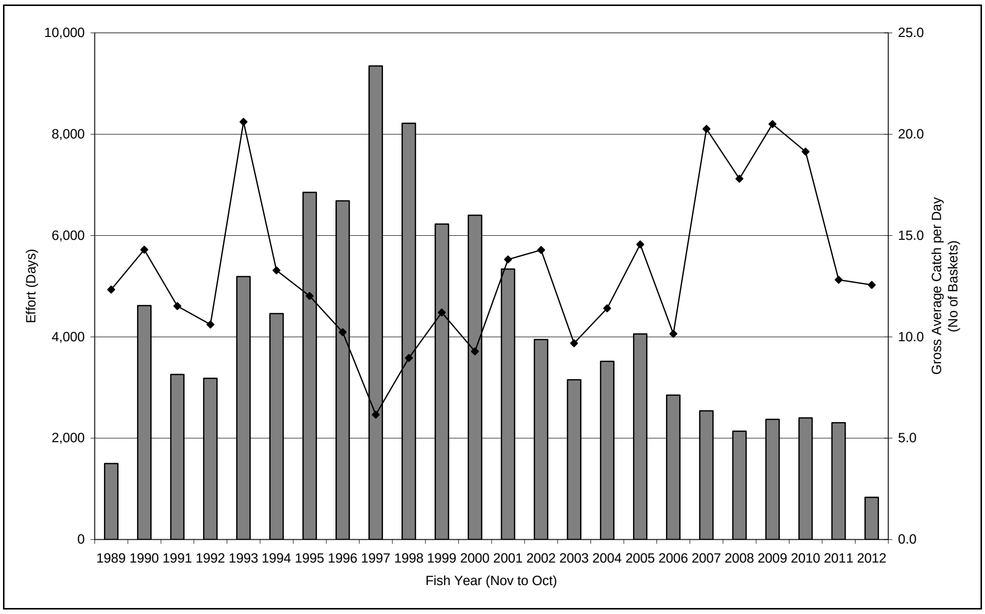

Figure 8.31 Reported effort and gross average catch per day of scallops within the effort standardisation subset of the Queensland east coast otter trawl fishery.

Daily catches per boat were highly variable (average = 16.4 baskets, s.e. = 0.143, min. = 0.1 baskets, max. = 294 baskets); reflecting inter- and intra-year differences in the catch of scallops by different boats. The high variability in daily catch also reflects the large differences in scallop abundance at small spatial scales i.e., within as well as between CFISH grids.

Best all sub-sets regression models were used to explore relationships between the daily catch rates of scallops with seasonal Sea Surface Temperature (SST), seasonal Chlorophyll *a*, seasonal and regional river discharge (Flow) and eddy presence (EddyDays). Overlap in the time series of catch data with all environmental variables permitted analyses of the data between 2005 and 2011 FishYears inclusive, where 17,728 daily records of catch were available. The forcing month and grid into the model explained ~26.3% of variation in the daily catch of scallops. Significant effort terms of PrawnCatch (-), Lunar(-), LunarAdv, Hrs, Hp, NetType, Gear, Speed (-) and Nozzle were then forced into the model and increased the adjusted R^2 to 44.0%. Best-all subsets identified several alternate complex models that significantly explained variation in daily scallop abundance, with the adjusted R^2 increasing to ~49% (Table 8.27). The environmental terms significantly increased the variation of daily scallop catches explained. However, there remained >50% of the variation in daily scallop catch rates between 2005 and 2011 that could not be attributed to month, grid, effort terms or environmental terms.

In the most models, the main significant factors were Spring sea surface temperature ($p<0.001$) in the year immediately prior to harvest (i.e., ≤4 months prior to the majority of the scallop catch in the January and February), and eddy presence between May and July ($p<0.001$) in the year immediately prior to harvest (i.e., ~7 months prior). Spring SST and EddyDays MJJ accounted for the increase in adjusted R^2, with other significant factors making relatively minor improvements to the adjusted R^2.

The significant models identified for the spatial recruitment index data (i.e., 0+ and 1+ scallop abundance) were also applied to the effort standardisation 2005 to 2011 sub-set (Table 8.27). Although the SRI models held consistent for the commercial catch data, the adjusted R^2 were lower than other models identified by best all-subsets analysis.

Daily catches per boat were highly variable (average = 12.1 baskets, s.e. = 0.0527, min = 0.1 baskets, max = 294 baskets); reflecting inter- and intra-year differences in the catch of scallops by different boats.

Best all sub-sets regression models were used to explore relationships between the daily catch rates of scallops in the effort standardisation sub-set with seasonal SST, seasonal and regional Flow and EddyDays i.e., seasonal Chlorophyll *a* was excluded. Overlap in the time series of catch data with these environmental factors permitted analysis of the data between 1996 and 2011 FishYears inclusive, providing 63,142 daily catch records. Forcing month and grid into the model explained ~18.2% of variation in the daily catch of scallops. Significant effort factors of PrawnCatch (-), Lunar(-), LunarAdv, Hrs, Hp, NetType, Gear, Speed (-) and Nozzle were then forced into the model and increased the adjusted R^2 to 37.8% (Table 8.28).

Best-all subsets identified several alternate complex models that significantly explained variation in daily scallop abundance, with the adjusted R^2 around 40% (Table 8.28). Whilst environmental factors significantly increased the adjusted R^2, there remained >60% of the variation in daily scallop catch rates between 1996 and 2011 that could not be attributed to month, grid, effort or environmental factors.

The significant models identified for the spatial recruitment index data (i.e., 0+ and 1+ scallop abundance) were applied to the effort standardisation 1996 to 2011 sub-set (Table 8.28).

Table 8.27 Best all sub-set regression models for the daily catch of scallops reported in the commercial logbooks of the Queensland east coast otter trawl fishery – effort standardisation sub-set for the Capricorn region 2005 to 2011 FishYears (incl. Chl-a data). Base model = Month + Grid + Effort Factors, Adj. R^2 = 44.0.

Adj. R^2	EddyDays MJJ	EddyDays ASO	EddyDays MJJ01	EddyDays ASO01	SST Sum01	SST Aut01	SST Win01	SST Spr01	SST Sum	SST Aut	SST Win	SST Spr	Chla Sum01	Chla Aut01	Chla Win01	Chla Spr01	Chla Sum	Chla Aut	ChlA Win	Chla Spr	Flow
1 terms																					
46.0					***																
45.7																					*** Spawn
45.6												***									
2 terms																					
48.5	***											***									
47.6										***		***									
47.2				***												***					
3 terms																					
48.8	***	***										***									
48.8	***											***			***						
48.7	***											***				***					
4 terms																					
49.2	***											***			***		***				
49.2	***										***	***			***						
49.1	***			***								***				***					
5 terms																					
49.5	***			***		***						***				***					
49.4	***			***		***						***			***						
49.3	***									***		***			***	***					

SRI 0+ model																					
46.7	***										***										*** Gonads
SRI 1+ models																					
46.7					***					***											
47.1	***				***	***															
SRI 0+ and 1+ combined																					
47.3	***				***	***					**										*** Gonads
46.2					***						***										
47.1	***				***	***															
46.6					***	***					***										
47.2	***				***	***															*** Gonads

Factors in the multiple regression are positively related to the standardised scallop catch unless otherwise indicated in red. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Table 8.28 Best all sub-set regression models for the daily catch of scallops reported in the commercial logbooks of the Queensland east coast otter trawl fishery – effort standardisation sub-set for the Capricorn region 1996 to 2011 FishYears (No Chl-a data). Base model = Month + Grid + Effort Factors; Adj. R^2 = 37.8.

Adj. R^2	EddyDays MJJ	EddyDays ASO	EddyDays MJJ01	EddyDays ASO01	SSTS um01	SST Aut01	SST Win01	SST Spr01	SST Sum	SST Aut	SST Win	SST Spr	Flow Gonads
1 term													
38.5												***	
38.4									***				
38.3						***							
2 terms													
39.1									***			***	
39.0											***	***	
38.9		***							***				
3 terms													
39.5								***	***			***	
39.5						***		***	***				
39.4		***							***			***	
4 terms													
40.1						***		***			***	***	
39.9						***		***	***			***	
39.8					***			***	***			***	
5 terms													

40.5						***		***	***		***	***	
40.2	***					***		***			***	***	
40.2				***				***	***		***	***	
40.2					***			***	***		***	***	
40.1						***	***	***			***	***	
SRI 0+ model													
38.1	***										***		***
SRI 1+ models													
38.3					***	***				**			
38.3	***				***	***							
SRI 0+ and 1+ combined													
38.6	***				***	***					***		*
38.2					***				***				***

Factors in the multiple regressions are positively related to the standardised scallop catch unless otherwise indicated in red. *** p < 0.001; ** p < 0.01; * p < 0.05.

8.4.6.4 Discussion

Worldwide, scallop fisheries are notorious for their large fluctuations in abundance and subsequent variability in catch. Queensland saucer scallops are no exception.

Analysis of the fishery-independent recruitment survey data (i.e., spatial recruitment index) indicated that SST may play a significant role in influencing Queensland scallops during their larval and juvenile phases, with cooler temperatures have a positive influence. This fits with the known literature for Queensland saucer scallops, where a key trigger for spawning under laboratory conditions is falling water temperatures. The presence of a cyclonic eddy in the Capricorn region over of the spawning season was indicated in the analysis to have a positive effect on scallop abundance, although results were somewhat ambiguous as to the importance of timing. The significant and positive effect of river discharge on the abundance of 0+ scallops in the seven months prior to the survey may reflect enhanced nutrient conditions leading to better growth and survival of young-of-the-year scallops.

Analysis of the fishery-dependent daily commercial catch data provided ambiguous results. Despite finding many significant environmental effects, these ultimately only increased the amount of variation explained by a small amount. Many issues complicated the commercial catch data including major management changes, the reliability of reported data, and its low spatial resolution (i.e., CFISH grid = ~167 km^2). As a coarse generalisation, sea surface temperature was a consistently significant factor in many of the GLMs for the daily commercial catch, but its seasonality varied between models making interpretation difficult.

Despite significant results for the fishery-independent scallop recruitment survey data, >50% of the variation in the abundance of 0+ and >60% for 1+ scallops remained unexplained by environmental factors. Results were similar for the more complex commercial catch data. This indicates that there are probably other factors influencing scallop abundance. Some are known, such as the spatial and temporal closures used as part of the management regime for Queensland saucer scallops, but which were difficult to include in the present analysis. It is highly likely factors occurring at very small spatial scales (e.g. <1km^2) play a significant role in determining the abundance of Queensland saucer scallops. Such factors could include bottom composition, bottom aspect, or exposure to tidal currents. Queensland saucer scallops have a known preference for substrates that are soft (to enable the scallops to burrow), and with a high sand content. Survey results indicate that substrate composition can vary at quite small spatial scales (Pitcher et al. 2007).

Queensland saucer scallops occur in a relatively narrow area on the Queensland east coast between 22°30’ S, 151° E and 26° S, 153°30’ E. Occasionally, significant patches of scallops are reported north (up to Hydrographers Passage) and south (in front of Fraser Island) of this key area. Their current distribution indicates that saucer scallops are spatially constrained, probably by several environmental factors in addition to depth. The results from the current analysis indicate that water temperature is probably a key factor. This is consistent with the observed effects of a Marine Heat Wave in Shark Bay Western Australia where water temperatures >3°C above average resulted in reduced growth rates of saucer scallops and recruitment failure (Pearce *et al*. 2011). The WA experience suggests that extreme events (particularly high temperature combined with lowered salinity i.e., a flood) had major negative effects on saucer scallops. It is unknown whether such extreme events can occur in the Capricorn region, given its differing geographic and hydrographic conditions to that of Shark Bay in Western Australia.

Results were somewhat ambiguous as the effect on saucer scallops of cyclonic eddies derived from the East Australian Current. This is probably the consequence of the simplistic index of eddy presence generated in the current study. Further work on understanding the (probably complex) influence of large scale hydrographic features on larval dispersal and spatfall would assist our understanding of potential changes to saucer scallops that may result from a changed East Australian Current.

8.4.7 Spanish mackerel

8.4.7.1 Year class strength

Monitoring of the length- and age-structure of east coast Spanish mackerel occurred between 2001 and 2011. Age-length keys derived from 8270 aged fish were used to assign ages to a further 22145 measured fish resulting in a total sample of 30415 Spanish mackerel (see Appendix 10). Full selectivity to the fishing gear and recruitment to the line fishery appeared to occur at age two, and fish >11 years were rare. Consequently fish 2–11 years old were included in the analysis. Based on catch-curve residuals it was possible to reconstruct the relative YCS of Spanish mackerel over the 16-year period from 1993-2009.

Comparing time-series of mean YCS from four different regions along the east coast of Townsville indicated that trends in recruitment were homogenous across the study area (Table 8.29, Figure 8.32). All regions were highly significantly correlated. Townsville and Mackay showed the least amount of similarity (0.78) while the greatest similarity was between Townsville and South (0.96). Over the range of years available there appeared to be evidence of one particularly strong year of recruitment in 2007, and two relatively weak periods of recruitment; 1998-1999 and 2004-2006. The r^2 values from catch curve linear regression models that included age, *x,* and sample year, *i,* ranged from 0.71 from Rockhampton (most variability in recruitment) to 0.87 for Mackay (least variability in recruitment). The Townsville and South regions were relatively similar with r^2 values of 0.80 and 0.82, respectively.

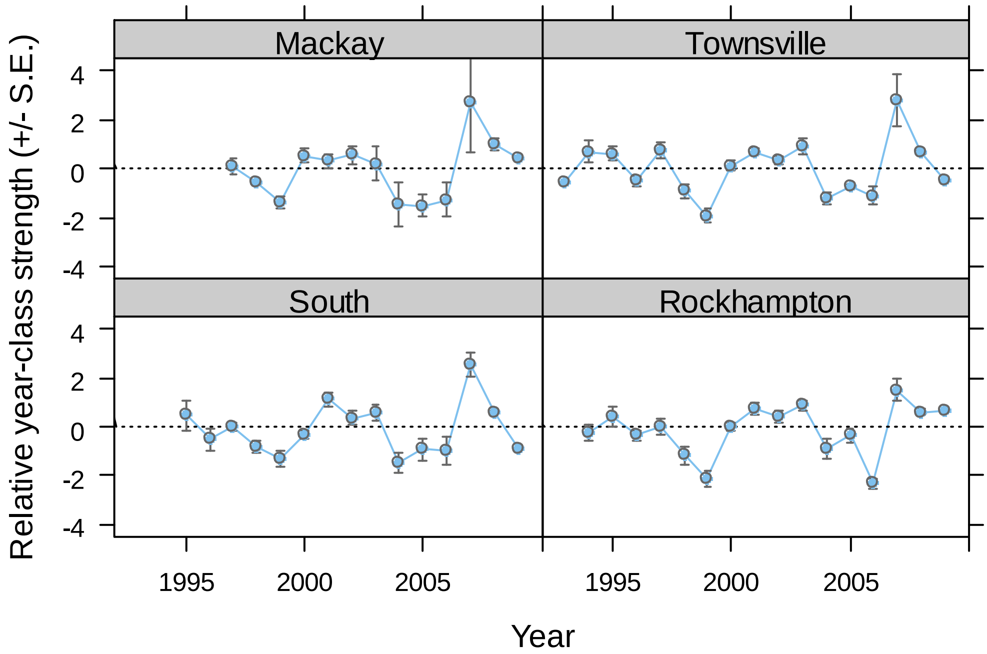

Figure 8.32 Relative year-class-strength of Spanish mackerel in four regions on the east coast of Queensland.

Table 8.29 Pearson's correlation coefficient between indices of year-class-strength of Spanish mackerel in four geographical regions. Values > 0.76 are significant at the 0.005 level.

	Townsville	Mackay	Rockhampton	South
Townsville				
Mackay	0.78			
Rockhampton	0.89	0.82		
South	0.96	0.86	0.91	

8.4.7.2 Catch per unit effort

All fitted terms included in the linear mixed model for standardising CPUE were highly significant (Table 8.30). Despite this, there was relatively little difference between the fitted year coefficients and the geometric mean daily catch rates. CPUE initially showed a declining trend however from the mid-1990s but increased steadily with a noticeable peak in 2009 (Figure 8.33).

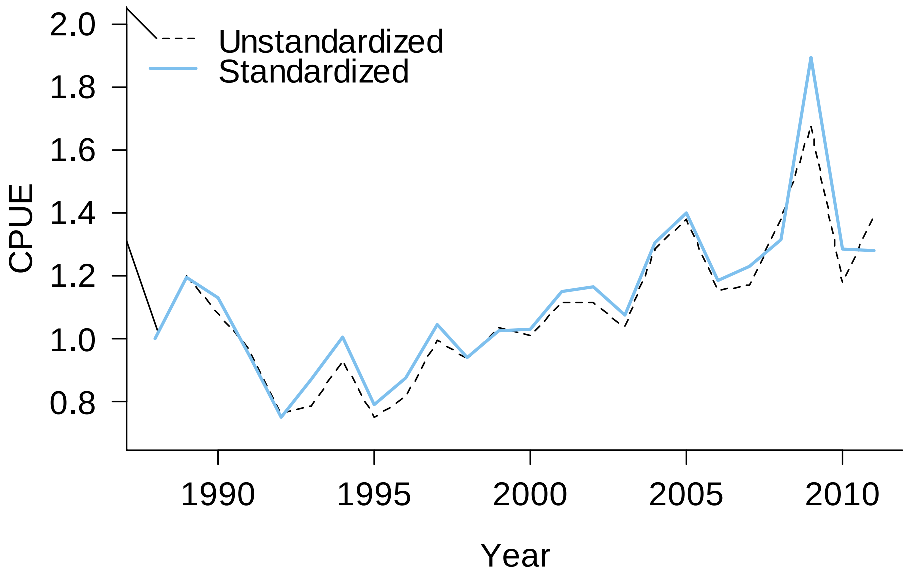

Figure 8.33 Comparison of standardised CPUE and geometric mean of daily unstandardised catch rates relative to 1988 levels.

Table 8.30 Wald tests showing statistical significance of fitted terms in the linear mixed model used to standardise CPUE.

Fitted terms	Numerator *d.f.*	Denominator *d.f.*	*F*	*P*
Intercept	1	27270	5064.27	<0.0001
Year	23	27270	29.444	<0.0001
Month	11	27270	136.213	<0.0001
Lunar (sine)	1	27270	273.971	<0.0001
Lunar advance (cosine)	1	27270	161.802	<0.0001
Lunar (sine 2)	1	27270	23.168	<0.0001
Lunar advance (cosine 2)	1	27270	63.44	<0.0001
Grid	8	27270	20.965	<0.0001

8.4.7.3 Comparison of abundance indices

Pearson's correlation coefficient between CPUE and the YCS (pooled across regions) from two years prior was 0.52 indicating a significant positive correlation between the two indices (t = 2.3729, *d.f.* = 15, p = 0.03). This correlation was not particularly robust, however, and appeared mainly to be driven by data from the period between 2004 and 2011 (Figure 8.34). During this time the period of relatively weak recruitment (2004-2006) and the strong year of recruitment (2007) were both evident in the CPUE. After removal of the strong recruitment year the correlation was no longer significant.

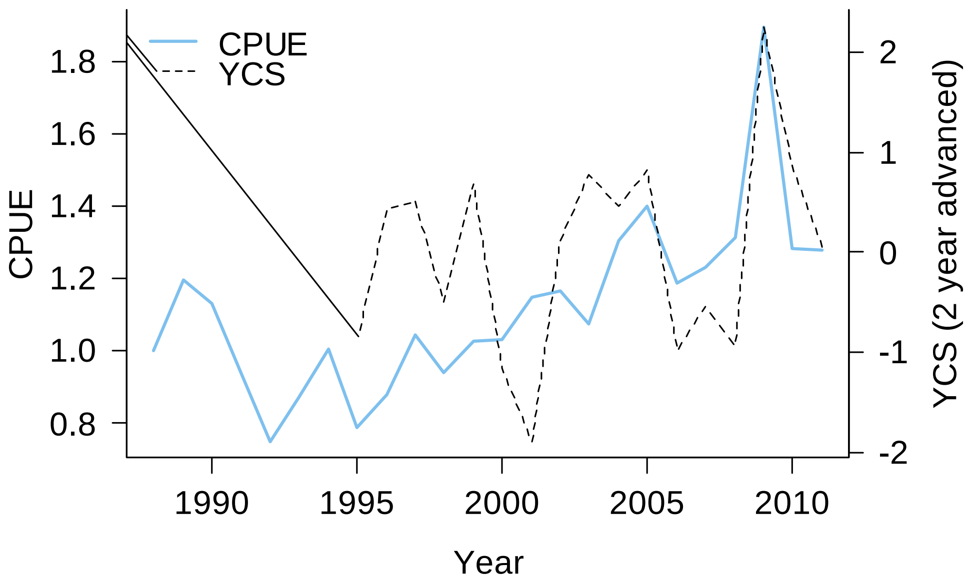

Figure 8.34 Comparison of CPUE with the YCS advanced two years, corresponding with the lag between spawning and full recruitment to the fishery. Both indices are dimensionless.

8.4.7.4 Regression analysis — Year class strength

A total of 48 bivariate linear regression models correlating environmental variables against YCS residuals were analysed, six of which were statistically significant ($P < 0.01$) (Table 8.31). SST was the only variable that had a strong and consistent correlation with YCS; in all regions there was a strong negative and one year lagged response of Spanish mackerel YCS with Spring SST. The greatest statistical significance was in the Townsville and Rockhampton regions where regressions explained 35% and 44% of the remaining variability in YCS not accounted for in the base model, respectively (Figure 8.35, Figure 8.36). The strong negative lagged correlation in the Townsville and Rockhampton region also manifested as a year advanced positive correlation that was statistically significant. The same regressions in the Mackay and South region were still statistically significant however only explained 18% of the remaining variability.

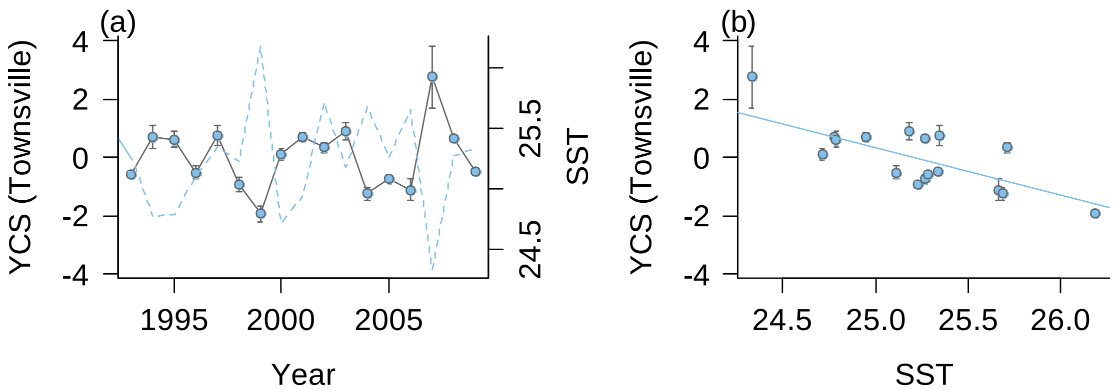

Figure 8.35 Comparison of mean Spanish mackerel YCS against lagged Spring SST (dashed blue line) (a), and YCS as a function of lagged SST in the Townsville region (b). The solid blue line in (b) is a linear regression between the two variables (Table 8.31).

Other environmental variables had a less consistent response. There was a strong positive lagged response of YCS to Spring Chl-a, however only in the Townsville region. One year advanced SOI had a strong positive correlation in the Rockhampton region. A statistically significant but weaker negative correlation occurred with no lag.

Table 8.31 Results of linear regression of single environmental variables against catch-curve residuals. Models that were statistically significant at p ≤0.01 are denoted in bold.

Variable	Offset	Region	+/-	*F*	*d.f.*	*P*	r^2	Region	+/-	*F*	*d.f.*	*P*	r^2
SST	0	Townsville	+	2.33	1,96	0.13	0.02	Mackay	+	0.33	1,52	0.57	0.01
	-1		**-**	**52.79**	**1,96**	**<0.01**	**0.35**		**-**	**11.66**	**1,52**	**<0.01**	**0.18**
	+1		**+**	**12.58**	**1,95**	**<0.01**	**0.12**		+	3.92	1,51	0.05	0.05
SOI	0		-	4.98	1,96	0.03	0.05		+	0.67	1,52	0.42	0.01
	-1		-	4.40	1,96	0.04	0.04		+	0.00	1,52	0.96	0.00
	+1		-	1.80	1,96	0.18	0.02		-	0.10	1,52	0.76	0.00
Chl-a	0		-	0.19	1,34	0.66	0.01		-	1.84	1,30	0.19	0.06
	-1		+	**52.99**	**1,26**	**<0.01**	**0.67**		-	2.19	1,23	0.15	0.09
	+1		+	0.58	1,43	0.45	0.01		+	0.58	1,36	0.45	0.02
River flow	0		-	5.03	1,96	0.03	0.05		+	1.89	1,52	0.04	0.18
	-1		-	5.12	1,96	0.03	0.05		-	5.20	1,52	0.03	0.09
	+1		-	3.31	1,96	0.07	0.03		-	0.19	1,52	0.66	0.00
SST	0	Rockhampton	+	1.71	1,81	0.19	0.02	South	+	0.00	1,67	0.96	0.00
	-1		-	**64.77**	**1,81**	**<0.01**	**0.44**		-	**14.27**	**1,67**	**<0.01**	**0.18**
	+1		**+**	**6.61**	**1,80**	**0.01**	**0.08**		+	4.41	1,66	0.04	0.06
SOI	0		-	1.23	1,81	0.27	0.01		-	0.06	1,67	0.80	0.00
	-1		-	3.71	1,81	0.06	0.04		-	0.62	1,67	0.44	0.01
	+1		-	**11.04**	**1,81**	**<0.01**	**0.12**		-	4.69	1,67	0.03	0.07
Chl-a	0		-	0.77	1,34	0.39	0.02		+	5.43	1,34	0.03	0.14
	-1		+	0.16	1,26	0.69	0.01		-	0.01	1,26	0.94	0.00
	+1		+	1.44	1,43	0.24	0.03		-	0.21	1,42	0.65	0.00
River flow	0		+	2.96	1,81	0.04	0.09		-	3.21	1,67	0.08	0.05
	-1		-	0.15	1,81	0.70	0.00		-	2.81	1,67	0.10	0.04
	+1		+	2.23	1,81	0.14	0.03		-	0.16	1,67	0.69	0.00

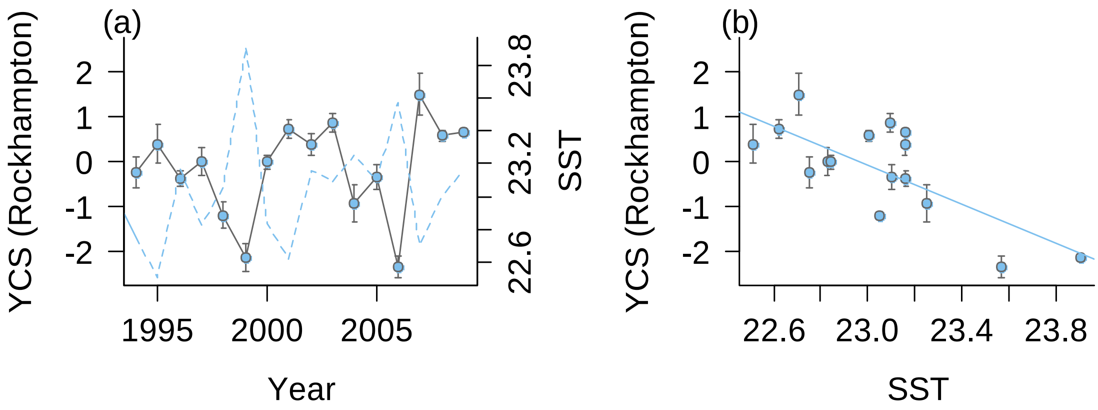

Figure 8.36 Comparison of mean Spanish mackerel YCS against lagged Spring SST (dashed blue line) (a), and YCS as a function of lagged SST in the Rockhampton region (b). The solid blue line in (b) is a linear regression between the two variables (Table 8.31).

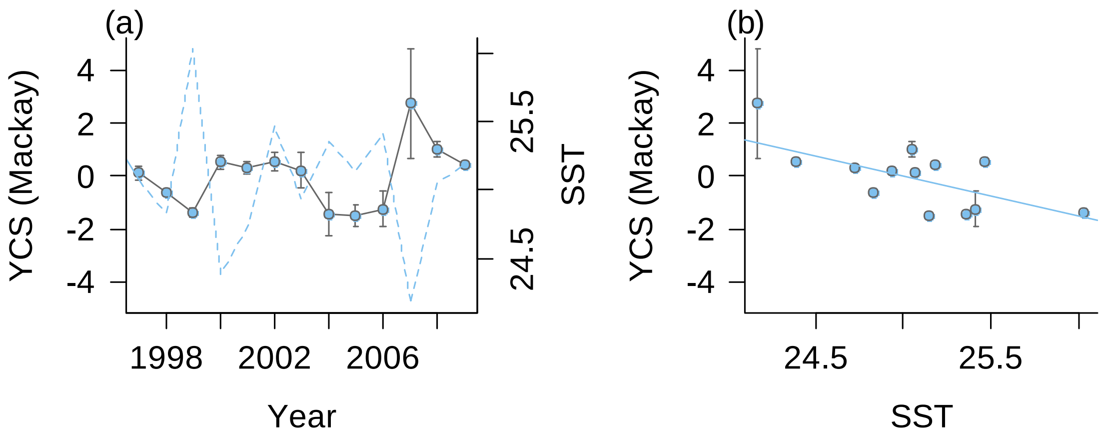

Figure 8.37 Comparison of mean Spanish mackerel YCS against lagged Spring SST (dashed blue line) (a), and YCS as a function of lagged SST in the Mackay region (b). The solid blue line in (b) is a linear regression between the two variables (Table 8.31).

8.4.7.5 Regression analysis — Catch per unit effort

A total of 12 bivariate linear regression models correlating environmental variables against standardised annual CPUE were analysed, 3 of which were significant at the 0.05 level. Both SOI and CPUE increase at a similar rate from 1993 to 2011 and the most statistically significant relationship was a positive correlation between lagged SOI and CPUE. Lagged river flow, which was correlated with lagged SOI had a weak but statistically significant correlation with CPUE. One year advanced SOI was also weakly statistically significant.

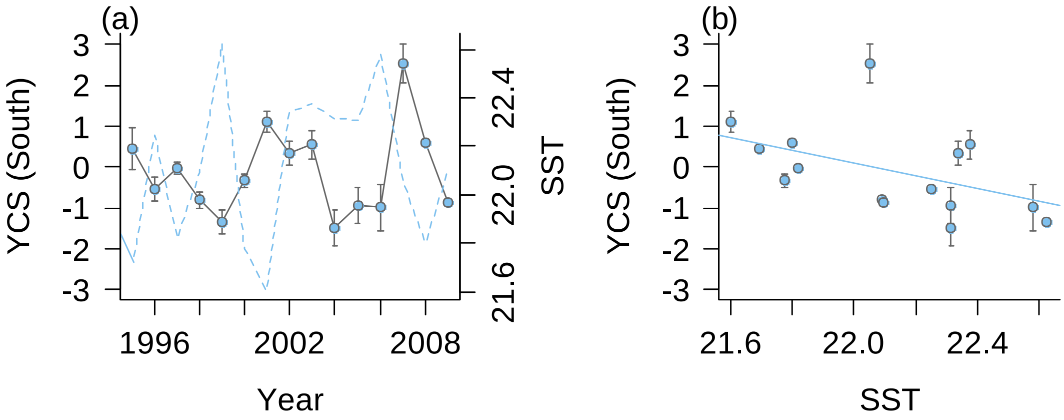

Figure 8.38 Comparison of mean Spanish mackerel YCS against lagged Spring SST (dashed blue line) (a), and YCS as a function of lagged SST in the South region (b). The solid blue line in (b) is a linear regression between the two variables (Table 8.31).

Table 8.32 Results of linear regression of single environmental variables against CPUE in the Townsville region. Models that were statistically significant at p ≤0.05 are denoted in bold.

Variable	Offset	+/-	*F*	*d.f.*	*P*	r^2
SST	0	+	1.22	1,20	0.28	0.06
	-1	+	1.15	1,21	0.30	0.05
	+1	+	0.21	1,19	0.65	0.01
SOI	0	+	0.24	1,22	0.63	0.01
	-1	+	**7.74**	**1,22**	**0.01**	**0.26**
	+1	+	**4.64**	**1,21**	**0.04**	**0.18**
Chl-a	0	+	0.20	1,8	0.67	0.02
	-1	+	0.00	1,7	0.96	0.00
	+1	+	0.18	1,8	0.68	0.02
River flow	0	+	0.97	1,22	0.34	0.04
	-1	+	**4.81**	**1,22**	**0.04**	**0.18**
	+1	+	3.29	1,21	0.08	0.14

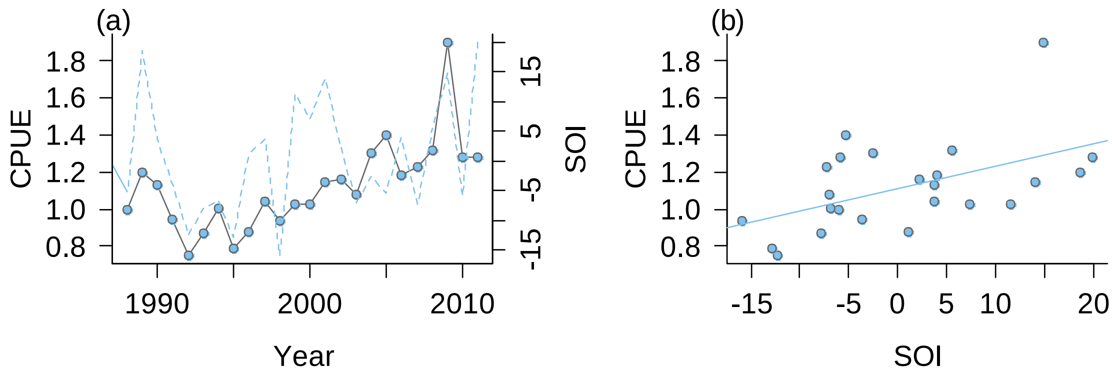

Figure 8.39 Comparison of standardised annual CPUE against lagged SOI (dashed blue line) (a), and CPUE as a function of lagged SOI in the Townsville region (b). The solid blue line in (b) is a linear regression between the two variables (Table 8.32).

8.4.7.6 Discussion

We tested four hypotheses relating environmental variables with a catch-curve based YCS index and a CPUE based abundance index for *S. commerson* on the east coast of Queensland. We found that 71-87% of variation in YCS in four broad-scale regions on the east coast of Queensland was explained by age and sample year, suggestive of moderately variable recruitment in this species. Additionally, trends in recruitment were found to be highly consistent throughout the study region with values of Pearson's correlation coefficient between all four YCS regions ranging from 0.78 to 0.96. One-year lagged Spring SST was found to a have a strong negative correlation with YCS, explaining up to 44% of the remaining variation not accounted for in the base models. Although this correlation was consistent across all four regions where YCS was measured, it was not consistent with the original hypotheses that suggested SST at the time of spawning itself and during the period of larval development (rather than one year lagged) would affect recruitment. As such, we could not immediately establish a causal mechanism to explain this correlation. A strong positive correlation was also found between standardised CPUE and one-year lagged SOI, however this was also inconsistent with our hypothesis, and a causal mechanism was not clear. There was a weakly significant positive correlation between YCS and CPUE indices at the expected lag of two years (age at full recruitment to the fishery), providing some indication that the effects of strong and weak year classes influence catch rates in this fishery. This has been assumed in the past but until now had not been tested.

Sea surface temperature

The negative and one-year lagged correlation between spring SST and *S. commerson* YCS is an intriguing but unexpected finding from this study. Review of the lifecycle of *S. commerson* indicated that spring SST could potentially be a key environmental variable, affecting recruitment by influencing the timing of spawning, egg production and larval survival, and potentially affecting growth and catchability. The one-year lag between the correlation, however, suggests an indirect effect. Furthermore, the correlation was in the opposite direction to what was expected, and implied that increasing temperature has a negative effect on *S. commerson*. While a negative response to higher temperature is not uncommon in itself, this would typically be expected to occur at the lower-most latitude that the species occurs in (Myers 1998). One possibility is that juvenile *S. commerson* survival is enhanced by higher baitfish recruitment from the previous year. Townsville is known as the main spawning ground, and therefore the main source of recruits, for the east coast. Cross-shelf incursions of cooler upwelled water, typically nutrient-rich, have been reported for the Townsville region and there was a significant *positive* and one-year lagged correlation between Chlorophyll-a. and *S. commerson* YCS in the Townsville region only. This could promote increases in baitfish populations that juvenile mackerel take advantage of in the first 6 months of life. If so, this would suggest that survival at the juvenile stage, rather than the larval stage, is more critical for recruitment to the fishery population. This is a possible indirect response that would explain the results here, however is a new hypothesis that would require testing. Also, as pointed out already, it would be assumed that higher nutrients in the year of spawning and larval development would enhance survival through greater food availability. This was not observed from the analyses. It is interesting to note that during the 1970s, fishers targeted spawning aggregations of *S. commerson* on reefs between Townsville and Lizard Island. However, present day aggregations reportedly only occur around Townsville, suggesting a southward contraction in the spawning aggregation has occurred. If environmentally driven, this could be consistent with a negative response to temperature.

Southern Oscillation Index

The existence of a correlation between broad-scale climate variables has been documented in many of Australia's commercially important fish and invertebrates and also appears to affect Queensland east coast *S. commerson*. We found that one-year lagged SOI explained approximately 26% of variation in the annual CPUE of *S. commerson* over the 24-year period. Generally speaking, La Nina events that led to higher values of SOI resulted in higher catch rates, while El Nino events resulted in lower catch rates. However, the relationship was not definitive. For instance, during the prolonged La Nina conditions between 1998 and 2001 catch rates were relatively stable and the year of highest SOI (financial year 2010/11) did not result in especially high catches.

Strong and consistently positive values of SOI (La Nina events) are associated with higher rainfall across much of Australia leading to increasing coastal and estuarine productivity that has positive effect on the recruitment of many fish species. Since larval *S. commerson* settle in estuaries after a two to four week pelagic phase, we hypothesised that a similar positive effect on recruitment might be observed in this species. Only weak evidence was found that YCS was affected by SOI (a one-year advanced correlation in Rockhampton). The one year lagged correlation with CPUE was also inconsistent with hypotheses that SOI affect recruitment or catchability directly. The correlations between SOI and CPUE suggest a general association between the variables where higher values of SOI lead to greater coastal productivity, indirectly benefiting Spanish mackerel.

River flow

Although SOI is often a proxy for increased estuarine productivity, in many species a more direct correlation can be found between recruitment and the volume of water discharged from the river itself (Balston 2009, Halliday *et al.,* 2011). In this study the one-year lagged correlation between CPUE and spring and summer flow of the Herbert river system was significant, however explained only 18% of the variation. Although not presented, a similar statistical correlation was found with the Burdekin River system. These results are concordant with the above findings that suggest La Nina conditions are associated with a general increase in productivity, however they did not provide any more definitive evidence of a mechanism, and the correlation was weaker than with SOI itself.

Chlorophyll-a

A highly significant positive correlation ($r^2 = 0.67$) was found between YCS and spring Chl-a in the coastal grid directly adjacent and inshore of the Townsville spawning reefs. Although also a lagged response, this finding is an interesting outcome and warrants further investigation. Unfortunately, data for this variable was available for only 10 years of the time-series and heavily influenced by the particularly strong year of recruitment in 2009. As such it wasn’t possible to draw strong conclusions about the nature of this correlation.

Study limitations

In this study we considered four environment-recruitment hypotheses for *S. commerson.* To help separate causal relationships from general associations between variables, each hypothesis was tested against the year of recruitment itself, one year lagged and one year advanced. A challenge faced was the lack of detailed information on the early life history of *S. commerson* from eastern Australia, making it difficult to develop and test very specific environment-recruitment hypotheses on an appropriate spatial scale. This lack of knowledge was a major factor in the choice to only use single variable linear regressions, as opposed to considering multiple regression models with many variables and interactions. Such models would undoubtedly have led to many more significant correlations, but assessing their biological validity would have been challenging. A better understanding of the dispersal and movement of larval *S. commerson*, and the linkage between the reef and estuary would be useful to help devise more tractable environment-recruitment hypotheses.

Management implications

This study confirms the long-held suspicion that recruitment of *S. commerson* is variable and, at least partly, environmentally driven. In comparison to estuarine species, however, recruitment of *S. commerson* was relatively more stable; the base YCS models with age and sample year as explanatory variables accounted for 71–87% of total variation. This compares to 52–62% for *L. calcarifer* from the Fitzroy river (Staunton-Smith et al. 2004, Halliday et al. 2011) and 55% for king threadfin, *Polydactylus macrochir* (Halliday et al. 2008). Another important outcome of this study was the finding that patterns in recruitment of *S. commerson* were similar over the entire spatial extent of the study area. This supports the current view that fish on the east coast are a single stock for management purposes. This also could suggest that either (a) the majority of fish originate from the main spawning aggregation around Townsville or (b) spawning occurs at various locations but is influenced by the same oceanographic conditions over a broad scale. Given the high degree of collinearity between SST in each region, it wasn't possible to establish which of these situations is most likely at present. The findings of this study also confirm an important link between CPUE and SOI in the Townsville region. Overall we found some degree of support for all of our original hypotheses, and strong support that SST and SOI affect recruitment in particular. Although many of the direct mechanisms by which these variables effect recruitment are not yet clear, they do provide preliminary evidence that management of this species may need to factor in climate variability.

8.5 Vulnerability assessment

8.5.1 Overall vulnerability and potential impacts

The vulnerability assessments for key fishery species of northern Australia are presented below for each of the three regions: north-western Australia, Gulf of Carpentaria and the east coast. Given the framework structure, species with the highest vulnerability will be exposed to changes in the environment, will have a high sensitivity to these changes, and will have a low capacity to adapt. There were several factors that made a species vulnerable to climate change. Generally, species that tended to have the highest exposure were those with an estuarine and/or nearshore distribution (e.g. golden snapper, mud crab, mangrove jack), low mobility (e.g. sandfish, black teatfish, banana prawn), and a dependency during critical parts of their life cycle on habitat types more likely to be impacted by climate change (e.g. tiger prawns, sandfish, tropical rock lobster that are dependent on coral reefs and/or seagrass meadows). Those with low exposure tended to have deep water and/or pelagic habitat preferences (e.g. red emperor, scallops, blacktip sharks, billfish) and high mobility (e.g. blacktip sharks, scalloped hammerhead sharks, billfish, spotted mackerel). This is because nearshore shallow areas are directly exposed to changes in most key climate variables that are predicted to change, including rainfall, riverflow, salinity, SST, pH, and include vulnerable habitats such as seagrass meadows and mangroves. Also, more mobile animals are better able to moderate their exposure to environmental changes, particularly during periods of rapidly changing conditions caused by extreme events such as cyclones and floods.

The environmental variables that north-western Australian and Gulf of Carpentaria fishery species are likely to have greatest exposure to in the future are ocean acidification, reduced salinity, increasing SST and altered rainfall/riverflow. The indirect effects of changes in habitats are also likely to be important. The environmental driver likely to be most influential on the east coast is altered riverflow (rainfall) since there is a known positive correlation between riverflow (rainfall) and abundance/growth/catch rates of several fishery species. Rainfall is projected to decrease on the east coast by 0 to 10% by 2030, however due to the likely increase in water extraction this is likely to be closer to the lower end (-10%) or worse. Increasing SST and habitat changes are also likely to be important drivers that will affect fishery species on the east coast.

Species with a high sensitivity tended to be low productivity species (i.e. late maturing, low fecundity) (e.g. scalloped hammerhead, black teatfish, bull shark) and/or have a known reliance on environmental drivers (e.g. for successful recruitment) (e.g. tropical rock lobster, mud crab, barramundi, king threadfin). Species with low sensitivity to future climate change tended to be highly productive (e.g. blue threadfin, Spanish mackerel, tiger prawns) or deep-water species (e.g. red emperor, goldband snapper). It is worth noting that the sensitivity of individual species to particular environmental variables is poorly understood overall. However, where knowledge was relatively good for a particular species they tended to receive a higher sensitivity score, while other species where information was lacking may have received a lower sensitivity score. Expert opinion was incorporated into the assessment process in an attempt to address this potential bias.

Species with a low adaptive capacity tended to be those that are overfished to some degree (e.g. golden snapper, king threadfin, black teatfish, black jewfish), have low productivity (e.g. golden snapper, mangrove jack, bull shark, scalloped hammerhead shark) and have low mobility (e.g. Moreton Bay bug, black teatfish, sandfish). Species with high adaptive capacity tended to be those with high mobility. The full scores for Exposure, Sensitivity and Adaptive Capacity indicators, as well as the direction of impact, for each of the three regions are in Appendix 7.

8.5.2 Individual species vulnerability for 2030

Based on the species reviews and expert opinion, the likely impacts of climate change on key northern Australian fishery species by 2030 are provided in Table 8.33. This table was central in informing the vulnerability assessment and also the scenarios provided to stakeholders for identifying adaptation options that were relevant (see Section 8.6).

There were 23 species included in the ecological vulnerability assessment for north-western Australia based on projected climate change for 2030. The three species with the highest vulnerability were golden snapper, king threadfin and sandfish while mangrove jack also had a high relative vulnerability score (Figure 8.40). The least vulnerable species were the shark species (with the exception of bull shark and pigeye shark) and the pelagic Spanish mackerel and sailfish. Golden snapper are one of the most important recreational species in the Northern Territory where they are at the northern limit of their range in Australia. King threadfin are also relatively important both commercially and recreationally.

In the Gulf of Carpentaria there were 21 species included in the vulnerability assessment for 2030. The species with the highest relative vulnerability were golden snapper, king threadfin, sandfish, tiger prawn, mangrove jack and banana prawn. Similar to north-western Australia the least vulnerable species were sailfish and Spanish mackerel, as well as the blacktip shark (*C. limbatus* only), spot tail shark and scalloped hammerhead shark (Figure 8.41).

On the east coast there were 24 species included in the final vulnerability assessment. Two species had much higher vulnerability scores than any other: black teatfish and king threadfin. Other species that had moderately high vulnerability were sandfish, barramundi, tiger prawn, golden snapper, white teatfish, banana prawn and mangrove jack. The least vulnerable were Moreton Bay bug, spotted mackerel, black marlin and eastern king prawn (Figure 8.42).

Table 8.33 Likely impacts on key northern Australian fishery species based on climate change projections for 2030 (A1B & A1FI).

Species	Key potential effects of climate change (based on 2030 projections)
Banana prawn	• Sea-level rise may increase/decrease abundance due to alteration of mangrove habitat availability, depending on local barriers for mangrove replenishment and migration (e.g. coastal development) (+/-) • Altered rainfall will likely result in concomitant changes in population abundance (slight increase in NWA and GoC, decrease on the EC)(+/-) • Increasing SST will likely result in a poleward distributional shift into NSW waters on the EC (+/-)
Eastern king prawn	• Changes in the EAC and onshore wind patterns may affect larval movement and recruitment (+/-) • Increased SST may result in lower abundance in the SE Queensland region (-) • Increasing SST may result in a poleward range contraction from SE Queensland (-ve for Qld, +ve for NSW)
Tiger prawns (Brown and Grooved)	• Predicted negative impacts on seagrass beds may reduce abundance due to decreased juvenile growth and survival (-) • Increasing SST may compromise growth and survival of Torres Strait stock of brown tiger prawn as they are near their northern range limit (-) • Altered rainfall may affect the catchability of tiger prawns (slight increase in NWA and GoC, decrease on the EC) (+/-)
Mud crab	• Increased SST may result in higher catch rates (+) • Altered rainfall (riverflow) and may increase mud crab abundance in NWA and GoC, and decrease abundance on the EC (+/-) • Sea-level rise may increase/decrease abundance due to alteration of mangrove habitat availability, depending on local barriers for mangrove replenishment (eg. coastal development) (+/-)
Sandfish	• The effects of climate variables on sandfish life history stages are poorly understood. • Predicted impacts on seagrass meadows may affect survival of juvenile sandfish as it is their preferred habitat for settlement.
Saucer scallop	• Increasing SST may result in poleward movement of SE Qld spawning grounds or into deeper water as spawning occurs at the coolest time of year (-) • Lower rainfall in SE Qld may reduce recruitment (-) • Changes in major currents (Leeuwin in WA, EAC on EC) may impact recruitment success (+/-)
Black teatfish	• Increasing SST may compromise reproductive success since they spawn during winter in far northern areas, e.g. Torres Strait, resulting in range contraction poleward (-)

Species	Key potential effects of climate change (based on 2030 projections)
Tropical rock lobster	• Increasing SST may promote faster growth and higher larval supply, but may decrease juvenile survival. The net result may be a reduction in spawning biomass (-) • Adults are likely to move to deeper to less accessible fishing areas or father south with increases in water temperature (and extremes) (-) • Changes in currents in the northwest Coral Sea may alter settlement areas and recruitment rates (+/-)
Barramundi	• Altered rainfall may affect the abundance, growth and catchability of barramundi (slight increase in NWA and GoC, decrease on the EC). A potential increase in the GoC may be offset by proposed water extraction from Gulf rivers for land use (+/-) • Sea-level rise may alter the availability of suitable floodplain nursery areas for post-larvae and juveniles: NWA and GoC (+/-) and EC (-) • Increased variation in rainfall may reduce the frequency of large flood events reducing overall population sizes on the EC. Longer periods of drought predicted for the east coast could significantly reduce barramundi populations (especially periods > ~7 years). This is likely to be exacerbated by increased water extraction for land use (-)
Coral trout – common/barcheek/ passionfruit	• Increases in intense storm activity may periodically reduce the catchability of coral trout (-) • Increased water temperatures (particularly in areas where SST exceeds 30 °C) may reduce survival and development of egg and larval stages resulting in lower population sizes. Adults may also move poleward or to deeper water: In northern regions (-); in southern regions (+) • Increased SST compromising coral reef habitat may affect juvenile survival (-) • Spawning may occur earlier than currently (region-specific) (+/-)
Golden snapper	• Potential range expansion poleward on the east and west coasts (+) • Relationships with climate variables poorly understood however their resilience to future changes may be poor due to their late maturity and overfished status in some areas (-)
King threadfin	• Altered rainfall may affect the recruitment and abundance of king threadfin (slight increase in NWA and GoC, decrease on the EC) (+/-) • Increased SST may result in a range extension poleward on the east and west coasts (+) • Resilience to future changes may be poor due to their large size and older age at sex change (to female) and overfished status in some areas (-) • Localised population impacts may be evident due to their fine scale stock structure (+/-)

Species	Key potential effects of climate change (based on 2030 projections)
Red throat emperor	• Increases in intense storm activity may periodically increase the catchability of red throat emperor (+) • Increasing SST may result in a range shift poleward associated with a contraction of the northern range limit (+/-)
Spanish mackerel	• Increasing strength of the EAC likely to cause a poleward range extension (+ve for SE Qld/NSW & SW WA) • Increasing SST could also cause a poleward shift of the main spawning (and fishery) area on the east coast and/or lower east coast population sizes (+/-)
Mangrove jack	• Altered rainfall may affect the juvenile survival and therefore population abundance; NWA and GoC (+/-) and EC (-) • Sea-level rise may alter the availability of suitable floodplain nursery areas for juveniles: NWA and GoC (+/-) and EC (-)
Black jewfish	• Altered rainfall may affect the juvenile survival and therefore population abundance; NWA and GoC (+/-) and EC (-) however this is poorly understood for this species • Their current overfished status in all regions reduces their resilience to cope with potential negative impacts of climate change (-)
Grey mackerel	• Altered rainfall may affect the juvenile survival and therefore population abundance; NWA and GoC (+/-) and EC (-) however this is poorly understood for this species

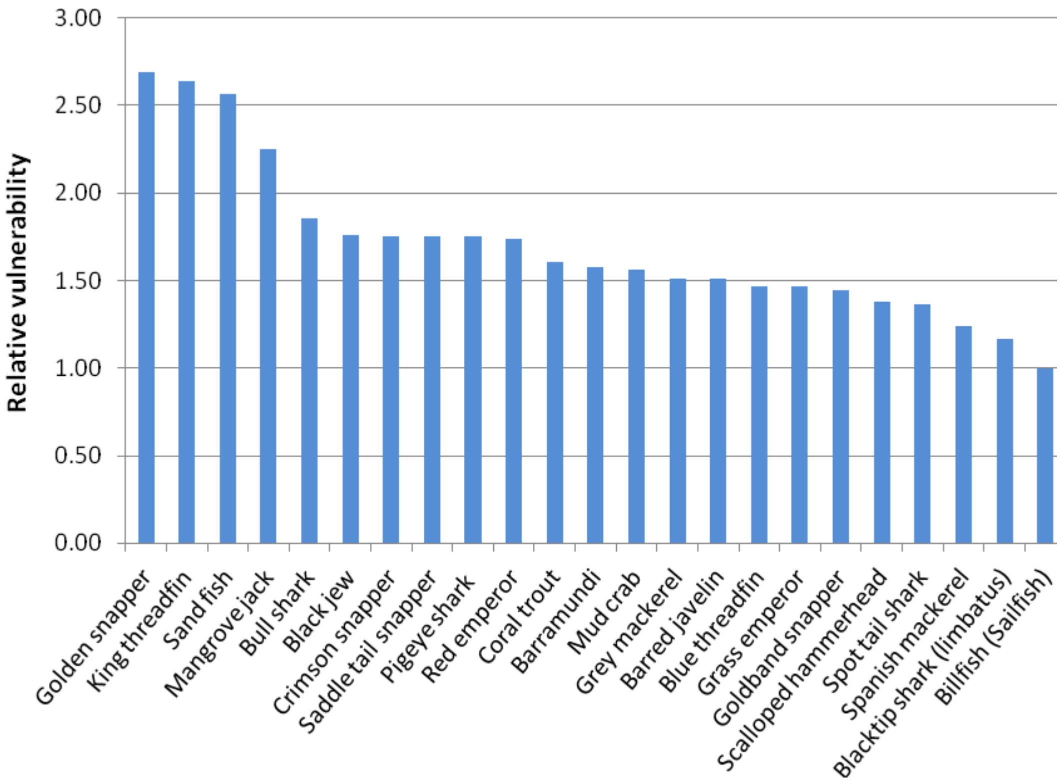

Figure 8.40 Relative vulnerability scores for key fishery species of north-western Australia (2030).

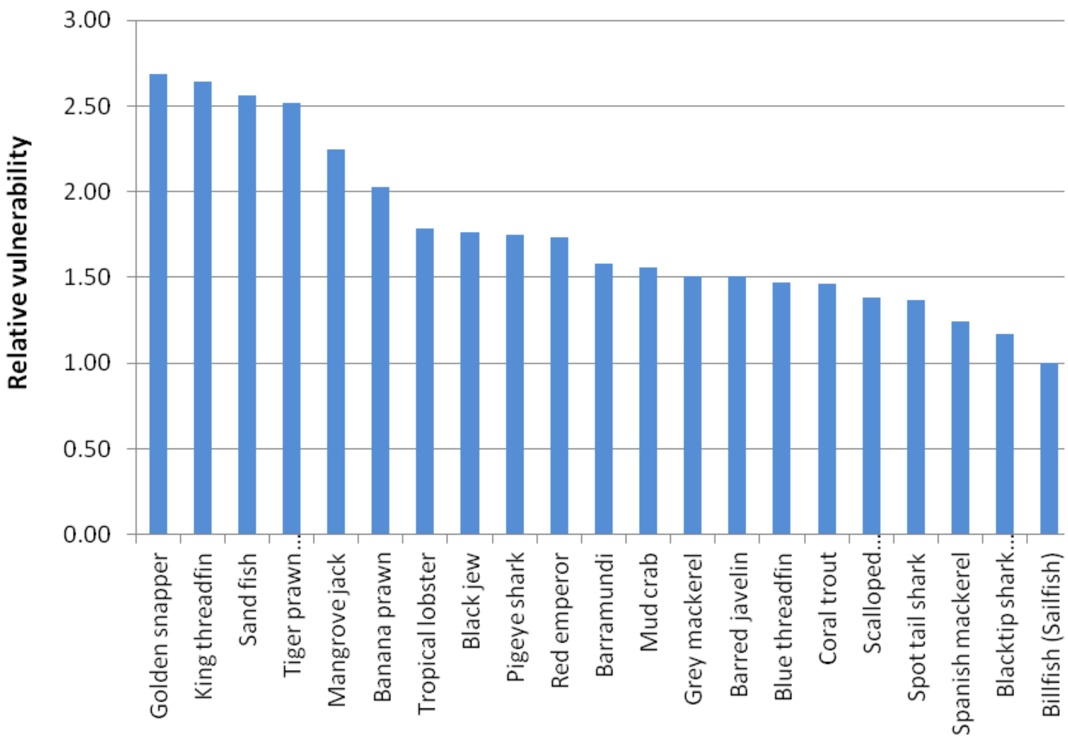

Figure 8.41 Relative vulnerability scores for key fishery species of the Gulf of Carpentaria (2030).

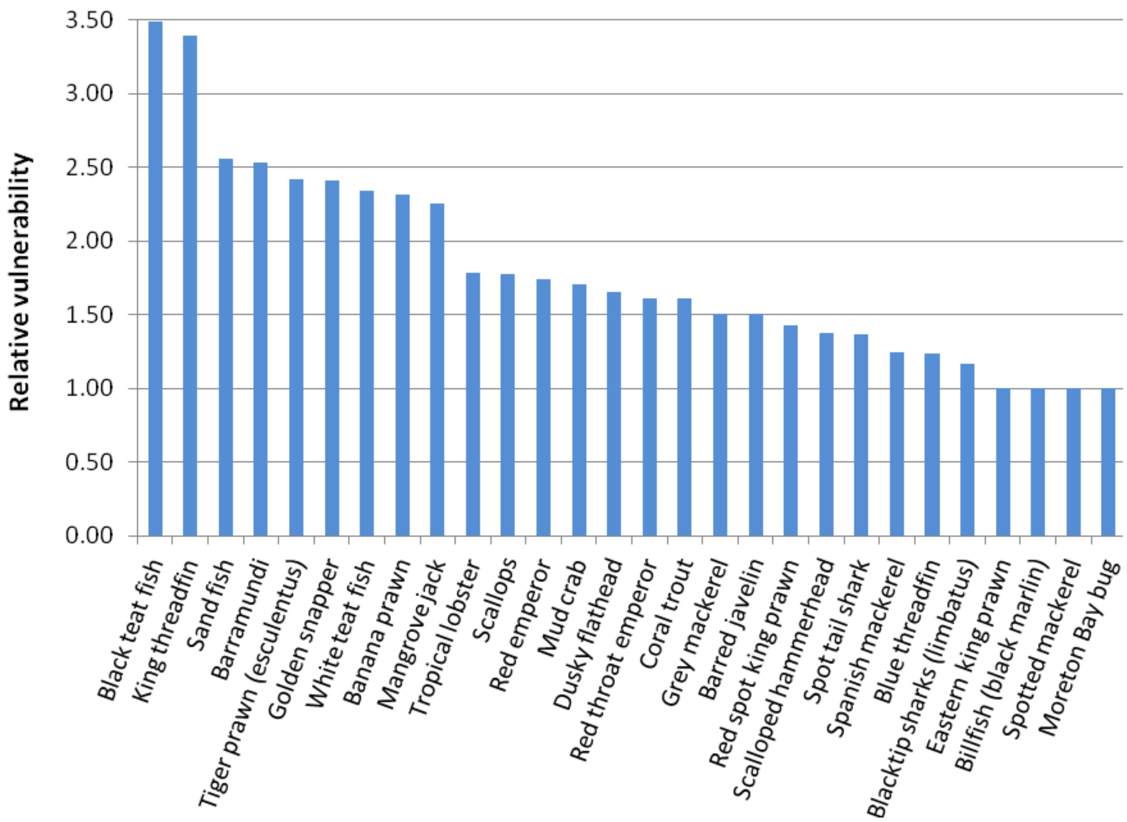

Figure 8.42 Relative vulnerability scores for key fishery species of the tropical east coast (2030).

8.5.2.1 King threadfin

High vulnerability. Similar to golden snapper, king threadfin had very high vulnerability scores in all regions. They have high exposure and low adaptive capacity, but with a relatively higher sensitivity primarily due to their known reliance on riverflow as a driver of recruitment. Compared to golden snapper they have greater replenishment potential overall, notwithstanding their large size and late age at sex change to female, however they are also potentially overfished in some areas suggesting that prudent fisheries management intervention is needed including setting appropriate size limits.

By 2030 the projected increase in rainfall (and riverflow) in north-western Australia and the Gulf of Carpentaria may benefit king threadfin populations. However, the projected increase is small (0 to +5%) and any increase may be offset by future water extraction for land-based use. On the east coast, rainfall (and riverflow) is projected to show a decrease by 2030 (0 to -10%) with water extraction also likely to increase from current levels, possibly resulting in a decrease in king threadfin populations. Given projected increases in SST there is the potential for poleward range extensions on the east and west coasts. Given the recent example in the Brisbane River where king threadfin numbers have increased in recent years and may be linked to improving water quality, any southerly range extension may depend on local estuary water quality characteristics. Monitoring projects such as Redmap (www.redmap.org.au) may help to shed more light on future range extensions of this and other tropical species.

8.5.2.2 Black teatfish

High vulnerability. Black teatfish were only assessed on the east coast where they have historically been the main target species for the east coast sea cucumber fishery on the Great Barrier Reef. However, fishing has been banned since 1999 due to overfishing. Despite this history, their continued high value and demand from SE Asian countries justified their inclusion for the east coast assessment.

Black teatfish had the highest relative vulnerability score for the east coast. Although they are a reef-based species generally found offshore, they are highly exposed to increasing SST and intense cyclones due to their shallow water preferences and low mobility, resulting in moderate exposure. Their overall high vulnerability comes from having high sensitivity to future projected climate change and low adaptive capacity. Black teatfish are strongly associated with coral reef habitats, which are projected to be negatively impacted by 2030, and they spawn in winter so increasing SST may cause animals to cease spawning in northern areas (e.g. Torres Strait/far northern GBR) with a possible poleward range contraction. They have low adaptive capacity due to their low mobility, their status as overfished in the GBR, and an apparent low replenishment potential.

The key fisheries for black teatfish in northern Australia are currently closed due to overfishing, and have been for some time. Given the lack of recovery evident and the outlook based on this assessment, the future of fisheries for black teatfish in Australia is not promising.

8.5.2.3 Golden snapper

High – moderately high vulnerability. Golden snapper had the highest, or near highest, relative vulnerability scores for all three regions. Across northern Australia, and particularly around Darwin in north-western Australia, they represent an iconic and highly sought after target species. They have high vulnerability to projected climate change because they will be highly exposed due to their nearshore habitat preference, and particularly the preference for juveniles (and possibly larvae) to occupy estuaries. They also have very low adaptive capacity because they are experiencing localised overfishing in many areas, have low replenishment capacity (late maturing), and may be subject to non-fishing pressures given their estuarine/nearshore habitat preference.

No studies have explored the importance of environmental variability on the different life history stages of golden snapper, somewhat hindering the ability to confidently score assessment indicators. Given projected increases in SST there is the potential for poleward range extensions on the east and west coasts, although the availability of preferred habitats may be a limiting factor. Given their overfished status in some areas prudent fisheries management intervention is needed especially the implementation of appropriate size limits. Maintenance of healthy nearshore/estuarine habitats is also likely to be critical for golden snapper and many other key fishery species.

8.5.2.4 Sandfish

High – moderately high vulnerability. Sandfish also had a high vulnerability in all three regions. Their level of harvest has historically been variable across northern Australia however they are targeted in all regions, being the predominant species (historically) in the Northern Territory and Western Australia. They are highly exposed to environmental changes because they have a nearshore/shallow water habitat preference. They have moderate sensitivity to environmental changes and very low adaptive capacity. Sandfish juveniles rely on seagrass meadows for settlement and feeding, which has implications for the species since seagrass habitats are predicted to decrease in area by 2030. This is likely to have a knock-on effect reducing sandfish populations. Their low adaptive capacity is influenced by their low mobility but also by the fact that they are locally overfished in some areas (e.g. Torres Strait) and have a low replenishment potential.

Generally, very little is known about the effects of climate variability on sandfish populations. Given their shallow nearshore habitat preferences, increases in SST, ocean acidification and reduced salinity may negatively impact on larval development of sandfish (and other sea cucumbers) however the time horizon for such effects are uncertain. Management options are for the conservation and rehabilitation of seagrass habitat.

8.5.2.5 Tiger prawn

High – moderately high vulnerability. Tiger prawns are comprised of two species: the brown tiger prawn and the grooved tiger prawn. The brown tiger prawn is the dominant species and so was the focus of this assessment. Tiger prawns were not assessed in north-western Australia where fisheries don't operate. They represent a key species in the Gulf of Carpentaria Northern Prawn fishery (along with banana prawns) and in the east coast trawl fishery. Tiger prawns were assessed as highly vulnerable to climate change by 2030 in the GoC and moderately highly vulnerable on the east coast. This is mainly due to the fact that they have very high exposure to almost all environmental variables predicted to change, as well as changes in seagrass habitats, which provide critical habitat during the juvenile life history stage. Tiger prawns are only moderately sensitive to environmental change mainly due to their high productivity and rapid rate of population turnover, however their reliance on seagrass meadows as juveniles means that likely impacts on seagrass will reduce juvenile growth and survival and ultimately reduce tiger prawn population sizes. Obvious management options involve the conservation and rehabilitation of seagrass habitats, particularly as they serve as important nursery areas for many other fishery species.

8.5.2.6 Mangrove jack

Moderately high vulnerability. Mangrove jack were assessed as having moderately high vulnerability to climate change, due to their moderately high exposure and sensitivity, and moderately low adaptive capacity. They will be highly exposed due to their nearshore and estuarine habitat preference during the critical juvenile phase. They have a similar life history to golden snapper and are therefore sensitive to environmental changes for similar reasons, although their reliance on environmental drivers for spawning/settlement increases their sensitivity. They have higher adaptive capacity than golden snapper as they are not considered overfished and the availability of suitable habitat outside their current range is very high. The likely impacts of climate change on mangrove jack are unknown due to a lack of relevant research.

8.5.2.7 Barramundi

Moderate – High vulnerability. Barramundi were assessed as moderately vulnerable in north-western Australia and the Gulf of Carpentaria, and as highly vulnerable to climate change on the east coast. Overall, barramundi will be highly exposed due to their nearshore and estuarine habitat preference, particularly given their close association with river systems at all life history stages. They tend to be adaptable to changes and have been shown to have a wide thermal tolerance (Jerry et al. 2014), however have a known strong reliance on rainfall (and associated linkages: riverflow, flood plain inundation, higher nutrient levels/food availability) as a trigger for spawning but also for downstream movement of adults and upstream movement of juveniles into floodplain areas. Riverflow also influences growth rates and fishery catch rates all of which may be enhanced in north-western Australia and the GoC by projected slight increases in rainfall. Further, increased rainfall and rising sea level may increase the availability of important flood plain habitat that would enhance juvenile survival. However, this will be dependent on local factors such as coastal development and topography, which may prevent landward migration of habitat as sea level rises, and the extent of water extraction for land use.

Although their ecological adaptive capacity is generally high, they have a high dependence on riverflow (rainfall) for growth, and for facilitating juvenile survival as recruits to the next generation. Riverflow also enhances fishery catch rates. Barramundi vulnerability in the three regions across northern Australia is largely influenced by regional projections in rainfall (riverflow). Rainfall is projected to decrease on the east coast and water extraction is projected to also increase, exacerbating a future of lower riverflow. Further, coastal development on the east coast is far more progressed than in other parts of northern Australia and is likely to limit any positive effects of sea-level rise on flood plain inundation.

On the east coast, localised impacts on barramundi populations into the future could be significant.

8.5.2.8 White teatfish

Moderately high vulnerability. White teatfish have a similar life history to black teatfish, however they were assessed as being less vulnerable to climate change due to several factors. Firstly, white teatfish are likely to be less exposed due to a preference for deeper reef slopes. White teafish are not a winter spawner and so are less likely to be sensitive to increasing SST. Their adaptive capacity is likely to be greater, since they are not overfished and remain a target species in the Great Barrier Reef sea cucumber fishery. Despite this, the effects of climate change on white teatfish are poorly understood and their close association with coral reefs and low mobility contribute to their assessment as moderately high vulnerability.

8.5.2.9 Banana prawn

Moderately high vulnerability. Possible opportunity species. Banana prawns were assessed in the Gulf of Carpentaria and on the east coast where they have a moderately high vulnerability. Like many other prawn species, banana prawns have a high exposure to most of the key environmental variables that are projected to change. Their sensitivity is higher than other prawns however largely due to their known reliance on rainfall for recruitment. In years of high rainfall (and high riverflow) banana prawn recruitment and catches are greater. Further, banana prawns use mangroves as important juvenile habitat. Projected sea-level rise impacts on mangroves vary by region, depending on local topography and coastal development. Although mangrove habitat areas may shift inland from current locations, it is unlikely that the total habitat area will increase and in some areas may decrease depending on barriers to migration. It is possible that there will be an increase in banana prawn population sizes by 2030 in the Gulf of Carpentaria due to increased mangrove habitat, and predicted slight increases in rainfall that will not only enhance recruitment but also catchability. On the east coast however, there is more likely to be a decrease in banana prawn populations by 2030 due to lower rainfall and the higher likelihood that mangrove habitat area will decrease due to sea-level rise and coastal development.

8.5.2.10 Mud crab

Moderate vulnerability. Possible opportunity species. Mud crabs are widespread across tropical and sub-tropical Australia and are popular target species throughout this range. They were assessed as being moderately vulnerable to climate change by 2030 in all three regions. Mud crabs have high exposure mainly due to their preference for shallow nearshore/estuarine environments. They also have high sensitivity meaning the potential impacts of climate change on populations could be high. Although they are not very mobile they can be highly productive and have a very wide range across northern Australia giving them moderately high adaptive capacity.

By 2030 mud crab populations in north-western Australia and the Gulf of Carpentaria are likely to benefit from increased rainfall (and riverflow), and increased SST that is likely to enhance growth rates and fishery catch rates. Mud crabs have been shown to use both seagrass meadows (crablet stage) and mangrove forests (juvenile stage) during their early life history. Increases in sea level will probably increase the availability of mangrove habitat in the GoC, potentially resulting in larger mud crab population sizes. This may be negated in areas where local coastal development restricts mangrove migration. On the east coast, increasing SST is also likely to enhance mud crab growth and fishery catch rates. However, increases in sea level will potentially decrease the availability of mangrove habitat in some areas, and lower rainfall (riverflow), exacerbated by greater water extraction for land use, will likely offset any positive effects on populations and may result in lower population sizes by 2030.

The management implications for this in northern Australia are that fishery catches may be greater in the Gulf of Carpentaria and north-western Australia, while on the east coast it may remain similar or lower depending on local rainfall patterns. One of the key unknowns is the effect that ocean acidification will have on mud crabs. This has the potential to significantly impact on crab development and survival at all life history stages. This makes mud crab one of the high priority species for investigating the effects of lowered ocean pH.

8.5.2.11 Coral trout

Moderate vulnerability. Coral trout were assessed as being moderately vulnerable to climate change by 2030. This is mainly because, as a primarily offshore and sometimes deep-water species, they are less exposed to environmental change compared to shallow nearshore species. They are also a highly productive species, relatively mobile and have a wide distribution. Despite these attributes and this assessment, the vulnerability of coral trout to climate change beyond 2030 is likely to be greater. Recent research has highlighted that SST above 28°C negatively impacts on the development of early life history stages (Pratchett et al 2013). Coral trout may be able to adapt to this by spawning earlier than they do currently, however northern-most populations are likely to be affected in the medium-term as this critical temperature threshold is reached (see Pratchett et al 2013). Coral trout also use coral reefs as key habitats throughout their life history stages. Coral reef habitats are predicted to be impacted by 2030, which is likely to have indirect impacts on coral trout populations due to the reduced availability of preferred juvenile habitat that is likely to reduce juvenile survival (Pratchett et al 2013). Increased intensity of cyclones is likely to result in more frequent periods where catchability is reduced (Tobin et al 2010). Although from an ecological perspective this is not likely to be a threat to coral trout, from a fishery perspective this would have significant economic and social impacts due to the high reliance on operations specialised for live product. Increasing acidification will also impact coral trout populations through lower survival of juveniles (Munday et al 2012), however the pH levels at which this is likely to occur will not be evident until later this century. One of the key research questions this raises is the capacity of coral trout to adapt to altered conditions (e.g. elevated SST) in the future. The interesting and surprising result of acidification on coral trout early development and survival also raises questions of how other species may be affected by pH. Similar research to that by Pratchett et al (2013) on acidification should be carried out on other key fishery species.

Given the potential impacts identified for coral trout, and the highly targeted nature of the fishery, future fishery operations may need to be diversified in terms of target species. Coral trout are likely to remain in demand throughout south-east Asia, however in the event of lower supply potential other less valuable species will need to be considered. The profitability of fishing businesses would also suffer unless operational costs can be reduced using, for example, cheaper fuel options. Given the importance of this fishery to all sectors, on the Great Barrier Reef in particular, fishery-specific in depth analysis of adaptation options with stakeholders is warranted.

8.5.2.12 Tropical rock lobster

Moderate vulnerability. Tropical rock lobster (TRL) was assessed in the Gulf of Carpentaria and the east coast and was moderately vulnerable. They are highly exposed to climate change by 2030 mainly because they use both coral reefs and also nearshore habitats, and have relatively low mobility. Although their overall sensitivity to environmental change is low, they are highly sensitive to increases in SST. In far northern areas of their range (e.g. Torres Strait) TRL already show a response to warm ocean conditions by moving into deeper water, with negative consequences for fisheries. They may also begin to range shift further south. From a fishery perspective, there are no comparable alternative species given the market price and demand for rock lobster and the high degree of gear and fishing technique specialization. Managing the fishery to mitigate these types of potential impacts is difficult, however fishery participants in the Torres Strait in particular should be consulted regarding potential implications of climate change and future actions.

One of the key unknowns that may impact on TRL populations, is the effect climate change will have on ocean circulation in the western Coral Sea (Coral Sea gyre). Given the role this current plays in the transport of larvae and the duration of oceanic larval development, recruitment of TRL to Australian waters could be impacted significantly. Improved understanding of the likely future ocean circulation in the north-western Coral Sea is therefore important future research needed.

8.5.2.13 Saucer scallops

Moderate vulnerability. Scallops were assessed on the east coast only since this region has an important fishery operating in a narrow area of south-eastern Queensland with saucer scallop the major target species. They are found in relatively deep water in offshore sandy habitats and for this reason have a low exposure to environmental changes. They are moderately sensitive to environmental changes, which is influenced by their likely reliance on certain environmental conditions for successful recruitment. This appears to be quite complex, as evidenced by the exhaustive analyses on this species carried out during this project, with SST, local currents and local riverflow (rainfall) potentially important. Cooler SST appears to favour high recruitment and so increasing SST over time may have the effect of reducing the population and/or causing a poleward range shift into NSW waters and/or populations moving deeper in south-east Queensland. Riverflow also appears to have a positive effect on recruitment, probably through increased nutrient loads and therefore food availability at the critical early life history stages. Projections of lower rainfall on the east coast may therefore be detrimental to scallop populations. The annual presence of a cyclonic current eddy in the Capricorn region was also shown to positively influence scallop recruitment. It was not clear from the analyses however, how important the timing of this eddy is, and the effects of climate change on local current patterns are poorly understood. A better understanding of this through hydrodynamic modelling would be useful research as any changes in local current patterns could significantly affect scallop recruitment. In the meantime, continued monitoring of annual recruitment and catch in the fishery will help to detect any changes in the future such as those postulated here.

8.5.2.14 Bull shark/Pigeye shark

Moderate vulnerability. Bull shark were not initially identified as being a key fishery species in northern Australia, however since the project inception it has been discovered that at least half (approximately) of the NT pigeye catch is actually bull shark. Bull shark was therefore included in the vulnerability assessment for north-western Australia. Of all the shark species assessed bull shark and pigeye sharks had the highest vulnerability with the rest having low vulnerability. Although moderately exposed, largely due to their close association with estuarine and/or nearshore habitats, and with a high adaptive capacity, both species have a high sensitivity to climate change. This is largely due to their very low productivity, typical of many elasmobranch species, but also because they use nearshore and estuarine waters as important pupping habitat, probably as feeding and predator avoidance strategies. Bull shark in particular use estuaries and upper reaches of rivers as juvenile areas. Continued monitoring of the relative catch of each species is therefore warranted as well as management consistent with low productivity species.

8.5.2.15 Spanish mackerel

Low vulnerability. Possible opportunity species. Spanish mackerel are important in all regions of northern Australia and were consistently assessed as having low vulnerability to future climate change. They have a moderately high exposure, mainly due to their use of nearshore habitats during much of their life, and the use of estuaries by juveniles. To offset this exposure they have moderately low sensitivity and high adaptive capacity. Spanish mackerel are highly productive and mobile with a range of habitat preferences and bait types making them less vulnerable overall relative to other species. The key important drivers are likely to be increased SST and possibly changing currents and rainfall. Higher SST may result in smaller population sizes of Spanish mackerel in eastern Australia, since the preliminary analyses conducted during this project suggest higher recruitment at lower spawning temperatures. It may also result in a later onset of spawning or a poleward shift of the east coast spawning (and fishery) grounds. Similar impacts are possible on the west coast are likely as SST increases. This could also mean lower population sizes in the future for Gulf of Carpentaria and Northern Territory fisheries.

The effect of rainfall and riverflow on recruitment was also investigated but produced equivocal results, however given juveniles spend several months in estuaries rainfall is likely to have some influence on recruitment. Increasing SST, along with the projected strengthening of the East Australian Current, will likely result in a poleward range extension. This would result in longer fishing seasons and higher catches in south-east Queensland and NSW, providing a potential opportunity for these fisheries. This presents management implications that involve better inter-jurisdictional co-operation and should at least involve close monitoring of catch levels in these regions over the coming years. It may also require a review of current management arrangements in NSW. Future research should assess the relationship between the strength of the East Australian Current and catches in SE Queensland and NSW.

8.5.2.16 Grey mackerel

Moderate vulnerability. Grey mackerel are a very important fishery species in all three regions and were assessed as being only moderately vulnerable to climate change by 2030. They have a moderately high exposure largely due to their nearshore habitat preferences and because juveniles prefer estuarine systems. Unusually, their distribution at certain times of the year is unknown, on the east coast in particular, making the assessment of exposure slightly uncertain. Their sensitivity is low, largely because it is poorly understood and it is highly possible that populations are influenced by rainfall (riverflow) events given larvae develop in nearshore areas and juveniles occupy estuaries during the annual wet season. For the east coast, where they have been community concerns in recent times about their sustainability, this may result in lower population sizes of grey mackerel by 2030 and beyond. Although commercial catch limits were introduced in Queensland recently, these results suggest careful monitoring of population levels into the future. ON a positive note, they are a species with high adaptive capacity due to their high productivity and high mobility. Although it is a reasonable assumption that grey mackerel recruitment is influenced by riverflow, as has been demonstrated for several other species with similar habitat use during their life histories, future research efforts should attempt to demonstrate this relationship.

8.5.2.17 Black jewfish

Moderate vulnerability. Black jewfish were assessed in north-western Australia and the Gulf of Carpentaria, where they are targeted by fisheries, primarily recreational. They have moderately high exposure because they occupy nearshore and estuarine habitats throughout their life. Their sensitivity was assessed as moderate however this is largely due to the fact that there is a very poor understanding of the influence of environmental variability on black jewfish population dynamics. Given that they occupy nearshore areas and juveniles live in estuaries, rainfall and riverflow are likely to be important drivers. This could mean a positive impact of climate change in the regions assessed. Black jewfish also have moderate adaptive capacity, despite being assessed as overfished across all areas of northern Australia, suggesting prudent fisheries management intervention is needed. Future research should focus on the importance of environmental variability on the life history stages of black jewfish.

8.5.3 Prioritising species for action

Due to the greater uncertainty in climate projections beyond 2030 (largely due to the unknown global response to reduce carbon emissions), and also in the responses of fishery species to the changes that do occur, we focused on the 2030 vulnerability assessment results for prioritising species for action. This near-term time frame is also more meaningful for all stakeholders in terms of making decisions based on these results. Actions in response to the below prioritisation will need to depend on the species and their particular attributes that make them vulnerable. For example, species that were considered to be overfished in these assessments (based on previous assessments and stakeholder views) would be obvious candidates for fisheries managers to review current harvest rates. Actions taken will vary and could include increased and/or introduction of fishery monitoring, revision and/or adjustment of current fisheries management, or changes in fishery targeting and/or operations.

Prioritisation of species from north-western Australia highlighted four species as highest priority: king threadfin, golden snapper, sandfish, and mangrove jack (Figure 8.43). King threadfin and golden snapper are currently key fishery target species in north-western Australia, while sandfish and mangrove jack are less targeted. King threadfin and golden snapper therefore stand out as key species for action in this region.

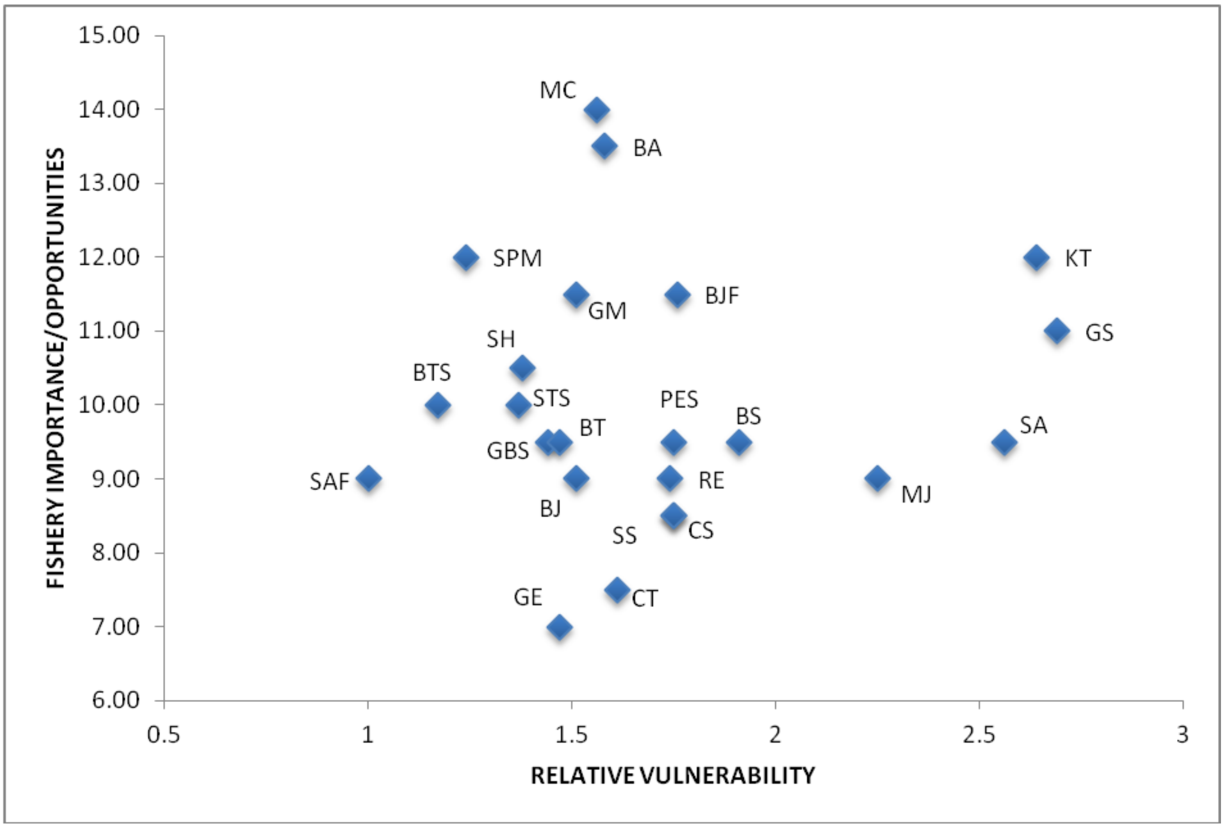

Figure 8.43 Relative vulnerability plotted against the level of fishery importance to assist managers and other fishery end-users in prioritising species for future action – north-western Australian species**. High vulnerability and high fishery importance species are the highest priority (top right of the graph). Species codes are: GS – golden snapper, KT – king threadfin, BJF – black jewfish, SA – sandfish, MJ – mangrove jack, CT – coral trout, GM – grey mackerel, SPM – Spanish mackerel, MC – mud crab, BA – barramundi, RE – red emperor, BT – blue threadfin, BJ – barred javelin, BS – bull shark, PES – pigeye shark, STS – spot tail shark, GE – grass emperor, CS – crimson snapper, SS – saddle tail snapper, SAF – sailfish, GBS – goldband snapper, SH – scalloped hammerhead shark, BTS – blacktip shark.**

Prioritisation of species from the Gulf of Carpentaria also highlighted four species as highest priority: king threadfin, tiger prawn, golden snapper, and banana prawn (Figure 8.44). King threadfin are a key target species for both commercial and recreational fishery sectors as well as having high vulnerability to climate change by 2030. While tiger prawns and banana prawns are the mainstay species of the economically important Northern Prawn fishery as well as having high-moderately high vulnerability. King threadfin, tiger prawns and banana prawns therefore stand out as key species for action in this region. Golden snapper, although having high vulnerability, are less targeted in the GoC and therefore considered of relatively lower priority, although it should be highlighted that they were assessed as overfished for this region.

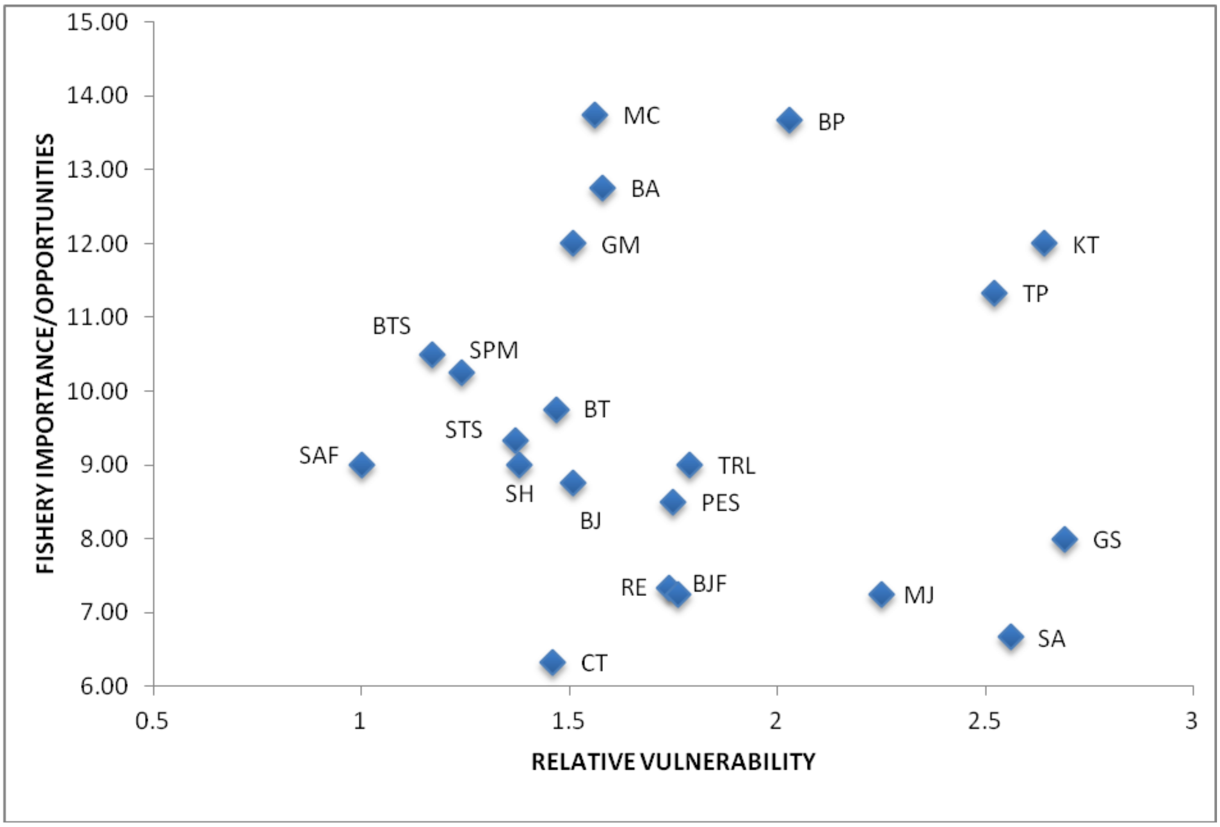

Figure 8.44 Relative vulnerability plotted against the level of fishery importance to assist managers and other fishery end-users in prioritising species for future action – Gulf of Carpentaria species**. High vulnerability and high fishery importance species are the highest priority (top right of the graph). Species codes are: GS – golden snapper, KT – king threadfin, BJF – black jewfish, SA – sandfish, MJ – mangrove jack, CT – coral trout, GM – grey mackerel, BP – banana prawn, TP – tiger prawn, SPM – Spanish mackerel, MC – mud crab, BA – barramundi, RE – red emperor, BT – blue threadfin, BJ – barred javelin, PES – pigeye shark, STS – spot tail shark, SAF – sailfish, SH – scalloped hammerhead shark, BTS – blacktip shark, TRL – tropical rock lobster.**

Prioritisation of species from the east coast highlighted five species as highest priority: king threadfin, black teatfish, barramundi, tiger prawn, and banana prawn (Figure 8.45). All five of these species are important fishery species, however, the fishery for black teatfish has been closed since 1999 and is still closed due to their overfished status. There is still a high demand for this high value species and therefore this assessment process, if nothing else, highlights the importance of maintaining the current fishery closure and the need to monitor for evidence of any recovery. Barramundi and the two prawn species represent important fishery species both economically, and also socially in the case of barramundi. These three species therefore stand out as key species for action in this region. King threadfin are more important at local levels on the east coast, particularly in the Fitzroy River region near Rockhampton, and therefore are relatively lower priority.

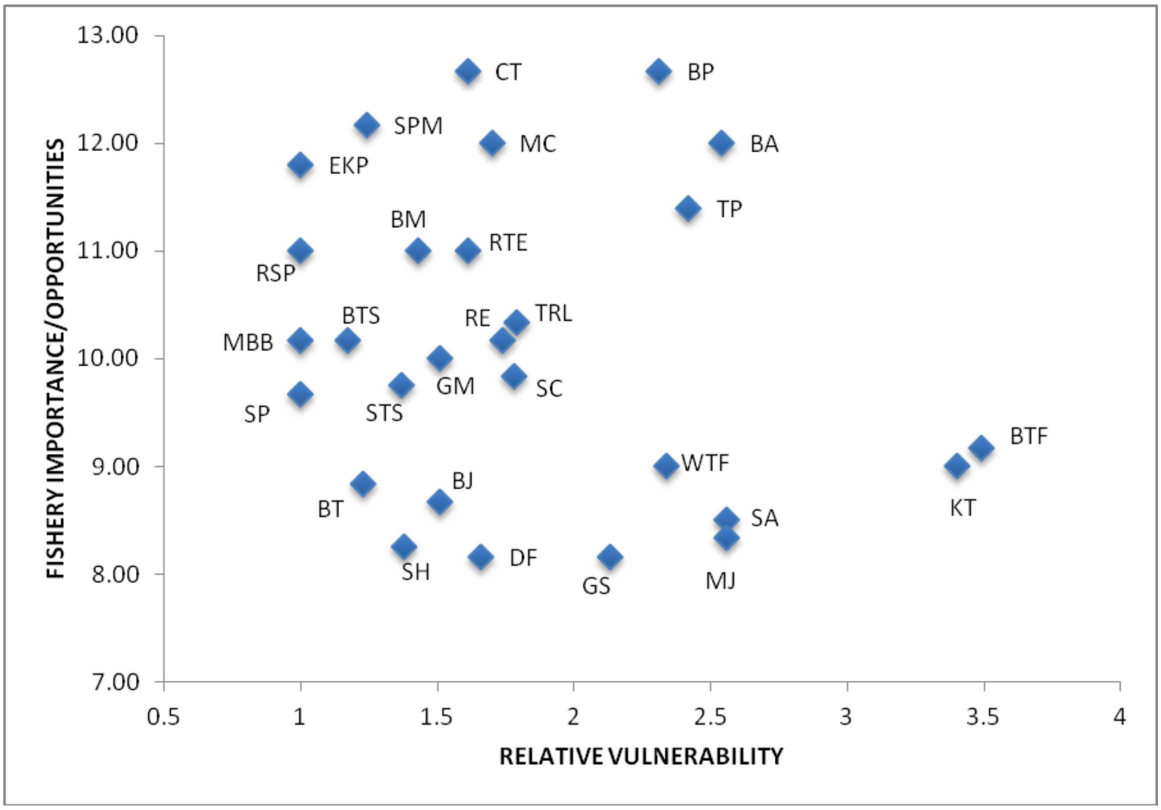

Figure 8.45 Relative vulnerability plotted against the level of fishery importance to assist managers and other fishery end-users in prioritising species for future action – east coast species**. High vulnerability and high fishery importance species are the highest priority (top right of the graph). Species codes are: GS – golden snapper, KT – king threadfin, SA – sandfish, MJ – mangrove jack, CT – coral trout , GM – grey mackerel, BP – banana prawn, TP – tiger prawn, SPM – Spanish mackerel, MC – mud crab, BA – barramundi, RE – red emperor, BT – blue threadfin, BJ – barred javelin, STS – spot tail shark, SH – scalloped hammerhead shark, BTS – blacktip shark, TRL – tropical rock lobster, DF – dusky flathead, WTF – white teatfish, BTF – black teatfish, SP – spotted mackerel, SC – saucer scallop, RTE – red throat emperor, EKP – eastern king prawn, BM – black marlin, RSP – red spot king prawn, MBB – Moreton Bay bug.**

8.5.4 Vulnerability assessments for 2070

The vulnerability assessments for 2070 were based on one future SRES emissions scenario: A1FI. This is the highest future emissions scenario and was chosen for two reasons. Firstly, the most recent assessment (IPCC 2013) shows that emissions are trending at or above the A1FI (high) emissions scenario, and secondly, the differences in relative species vulnerability between the high (A1FI) and low (A2/A1B) emissions scenarios were only slight.

Rather than present the relative vulnerability scores for each species based on 2070, below we highlight and discuss the species assessed as likely to be most impacted based on known or inferred environmental thresholds being exceeded. Thresholds for fishery species in northern Australia are not well known with any certainty for the vast majority of species. Where we do have reasonable information on likely thresholds for species, whether documented or inferred, we can make comments on the likely time frames for these being exceeded and the likely consequences. This does not mean that there are other species that will not be impacted by climate change to the same or even greater extent. Indeed, the vast majority of species assessed for their vulnerability in 2070 were assessed as having "Physiological thresholds unknown". It should also be noted that the likely impacts presented on species by 2030 (Table 8.33) continue to be relevant and are likely to be heightened given continuing trends in the projections for climate variables. There were two species in north-western Australia that were assessed to exceed thresholds by 2070, three in the Gulf of Carpentaria, and seven on the east coast (a total of seven different species overall).

8.5.4.1 Sea cucumbers (sandfish, black teatfish, white teatfish)

All three species of sea cucumber were assessed to exceed particular thresholds by 2070. The key impact on all species is likely to be due to a decrease in pH, which will compromise larval development and survival with potentially catastrophic impacts on populations. Increasing SST will likely cause the spawning season of sandfish to increase, however any benefit of this may be counteracted by a decrease in pH. The effects of ocean acidification on all life history stages of sea cucumber species are highly uncertain however, and are an area of high priority research. The projected increases in SST by 2070 mean that black teatfish populations are not likely to be viable in far northern areas, such as Torres Strait and the far northern Great Barrier Reef, because they prefer shallow water and are a winter spawning species. Black and white teatfish are dependent on coral reef habitats while sandfish are dependent on seagrass meadows. These two habitats are projected to be degraded by 2070 with unknown, but likely negative, consequences for populations of these and other sea cucumber species.

8.5.4.2 Coral trout

The assessments for coral trout are based on knowledge of thresholds for *P. leopardus*, the most common and widespread coral trout species across northern Australia. By 2070 the projected increase in SST will have deleterious effects on the early life history stages. Temperatures above 28 °C will reduce fertilisation rates, hatching rates, larval feeding and development rates, and ultimately will reduce larval survival (Pratchett et al. 2013; see coral trout review in Part 2 companion report). Further, northern populations are as sensitive to thermal changes as southern populations so impacts will be seen first in populations in north-western Australia, the Gulf of Carpentaria, Torres Strait and the northern GBR (Pratchett et al. 2013). Coral trout populations in northern Australia will need to spawn earlier in the season to correspond with SST regimes that are suitable for successful larval survival or there will be much lower population sizes in these regions. It is also possible that by 2070 the negative effects of ocean acidification on juvenile survival demonstrated experimentally (Munday et al. 2012), will manifest. Further, coral reefs are projected to be degraded by 2070 and this will also have negative consequences for post-settlement coral trout.

8.5.4.3 Tropical rock lobster

The main fishery region for tropical rock lobster (TRL) in northern Australia is Torres Strait and in the northern part of he GBR. With recent warmer than usual SST being experienced in several parts of northern Australia (and elsewhere) TRL have been observed to move to deeper cooler parts of coral reefs. It is not well understood what ecological and/or physiological impacts higher SST may have on TRL, however from a fishery perspective the catchability of TRL will be reduced with impacts on fishers. By 2070 ocean acidification and local currents in the north-western Coral Sea could have serious ecological consequences for TRL however, as stated earlier, these are poorly understood in relation to TRL.

8.5.4.4 Saucer scallops

Saucer scallops are taken in only a narrow latitudinal range in southeast Queensland and by 2070 increasing SST are likely to have exceeded their tolerance level, especially since they spawn at the cooler time of year. It may be that scallop populations will shift their range poleward into NSW, or into deeper waters, however this will depend on the availability of local habitat and possibly hydrological characteristics, which appears may also affect successful recruitment.

8.5.4.5 Red throat emperor

Red throat emperor, like saucer scallops, has a narrow latitudinal range on the GBR and SST has been shown to influence movement and catchability (Tobin et al. 2010). Given that they have a preference for coral reefs it is highly possible that increases in SST by 2070 will result in less of a poleward range shift but more of a shift into deeper waters adjacent to the GBR, a habitat they are currently known to occupy. As a consequence of this it is unlikely that there would still be a targeted fishery for this species on the GBR, unless modifications to fishing operations are made.

The project has identified the fishery species of northern Australia that are likely to be most vulnerable to climate change, documented the likely impacts on the key species, and has analysed the reasons for their vulnerability. This provides the basis for what actions are appropriate for these species, whether they be filling information gaps through research, or for industry and/or managers to take action in preparation for the likely changes to fishery species (adaptation options; Section 8.6.2). Further, the project has prioritised species so that the next steps focus on species that are not only likely to experience impacts from climate change but also those that represent the most important socially and/or economically to the people of the different regions in northern Australia.

8.6 Identifying adaptation options

8.6.1 Fisher observations

During the adaptation workshops held with fishing industry members in Darwin and Townsville, we asked participants to convey any changes they had observed over time that related to specific species or to the environment in general. The results of this are given in Tables 8.34 and 8.35 for Darwin and Townsville respectively. The observations from the Darwin workshop relate to Northern Territory including the Gulf of Carpentaria, while observations from the Townsville workshop relate to the east coast.

In general, many of the observations noted are known about but are not well documented, if at all. This is often the case with anecdotal information however in some cases they provide examples of potential impacts, previously documented in this report, that may occur by 2030 or may already be occurring. Without robust monitoring in place, anecdotal reporting is potentially one of the key early warnings for the detection of impacts on fisheries from climate change (or other causes). Stakeholder surveys into the future are likely to be a cost-effective and informative fisheries monitoring tool and should be encouraged.

Table 8.34 Observed fishery changes identified by fishery stakeholders at the Darwin workshop and relating to the Northern Territory, including the Gulf of Carpentaria.

Observation	Attributed cause	Knowledge of observation
In the past 10-20 years there has been increasing saltwater inundation of freshwater floodplains	Sea-level rise	Known. Documented
In some years (more recently) black jewfish spawn in the middle of the year; something very unusual historically	Unknown	Known? Not documented
Poor years for barramundi and mud crab can be attributed to years of lower rainfall	Lower rainfall	Well documented for both species
This year (2013) was a poor banana prawn season	Poor wet season	Relationship well documented
Species preferences for golden snapper and black jewfish commercial fishing has shifted from golden snapper to jewfish	Less golden snapper & increased value for black jewfish (e.g. selling swim bladders)	Known. Not well documented
Fewer sandfish	Too much fishing effort	Not documented. No surveys but shifts in spatial effort in commercial fishing observed

Table 8.35 Observed fishery changes identified by fishery stakeholders at the Townsville workshop and relating to the east coast.

Observation	Attributed cause	Knowledge of observation
Destruction of habitats in recent years (mangroves/seagrass inshore, coral reef shoals offshore). Will decrease tiger prawn/mud crab/red emperor recruitment potentially for many years	Cyclones	Habitat damage is known and documented; impacts have not unequivocally been established
In recent years water temperatures inshore have been too high for large Spanish mackerel	Higher SST	Not known and not yet established
Mackerel, grunters and red snapper are spawning earlier than they used to	Higher SST	Not documented
Baitfish in the southern Great Barrier Reef are less abundant than they used to be	Unknown	Not documented
A lack of longtail tuna coming inshore in recent years	Unknown	Known. Not documented
This year juvenile billfish appeared in Bowling Green Bay in August; earlier than usual and the most in 7 years	Unknown	Known. Not documented

8.6.2 Adaptation options to future scenarios

In the workshop session's stakeholders identified a range of adaptation options based on future impact scenarios derived from the species reviews, data analyses and vulnerability assessments (see Table 8.33 for a summary of potential impacts). These adaptation options were listed as either autonomous or planned. Autonomous adaptation options are changes made by industry based on changed situations within their relevant industry space and are a reactive response to change. For example, with changes in the timing of a target species aggregating on fishing grounds fishers will adapt simply by targeting the fish when they do arrive at the fishing grounds; they change their fishing practices as necessary. Planned adaptation is a more deliberate action taken with pre-planning based on an awareness or anticipation of changing conditions and can include policy changes, business restructuring, altered fishing practices/gear, fish stocking or habitat restoration (e.g. Creighton et al 2013). For each of the adaptation options identified, stakeholders were also asked to consider the potential barriers or challenges to implementing each option. The complete tables of potential impact scenarios and the adaptation options for the Darwin and Townsville workshops are provided in Appendix 8 with summaries presented below.

The types of autonomous adaptation options identified from both workshops are given in Table 8.36. The list of autonomous adaptation options are the types of actions that fishers already take as part of their routine fishing activities depending on season, species availability/catch rates, weather, and market prices. Both the commercial and recreational fishing sectors have always used these options, however, for the commercial sector there is an underlying economic cost factor in their decision-making. In making these decisions, the commercial sector relies on flexibility in regulatory arrangements to access multiple fisheries and/or species, while the marketability of product is also important since prices paid for product can be variable.

Table 8.36 Summary of the types of autonomous adaptation options identified by stakeholders at both workshops. NB. Some of these options can be both autonomous and planned depending on species and fishery characteristics.

Autonomous adaptation options
Changing the level of effort (increase or decrease catch)(commercial)
Change target species (recreational & commercial)
Change spatial dynamics of fishing effort (commercial)
Change the temporal dynamics of fishing (commercial & recreational)
Increase the level of catch and release (recreational)
Change fishing techniques (e.g. from net to line (commercial); use circle hooks (recreational))
Diversify marketed catch (commercial)
Move to other fisheries (commercial)

The types of planned adaptation options and barriers identified from both workshops, and the entities responsible for their adoption, are summarised in Table 8.37. The range of planned adaptation options identified were placed into four groups: *Alteration of fishing operations*, *Management-based options*, *Research and Development*, and *Looking for alternatives* (Table 8.37). Adaptation options grouped under 'Alteration of fishing operations' were generally adaptation options for industry, although government support in some instances may be needed, and some of which may be autonomous depending on the nature. Examples include more targeting of banana prawns to offset the likely reduced abundance of tiger prawns due to the degradation of seagrass habitat which is critical for juvenile survival. For other species likely to experience population declines adaptation options included: reduced target effort and diversification of target species and fishing locations (e.g. golden snapper, king threadfin, barramundi, coral trout, Spanish mackerel), and changes in gears and/or fuel types to cheaper alternatives (e.g. biofuels) to reduce running costs (Table 8.37 and Appendix 14.8). The consistent potential barrier identified to these options was the cost involved that is incurred by the fisher. These could be increased fuel costs for travelling further, lower value of alternate species, or costs of changing gears and other operational equipment.

'Management-based options' included the greatest number of adaptation options identified than any other group, highlighting that many options may need to involve regulatory changes and/or policy decision-making. Some of these options involve a review of existing management or the potential introduction of new more flexible arrangements. They included fishery input and output controls, however also included management of land-based influences (river flow), resource allocation among the different fishing sectors (principally recreational and commercial), and development of fishery harvest strategies. For example, in response to future declines in target species population size, adaptation options included: the introduction of catch limits (e.g. king threadfin, barramundi), introduce spawning closures (spatial/temporal; e.g. Spanish mackerel), resource allocation initiatives (e.g. grey mackerel, coral trout, golden snapper), and licence buyouts (e.g. east coast Spanish mackerel) (Table 8.37 and Appendix 14.8). An important option identified in response to likely declining inshore populations due to lower river flows, especially for barramundi, was the improved management of river flows to better balance the needs of agriculture, human consumption and maintenance of ecological processes. The key barriers identified for this group of options were political opposition, cost and bureaucracy. Not surprisingly, the key responsibility in implementing these types of adaptation options lies with government, acknowledging the need for relevant stakeholder involvement (Table 8.37).

Adaptation options grouped under 'Research and Development' included research, monitoring and education, as well as development ideas such as development of Codes of Conduct, improving markets for alternate species and improving product quality. For example, a commercial fisher in one of the workshops produced a dried product not currently marketed being dried wings of queenfish. These are caught as a by-product in inshore net fisheries and occasionally in large numbers. This is a good example of potential value-adding to what is normally a low value product and providing a potential alternative to species currently targeted. The main potential barrier was again perceived to be cost. Although some of these types of options can be industry lead, most would need to involve government in some capacity, particularly as a source of funds, although some may be self-funded options.

The final group of adaptations was 'Looking for alternatives' and included options such as restocking and aquaculture, as well as artificial reefs and habitat restoration. For example, one of the adaptation options identified for tiger prawns was habitat restoration given their reliance on seagrass meadows for successful juvenile survival. Creighton et al (2013) states that investment into habitat restoration in the Great Barrier Reef region would provide economic benefit from prawn catches (tiger and banana) of at least $45m per annum (post-2018) with a break-even point of less than two years. The key potential barriers identified by stakeholders were cost and political opposition and they all required government to play a key role in their being implemented, with relevant stakeholder involvement (Table 8.37).

It is not surprising that costs were identified as they major barrier to the effective implementation of the identified adaptation options, regardless of their type. The other barriers perceived to be important were political opposition and bureaucracy. Although these are less tangible types of barriers to change, they were the most prominent in the view of the stakeholders present during the workshops. They are therefore very real barriers that need to be addressed. With the development of business case examples such as that described for tiger prawn by Creighton et al (2013), these types of barriers can be more readily overcome.

With limited resources, any future efforts to put adaptation actions into play should involve a process to prioritise actions, but in a transparent way involving relevant stakeholders. Although individuals can lead adaptation actions in response to changes or anticipated changes that affect fisheries, it is clear that government needs to play a key role in facilitating the implementation of actions that fishers, particularly commercial fishers, can adopt. This is because most of the adaptation options identified in the workshops involve regulatory changes, thereby requiring political will and support. Such changes would also require flexible, responsive and adaptive management systems. Clearly, governments will need to play a lead role in climate change adaptation for fisheries in northern Australia.

Given the vast area of northern Australia and the large number of fishery species involved, we have necessarily taken a broad approach in identifying priority species for future attention and the likely climate change impacts on those species. Therefore, the potential adaptation options presented here based on these species and the likely impacts, although identified by the fishery stakeholders present at our workshops (fishery managers, conservation managers, commercial and recreational fishers, and scientists), are also broad in scope and detail. Further, despite industry bodies having good representation, there was a lack of presence from commercial fishers at the adaptation workshops; a key stakeholder group for such workshops. To further develop adaptation options we suggest the need for a regional focus with strong representation of all relevant stakeholder groups and multiple workshops that consider: priority species and likely impacts identified in this project (as well as the underlying mechanisms behind the impacts), and current management and government policy. There is also a need to rigorously prioritise adaptation options, identify complementarity among regions and species, and to identify clear pathways for adoption. Building a solid business case for each option that articulates costs and tangible benefits will maximise the likelihood of the commitment of the associated resources required for successful adoption.

Table 8.37 Summary of the *types* of planned adaptation options identified by stakeholders from both workshops. Barriers for each adaptation option type are given, and who is responsible for the auctioning of options. The main fishery sector that the adaptation option applies to is given in parentheses.

	Planned adaptation options	Barriers	Responsibility
Alteration of fishing operations	Change target species (commercial)	Cost, public perception	Industry
	Change spatial dynamics of fishing effort (commercial)	Cost	Industry
	Move to other fisheries (commercial)	Cost	Industry
	Change or modify gear types (commercial)	Cost	Industry, Government
	Reduce operating costs, e.g. biofuels	??	Industry, Government
Management-based options	Protection of critical habitats	Cost	Government, stakeholders
	Introduce/revise catch limits (quota – commercial; bag limits – recreational)	Political opposition, bureaucracy, lack of data, cost to commercial sector	Government, stakeholders
	Introduce more flexible management systems	Political opposition, bureaucracy	Government
	Resource allocation (commercial & recreational)	Political opposition, inter-sector conflict, bureaucracy	Government, stakeholders
	Introduce/revise size limits (commercial & recreational)	Political opposition, stakeholder opposition	Government, stakeholders
	Introduce/revise spatial & temporal closures (commercial & recreational)	Political opposition, stakeholder opposition, bureaucracy	Government, stakeholders
	Better management of land-based water for optimal river flows (commercial & recreational)	Competition for water (e.g. agriculture), cost, political opposition, bureaucracy	Government, stakeholders
	Introduce gear restrictions/modifications for specific species (commercial)	Inter-sector conflict, cost	Government, stakeholders
	Develop harvest strategies for all fisheries (commercial & recreational)	Lack of data, lack of education for consumers, bureaucracy	Government, stakeholders
	Government support for effort reduction strategies (e.g. licence buyouts) (commercial)	Political opposition, cost	Government, industry

	Adaptation options	Barriers	Responsibility
Research and Development	Targeted research to inform future fishing levels (commercial & recreational)	Cost	Government, stakeholders
	Better education about fish stocks and regulatory mechanisms (commercial & recreational)	Cost, Political opposition	Government, stakeholders
	Develop and implement Codes of Conduct (commercial & recreational)	??	Government, stakeholders
	Improved product handling and grading standards (commercial)	??	Industry
	Educate and promote targeting of alternate species (commercial & recreational)	Cheap imports	Government, stakeholders
	Improve marketing of target and non-target species to maximise value (commercial)	Cheap imports, marketing costs, oversupply/product value	Industry
	Introduce/maintain fisheries monitoring	Cost, bureaucracy, political opposition	Government
Looking for alternatives	Translocation of mature fish (commercial & recreational)	Cost	Government, stakeholders
	Restocking (commercial & recreational)	Disease/genetic risk, political opposition, costs, technical knowledge	Government, stakeholders
	Provide infrastructure for increased access to fishing areas (commercial & recreational)	Cost, land ownership, political opposition	Government, stakeholders
	Develop aquaculture	Cost	Government, stakeholders
	Introduce artificial habitats (recreational)	Cost, political opposition, green group opposition	Government, stakeholders
	Habitat restoration (commercial & recreational)	Cost	Government, stakeholders

9 BENEFITS AND ADOPTION

This project has taken a deliberate structured and logical approach to inform managers and other fishery stakeholders on appropriate responses to climate change for fisheries in northern Australia. This report provides a concise compendium of all this information relevant to northern Australia and presents this information based on three regional areas: north-western Australia, the Gulf of Carpentaria, and the east coast. Although these regions are expansive and variable in their conditions, they nevertheless ensure relevance for the respective species assessed and the local climate changes expected to occur.

The information generated during this project can be described as discrete outputs each helping to provide the basis for decision-making from fishery and conservation managers, as well as fishers themselves, particularly the commercial sector and related industries who rely on fisheries for their income. A summary of these outputs are given below:

1. Comprehensive fishery species lists for each of the three regions of northern Australia determined through consultation with fishing stakeholders.
2. A summary of the observed and projected climate for the three regions of northern Australia using key climate variables relevant to marine fisheries and supporting habitats, and using the most recent information. This information provides an important baseline from which to assess potential impacts (positive or negative) on species in the future.
3. A review of the key habitats important for marine fishery species and how they are likely to be affected by climate change across each of the three regions.
4. A comprehensive compendium of reviews for 23 key fisheries species/species groups important for northern Australian fisheries. These include 8 invertebrate species/species groups and 15 fish and shark species, and describe the main fisheries, the species life cycle characteristics and known and inferred information on the sensitivity and response of species to changes in climate variables.
5. Relative vulnerability assessments carried out for a total of 36 key northern Australian fishery species to climate change by 2030. This is a medium-term time frame that has relevance to stakeholder and management planning horizons. The vulnerability assessment results identified: (i) species that are highly vulnerable to projected climate change and the reasons why, and (ii) species that, because of their economic and/or social importance, should be given a higher priority for action by managers, industry and future research.
6. The types of adaptation options as identified by stakeholders and based on the types of changes expected to occur in a range of fishery species.

These outputs all documented here together provide a valuable resource for any stakeholder and provide the following outcomes for fishery managers and key stakeholders:

- *Improved understanding of the climate-related changes predicted for the northern Australian region.* The project has documented the most up-to-date climate projections for northern Australia that are relevant to marine fisheries and supporting habitats.
- *A greater understanding of the potential consequences of climate change on northern Australian fishery habitats.* The current and potential impacts of projected changes in climate variables on key fisheries habitats have been identified based on the best available scientific and local knowledge, and cover the following habitats: coral reefs, mangroves, flood plains, bays and estuaries and seagrass meadows.
- *A greater understanding of the potential consequences of climate change on northern Australian fishery species.* The current and potential impacts of projected changes in climate variables on key fisheries species 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 species that had the highest relative vulnerability and the reasons for this. Furthermore, the framework represents a tool that can be revised and/or modified as new and relevant information becomes available.
- *Prioritisation of fishery species for actions and research based on their vulnerability and level of fishery importance.* Using the correlation between fishery vulnerability and importance, the project provides a tool to assist managers, industry and researchers in determining where best to put resources for futures actions including research.
- *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.
- *Identification of the types of adaptation responses that are relevant and appropriate.* Based on the likely potential impacts on key fishery species stakeholders identified a range of potential adaptation options that are relevant to the species and appropriate for the fishery circumstances. They also identified the types of issues that need to be overcome for different options, and therefore the options that are able to be implemented easiest, and who is to be responsible if particular adaptation options are to be actioned.
- *Improved capacity of northern Australian fisheries stakeholders 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 fishing 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. Better planning is facilitated through the identification of the main types of adaptation options and the likely barriers that may impede their implementation.

These project outcomes should be of benefit to all fishery stakeholders in northern Australia and provides a strong basis upon which to engage stakeholders about climate change and its implications for fisheries. Accepting and making the changes to adapt to the effects of climate change will be a long and evolving process. The key outputs from this project, particularly the identification of the most vulnerable fisheries to climate change in the respective regions and the causal mechanisms, provide the basis for the process to progress whether through action, education, research, or a combination of these.

Throughout this project several northern Australia fishery stakeholder representatives were involved including fishery and conservation managers, recreational fishers, commercial fishers, and researchers. This involvement has maximised the potential benefits and uptake of project outcomes by the respective groups/agencies.

10 FURTHER DEVELOPMENT

The results of this project have highlighted a number of activities and research priorities for consideration for northern Australian fisheries in the context of a changing climate. Identification of adaptation option types also provides a basis for management and government to begin further discussions and planning with stakeholders for fisheries to be as prepared as possible for climate-related changes to fishery populations and operations. Further development recommendations have been divided into four groups:

Research and monitoring to address key knowledge gaps

- Sea Surface Temperature (SST) was identified as a key environmental variable of significance for northern fishery species yet very little is known of the thermal tolerances of key life history stages of key fishery species. Similar research to that described above for coral trout should be replicated for a number of species notably: tropical rock lobster, Spanish mackerel, tiger prawn, sandfish (and other sea cucumber species), saucer scallops, and red throat emperor.
- Primary productivity changes, linked to rainfall & riverflow but also local hydrodynamics, under future climate scenarios is likely to also significantly affect successful recruitment of fishery species and their prey. Development of models to better understand these processes will be a key piece of research for being able to better predict likely futures for fishery populations in northern Australia. Research that also links habitat repair and re-connectivity with benefits to fisheries productivity will also help to inform these models as well as the efficacy of such strategies as adaptation options.
- Knowledge of the effects of decreasing pH on fishery species is very poor and so comments on the effects of acidification throughout this report are scant. However, given recent studies on coral trout and the effects on juvenile behaviour/olfactory function, this is an area of future research that should be pursued. Given the slow rate of change of pH and the prediction that critical levels are not likely to be reached until at

least 2070, there are other research areas that should be given higher priority. Research should replicate the coral trout work on other key fishery species across a range of taxa, and also include studies on the early development of invertebrates known to have calcium carbonate structures. These should include tropical rock lobster, sandfish (and other sea cucumber species), mud crab and prawn species.

- The continuation of effective and targeted monitoring of key habitats such as coral reefs and sea grass meadows, and the introduction of monitoring mangrove and flood plain habitats to better assess impacts and therefore consequences for important species such as barramundi. Research into the effects of habitat repair on productivity of key fishery species would also help build future efforts that go beyond monitoring.
- The continued efforts by local communities in collecting information on fisheries should be encouraged and supported. One example is the Suntag fish tagging program based near the Rockhampton area over the past ~30 years. Detecting change in fishery species due to long-term climate changes can only be detected by long-term fish data sets such as these.

Governance

- Riverflow to adjacent marine waters has been identified as critical in providing suitable conditions for survival and development of the early life history stages of many northern Australian fishery species. Management of land-based water use while ensuring adequate riverflows for fishery species survival is challenging but likely to be increasingly crucial in a future where rainfall is projected to decrease in many areas, particularly the east coast. Given the many competing uses for water resources (e.g. agriculture) research should be conducted that clearly demonstrates the productivity increases and in particular how this translates to benefits and the extent of these benefits, from adequate water to the environment.
- As with above, the freshwater/estuarine/marine interface represents a critical phase in the life cycle of a plethora of nearshore and offshore fishery species and so healthy waterways will help increase the resilience of fishery species in the future. Therefore, there should be a renewed focus on improving catchment management, e.g. healthy riparian zones, as well as habitat repair and barrier removal from river systems in priority regions.
- To maximize the resilience of key fishery species to climate change and other potential impacts, prudent fisheries management practices that ensures sustainability is essential. Examples of some management measures identified during the vulnerability assessments and species reviews as being needed are: address questions of overfishing for some species, e.g. golden snapper, black jewfish, king threadfin and some sea cucumber species; ensure appropriate management measures are in place for low productivity species (e.g. appropriate minimum size limits to allow maturation and spawning for species such as golden snapper); and maintain and rehabilitate habitats important for sensitive life history stages (e.g. estuaries and sea grass meadows).

- Combining the types of adaptation options identified here with other similar recent studies should be a careful and considered process to best describe these and to take the best approach to facilitate needed actions in the future. This will involve funding and government taking a leading role, particularly for the necessary regulatory/policy changes required to arrive at a management system that is flexible and responsive; a system that would allow management needs and industry needs to respond as needed to the changes predicted. Jurisdictional co-operation will be necessary particularly as species shift.

Extension

- Extension of key aspects of this report to northern Australia fishery regional stakeholders to educate and better inform about potential changes: likely changes in climate; likely impacts on habitats; likely impacts on key fishery species; priority species; potential adaptation options.

Adaptation planning

- To further develop adaptation options we suggest the need for a regional focus with strong representation of all relevant stakeholder groups and multiple workshops that consider: priority species and likely impacts identified in this project (as well as the underlying mechanisms behind the impacts), and current management and government policy. There is also a need to rigorously prioritise adaptation options, identify complementarity among regions and species, and to identify clear pathways for adoption. Building a solid business case for each option that articulates costs and tangible benefits will maximise the likelihood of the commitment of the associated resources required for successful adoption.

Improving future assessments

- This report presents results of an ecological vulnerability assessment; this is just one part of the process. Collection of the relevant information on the adaptive capacity of the fishery (social and economic indicators) would inform the assessment of the *fishery* vulnerability and therefore how fishery participants are best placed to cope with climate change impacts, and to take advantage of opportunities. This would require representatively surveying fishery stakeholders across regions, sectors, particularly commercial, recreational and management. Key fisheries across northern Australia are: inshore fisheries (barramundi), Great Barrier Reef line fishery (coral trout) and Spanish mackerel.
- Ensuring that updated climate modelling information is used in any future climate change assessments for fisheries, particularly where downscaled spatial models have been developed.

11 PLANNED OUTCOMES

Provision of scenario-driven recommendations of adaptive management approaches that provide for the sustainability of northern Australia fisheries in a changing climate.

- The final project workshops worked with stakeholders to identify adaptation options based on likely future fishery scenarios. These options also identified the likely barriers and who is responsible for their implementation and represents an initial, but important, step towards preparing for climate change.

Determination of the vulnerability of northern Australia's fisheries to climate change.

- A key output from the project was the development and application of vulnerability assessments of key fishery species from three key regions of northern Australia. The vulnerability assessments focused on 2030, a medium-term outlook, and one considered to be more relevant to all stakeholders. An assessment was also carried out based on the A1FI emissions scenario for 2070.

Greater understanding of the impacts of short and long term climate variability on northern Australia's key fisheries species, fisheries and regions of northern Australia, and the key environmental drivers. These include identification of priority species, fisheries and/or locations for targeted monitoring.

- The project has delivered as a major output, summary tables of the likely impacts for key northern Australian fishery species and habitats, also identifying the environmental variables of significance. This was done for three regional areas of northern Australia based on emissions scenarios for 2030. The key species likely to be impacted further by changes predicted for 2070 (A1FI emissions scenario) were also identified and the impacts discussed. The vulnerability assessment process also prioritised species for action.

Improved capacity for fisheries management agencies and industry to assess current practices and policies to optimise positioning for future predicted scenarios.

- Collectively, the key outputs of this project provide an informed basis for management and industry to assess current fisheries situations against likely future scenarios. Management as well as commercial and recreational fishing interests were key players during the course of the project having direct input into key outcomes providing a credible base for further extension and uptake by relevant fishery stakeholders.

12 CONCLUSIONS

There are several key conclusions that can be made based on this project. We have grouped these into different categories that generally reflect the different components of the project.

Key species

- Across northern Australia there are many species important to fisheries. The two major species across the entire area are barramundi and mud crab, while other species were important in some but not all regions: banana and tiger prawns, coral trout, golden snapper and black jewfish, Spanish mackerel and king threadfin.

- The knowledge of how environmental variation affects fishery species is good for 1-2 species, moderate for a few but generally is poor for most species. This means there is certainly scope for sensitivity-based research and the information in this report provides a basis for identifying priority species for such research.

Climate

- Changes in climate across northern Australia will be highly variable depending on the environmental variable and the specific region. The trend is for warmer, less saline and more acidic waters, a rising sea level, stronger cyclones and changed oceanographic conditions not well understood.
- By 2030, north-western Australia will be 0.6 – 0.9 °C warmer, the Gulf of Carpentaria will be 0.3 – 0.6 °C warmer, and both regions will have similar or slightly higher rainfall (0 – 5%)(and riverflow), a sea level rise of between 10 and 20 cm. There will be a weakening of the Leeuwin current on the west coast.
- By 2030, the east coast will be 0.3 – 0.6 °C warmer, will have -10 – 0 % less rainfall (and riverflow), a sea level rise of between 5 and 15 cm and a strengthening of the East Australian Current.

Habitats

- Projected increases in SST will cause more coral bleaching, and ocean acidification will reduce coral growth and structural integrity, resulting in a loss of reef diversity and structure.
- Increased storm severity and extreme riverflow events, resulting in increased turbidity and reduced solar radiation ill reduce seagrass cover and species diversity.
- Sea level rise will cause a landward migration of mangroves and, coupled with altered rainfall patterns, will change the connectivity between rivers and floodplains, resulting in the potential loss of freshwater floodplains.

Data analyses

- Analyses of barramundi CPUE in the Northern Territory provided further evidence of the positive influence of rainfall and riverflow (and floodplain inundation) on barramundi catchability and possibly recruitment.
- In southeast Queensland saucer scallop recruitment is enhanced in years of cooler water. Recruitment also appears to be positively influenced by higher local riverflow and by the presence of a cyclonic current eddy in the Capricorn region.
- Recruitment of Spanish mackerel on the east coast appears to be linked to SST with cooler years positively influencing recruitment, however the causal mechanism is unclear. Analyses did support the hypothesis of a single east coast stock.

Vulnerability and potential impacts

- The project has prioritised species so that the next steps focus on species that are not only likely to experience impacts from climate change but also those that represent the most important socially and/or economically to the people of the different regions in northern Australia.
- Species with the highest ecological vulnerability to climate change tend to have one or more of the following attributes: have an estuarine/nearshore habitat preference during at least part of their life cycle; have low mobility; rely on habitat types predicted to be most impacted by climate change; have low productivity (slow growth/late maturing/low fecundity); are known to be affected by environmental drivers; are fully or overfished.
- Certain species were assessed with a high vulnerability and also high fishery importance and so should be given priority. The highest priority species were **golden snapper, king threadfin, sandfish**, **black teatfish**, **tiger prawn, banana prawn**, **barramundi,** white teatfish and **mangrove jack** (higher priority in bold).
- In the medium-term (2030), the most common impact identified across all species were reduced sizes of populations due mainly to lower rainfall and riverflow which affects primary productivity and therefore survival of early life history stages, and also indirect effects of habitat degradation on key life history stages of certain species. SST is also likely to impact some species by 2030.
- In the longer-term (2070), while changes in rainfall/riverflow, SST and habitat alteration will continue to impact species, ocean acidification and salinity are likely to begin to impact species through disruption of early life history development and habitat effects (particularly coral reefs).
- Rainfall and riverflow are key environmental drivers for fisheries populations in northern Australia through enhancing local primary productivity and larval/juvenile survival, and by connecting key habitats such as estuaries and floodplains. The east coast in particular is a key area for concern due to projected lower rainfall, more extreme (longer) wet and dry periods, coupled with the expected increase in water extraction for land-based use and also having the estuarine habitats modified more than any other region of northern Australia (Creighton et al 2013). Many species use these and nearshore habitats and so are likely to be affected by these changed hydrological conditions, particularly barramundi that use all habitats during all stages of their life history.
- There is a high level of uncertainty in how species, particularly early life history stages, will be affected by changed SST, pH and salinity. However, recent research on coral trout demonstrating behavioural changes that are adverse for survival, suggest there will be surprises in terms of species responses.

Adaptation options

- We were able to group the adaptation options identified by stakeholders into four different types: Alteration of fishing operations, Management-based options, Research and

Development, and Looking for alternatives. Most of the adaptation options identified involved regulatory changes and/or policy decision-making.

- The major barriers to adaptation for northern Australian fisheries were identified as costs, political opposition and bureaucracy. For fisheries to adapt appropriately to climate change all stakeholders will need to play a role, however government will need to need to be a lead player in this process.

Due to the number of fishery species assessed across a vast area, this project took a broad approach to determining the relative vulnerability of key fishery species in northern Australia. Similarly the adaptation options identified by stakeholders were broad in scope and detail. For implementing appropriate adaptation options further, steps need to be considered: further engagement with stakeholders, especially commercial fishers; consideration of alternative options; prioritisation of adaptation responses; and identification and implementation of pathways for successful adoption.

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14 APPENDICES

14.1 Intellectual Property

No patentable or marketable products or processes have arisen from this research. All results will be published in scientific and non-technical literature. The raw data from compulsory fishing logbooks remains the intellectual property of QDAFF and NT Fisheries, whichever is applicable. The raw fishery-independent data from research and monitoring activities remains the intellectual property of QDAFF and NT Fisheries, whichever is applicable. Raw environmental data remains the intellectual property of the relevant agencies: DERM, Bureau of Meteorology, CSIRO, NASA, NOAA, IMOS, DSITIA, Infofish Australia, JCU, DLRM. Intellectual property accruing from analysis and interpretation of raw data vests jointly with JCU, QDAFF, NT Fisheries, Infofish Australia (golden snapper), and the Principal Investigator.

14.2 Staff

Below is a table of staff involved during the course of the project.

Name	Organisation	Funding
David Welch (PI)	C_2O Fisheries and JCU, New South Wales	FRDC and In-kind
Julie Robins	QDAFF, Queensland	FRDC and In-kind
Thor Saunders	DoR-Fisheries, Northern Territory	FRDC and In-kind
Richard Saunders	QDAFF @ JCU, Qld	FRDC and In-kind
Andrew Tobin	JCU, Qld	FRDC and In-kind
Alastair Harry	JCU, Qld	FRDC
Colin Simpfendorfer	JCU, Qld	In-kind
Jeffrey Maynard	Maynard Marine, USA	FRDC
Johanna Johnson	C_2O Consulting, NSW	FRDC
Gretta Pecl	UTAS, Tasmania	FRDC and In-kind
Bill Sawynok	Infofish Australia, Qld	FRDC
Eric Perez	QSIA, Queensland	FRDC and In-kind
Scott Wiseman	QSIA, Queensland	FRDC and In-kind
Mark Lightowler	QDAFF, Queensland	In-kind
Eddie Jebreen	QDAFF, Queensland	In-kind
John Kung	QDAFF, Queensland	FRDC and In-kind
Randall Owens	GBRMPA, Queensland	In-kind
Darren Cameron	GBRMPA, Queensland	In-kind
Rachel Pears	GBRMPA, Queensland	In-kind
Steve Matthews	DoR-Fisheries, NT	In-kind
Hockseng Lee	DoR-Fisheries, NT	In-kind
Emily Lawson	DoR-Fisheries, NT	FRDC

14.3 1st Workshop participants involved in species identification

Name	Organisation
David Welch (PI)	C_2O Fisheries and JCU, New South Wales
Julie Robins	QDAFF, Queensland
Thor Saunders	DoR-Fisheries, Northern Territory
Andrew Tobin	JCU, Qld
Jeffrey Maynard	Maynard Marine, USA
Johanna Johnson	C_2O Consulting, NSW
Gretta Pecl	UTAS, Tasmania
Bill Sawynok	Infofish Australia, Qld
Eric Perez	QSIA, Queensland
Mark Lightowler	QDAFF, Queensland
Anthony Roelofs	QDAFF, Queensland
Randall Owens	GBRMPA, Queensland

14.4 Vulnerability assessment workshop participants

Name	Organisation
David Welch (PI)	C_2O Fisheries and JCU, New South Wales
Julie Robins	QDAFF, Queensland
Thor Saunders	DoR-Fisheries, Northern Territory
Andrew Tobin	JCU, Qld
Johanna Johnson	C_2O Consulting, NSW
Gretta Pecl	UTAS, Tasmania
Bill Sawynok	Infofish Australia, Qld
Scott Wiseman	QSIA, Queensland
Eddie Jebreen	QDAFF, Queensland
Richard Saunders	QDAFF, Queensland
Randall Owens	GBRMPA, Queensland
Steve Newman	WA Department of Fisheries

14.5 Adaptation workshop agenda and participants

Darwin agenda

Time	Topic	Speaker(s)
0900	Welcome & purpose of workshop	Thor Saunders
0905	1. Project overview	David Welch
0930	2. Putting climate change into perspective: other key threats and issues across regions and fisheries	Thor Saunders
0940	3. Climate change and fisheries	Gretta Pecl
1000	4. Overview of climate change in north eastern Australia	David Welch
1010	5. Overview and outcomes of vulnerability assessment	David Welch
1035	*Morning tea*	
1100	6. Stakeholder input to finalise VA - questionnaire	All
1130	7. Collating industry perceptions regarding observed oceanographic, ecosystem or fishery changes • Specific species • General	All
1215	8. Climate change impacts on habitats and key species	Thor Saunders
1245	*Lunch*	
1330	9. Eliciting stakeholder responses to species change	David Welch, Gretta Pecl
1340	Exercise: stakeholder responses to species change	All
1515	*Afternoon tea*	
1535	Continued stakeholder exercise	All
1600	Summary of impact responses & follow-up	David Welch
1645	*Close*	

Darwin participants, October 9, 2013
David Welch, JCU/C_2O Fisheries (PI)
Thor Saunders, NT Fisheries (CI)
Gretta Pecl, UTas (CI)
Craig Ingram, Amateur Fishermens Association of the Northern Territory
Steve Sly, NT Fisheries (fisheries manager)
Lyn Lambeth, NT Seafood Council
Gilbert Hanson, Northern Land Council

Townsville participants, October 24, 2013
David Welch, JCU/C_2O Fisheries (PI)
Thor Saunders, NT Fisheries (CI)
Andrew Tobin, JCU (CI)
Richard Saunders, QDAFF (CI)
Darren Cameron, GBRMPA
Randall Owens, GBRMPA
Bill Sawynok, Infofish Australia
Trevor Fuller, recreational fisher
John Kung, QDAFF
Simon Barry, QDAFF
Scott Wiseman, Queensland Seafood Industry Association
Carolyn Smith-Keune, JCU
Morgan Pratchett, JCU
Glen Murray, commercial fisher

14.6 Species tables of possible environmental drivers

NB. Shaded cells indicate where documented evidence exists.

BARRAMUNDI	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	1	1	1	**H**
rainfall	1	1	1	1	**H**
pH	0	0	0	0	**L**
sea level	1	0	1	0	**M**
salinity (Sur)	1	1	1	1	**H**
upwelling	0	0	0	0	**L**
nutrients	1	1	1	1	**H**
wind/current	0	0	0	0	**L**
riverflow	1	1	1	1	**H**

CORAL TROUT	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	1	1	1	**H**
rainfall	0	0	0	0	**L**
pH	1	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	0	0	**L**
upwelling	1	1	1	1	**H**
nutrients	1	1	0	0	**M**
wind/current	1	0	1	0	**M**
riverflow	0	0	0	0	**L**

BANANA PRAWN	Recruitment	Growth	Distribution	Catchability	Impact
SST	1	1	0	1	**H**
rainfall	1	1	1	1	**H**
pH	0	0	0	0	**L**
sea level	1	0	1	0	**M**
salinity (Sur)	1	1	1	1	**H**
upwelling	0	0	0	0	**L**
nutrients	1	1	1	1	**H**
wind/current	1	0	1	1	**H**
riverflow	1	1	1	1	**H**

SPANISH MACKEREL	Recruitment	Growth	Distribution	Catchability	Impact
SST	1	1	1	0	**H**
rainfall	1	1	0	0	**M**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	0	0	**L**
upwelling	1	1	0	0	**M**
nutrients	1	1	0	0	**M**
wind/current	1	0	1	0	**M**
riverflow	1	1	0	0	**M**

GOLDEN SNAPPER	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	0	0	0	**L**
rainfall	1	1	0	0	**M**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	1	0	0	0	**L**
upwelling	0	0	0	0	**L**
nutrients	1	1	0	0	**M**
wind/current	0	0	0	0	**L**
riverflow	1	1	0	0	**M**

BLACK JEWFISH	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	0	0	0	**L**
rainfall	1	1	0	0	**M**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	1	0	0	0	**L**
upwelling	0	0	0	0	**L**
nutrients	1	1	0	0	**M**
wind/current	0	0	0	0	**L**
riverflow	1	1	0	0	**M**

REDSPOT KING PRAWN	Recruitment	Growth	Distribution	Catchability	Impact
SST	1	1	0	0	**M**
rainfall	0	0	0	0	**L**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	0	0	**L**
upwelling	1	1	0	0	**M**
nutrients	1	1	0	0	**M**
wind/current	0	0	0	0	**L**
riverflow	0	0	0	0	**L**

TROPICAL ROCK LOBSTER	Recruitment	Growth	Distribution	Catchability	Impact
SST	1	1	1	0	**H**
rainfall	0	0	0	0	**L**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	1	1	0	0	**M**
upwelling	1	1	0	0	**M**
nutrients	1	1	0	0	**M**
wind/current	1	0	1	0	**M**
riverflow	0	0	0	0	**L**

TIGER PRAWN	Recruitment	Growth	Distribution	Catchability	Impact
SST	1	1	1	0	**H**
rainfall	1	0	0	1	**M**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	1	1	1	1	**H**
upwelling	0	0	0	0	**L**
nutrients	0	1	0	0	**L**
wind/current	1	0	0	0	**L**
riverflow	1	1	0	1	**H**

EASTERN KING PRAWN	Recruitment	Growth	Distribution	Catchability	Impact
SST	1	1	0	0	**M**
rainfall	1	0	0	0	**L**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	1	1	0	1	**H**
upwelling	0	0	0	0	**L**
nutrients	0	0	0	0	**L**
wind/current	1	0	1	0	**M**
riverflow	1	0	0	1	**M**

SAUCER SCALLOP	Recruitment	Growth	Distribution	Catchability	Impact
SST	1	1	0	0	**M**
rainfall	0	0	0	0	**L**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	0	0	**L**
upwelling	0	0	0	0	**L**
nutrients	0	1	0	0	**L**
wind/current	1	0	1	0	**M**
riverflow	0	0	0	0	**L**

SANDFISH	Recruitment	Growth	Distribution	Catchability	Impact
SST	1	1	1	0	**M**
rainfall	0	0	0	0	**L**
pH	1	1	0	0	**M**
sea level	0	0	1	0	**L**
salinity (Sur)	1	1	1	0	**H**
upwelling	0	0	0	0	**L**
nutrients	1	1	1	0	**H**
wind/current	1	0	0	0	**L**
riverflow	0	0	0	0	**L**

BLACKTIP SHARKS	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	1	1	0	**M**
rainfall	0	0	0	0	**L**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	1	0	**L**
upwelling	0	0	0	0	**L**
nutrients	0	0	0	0	**L**
wind/current	0	0	0	0	**L**
riverflow	0	0	1	0	**L**

SCALLOPED HAMMERHEAD SHARK	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	1	1	0	**M**
rainfall	0	0	0	0	**L**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	0	0	**L**
upwelling	0	0	1	0	**L**
nutrients	0	0	0	0	**L**
wind/current	0	0	0	0	**L**
riverflow	0	0	0	0	**L**

KING THREADFIN	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	1	1	0	**M**
rainfall	1	1	0	0	**M**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	1	0	**L**
upwelling	0	0	0	0	**L**
nutrients	1	1	0	0	**M**
wind/current	0	0	0	0	**L**
riverflow	1	0	0	1	**M**

GOLD BAND SNAPPER	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	1	0	0	**L**
rainfall	0	0	0	0	**L**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	0	0	**L**
upwelling	1	1	0	0	**M**
nutrients	1	1	0	0	**M**
wind/current	1	0	0	0	**L**
riverflow	0	0	0	0	**L**

MUD CRAB	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	1	1	1	**H**
rainfall	1	1	1	1	**H**
pH	0	0	0	0	**L**
sea level	1	0	1	0	**M**
salinity (Sur)	1	1	1	1	**H**
upwelling	1	1	0	0	**M**
nutrients	1	1	1	0	**H**
wind/current	1	0	1	0	**M**
riverflow	1	1	1	1	**H**

GREY MACKEREL	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	1	1	1	**H**
rainfall	1	1	0	0	**M**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	1	1	0	0	**M**
upwelling	0	0	0	0	**L**
nutrients	1	1	1	0	**H**
wind/current	0	0	0	0	**L**
riverflow	1	1	0	0	**M**

RED THROAT EMPEROR	Recruitment	Growth	Distribution	Catchability	Impact
SST	0	1	1	1	**H**
rainfall	0	0	0	0	**L**
pH	0	0	0	0	**L**
sea level	0	0	0	0	**L**
salinity (Sur)	0	0	0	0	**L**
upwelling	1	0	1	1	**H**
nutrients	1	1	0	0	**M**
wind/current	0	0	1	0	**L**
riverflow	0	0	0	0	**L**

14.7 Full vulnerability assessment scores (2030, A2/A1FI)

North-western Australia

	Exposure								
	SST+	Altered rainfall	pH decline	Salinity changes	Habitat changes (e.g. loss of productivity, structure or function)	Altered wind/ currents	More severe cyclones/ storms	More extreme riverflow	*Exposure index*
Golden snapper	3	3	3	3	2	2	2	3	2.63
King threadfin	3	3	3	3	2	2	2	3	2.63
Sand fish	3	2	3	3	3	2	3	1	2.50
Mangrove jack	2	3	3	3	2	2	2	3	2.50
Bull shark	2	3	2	2	1	1	2	3	2.00
Black jew	2	3	3	3	1	2	2	3	2.38
Crimson snapper	1	2	2	2	3	2	1	1	1.75
Saddle tail snapper	1	2	2	2	3	2	1	1	1.75
Pigeye shark	2	2	2	2	1	1	2	2	1.75
Red emperor	1	1	2	2	1	2	1	1	1.38
Coral trout	3	1	2	2	3	2	2	1	2.00
Barramundi	3	3	3	3	2	1	2	3	2.50
Mud crab	3	3	3	3	2	2	2	3	2.63
Grey mackerel	3	2	3	3	2	2	2	2	2.38
Barred javelin	3	2	3	3	2	2	2	2	2.38
Blue threadfin	3	3	3	3	2	2	2	3	2.63
Grass emperor	3	2	3	3	2	2	2	2	2.38
Goldband snapper	1	1	2	2	1	2	1	1	1.38
Scalloped hammerhead	1	1	2	2	1	1	1	1	1.25
Spot tail shark	2	1	2	2	1	1	1	1	1.38
Spanish mackerel	2	3	2	2	2	2	2	3	2.25
Blacktip shark (limbatus)	1	1	2	2	1	1	1	1	1.25
Billfish (Sailfish)	1	1	1	1	1	3	1	1	1.25

	Sensitivity								
	Fecundity (egg production)	Average age at maturity	Generalist vs specialist (food & habitat)	Early development duration	Physiological tolerance of stock	Capacity for larvae to disperse	Reliance on environmental drivers (for spawning, settlement)	Potential for timing mismatch (duration of spawning, breeding, moulting)	*Sensitivity index*
Golden snapper	1	2	2	2	1	2	1	1	1.50
King threadfin	1	2	2	2	1	1	3	2	1.75
Sand fish	1	2	2	2	2	2	2	1	1.75
Mangrove jack	1	2	2	2	1	2	2	2	1.75
Bull shark	3	2	2	3	1	1	2	2	2.00
Black jew	1	1	2	2	1	2	2	1	1.50
Crimson snapper	1	2	2	2	1	2	1	1	1.50
Saddle tail snapper	1	2	2	2	1	2	1	1	1.50
Pigeye shark	3	2	2	3	1	1	2	2	2.00
Red emperor	1	2	1	2	1	3	1	1	1.50
Coral trout	1	1	2	2	1	2	2	2	1.63
Barramundi	1	1	2	2	1	1	3	2	1.63
Mud crab	1	1	2	2	1	3	3	2	1.88
Grey mackerel	1	1	2	2	1	2	2	1	1.50
Barred javelin	1	1	2	2	1	2	2	1	1.50
Blue threadfin	1	1	2	2	1	1	1	1	1.25
Grass emperor	1	1	2	2	1	2	1	1	1.38
Goldband snapper	1	2	2	2	1	2	1	1	1.50
Scalloped hammerhead	3	3	1	3	1	1	2	3	2.13
Spot tail shark	3	2	2	3	1	1	1	2	1.88
Spanish mackerel	1	1	2	2	1	2	2	1	1.50
Blacktip shark (limbatus)	3	2	1	3	1	1	1	3	1.88
Billfish (Sailfish)	1	2	2	2	1	3	2	1	1.75

	Adaptive Capacity							
	Stock status	Replenishment potential	Suitable alternate habitat availability	Species mobility	Non-fishing pressures on stock	***Adaptive Capacity index***	**AC normalisation**	**1-AC**
Golden snapper	1	1	2	2	2	1.60	0.57	0.43
King threadfin	1	2	2	2	2	1.80	0.64	0.36
Sand fish	2	2	2	1	2	1.80	0.64	0.36
Mangrove jack	2	1	3	2	2	2.00	0.71	0.29
Bull shark	2	1	2	3	3	2.20	0.79	0.21
Black jew	1	3	3	2	2	2.20	0.79	0.21
Crimson snapper	3	1	2	2	2	2.00	0.71	0.29
Saddle tail snapper	3	1	2	2	2	2.00	0.71	0.29
Pigeye shark	2	1	2	3	3	2.20	0.79	0.21
Red emperor	2	1	2	2	2	1.80	0.64	0.36
Coral trout	3	3	2	2	2	2.40	0.86	0.14
Barramundi	3	2	3	2	2	2.40	0.86	0.14
Mud crab	3	3	3	1	2	2.40	0.86	0.14
Grey mackerel	3	3	2	2	2	2.40	0.86	0.14
Barred javelin	2	3	3	2	2	2.40	0.86	0.14
Blue threadfin	3	3	2	2	2	2.40	0.86	0.14
Grass emperor	2	3	3	2	2	2.40	0.86	0.14
Goldband snapper	3	1	2	2	3	2.20	0.79	0.21
Scalloped hammerhead	3	1	3	3	2	2.40	0.86	0.14
Spot tail shark	3	1	2	3	3	2.40	0.86	0.14
Spanish mackerel	3	3	2	3	2	2.60	0.93	0.07
Blacktip shark (limbatus)	3	1	3	3	3	2.60	0.93	0.07
Billfish (Sailfish)	2	3	3	3	3	2.80	1.00	0.00

	Potential Impacts (PI) (negative)		
	PI = E * S	Direction of impact	**PI Index**
Golden snapper	3.94	0	3.94
King threadfin	4.59	0	4.59
Sand fish	4.38	0	4.38
Mangrove jack	4.38	0	4.38
Bull shark	4.00	0	4.00
Black jew	3.56	0	3.56
Crimson snapper	2.63	0	2.63
Saddle tail snapper	2.63	0	2.63
Pigeye shark	3.50	0	3.50
Red emperor	2.06	0	2.06
Coral trout	3.25	1	4.25
Barramundi	4.06	0	4.06
Mud crab	4.92	-1	3.92
Grey mackerel	3.56	0	3.56
Barred javelin	3.56	0	3.56
Blue threadfin	3.28	0	3.28
Grass emperor	3.27	0	3.27
Goldband snapper	2.06	0	2.06
Scalloped hammerhead	2.66	0	2.66
Spot tail shark	2.58	0	2.58
Spanish mackerel	3.38	0	3.38
Blacktip shark (limbatus)	2.34	0	2.34
Billfish (Sailfish)	2.19	0	2.19

Gulf of Carpentaria

	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***
Golden snapper	3	3	3	3	2	2	2	3	2.63
King threadfin	3	3	3	3	2	2	2	3	2.63
Sand fish	3	2	3	3	3	2	3	1	2.50
Tiger prawn (esculentus)	3	3	3	3	3	2	3	3	2.88
Mangrove jack	2	3	3	3	2	2	2	3	2.50
Banana prawn	3	3	3	3	2	1	3	3	2.63
Tropical lobster	3	1	2	2	3	3	2	1	2.13
Black jew	2	3	3	3	1	2	2	3	2.38
Pigeye shark	2	2	2	2	1	1	2	2	1.75
Red emperor	1	1	2	2	1	2	1	1	1.38
Barramundi	3	3	3	3	2	1	2	3	2.50
Mud crab	3	3	3	3	2	2	2	3	2.63
Grey mackerel	3	2	3	3	2	2	2	2	2.38
Barred javelin	3	2	3	3	2	2	2	2	2.38
Blue threadfin	3	3	3	3	2	2	2	3	2.63
Coral trout	3	1	2	2	3	2	2	1	2.00
Scalloped hammerhead	1	1	2	2	1	1	1	1	1.25
Spot tail shark	2	1	2	2	1	1	1	1	1.38
Spanish mackerel	2	3	2	2	2	2	2	3	2.25
Blacktip shark (limbatus)	1	1	2	2	1	1	1	1	1.25
Billfish (Sailfish)	1	1	1	1	1	3	1	1	1.25

	Sensitivity								
	Fecundity (egg production)	Average age at maturity	Generalist vs specialist (food & habitat)	Early development duration	Physiological tolerance of stock	Capacity for larvae to disperse	Reliance on environmental drivers (for spawning, settlement)	Potential for timing mismatch (duration of spawning, breeding, moulting)	***Sensitivity index***
Golden snapper	1	2	2	2	1	2	1	1	1.50
King threadfin	1	2	2	2	1	1	3	2	1.75
Sand fish	1	2	2	2	2	2	2	1	1.75
Tiger prawn (esculentus)	1	1	2	2	2	1	2	1	1.50
Mangrove jack	1	2	2	2	1	2	2	2	1.75
Banana prawn	1	1	2	2	1	1	3	3	1.75
Tropical lobster	2	2	2	1	3	3	3	1	2.13
Black jew	1	1	2	2	1	2	2	1	1.50
Pigeye shark	3	2	2	3	1	1	2	2	2.00
Red emperor	1	2	1	2	1	3	1	1	1.50
Barramundi	1	1	2	2	1	1	3	2	1.63
Mud crab	1	1	2	2	1	3	3	2	1.88
Grey mackerel	1	1	2	2	1	2	2	1	1.50
Barred javelin	1	1	2	2	1	2	2	1	1.50
Blue threadfin	1	1	2	2	1	1	1	1	1.25
Coral trout	1	1	2	2	1	2	2	2	1.63
Scalloped hammerhead	3	3	1	3	1	1	2	3	2.13
Spot tail shark	3	2	2	3	1	1	1	2	1.88
Spanish mackerel	1	1	2	2	1	2	2	1	1.50
Blacktip shark (limbatus)	3	2	1	3	1	1	1	3	1.88
Billfish (Sailfish)	1	2	2	2	1	3	2	1	1.75

	Adaptive Capacity							
	Stock status	Replenishment potential	Suitable alternate habitat availability	Species mobility	Non-fishing pressures on stock	***Adaptive Capacity index***	**AC normalisation**	**1-AC**
Golden snapper	1	1	2	2	2	1.60	0.57	0.43
King threadfin	1	2	2	2	2	1.80	0.64	0.36
Sand fish	2	2	2	1	2	1.80	0.64	0.36
Tiger prawn (esculentus)	3	3	2	1	1	2.00	0.71	0.29
Mangrove jack	2	1	3	2	2	2.00	0.71	0.29
Banana prawn	3	3	1	1	2	2.00	0.71	0.29
Tropical lobster	3	2	3	2	2	2.40	0.86	0.14
Black jew	1	3	3	2	2	2.20	0.79	0.21
Pigeye shark	2	1	2	3	3	2.20	0.79	0.21
Red emperor	2	1	2	2	2	1.80	0.64	0.36
Barramundi	3	2	3	2	2	2.40	0.86	0.14
Mud crab	3	3	3	1	2	2.40	0.86	0.14
Grey mackerel	3	3	2	2	2	2.40	0.86	0.14
Barred javelin	2	3	3	2	2	2.40	0.86	0.14
Blue threadfin	3	3	2	2	2	2.40	0.86	0.14
Coral trout	3	3	2	2	2	2.40	0.86	0.14
Scalloped hammerhead	3	1	3	3	2	2.40	0.86	0.14
Spot tail shark	3	1	2	3	3	2.40	0.86	0.14
Spanish mackerel	3	3	2	3	2	2.60	0.93	0.07
Blacktip shark (limbatus)	3	1	3	3	3	2.60	0.93	0.07
Billfish (Sailfish)	2	3	3	3	3	2.80	1.00	0.00

	Potential Impacts (PI) (negative)		
	PI = E * S	Direction of impact	**PI Index**
Golden snapper	3.94	0	3.94
King threadfin	4.59	0	4.59
Sand fish	4.38	0	4.38
Tiger prawn (esculentus)	4.31	1	5.31
Mangrove jack	4.38	0	4.38
Banana prawn	4.59	-1	3.59
Tropical lobster	4.52	1	5.52
Black jew	3.56	0	3.56
Pigeye shark	3.50	0	3.50
Red emperor	2.06	0	2.06
Barramundi	4.06	0	4.06
Mud crab	4.92	-1	3.92
Grey mackerel	3.56	0	3.56
Barred javelin	3.56	0	3.56
Blue threadfin	3.28	0	3.28
Coral trout	3.25	0	3.25
Scalloped hammerhead	2.66	0	2.66
Spot tail shark	2.58	0	2.58
Spanish mackerel	3.38	0	3.38
Blacktip shark (limbatus)	2.34	0	2.34
Billfish (Sailfish)	2.19	0	2.19

East coast

	Exposure								
	SST+	Altered rainfall	pH decline	Salinity changes	Habitat changes (e.g. loss of productivity, structure or function)	Altered wind/ currents	More severe cyclones/ storms	More extreme riverflow; total reduced	***Exposure index***
Black teatfish	3	1	2	2	3	2	3	1	2.13
King threadfin	3	3	3	3	2	2	2	3	2.63
Sand fish	3	2	3	3	3	2	3	1	2.50
Barramundi	3	3	3	3	2	1	2	3	2.50
Tiger prawn (esculentus)	3	3	3	3	3	2	3	3	2.88
Golden snapper	3	3	3	3	2	2	2	3	2.63
White teat fish	2	1	2	2	3	2	3	1	2.00
Banana prawn	3	3	3	3	2	1	3	3	2.63
Mangrove jack	2	3	3	3	2	2	2	3	2.50
Tropical lobster	3	1	2	2	3	3	2	1	2.13
Scallops	1	1	2	2	2	2	1	1	1.50
Red emperor	1	1	2	2	1	2	1	1	1.38
Mud crab	3	3	3	3	2	1	3	3	2.63
Dusky flathead	3	3	3	3	2	2	2	3	2.63
Red throat emperor	1	1	2	2	3	2	2	1	1.75
Coral trout	3	1	2	2	3	2	2	1	2.00
Grey mackerel	3	2	3	3	2	2	2	2	2.38
Barred javelin	3	2	3	3	2	2	2	2	2.38
Red spot king prawn	2	1	2	2	3	2	3	1	2.00
Scalloped hammerhead	1	1	2	2	1	1	1	1	1.25
Spot tail shark	2	1	2	2	1	1	1	1	1.38
Spanish mackerel	2	3	2	2	2	2	2	3	2.25
Blue threadfin	3	3	3	3	2	2	2	3	2.63
Blacktip sharks (limbatus)	1	1	2	2	1	1	1	1	1.25
Eastern king prawn	1	2	2	2	1	3	1	1	1.63
Billfish (black marlin)	1	1	1	1	1	3	1	1	1.25
Spotted mackerel	3	3	3	3	2	2	1	3	2.50
Moreton Bay bug	1	1	2	2	1	3	1	1	1.50

	Sensitivity								
	Fecundity (egg production)	Average age at maturity	Generalist v specialist (food & habitat)	Early development duration	Physiological tolerance of stock	Capacity for larvae to disperse	Reliance on environmental drivers (for spawning, settlement)	Potential for timing mismatch (duration of spawning, breeding, moulting)	***Sensitivity index***
Black teat fish	1	2	3	2	2	2	1	2	1.88
King threadfin	1	2	2	2	1	1	3	2	1.75
Sand fish	1	2	2	2	2	2	2	1	1.75
Barramundi	1	2	2	2	1	1	3	2	1.75
Tiger prawn (esculentus)	1	1	2	2	1	1	2	1	1.38
Golden snapper	1	2	2	2	1	2	1	1	1.50
White teat fish	1	2	3	2	2	2	1	2	1.88
Banana prawn	1	1	2	2	1	1	3	3	1.75
Mangrove jack	1	2	2	2	1	2	2	2	1.75
Tropical lobster	2	2	2	1	3	3	3	1	2.13
Scallops	1	1	2	2	1	2	3	2	1.75
Red emperor	1	2	1	2	1	3	1	1	1.50
Mud crab	1	1	2	2	1	3	3	2	1.88
Dusky flathead	1	2	2	2	1	2	2	2	1.75
Red throat emperor	1	2	2	2	1	2	2	1	1.63
Coral trout	1	1	2	2	1	2	2	2	1.63
Grey mackerel	1	1	2	2	1	2	2	1	1.50
Barred javelin	1	1	2	2	1	2	2	1	1.50
Red spot king prawn	1	1	2	2	2	2	1	1	1.50
Scalloped hammerhead	3	3	1	3	1	1	2	3	2.13
Spot tail shark	3	2	2	3	1	1	1	2	1.88
Spanish mackerel	1	1	2	2	1	2	2	1	1.50
Blue threadfin	1	1	2	2	1	1	1	1	1.25
Blacktip sharks (limbatus)	3	2	1	3	1	1	1	3	1.88
Eastern king prawn	1	1	1	2	1	3	2	2	1.63
Billfish (black marlin)	1	2	2	2	1	3	3	2	2.00
Spotted mackerel	1	1	2	2	2	2	1	2	1.63
Moreton Bay bug	2	1	2	1	2	3	1	2	1.75

	Adaptive Capacity							
	Stock status	Replenishment potential	Suitable alternate habitat	Species mobility	Non-fishing pressures on stock	***Adaptive Capacity index***	**AC normalisation**	**1-AC**
Black teatfish	1	1	2	1	2	1.40	0.50	0.50
King threadfin	1	2	2	2	1	1.60	0.57	0.43
Sand fish	2	2	2	1	2	1.80	0.64	0.36
Barramundi	3	2	2	2	1	2.00	0.71	0.29
Tiger prawn (esculentus)	3	3	2	1	1	2.00	0.71	0.29
Golden snapper	2	1	2	2	2	1.80	0.64	0.36
White teat fish	2	2	2	1	2	1.80	0.64	0.36
Banana prawn	3	3	1	1	2	2.00	0.71	0.29
Mangrove jack	2	1	3	2	2	2.00	0.71	0.29
Tropical lobster	3	2	3	2	2	2.40	0.86	0.14
Scallops	3	3	3	1	1	2.20	0.79	0.21
Red emperor	2	1	2	2	2	1.80	0.64	0.36
Mud crab	3	3	3	1	2	2.40	0.86	0.14
Dusky flathead	3	2	3	2	2	2.40	0.86	0.14
Red throat emperor	3	2	2	2	2	2.20	0.79	0.21
Coral trout	3	3	2	2	2	2.40	0.86	0.14
Grey mackerel	3	3	2	2	2	2.40	0.86	0.14
Barred javelin	2	3	3	2	2	2.40	0.86	0.14
Red spot king prawn	3	3	2	1	3	2.40	0.86	0.14
Scalloped hammerhead	3	1	3	3	2	2.40	0.86	0.14
Spot tail shark	3	1	2	3	3	2.40	0.86	0.14
Spanish mackerel	3	3	2	3	2	2.60	0.93	0.07
Blue threadfin	3	3	2	2	3	2.60	0.93	0.07
Blacktip sharks (limbatus)	3	1	3	3	3	2.60	0.93	0.07
Eastern king prawn	3	3	3	2	3	2.80	1.00	0.00
Billfish (black marlin)	3	2	3	3	3	2.80	1.00	0.00
Spotted mackerel	3	3	3	3	2	2.80	1.00	0.00
Moreton Bay bug	3	3	3	2	3	2.80	1.00	0.00

	Potential Impacts (negative)		
	PI = E * S	Direction of impact	**PI Index**
Black teatfish	3.98	1	4.98
King threadfin	4.59	1	5.59
Sand fish	4.38	0	4.38
Barramundi	4.38	1	5.38
Tiger prawn (esculentus)	3.95	1	4.95
Golden snapper	3.94	0	3.94
White teatfish	3.75	0	3.75
Banana prawn	4.59	0	4.59
Mangrove jack	4.38	0	4.38
Tropical lobster	4.52	1	5.52
Scallops	2.63	1	3.63
Red emperor	2.06	0	2.06
Mud crab	4.92	0	4.92
Dusky flathead	4.59	0	4.59
Red throat emperor	2.84	0	2.84
Coral trout	3.25	1	4.25
Grey mackerel	3.56	0	3.56
Barred javelin	3.56	0	3.56
Red spot king prawn	3.00	0	3.00
Scalloped hammerhead	2.66	0	2.66
Spot tail shark	2.58	0	2.58
Spanish mackerel	3.38	0	3.38
Blue threadfin	3.28	0	3.28
Blacktip sharks (limbatus)	2.34	0	2.34
Eastern king prawn	2.64	1	3.64
Billfish (black marlin)	2.50	0	2.50
Spotted mackerel	4.06	0	4.06
Moreton Bay bug	2.63	0	2.63

14.8 Raw adaptation option tables

Appendix 14.8.1. Potential adaptation options identified by stakeholders at the adaptation workshop held in Darwin. Stakeholder identified autonomous and planned adaptation options as well as potential barriers to each option. Causal climate factors of the potential impacts are given in parentheses.

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
Tiger prawns: Decreased juvenile growth and recruitment (seagrass habitat degradation)	• More targeting of banana prawns	• Habitat restoration	• Cost
Banana prawns: Increased population size (rainfall, riverflow); increased juvenile survival (sea level rise; increased mangrove habitat)	• Increased effort/extend season		
Golden snapper: Reduced spawning biomass (SST)	• Reduce effort, cap catch • Target other species (recreational)	• Target other species (commercial) • Shift to new areas (commercial) • Translocation of mature fish • Release of juveniles (hatchery reared)	• Costs associated with moving (fuel, lack of access and infrastructure) • Cost of translocation
Barramundi: Decreased abundance (rainfall, riverflow, sea level rise, habitat changes)	• Reduce effort • Target other species • Spread effort • Improve value of product	• Increase access (physical access points) to currently available areas • Introduce catch limits • Promote/educate to target other species • Marketing to improve value • Marketing to increase value	• Cost of access and land tenure • Indigenous and pastoral land rights • Political will • Cost of marketing • Cost of advertising • Competing with cheap imports

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
Barramundi: increased abundance (rainfall, riverflow, sea level rise)	• Increase effort in 1-3 years time		
King threadfin: Decreased abundance (rainfall, riverflow, sea level rise, habitat changes)	• Reduce effort • Target other species • Spread effort • Improve value of product	• Increase access (physical access points) to currently available areas • Introduce catch limits • Promote/educate to target other species • Marketing to improve value • Promote product to increase value	• Cost of access and land tenure • Indigenous and pastoral land rights • Political will • Cost of marketing • Cost of advertising • Competing with cheap imports
Sandfish: Reduced survival of juveniles (seagrass habitat degradation)	• Reduce effort	• Target new species • Ranching • Habitat restoration • Monitoring	• Gaining access to offshore areas • Concerns over disease risk and genetic risk • Cost of restoring habitat/monitoring • Permits, applications, approvals, trials
Mud crab: Increased abundance (rainfall, riverflow, sea level rise, habitat changes)	• Increase effort	• Improve export market • Reduction in size limit (commercial)	• Cost of marketing • Political will • Regulation change
Mud crab: Increased catchability (SST)	• Increase effort	• Monitor to assess whether is an increase in abundance	• Ensure sustainable fishing

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
Black jewfish: Decreased abundance (rainfall, riverflow)	• Reduce effort, cap catch • Target other species (recreational)	• Target other species (commercial) • Shift to new areas (commercial) • Translocation of mature fish • Release of juveniles (hatchery reared)	• Costs associated with moving (fuel, lack of access and infrastructure) • Cost of translocation
Spanish mackerel: Decreased survival of larvae/juveniles (SST)	• Reduce effort	• Change Fisheries • Introduce catch limits • Introduce monitoring	• Cost of monitoring • Changing management
Grey mackerel: Decreased abundance (riverflow, rainfall, SST)	• Reduce effort • Target other species	• Target other species • Change gear types (issues longline catching large sharks)	• Public perception of taking more shark
All species: Higher inter-annual variability in catch rates of all species	• Diversify species and location	• Reduce operating costs, eg. Biofuels • Develop niche markets, eg. Promote local markets to reduce costs such as freight • 'Green' marketing	• Market barriers with taking advantage of 'good years' • Additional marketing costs • Local purchase value

Appendix 14.8.2. Potential adaptation options identified by ***recreational fishing*** stakeholders at the adaptation workshop held in Townsville. Stakeholder identified autonomous and planned adaptation options as well as potential barriers to each option. Causal climate factors of the potential impacts are given in parentheses.

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
Barramundi: Decreased abundance, growth and catchability (rainfall, riverflow, sea level rise, habitat changes)	• Change target species • Increase catch and release • Reduce harvest • Change fishing techniques while still targeting species	• Enhanced restocking rates • Remove barriers to habitats critical in their life cycle (habitat & connectivity restoration) • Improve infrastructure to access other areas where barramundi are caught • Better management of environmental flows from impoundments on rivers • Reduce commercial catch/effort • Restriction of access to currently fishable waters	• Government & public opposition to restocking • Fingerling availability • Genetic integrity of wild stocks • High costs and lack of expertise • Competition for water use • Industry and political opposition
Coral trout: Decreased abundance and catchability (SST, coral reef degradation, cyclones)	• Change target species • Reduce targeted effort	• Introduce artificial habitats	• Government & and green group opposition
Coral trout: Earlier timing of spawning in northern regions (SST)	•	• Change the current spawning closure months	•

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
Mud crab: Decreased abundance (rainfall, riverflow, sea level rise)	•	• Establish commercial aquaculture to reduce effort by recreational fishers on wild stocks • Reduce catch/effort (e.g. bag limits, pot limits) • Better management of environmental flows • Preserve mangrove habitats • Introduce closed areas/seasons	• Costs; cannibalism reducing grow-out survival • Political opposition • Cost; politics • Cost • Political opposition
Spanish mackerel: Earlier timing of spawning in the north (SST)	• Target Spanish mackerel earlier in the season	•	•
Spanish mackerel: Southerly range extension (SST)	• New fisheries in northern NSW	• New fisheries in northern NSW	•
Spanish mackerel: Decreased abundance (SST)	• Target alternative species	• Reduce catch (TAC, bag limits) • Introduce flexible management systems • Reduce effort (licenses) • Protect spawning stock (closed season)	• Political opposition • Political opposition • Political opposition • Political opposition

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
Grey mackerel: Decreased abundance (SST, rainfall, riverflow)	•	• Ban netting for grey mackerel • Make them a recreational only species • Make them a line-caught only species • Resource allocation among sectors	• Political opposition • Political opposition • Political opposition • Political opposition
King threadfin: Decreased abundance (rainfall, riverflow)	• Change target species • Increase catch and release • Reduce harvest • Change fishing techniques while still targeting species	• Better management of environmental flows from impoundments on rivers • Reduce commercial catch/effort • Restriction of access to currently fishable waters	• High costs and lack of expertise • Competition for water use • Industry and political opposition • Industry and political opposition
Golden snapper: Reduced spawning biomass (SST)	•	• Reduce commercial net effort (deep set gillnets in particular) • Recreational only species • Increase the minimum legal size	•
Tropical rock lobster: Reduced abundance and catchability in northern areas/Increased abundance in southern areas (SST, currents)	• Change target species	• Move southern commercial fishery boundary • Change the commercial TAC • Change recreational catch limits • Contained recreational access on the east coast & Torres Strait	• Bureaucratic processes

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
Banana prawns: Decreased abundance (rainfall, riverflow, sea level rise, SST)	• Less targeted effort	• Review restrictions on recreational limits	• Political sensitivity/resistance
Banana prawns: Increased abundance (rainfall, riverflow, sea level rise)	• Increase effort	• Review restrictions on recreational limits	• Political sensitivity/resistance
All species: Higher inter-annual variability in catch rates	• Change target species	• Educate to change values/behaviour based on status of stocks (e.g. release more to maintain larger more fecund fish) • Research to improve recruitment knowledge and predictions of strong year classes which may support increased harvest levels	• Cost and lack of government support • Cost
All species: Changes in the timing of spawning and/or recruitment	•	• Better protection of spawning fish by education and regulatory mechanisms	• Political resistance to regulatory intervention

Appendix 14.8.3. Potential adaptation options identified by ***commercial fishing*** stakeholders at the adaptation workshop held in Townsville. Stakeholder identified autonomous and planned adaptation options as well as potential barriers to each option. Causal climate factors of the potential impacts are given in parentheses.

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
Barramundi: Decreased abundance, growth and catchability (rainfall, riverflow, sea level rise, habitat changes)	• Retain other species • Move to alternate fishing areas	• Through improved marketing increase the value of barramundi and other species • Restocking	• Lack of knowledge of other areas • Additional costs to fishers • Logistical constraints • Hostility
Coral trout: Decreased abundance and catchability (SST, coral reef degradation, cyclones)	• Change fisheries (move into another fishery) • Stop fishing for trout • Target alternate species	• Rotational opening of green zones • Change to other fisheries (flexible licensing) • Improve the value of coral trout/other species (marketing)	• Already high value of coral trout
Coral trout: Earlier timing of spawning in northern regions (SST)	•	• Adjust timing of spawning closure • Possible further closures • Restocking • Resource allocation	• Legislative processes • Lack of information
Mud crab: Decreased abundance (rainfall, riverflow, sea level rise)	• Move to other areas • Change to other fisheries	• Develop a harvest strategy • Develop and implement a Code of Practice • Introduce a levy to support industry quota • Resource allocation	• Legislative processes

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
Mud crab: Increased catchability (SST)	• Catch more crabs • Increase effort	• Introduce fisheries dependent quota • Improve stock assessments • Introduce higher grading standards	• Over supply of product leading to lower prices
Spanish mackerel: Earlier timing of spawning in the north (SST)	• Adjust the timing of peak effort • Switch to targeting other species in the interim	• Resource allocation	• Conflict with other fisheries
Spanish mackerel: Southerly range extension (SST)	• Move fishing operations • Target other species	• Resource allocation	• Conflict with other fisheries
Spanish mackerel: Decreased abundance (SST)	• Reduce effort • Switch target species	• Introduce exit options for the commercial sector (licence buyout) • Apply appropriate quota • Resource allocation	• Lack of funding • Lack of data • Legislative processes
Grey mackerel: Decreased abundance (SST, rainfall, riverflow)	• Reduce effort • Switch target species	• Adapt fishing technology to be line caught species only • Switch targeting to other species • Shorten net shots • Implement a Code of Conduct • Improve product quality control	• Changing fisher behaviour and fishing operations • Lower catch rates • Funding • Legislative processes • Clashes with the recreational sector

Potential Impact	Autonomous adaptation	Potential adaptation actions	Potential barriers
King threadfin: Decreased abundance (rainfall, riverflow)	• Switch to target other species	• Use a smaller net mesh size • Reduce the recreational bag limit • Conduct research for strategies to increase abundance	• Need for specialist nets • Education • Lack of funding
Tiger prawns: Decreased abundance and catchability (seagrass, SST, rainfall)	•	• Bycatch reduction and improvement • Utilisation of bycatch • Marketing of permitted catch • Develop harvest strategies for optimisation of seasons and catch to maximise economic return	• Regulatory impediments • Fishers perception of extra competition by trawl • Lack of labelling requirements • Education of consumers
Eastern king prawns: Decreased abundance (SST, wind/currents)	•	• Bycatch reduction and improvement • Utilisation of bycatch • Marketing of permitted catch • Develop harvest strategies for optimisation of seasons and catch to maximise economic return	• Regulatory impediments • Fishers perception of extra competition by trawl • Lack of labelling requirements • Education of consumers
Banana prawns: Decreased abundance and catchability (rainfall, sea level rise, SST)	•	• Bycatch reduction and improvement • Utilisation of bycatch • Marketing of permitted catch • Develop harvest strategies for optimisation of seasons and catch to maximise economic	• Regulatory impediments • Fishers perception of extra competition by trawl • Lack of labelling requirements • Education of consumers

		return	

14.9 R code for Spanish mackerel CPUE standardisation

```
lme(log(Wgt)~as.factor(Finyear)+sin(2*pi*Moon)+cos(2*pi*Moon)+sin(4*pi*Moon)+cos(4*pi*Moon)+Grid,data=Catch,random=~1|Fisher,na.action=na.omit)
```

Wgt: Single day catch of *S. commerson* in kg (multi-day records were removed)
Finyear: Financial year (1st July in calendar year to 30th June in following calendar year)
Moon: Luminosity or lunar phase (calculated from 'phenology' package in R)
Grid: Catch reporting grid
Fisher: Unique vessel ID

14.10 Spanish mackerel age-length key generated age structure

Population age structure of *S. commerson* from four regions off northeastern Australia, 2001- 2011, showing numbers of fish, *N*, sampled of age, *x*. For each year of sampling, *i,* the Studentized residuals from a linear regression of log(N_i) = $a+bx_i$ were used to provide replicate estimates of relative abundance in the year, *i* - *x*. Only fish aged 2-11 were included in the analysis since 0-1 year old fish were not fully recruited the fishing gear, and fish > 11 years (excluded below) were relatively rare.

Region	Age	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Region	2004	2005	2006	2007	2008	2009	2010	2011
Townsville	0								5	1	2		Mackay					1	2		
	1	50	48	1	42	161	34	46	436	143	86	104		10		35	1	61	121	63	40
	2	66	1098	528	473	485	164	296	548	698	749	1084		81	37	69	25	84	431	431	217
	3	197	249	298	422	345	350	178	312	129	593	812		76	62	156	10	37	55	213	130
	4	748	228	42	274	252	189	288	215	90	144	596		23	21	71	4	37	26	40	68
	5	74	405	48	44	116	125	107	223	38	107	128		3	12	37		39	11	19	15
	6	68	36	161	41	35	70	81	119	63	47	106		3	3	16		22	9	19	13
	7	154	100	56	60	19	11	26	116	39	68	49		4		2		12	8	11	6
	8			50	18	29	28	8	65	27	34	54			2	2		9	4	6	7
	9	9		17	16	18	24	7	5	14	26	35				2		1	2	2	3
	10			8	11	17	8	8	7	12	10	15						1		4	1
	11					15	21	3	7	1		5				1		3		1	2
Rockhampton	0								2				South					3			
	1				60	75	49	31	70	32	40	23		20	4	18	11	320	203	58	32
	2			16	327	375	34	92	29	159	82	162		83	30	37	58	225	998	271	199
	3			17	212	159	65	64	46	14	69	113		71	29	83	92	111	168	255	215
	4			4	102	162	53	78	39	37	14	96		27	20	55	182	46	145	51	241
	5			1	22	72	47	39	37	12	22	27		3	6	44	95	43	51	45	50
	6			11	23	20	17	48	16	24	5	24		6	2	21	83	14	66	25	46
	7			5	25	15	2	15	23	14	24	20		3	1	1	27	20	27	51	28
	8			5	15	21	2	5	16	15	14	19			1	4	12	6	31	34	25
	9			3	7	17	7	1	4	4	12	22		1		7	10	2	6	21	34
	10			1	3	14	4	9	1	1	7	8		2	2	2	16		5	13	21
	11				3	11	13	3	4	2	3	7				3	9	1	2	3	7